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16. Abstract

This synthesis documents the results of a comprehensive review of worldwide information dealing with the following issues as related to warm-mix asphalt (WMA) technology:

- current state of the art/practice of WMA,
- benefits and costs of WMA technology
- plant modifications to accommodate certain WMA processes,
- mixture design and analysis,
- pavement structural design,
- durability and performance,
- performance-related testing,
- quality control,
- specifications, and
- construction guidelines.

A summary of findings and recommendations is provided. Also included in this synthesis is a complete documentation of the first warm-mix asphalt field trial conducted by the Texas Department of Transportation.

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# A SYNTHESIS OF WARM-MIX ASPHALT

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# A SYNTHESIS OF WARM-MIX ASPHALT

"There is one thing stronger than all the armies in the world,
and that is an idea whose time has come."
- Victor Hugo -

## INTRODUCTION

### Background

According to Dorchies et al. (2005), the United Nations conference on the environment and sustainable development that was held in Rio de Janeiro in 1992 marked the beginning of universal awareness of the risks of damage facing this planet. The destruction of natural resources and climate change are the main causes of damage and disruption of ecosystems. Industry, agriculture, and transport are blamed for being the main contributors. This awareness was formalized in 1997 by the Kyoto Protocol to the United Nations Framework Convention on Climate Change which featured, in particular, a commitment made by signatory states to bring greenhouse gas emission rates down to 1990 levels. This agreement came into force on February 13, 2005. Warm-mix asphalt technology addresses this issue in a rather small but important way.

Hot-mix asphalt (HMA) is typically produced in either batch or drum mix plants at a discharge temperature ranging from 280°F to 325°F. It has been necessary to use these elevated temperatures to dry the aggregates, coat them with the asphalt binder, achieve the desired workability, and provide sufficient time to compact the HMA mat. Researchers have been trying to reduce the mixing/compaction temperature of HMA since the 1970s (Zettler 2006) by utilizing the moisture in the aggregate, foaming the binder, and, of course, using emulsified asphalts. Reducing the HMA production temperature and the placement temperature could bring several economical, environmental, and even performance benefits. Certain members of the asphalt industry are studying technology for reducing production temperatures by 50°F or more within the next decade. One category of current promising products is termed warm-mix asphalt (WMA). Although WMA is in its infancy, the technology and its potential benefits are stirring significant interest in Europe (Els, 2004), North America, and other countries interested in economical, environmentally friendly paving materials. Without question, the need for an environmentally friendly and economically attractive asphalt paving material is here, the product is here…the time has come.

Reducing production (mixing) and paving (compaction) temperatures by using WMA in place of HMA will yield beneficial environmental effects:

- decreased fuel or energy consumption (with consequential decreased cost);
- reduced emissions and odors from plants;
- reduced smoke and, thus, consternation from the public; and
- improved working conditions at the paving site.

These benefits will improve public perception of the asphalt paving process and vividly elucidate efforts by TxDOT and the industry to promote innovation and raise the standards.

Technologies that allow lower HMA production temperatures may demonstrate positive impacts on pavement performance. Because the technologies improve the workability of the mix, they should reduce (or, at least, certainly not increase) compaction energy requirements and, thus, enhance in-place density (Hurley and Prowell, 2006). Enhanced compaction is, of course, a key parameter regarding performance. Further, the majority of aging of asphalt binder in HMA occurs in the plant when exposed to elevated temperatures. Lower mixing temperature will reduce oxidative hardening, which should reduce susceptibility to cracking by improving pavement flexibility and longevity.

Today's versions of WMA are the brainchild resulting from the 1997 German Bitumen Forum (Zettler, 2006). In fact, the Europeans are already using technologies to lower mixing/placement temperatures, and the results have been very promising (Barthel and Von Devivere, 2003). In the U.S., these technologies are being tried in an attempt to realize these potential benefits (Kuennen, 2004a). WMA technology has been successfully demonstrated for standard dense-graded mixtures as well as stone mastic asphalt (SMA) and offers potential for essentially any mix from interstates to parking lots (Zettler, 2006).

Newcomb (2006) indicated that WMA is distinguished from other asphalt mixtures by the temperature regimes at which they are produced and the strength and durability of the final product. He holds that cold asphalt mixtures are manufactured at ambient temperatures (e.g., 68°F to 120°F), while HMA is typically produced in the range of 285°F to 340°F. Warm mixes are those generally produced in the temperature range of 200°F to 275°F. HMA has higher stability and durability than cold-mix asphalt, which is why cold mix is used in the lower pavement layers of low-volume roadways. The goal with warm mix is to obtain a level of strength and durability that is equivalent to HMA.

There are far-reaching implications for WMA technology. Information available from manufacturers and materials suppliers indicates that, compared to standard HMA, reductions of about 30 percent in energy consumption (Asphalt Pavement Association of Oregon [APAO], 2003; Stroup-Gardiner and Lange, 2002) and $CO_2$ emissions are possible. According to Hampton (2005), 30 percent to 50 percent of an HMA producer's overhead cost can be attributed to emissions control; thus by reducing $CO_2$, significant cost reductions are possible. For WMA, the harmful fumes in the vicinity of workers are often below the detection limits, and there is a 50 to 60 percent decrease in dust generation.

The ability to improve the environmental friendliness of asphalt paving creates opportunities to expand production. For instance, by lowering the paving and compaction temperature, the ability to perform late/early-season paving is enhanced, thus extending the paving season. Because the mix starts at a lower temperature, it does not cool as rapidly, allowing longer haul distances and/or time periods to compact the mat. Other benefits include paving in ozone nonattainment areas and/or more plant operation during daylight hours in these regions.

**A Brief History Leading to Current WMA Technologies**

Using lower temperatures to produce asphalt paving mixes is not a new concept. In 1956, Prof. Ladis Csanyi, Iowa State University, realized the potential of foamed bitumen for use as a soil binder. Since then, foamed asphalt technology, which allows lower mixing temperatures, has been used successfully in many countries. The original process consisted of injecting steam into hot bitumen. In 1968, Mobil Oil Australia, which had acquired the patent rights for Csanyi's invention, modified the original process by adding cold water rather than steam into the hot bitumen. The bitumen foaming process then became more practical (Kristjansdottir, 2006; Muthen, 1998). Conoco was later licensed to market foamed asphalt in the U.S. and further advanced the technology and evaluated the product as a base stabilizer both in the laboratory and in the field (Ruckel et al., 1980; Little et al., 1983).

In the early 1970s, Chevron developed mixture design and thickness design methodologies for paving mixtures (base, open-graded, and dense-graded) stabilized with emulsified asphalt. In 1977, Chevron published their "Bitumuls Mix Manual" (Chevron, 1977) as a practical guideline, which contains much valuable information for specifying, designing, and producing emulsion-stabilized mixtures. Later, other similar guidelines followed (FHWA, 1979; Asphalt Emulsion Manufacturers Association [AEMA], 1981). Kuennen (2004b) reported that emulsified asphalt mixes are popular in rural settings where distances from HMA plants and lower traffic volumes may preclude HMA. Further, cold-mix plants have a lower initial cost than conventional HMA plants, are more easily transported, and may be situated anywhere without Environmental Protection Agency (EPA) permits due to their lack of emissions. Furthermore, they are amenable to mixes with high percentages of reclaimed asphalt pavement.

In 1994, Maccarone et al. (1994) studied cold-mixed asphalt-based foamed bitumen and very high binder content emulsions and concluded that the use of cold mixes for use on roads was gaining acceptance worldwide due to energy efficiency and lower emissions. In fact, they stated that, "Cold technologies represent the future in road *surfacing*."

In 1995, Shell Bitumen filed a patent to cover a warm-mix asphalt technique that used a two-component technique (Harrison and Christodulaki, 2000). Koenders et al. (2000), of Shell Global Solutions, described an innovative WMA process that was tested in the laboratory and evaluated in large-scale field trials (in Norway, the United Kingdom, and the Netherlands) with particular reference to the production and placement of dense-graded wearing courses. Shell's work resulted in the development of WAM-Foam®.

In 1997, Sasobit® began to be marketed in Europe as an asphalt mixture compaction aid by Sasol Wax International AG (http://www.sasolwax.com/Applications.html). The technology later grew into the WMA process.

Jenkins et al. (1999) introduced a new process involving a half-warm foamed bitumen treatment. They explored the concepts and possible benefits of heating a wide variety of aggregates to temperatures above ambient but below 212°F before the application of foamed bitumen. Preheating aggregates enhanced particle coating, mix cohesion, tensile strength, and compaction. This is particularly beneficial for mixes containing reclaimed asphalt pavement (RAP) or densely graded crushed aggregates.

Probably due to their relatively higher prices of fossil fuels and asphalt, Europe (Koenders et al., 2000), South Africa (Jenkins et al., 1999; Jenkins et al., 2002), and Australian Asphalt Pavement Association (AAPA, 2001) began early to examine the benefits and performance of WMA.

Cold/warm asphalt mixes occupy certain market areas in the paving industry, but to date, they have had no significant impact on HMA as the primary road surfacing material…but the potential for significant impact is now in view. Although WMAs have been used in the U.S. for less than 3 years, they are being evaluated at a rapidly increasing rate (Zettler, 2006). For example, WMA paving projects in North America have been or are being constructed in Alabama, Florida, Indiana, Kansas, Maryland, Missouri, Ohio, Vermont, North Carolina, New York, Tennessee, Texas (San Antonio), Wisconsin, Ontario, Alberta, and Washington, D.C. Additionally, several municipalities have conducted tests of WMA. Most, if not all of these tests, involve overlays on existing pavements.

Most of the work on WMA has involved dense-graded mixtures; however, Koenders et al., 2000, stated that, in principle, WMA technology is equally applicable to other types of asphalt mixtures (e.g., open-graded, gap-graded, and stone mastic asphalts). He further stated that use can be made of conventional asphalt mixing plants as well as traditional paving equipment and techniques.

## EXAMPLES OF SPECIFIC WMA TECHNOLOGIES

The three most widely used technologies in Europe for producing WMA (Aspha-Min®, WAM-Foam®, and Low-Energy Asphalt®) are all proprietary processes and are described below. A fourth proprietary product (Sasobit®) was developed in South Africa. A fifth non-proprietary product (Evotherm®) was developed by in the U.S. Another potential product, currently with little research, is Asphaltan B®. All six technologies allow the production of WMA by reducing the viscosity and/or expanding the volume of the asphalt binder at a given temperature. These technologies allow the aggregates to be fully coated at temperatures significantly lower than those traditionally required in HMA production. However, some of these technologies require significant equipment modifications at the asphalt mixing plant. Brief descriptions of these products are given below based on National Center for Asphalt Technology (NCAT), 2005; Hurley and Prowell, 2005a; Hurley and Prowell, 2005b; Corrigan, 2006; and others indicated.

These WMA technologies are being continuously refined and improved (Els, 2004), and other WMA technologies are being developed and are appearing on the market. For example, WMA technology has recently been applied for patching open-graded asphalt pavements (Soto and Blanco, 2004a) and for recycling flexible pavements (Soto and Blanco, 2004b). The need for WMA to replace certain HMA projects has never been greater, and the concept is sensible. The authors expect increased interest and use of the products and processes worldwide and that, ultimately, WMA will become a standard product for routine paving in specific situations.

The following subsections describe all known WMA products and/or processes.

**Aspha-Min**

Aspha-Min is supplied by Eurovia Services GmbH, Bottrop in Germany (http://www.aspha-min.com). It is a finely powdered synthetic zeolite (sodium aluminum silicate hydrate) that has been hydro-thermally crystallized. When Aspha-min® is added to the mix at the same time as the binder, water is released. This water release creates a foaming of the asphalt binder and, thereby, temporarily increases workability and enhances aggregate coating at lower temperatures.

Aspha-Min is typically added at 0.3 percent by total weight of HMA mix. When it is heated above 185°F to 360°F, it gives up 21 percent water by mass, which microscopically foams the asphalt to aid coating of the aggregate. This foaming action of the liquid binder acts as a temporary asphalt volume extender and mixture lubricant, enabling the aggregate particles to be rapidly coated and the mix to be workable and compactable at temperatures significantly lower than those typically used for HMA. Barthel (2004) said it is important that the additive particles are losing their water in several steps and not all at once. He further stated that the mix can be compacted until the temperature drops below 212°F.

In their promotional material, Eurovia indicates that Aspha-Min can yield a reduction in mixing temperature of more than 50°F, save 30 percent energy, and accommodate all commonly used asphalt and polymer-modified binders as well as the addition of RAP. Aspha-Min is available in a very fine white powdered form in 50-pound or 100-lb bags or in bulk for silos (Kuennen, 2004b). Currently, the process requires a specially built distributor to meter the Aspha-Min into the asphalt mixing plant. In a batch plant, it is introduced directly into the pugmill; in a drum mix plant, it is pneumatically fed into the drum via the RAP collar (Barthel and Von Devivere, 2003).

Corrigan (2006) indicated that zeolites are framework silicates that have large vacant spaces in their structures that allow space for large cations such as sodium, potassium, barium, and calcium and even relatively large molecules and cation groups such as water. In the more useful zeolites, the spaces are interconnected and form long, wide channels of varying sizes depending on the mineral. These channels allow the easy movement of the resident ions and molecules into and out of the zeolite structure. Zeolites are most used in water softeners. Zeolites are characterized by their ability to lose and absorb water without damage to their crystalline structures. They can have the water in their structures driven off by heat and other solutions pushed through the structure. They can then act as a delivery system for the new fluid.

**Sasobit**

Sasobit is a product of Sasol Wax (formerly Schumann Sasol) of South Africa. Sasobit is a Fischer-Tropsch (F-T) or synthetic wax that is created in the coal gasification process (http://www.sasolwax.com/www_sasobit_de.html). These organic waxes have longer chemical chain lengths and are different from petroleum or paraffin waxes (which are normally considered undesirable in asphalt) (Damm et al., 2002). The longer chains help keep the wax in solution, and it reduces binder viscosity at typical asphalt production and compaction temperatures. Sasobit has been used as a compaction aid and a temperature reducer. The Sasobit process incorporates a low melting point organic additive that chemically changes the temperature-viscosity curve of the binder. Both of these additives melt at about 210°F and produce a reduction in the binder viscosity by providing liquids in the binder above their melting points.

Blending 3 to 4 percent Sasobit by weight allows a reduction in production temperatures of 18°F to 54°F. The manufacturer anticipates that in-line blending of melted Sasobit with the asphalt binder stream at the plant will be finalized in the near future, thus eliminating the current use of the Sasobit distributor at the plant. Direct blending of solid Sasobit at the plant is not recommended because it will not give a homogeneous distribution of Sasobit in the asphalt. Further, Sasobit allows incorporation of Styrene Butadiene Styrene (SBS) modifier using a special cross-linking agent termed Sasoflex. Either Sasobit or Sasoflex can be blended into hot binder at the blending plant without the need for high-shear blending. Sasobit can negatively impact low-temperature mix properties (Hurley and Prowell, 2005b).

Corrigan (2006) explained that during coal gasification, the F-T process converts carbon monoxide and hydrogen into a mixture of hydrocarbons having molecular chain lengths of 1 to

100 carbon atoms and greater. The process is important in the preparation of hydrogen and as a fuel in the making of steel and in other industrial processes. The synthesis gas is reacted exothermally in the presence of an iron or cobalt catalyst, and products such as methane, synthetic gasoline, waxes, and alcohols are made.

Sasol emphasizes the difference between naturally occurring bituminous waxes and F-T waxes in terms of their structure and physical properties. The main difference is the much longer chain lengths and the fine crystalline structure of the F-T waxes. The predominant chain lengths of the hydrocarbons in Sasobit range from 40 to 115 carbon atoms; whereas, those in bituminous paraffin waxes range from about 25 to 50 carbon atoms (Butz et al., 2001), yielding lower melting points than F-T waxes. The longer carbon chains in the F-T wax yield a higher melting point. However, the smaller crystalline structure of the F-T wax, as compared to bitumen paraffin waxes, reduces the brittleness at low pavement service temperatures. Edwards et al. (2006) found that adding F-T paraffin decreased the physical hardening index for all bitumens tested.

Sasol states that the melting point of Sasobit is approximately 210°F and that it is completely soluble in asphalt at temperatures above 248°F. It reduces the binder viscosity and, thus, reportedly enables mix production temperatures to be reduced by 18°F to 54°F and improves compactability. At temperatures below its melting point, Sasobit forms a lattice structure in the asphalt binder that is the basis for the reported stability of asphalts that contain Sasobit. At service temperatures, Sasobit-modified mixes exhibit increased resistance to rutting.

Since 1997, more than 142 projects have been paved using Sasobit, which total more than 2.7 million square yards of pavement (Hurley and Prowell, 2005b). Projects were constructed in Austria, Belgium, China, Czech Republic, Denmark, France, Germany, Hungary, Italy, Macau, Malaysia, The Netherlands, New Zealand, Norway, Russia, Slovenia, South Africa, Sweden, Switzerland, the United Kingdom, and the United States. A wide range of aggregate types and mix types were included (e.g., dense-graded mixes, stone mastic asphalt, and Gussaphalt). Sasobit addition rates ranged from 0.8 to 4 percent by mass of binder.

**Evotherm**

Evotherm was developed in the U.S. by MeadWestvaco Asphalt Innovations, Charleston, South Carolina (http://www.evotherm.com). Evotherm uses a non-proprietary technology that is based on a chemical package that includes cationic emulsification agents; additives to improve aggregate coating, mixture workability, and compaction as well as adhesion promoters (anti-stripping agents). MeadWestvaco states that they can deliver an emulsion with a unique chemistry customized for aggregate compatibility. Evotherm utilizes a high-residue emulsion (approximately 70 percent binder) that improves adhesion of the asphalt to the aggregate. The product enhances mixture workability, while lowering mixing temperatures to as low as 200°F. Some steam is normally liberated upon mixing. No plant modifications are required, the mix can be stored in silos, and Evotherm may be utilized with or without polymer modifier.

According to Takamura (2005), thin water film between the aggregate and asphalt droplets improves workability of the mix even at temperatures below 195°F. The thin water film exerts up to 10 MPa of capillary pressure to promote quick coalescence of the asphalt droplets as it cures after compaction. He maintains that the cationic emulsifiers in the Evotherm emulsion adsorb onto the aggregate surface with their positively charged head groups and expose their hydrocarbon tails outward. This makes the aggregate surface oil-wet to promote strong asphalt adhesion for moisture resistance.

Unlike traditional asphalt binders, Evotherm is stored at about 180°F. Temperatures of oil-jacketed lines should be reduced to about 200°F prior to pumping the Evotherm to prevent the emulsion from breaking in the lines (Hurley and Prowell, 2006b).

During production, the Evotherm emulsion is simply used in place of the traditional asphalt binder. The emulsion is mixed with the aggregate in the HMA plant. Water in the emulsion is liberated in the form of steam when it is mixed with the hot aggregate. The resulting WMA has the appearance of HMA. MeadWestvaco reports that field testing has demonstrated a 100°F reduction in production temperatures and that the decreased production temperatures can lead to plant energy savings of 55 percent, which results in a 45 percent reduction in $CO_2$ and $SO_2$ emissions, a 60 percent reduction in $NO_x$, a 41 percent reduction in total organic material, and benzene soluble fractions below detectable limits.

At this writing, Evotherm has been successfully used on two projects in San Antonio, Texas, and several other projects in the U.S.

**WAM-Foam**

WAM-Foam is a product of a joint venture between Shell International Petroleum Company Ltd., London, United Kingdom, and Kolo-Veidekke, Olso, Norway (http://www.wamfoam.com) (Larsen et al., 2004). It is a two-component binder system that introduces a soft binder and a hard-foamed binder at different times in the mixing cycle during production. The extremely soft binder component is mixed with the aggregate in the first stage (210°F to 250°F) to fully coat the aggregate. In the second stage of production, an extremely hard binder component is then foamed into the pre-coated aggregate mixture. The harder binder is infused with a small quantity of cold water to induce foaming and enhance coating capabilities. This combination of soft binder and foaming of the hard binder acts to lower the mass viscosity of the mixture to provide the necessary workability, allowing the mixture to be placed and compacted at 175°F to 195°F.

In a batch plant, 1 to 5 percent water is injected into the hot bitumen pipe using a special nozzle system just before the bitumen enters the pugmill to induce foaming. To minimize clogging, an air gun is then used to blow the foaming chamber and pipes clean after each foam injection (Kristjansdottir, 2006; Koenders et al., 2002). In their field trials in Norway, the dryer was operated at about 250°F to 265°F with no problems regarding burner instabilities or the dust collection system. At the lower temperatures, less dust is generated so there is lower loading of the filter system.

Larsen et al. (2004) reports that, in a drum mixing plant, the foam can be produced continuously, which offers some operational advantages. That is, insulation of pipes and periodic cleaning is not necessary to the same degree as for the discontinuous process of the pugmill.

Shell (Jenkins et al., 1999; Jenkins et al., 2002; Koenders et al., 2000) indicates that a successful WAM-Foam product depends on careful selection of the soft and hard components. They sometimes recommend addition of an adhesion improver in the first mixing stage. A vital element in the first mixing stage is to prevent water from reaching the binder/aggregate interface and entering the aggregate; finally, the water must be expelled from the asphalt mix to ensure a high-quality end product. Shell reports that the decreased production temperatures of the WAM-Foam process can lead to plant fuel savings of 30 percent, which, consequently, yields a

30 percent reduction in $CO_2$ emissions. Independent testing has confirmed Shell's earlier findings (Larsen et al., 2004).

When RAP was used at levels from 15 to 25 percent in production of a wearing course in a drum mix plant, the amount of water coming from the RAP was about three times higher than the amount coming from the foam. Therefore, the temperature of the dryer was raised a little to accommodate the extra drying necessary. However, this would have also been necessary for HMA production (Larsen et al., 2004).

WAM-Foam requires plant modification to accommodate foaming, which is estimated to cost $50,000 to $70,000.

**Low-Energy Asphalt**

Low-Energy Asphalt (LEA) was developed by Fairco of Zozay, France (Romier et al., 2004; Romier et al., 2006). It is known in France as EBE (enrobage a basse energie). Because the LEA process differs substantially from typical HMA and WMA processes, Figures 1 and 2 are included to illustrate the process. The process mixes hot asphalt cement (280°F to 350°F) with hot coarse aggregates (about 290°F) and then incorporates wet fine aggregates at ambient temperature. The moisture in the fine aggregates in combination with heat and certain additives causes the asphalt binder to foam, thus increasing its volume/surface area many-fold, such that it can rapidly coat the aggregates. It is well known that foamed asphalt favors coating the fine aggregates, which is desirable at this point since the coarse aggregates are already coated. The final temperature of the mixture should ideally be below 212°F (140°F to 180°F). This temperature (212°F) is critical, below which significant energy savings can be realized and above which they cannot (Romier et al., 2006).

Romier et al. (2006) indicated that the LEA process is reaching the industrial stage. They have developed a LEA production kit that attaches to a batch plant. The kit includes a specific hopper that allows the metering of the amount of cold sand to be introduced into the mixer via a storage bin located over it. Also included is a device for adding water to the sand, if necessary. An asphalt binder metering device incorporates a surfactant addition system. The mixing phase of the process has been modified to implement the LEA sequential mixing of hot aggregate followed by wet sand and bitumen and finally cold filler. This kit also provides for introduction of RAP directly into the mixer.

The originality of the process lies in the best use of changes in the condition of the bitumen, fluid when it is hot and the ability to transform into foam or emulsion when in contact with water (Romier et al., 2006). It involves moderate heating of only the coarse aggregates, the rest of the aggregate skeleton being used at ambient temperature and wet. They reported that this technique yields significant savings in mixing energy while reducing the gas emissions. Interestingly, they also reported reduced soiling of production equipment (probably due to the presence of moisture), thus decreasing cleaning requirements and corresponding use of solvents.

According to the developer, these mixtures offer performance equivalent to that of HMA. Minor plant modifications are required to accommodate this product. This process originated in France (Romier et al., 2004). As of January 2006, 6000 metric tons had been placed in France. It was tested in The Netherlands using a mix containing RAP in December 2005. This process has not been used in the U.S. After additional laboratory and field evaluations, Gaudefroy et al. (2007) still hold that this is a viable WMA process.

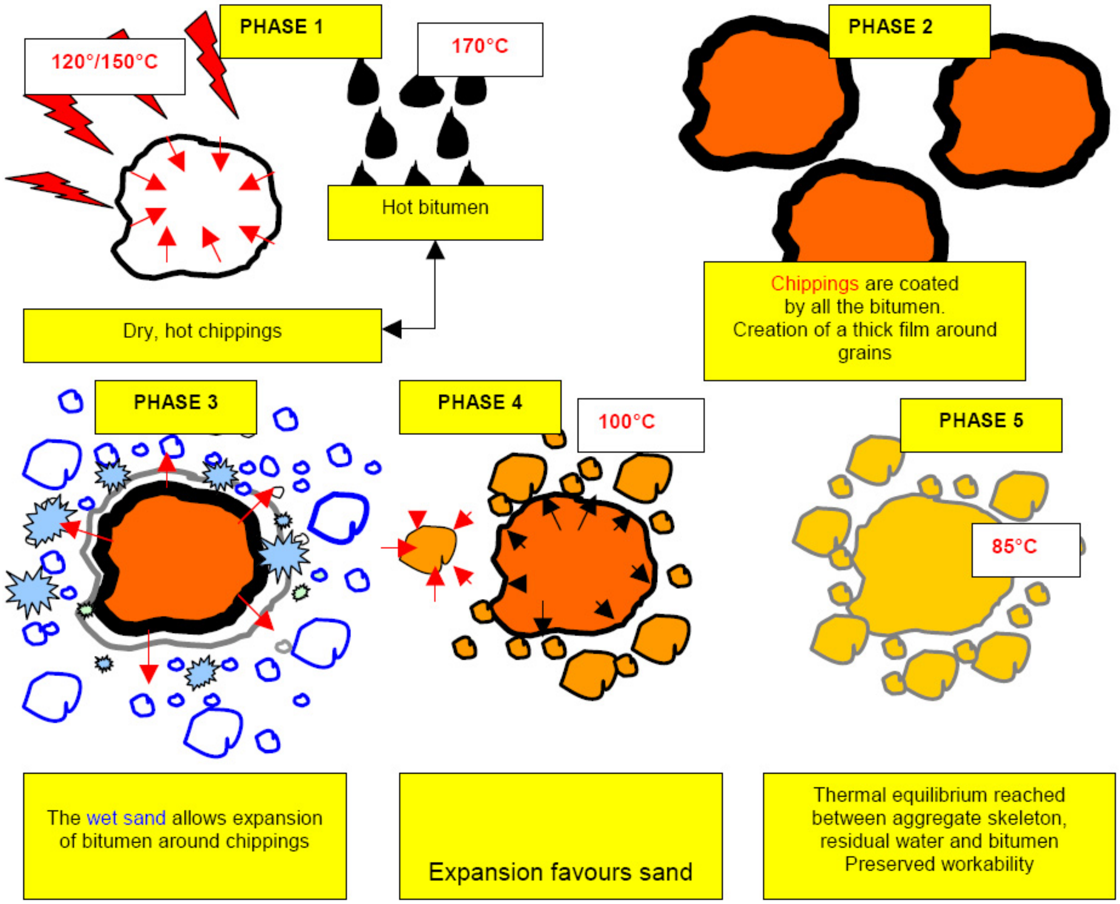


**Figure 1. Functional Diagram Low-Energy Asphalt Technique (after Romier et al., 2006).**

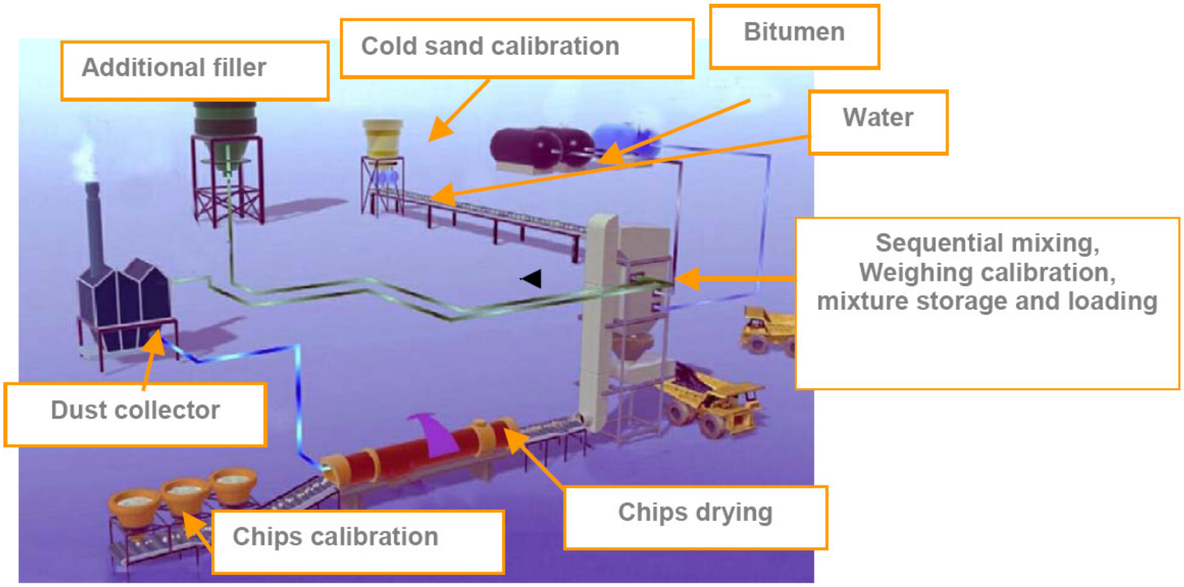


**Figure 2. Batch-Plant Equipped for Low-Energy Asphalt Processing (after Romier et al., 2006).**

**Asphaltan B**

Asphaltan B (Corrigan, 2006; Kristjansdottir, 2006) is a product of Romonta GmbH, Amsdorf, Germany. Asphaltan B is a mixture of substances based on montan wax constituents and higher molecular weight hydrocarbons. According to Corrigan (2006), it was created specifically for hot-rolled asphalt (a fine-grained HMA for pavement surfacing).

Crude montan wax is found in Germany, Eastern Europe, and areas of the U.S. in certain types of lignite coal deposits that have formed over geologic time by the transformation of fossilized vegetation. Apparently, wax, which once protected the plant leaves from extremes of climate, did not decompose, but instead enriched the coal. Due to its high stability and insolubility in water, the wax survived over long time periods. After mining, the montan wax is extracted from the coal by means of a toluene solvent that is distilled from the wax solution and removed with super-heated steam. Romonta GmbH has a global market share of 80 percent in the crude mined wax products sector.

Romonta recommends adding Asphaltan B to asphalt at 2 to 4 percent by weight. It can be added at the asphalt mixing plant or by the binder producer. It can be added to polymer-modified binders. The melting point of Asphaltan B is approximately 210°F. Similar to F-T waxes, it acts to improve asphalt flow at reduced temperatures. Romonta does not specify how much the production temperature can be lowered. Like F-T waxes, Romonta reports increased compactability, resistance to rutting, and moisture resistance of asphalt mixtures (http://www.romonta.de/ie4/english/romonta/i_wachse.htm). Work by Edwards et al. (2006) supports findings reported by Romonta. Asphaltan B is available in granular form in 25 kg bags. Little research has been performed with this product in asphalt.

**General Comments on Waxes**

According to Edwards et al. (2006), natural wax in straight run bitumen today is low in content and of a type that should not be particularly harmful for binder or asphalt concrete properties. However, wax can unintentionally be produced through refining procedures like visbreaking or hydrocracking and, thus, affect asphalt binder properties. The most feared influence of wax in bitumen is the sudden decrease in viscosity due to the melting of crystallized wax, particularly, if this should occur within a temperature range affecting the resistance to permanent deformation of the asphalt pavement.

She further reports that commercial wax, such as F-T paraffin and montan wax, is sometimes added to bitumen or asphalt concrete mixtures in order to obtain certain positive effects. These products, typically called "flow improvers," are mainly used for reducing the asphalt mixing temperature in order to reduce energy consumption and emissions and to improve workability. However, other effects of different kinds may result from such wax modification.

The magnitude and type of the effect on bitumen rheology depend on the properties of bitumen as well as type and amount of additive (Edwards and Redelius, 2002). That is, bitumen composition is of significant importance. Additionally, incorporation of commercial waxes (i.e., F-T paraffin, montan wax, and polyethylene wax) showed no or marginally positive influence on aging properties for the asphalts and test conditions used by Edwards (2006). Edwards and Redelius (2002) demonstrated that the effects due to wax content shown in dynamic mechanical analyzer temperature sweeps (for HMA mixes) are related to the corresponding effects shown in differential scanning calorimetry thermograms (for asphalt binders).

In the case of blown bitumens and/or wax-modified bitumens in road construction, which are frequently used in the U.S. and Canada in order to meet standard binder specifications, the effects on asphalt concrete properties may vary considerably (Hesp, 2004). In practice, commercial wax, like F-T paraffin or montan wax, is added to bitumen in order to achieve certain preferred properties, such as reduced asphalt mixing temperature and higher stiffness of the pavement layer.

## MIXTURE DESIGN OF WARM-MIX ASPHALT

An important issue regarding WMA is mixture design. One of the main issues is to determine if mixture design for WMA can be performed exactly like HMA. Based on findings published in current literature and discussions with WMA researchers, standard mix design procedures for HMA must be modified to accommodate WMA. The next section discusses specific elements in the mixture design process.

### Binder Grade Selection

Romier et al. (2006) stated that LEA mixes use the same asphalt grades in the same proportions as HMA; this is generally true for other WMA products. However, there is limited evidence that, with certain WMA processes, it may be possible or even advisable to use one grade harder asphalt than that normally used with HMA (Newcomb, 2006). For example, Hurley and Prowell (2005a, 2005b) observed that Sasobit and Aspha-Min mixtures (two mixtures each made using granite and limestone), containing PG 64-22 binder and mixed/compacted at temperatures significantly lower than that of the corresponding control HMA mixtures which contained PG 58-28, had nearly the same air void level. This suggests that the lubricating action of Sasobit and Aspha-Min processes lowered the mixing and compaction temperature by approximately one asphalt grade. They recommended bumping one grade to counteract any tendency for increased rutting. Additional research is needed to verify this finding. One should not arbitrarily use an asphalt in WMA that is one grade higher than that typically used in HMA.

### Selection of Optimum Binder Content

To date, NCAT has probably performed most of the WMA research in the U.S. In their laboratory studies, they used modified Superpave mixture design procedures including 125 gyrations of the Superpave gyratory compactor and standard HMA mixing and compacting temperatures (Hurley and Prowell, 2006a). Until more research is completed, NCAT recommended determining the optimum asphalt content (OAC) without inclusion of the warm-mix additive using standard HMA design procedures. This is because the WMA additives enhance compaction so effectively that the OAC is reduced by about one-half a percentage point below that of an equivalent HMA. This brought about concerns regarding durability, permeability, and water susceptibility of the resulting paving mixture.

When describing the LEA method, Romier et al. (2006) state that laboratory mix design methods for HMA apply to design of WMA paving mixtures. However, they further advise that laboratory procedures (mixing and compaction) must be adjusted to the temperature of the mixes resulting from the plant mixing process.

Newcomb (2006) suggests that, if any modifications to the Superpave mixture technology are required for designing WMA, research will be needed to establish them.

**Aggregate Gradation**

It appears that most of those marketing WMA technologies and most highway agencies worldwide, who have evaluated any of the WMA technologies in the laboratory and in the field, have used conventional dense-graded mixtures identical to those they typically use in HMA (Hurley and Prowell, 2005a; Hurley and Prowell, 2005b; Kuennen, 2004a; Romier et al., 2006). This is true even for asphalt mixtures produced at ambient temperature using foamed or emulsified asphalt (Maccarone et al., 1994). There currently appears to be no reason to alter the gradation of typical dense-graded HMA mixes to accommodate WMA mixes.

Koenders et al. (2000) and Romier et al. (2006) pointed out that WMA processes should be equally applicable to typical types of asphalt mixtures other than dense-graded mixes (i.e., SMA, open-graded, stone-filled, coarse-base mixtures). Personal communication with Mr. Larry Michaels (2007) indicates that he agrees with this assessment. Kristjansdottir (2006) reported that Sasobit has not only been used for dense-graded mixtures in Germany but also in SMA and gussasphalt.

Several WMA processes (e.g., WAM-Foam, LEA) have demonstrated success in mixtures containing RAP (Romier et al., 2006; Jenkins et al., 1999).

**Specimen Compaction**

As with HMA, laboratory compaction of WMA must simulate the density that will ultimately be achieved in the field. Standard HMA laboratory compaction procedures (i.e., 125 gyrations of the Superpave gyratory compactor) have proven to be acceptable for WMA mixtures (Hurley and Prowell, 2005a, 2005b, 2006a, 2006b). However, it currently appears that the compaction temperature must be reduced to simulate plant production temperatures.

Hurley and Prowell (2006a) demonstrated clearly that Aspha-Min, Sasobit, and Evotherm significantly lowered the required compaction temperature to achieve essentially equivalent air voids as an HMA mixture using the same aggregate type and gradation. They pointed out that earlier work (Bahia and Hanson, 2000; Huner and Brown, 2001) indicated that the Superpave gyratory compactor was rather insensitive to compaction temperature. Their work provided further verification of this finding (Tables 1 and 2). Incidentally, they also pointed out that the Marshall hammer had been found to be quite sensitive to compaction temperature.

**Specimen Cure Time before Testing**

For testing HMA in the laboratory, there are essentially no cure time requirements for compacted specimens. They are often tested as soon as they reach the specified test temperature. This is probably acceptable for those WMA products that do not depend on moisture to enhance workability and compaction (e.g., Sasobit and Asphaltan B). However, for those products that incorporate moisture to promote aggregate coating, workability, and compaction (e.g., Evotherm, Aspha-Min, and WAM-Foam), some cure time may be needed to expel the moisture and yield realistic predictions of performance. If this moisture is not expelled, laboratory tests to evaluate long-term performance may be negatively impacted (i.e., falsely predict unacceptable performance).

When using foamed asphalt, Maccarrone et al. (1994) stated that 3 days of curing at 140°F appeared relevant for 12 months of field curing for the binder systems he studied. That is, their oven-cured specimens yielded similar moduli as pavement cores taken 12 months after construction.

**Table 1. Volumetric Mix Design Data for Granite Aggregate Using the Superpave Gyratory Compactor (after Hurley and Prowell, 2006a).**

| Additive | Compaction Temp., °F | AC, % | $G_{mm}$ | $\%G_{mm}$ @ $N_i$ | $G_{mb}$ | Air Voids, % | VMA | Voids Filled w/ Asphalt (VFA) |
|---|---|---|---|---|---|---|---|---|
| Control | 300 | 5.1 | 2.467 | 88.0 | 2.365 | 4.1 | 13.6 | 69.6 |
| Control | 265 | 5.1 | 2.467 | 88.2 | 2.371 | 3.9 | 13.3 | 71.0 |
| Control | 230 | 5.1 | 2.467 | 87.7 | 2.360 | 4.4 | 13.8 | 68.4 |
| Control | 190 | 5.1 | 2.467 | 87.5 | 2.356 | 4.5 | 13.9 | 67.6 |
| Zeolite | 300 | 5.1 | 2.457 | 88.8 | 2.376 | 3.3 | 13.9 | 76.4 |
| Zeolite | 265 | 5.1 | 2.457 | 88.9 | 2.382 | 3.0 | 13.6 | 77.7 |
| Zeolite | 230 | 5.1 | 2.457 | 88.7 | 2.378 | 3.2 | 13.1 | 75.5 |
| Zeolite | 190 | 5.1 | 2.457 | 88.3 | 2.368 | 3.6 | 13.5 | 73.2 |
| Sasobit | 300 | 5.1 | 2.461 | 88.4 | 2.375 | 3.5 | 13.9 | 74.8 |
| Sasobit | 265 | 5.1 | 2.461 | 88.0 | 2.377 | 3.4 | 13.8 | 75.5 |
| Sasobit | 230 | 5.1 | 2.461 | 88.0 | 2.360 | 4.1 | 14.4 | 71.7 |
| Sasobit | 190 | 5.1 | 2.461 | NA | NA | NA | NA | NA |
| Evotherm | 300 | 5.1 | 2.465 | 88.7 | 2.389 | 3.1 | 12.7 | 75.7 |
| Evotherm | 265 | 5.1 | 2.465 | 88.5 | 2.387 | 3.2 | 12.8 | 75.2 |
| Evotherm | 230 | 5.1 | 2.465 | 88.4 | 2.384 | 3.3 | 12.9 | 74.5 |
| Evotherm | 190 | 5.1 | 2.465 | 88.6 | 2.390 | 3.0 | 12.7 | 76.0 |

**Table 2. Volumetric Mix Design Data for Limestone Aggregate Using the Superpave Gyratory Compactor (after Hurley and Prowell, 2006a).**

| Additive | Compaction Temp., °F | AC, % | $G_{mm}$ | $\%G_{mm}$ @ $N_i$ | $G_{mb}$ | Air Voids, % | VMA | VFA |
|---|---|---|---|---|---|---|---|---|
| Control | 300 | 4.8 | 2.544 | 85.4 | 2.433 | 4.4 | 15.0 | 70.8 |
| Control | 265 | 4.8 | 2.544 | 85.1 | 2.430 | 4.5 | 15.1 | 70.3 |
| Control | 230 | 4.8 | 2.544 | 85.3 | 2.435 | 4.3 | 14.9 | 71.3 |
| Control | 190 | 4.8 | 2.544 | 85.5 | 2.439 | 4.1 | 14.8 | 72.1 |
| Zeolite | 300 | 4.8 | 2.544 | 85.8 | 2.442 | 4.0 | 14.7 | 72.8 |
| Zeolite | 265 | 4.8 | 2.544 | 85.8 | 2.449 | 3.7 | 14.4 | 74.3 |
| Zeolite | 230 | 4.8 | 2.544 | 85.7 | 2.444 | 3.9 | 14.6 | 73.2 |
| Zeolite | 190 | 4.8 | 2.544 | 84.8 | 2.418 | 4.9 | 15.5 | 68.2 |
| Sasobit | 300 | 4.8 | 2.545 | 86.1 | 2.459 | 3.4 | 14.1 | 76.1 |
| Sasobit | 265 | 4.8 | 2.545 | 86.3 | 2.463 | 3.2 | 14.0 | 76.7 |
| Sasobit | 230 | 4.8 | 2.545 | 86.3 | 2.465 | 3.1 | 13.9 | 77.4 |
| Sasobit | 190 | 4.8 | 2.545 | NA | NA | NA | NA | NA |
| Evotherm | 300 | 4.8 | 2.547 | 86.0 | 2.472 | 3.0 | 13.6 | 78.4 |
| Evotherm | 265 | 4.8 | 2.547 | 85.6 | 2.458 | 3.5 | 14.1 | 75.3 |
| Evotherm | 230 | 4.8 | 2.547 | 86.2 | 2.477 | 2.8 | 13.5 | 79.6 |
| Evotherm | 190 | 4.8 | 2.547 | 85.2 | 2.451 | 3.8 | 14.4 | 73.9 |

### Mixture Evaluation

Mechanical characterization of mixtures should be performed using standard volumetric analyses and laboratory specimen testing. State departments of transportation (DOTs) are familiar with their analysis procedures and what the results mean regarding pavement performance. WMA mixtures should be held to the same standards as HMA mixtures; however, proper curing methods for those WMA specimens that initially incorporate water must be determined.

A routine analysis of WMA should include those few tests used in routine analysis of HMA (e.g., volumetrics, modulus, rut resistance, moisture susceptibility, and dust proportion) and the same testing conditions. Similarly, a complete analysis of WMA should include those tests typically performed on HMA specimens (e.g., all of the above plus creep and fatigue). This is even true for cold (foam) mix, after proper curing (Maccarrone et al., 1994).

## MATERIAL CHARACTERIZATION FOR STRUCTURAL DESIGN WITH WMA

Hurley and Prowell (2006a) studied Sasobit, Aspha-Min, and Evotherm in the laboratory and field and concluded that all products yielded resilient moduli similar to those of corresponding HMA mixtures. Others (Mallick et al., 2007; Kanitpong et al., 2007; and Wasiuddin et al., 2007) have reported similar findings. Therefore, the structural value of WMA using these products can be considered equivalent to that of typical HMA.

Hurley and Prowell (2006a) further concluded that Sasobit, Aspha-Min, and Evotherm did not increase rutting potential, as measured by the asphalt pavement analyzer (APA). In fact, the WMA product increased rutting resistance in some instances. However, rutting potential did increase with decreased mixing and compaction temperatures; they attributed this phenomenon to decreased aging of the binder. Furthermore, they reported no evidence of differing strength gain with time (up to 5 days) for the two WMA products when compared to similar HMA mixtures.

Based on findings during this review of current literature, the authors currently believe that WMA should provide the same structural values as HMA.

## CONSTRUCTION WITH WMA

Newcomb (2006) pointed out that, since certain WMA technologies require a mixing process that is different from conventional HMA, new guidelines need to be developed for proper Quality Control/Quality Assurance (QC/QA) of the mix. He further stated that the suitability of WMA for the high production rates of asphalt plants in the U.S. needs to be examined. There is concern by some engineers that those WMA products that utilize moisture may induce some clogging in bag houses; however, no such problems have been reported in the literature.

Except for the temperature of the mat, there are generally no differences in construction activities whether using HMA or WMA, after the product leaves the plant. Experience of the authors has shown that Evotherm can be stored in a silo in a manner similar to HMA. Romier et al. (2006) indicate this is also true for LEA.

When studying WAM-Foam, Koenders et al. (2000) recommended keeping the breakdown roller directly behind the paver; otherwise, the compaction effort required seemed to be considerably increased. This recommendation is likely to maximize the advantages of the lubricating effects of the moisture in the mat before it dissipates. Compaction temperature of a WMA mat is apparently less critical than that of HMA, but it is still important to complete compaction quickly and efficiently while the mat temperature is within the appropriate window for the specific WMA product.

## WMA PROPERTIES AND PERFORMANCE

### NCAT Laboratory Results for WMA

NCAT has probably conducted more studies of WMA than any other agency in the U.S. (Hurley and Prowell, 2005a, 2005b, 2006a, 2006b; NCAT, 2005). They have demonstrated that Aspha-Min, Sasobit, and Evotherm improve compactability in the Superpave gyratory compactor and reduce air voids by an average of 0.65, 0.87, and 1.5 percent, respectively, over that of their corresponding control HMA mix. Improved compaction was noted at temperatures as low as 190°F. Addition of Aspha-Min, Sasobit, and Evotherm did not affect the resilient modulus of the mixes. Decreased aging due to lower mixing and compacting temperatures may have contributed to lower indirect tensile strengths of the WMA mixes. Aspha-Min did not increase rutting potential of the mix, while Sasobit and Evotherm generally decreased the rutting potential of the mixes evaluated. The rutting potential increased with decreasing mixing and compaction temperatures, which may be related to the decreased aging of the binder. NCAT recommended bumping the high-temperature grade of the asphalt by one grade to offset any slight increase in rutting potential that may occur when using a WMA product. The reports also indicated that lower mixing and compaction temperatures can result in incomplete drying of the aggregate and that water trapped in the coated aggregate may cause moisture damage. However, they indicated that anti-stripping agents were effective in addressing this problem in the laboratory. Their results suggested that, when hydrated lime is used as anti-strip, it will stiffen the WMA and assist rutting resistance.

For all three WMA products, NCAT personnel aged the densification samples for 2 hours at the compaction temperature prior to compaction. These samples were tested for resilient modulus and APA rut depth.

**Aspha-Min**

**Tennessee.** A warm-mix asphalt paving demonstration was conducted at the World of Asphalt 2004 Conference in Nashville, Tennessee, using the Aspha-Min process (Jones, 2004). In this 3-hour demonstration, conventional HMA and WMA were placed side by side. Temperature readings taken behind the screed on the two different materials showed about 80°F difference. Workability and compaction are concerns with conventional mixes as they cool, but the WMA technology performed as predicted. Despite the 80°F temperature difference, the same density was achieved on both the HMA and WMA mat. Comments made by the construction crew were that the WMA was easier to handle and place than the HMA.

**Florida.** In February 2004, a control mix and a WMA using Aspha-Min were placed on a parking lot in Orlando, Florida, for a demonstration project. NCAT personnel were present at this project and obtained samples from the plant for both mixes (Hurley and Prowell, 2005a). The control mix consisted of a fine-graded Superpave mix with crushed granite aggregate and 20 percent RAP; it was designed for 3 to 10 million (equivalent single axle loads (ESALs) with an $N_{design}$ of 75 gyrations. The WMA was produced by adding 0.3 percent Aspha-Min by weight to the control mix; the additive was introduced to the mix using a specially built feeder. The WMA mix discharge temperature was 36 degrees lower than the control mix (336°F for the control and

300°F for the WMA). The mat temperature behind the screed ranged from 293°F to 315°F for the control mix and from 256°F to 260°F for the WMA.

NCAT personnel compacted samples at the plant using both the Superpave gyratory compactor (SGC) and the Marshall method. They compacted the control mix at 310°F and the warm mix at 270°F.

In their report, Hurley and Prowell (2005a) state that additional warm-mix samples were compacted after a 1-hour oven-aging period at the compaction temperature and that oven aging was performed to assess the ability to store the WMA in a silo.

Table 3 shows volumetric properties.

**Table 3. Volumetric Properties of WMA and HMA Using Marshall Hammer and Superpave Gyratory Compactor (Hurley and Prowell, 2005a).**

| Volumetric Property | Control Mix Unaged | Aspha-Min Warm Mix Unaged, Aged | |
|---|---|---|---|
| SGC Air Voids, % | 4.96 | 5.24 | 5.04 |
| SGC VMA, % | 14.8 | 15.0 | 14.8 |
| Marshall Air Voids, % | 6.43 | 6.50 | 6.95 |
| Marshall Stability (lb) | 2930 | 2853 | 2733 |
| Marshall Flow | 12.5 | 13.0 | 12.0 |

The NCAT laboratory test trends of the samples obtained from the Florida project matched the trends that NCAT observed in their previous laboratory study. Hurley and Prowell (2005a) deduced that the average air voids of both mixes were essentially identical even though the compaction temperature of the warm mix was 40°F lower. The gyratory air voids for the unaged warm mix was slightly higher than the control, but this also corresponds to a slightly higher voids in the mineral aggregate (VMA). All Marshall specimens were compacted using 75 blows per face. They further stated that the Marshall method air voids of the two unaged mixes were identical even though the Marshall hammer has historically been very sensitive to compaction temperature. The Marshall method air voids for the aged specimens were higher, which could be due to aging of the binder or a dissipation of the moisture released by the zeolite. Furthermore, 75 blows with the Marshall hammer produced significantly less compaction than 75 gyrations with the SGC.

According to their report, the paving crew at the site noted that the WMA mix was more workable than the control mix; in addition, the densities were the same for both sections.

NCAT personnel visited the site again in March 2005 to conduct a pavement condition assessment of the WMA and control sections and to obtain cores from both sections for moisture damage testing. According to Hurley and Prowell (2005a), no distress was observed in either section. In addition, the testing of the cores indicated that there was no difference in moisture damage resistance between the WMA and the control mix. However, the report states, “it should be noted that these sections do not receive regular traffic. It is believed that traffic contributes to the occurrence of moisture damage.”

**Europe.** Eurovia constructed test sections with WMA mixes using Aspha-Min and HMA control sections in Europe. Barthel et al. (2004) reported that 3 years after construction of the first WMA test section using zeolite measurements indicated no significant changes in the surface characteristics. When pavement cores were taken from the road surface and the connection between the several layers was tested, no changes were found when compared to traditionally constructed pavement layers.

**Evotherm**

**NCAT Facility—Auburn, Alabama.** NCAT conducted laboratory studies of WMA using Evotherm and installed test sections on their test track in late October to early November 2005. In the June 2006 issue of *Better Roads*, Brian Prowell, Assistant Director at NCAT, stated, “After 500,000 ESALS, we had only 1 mm of rutting in the two Evotherm test sections and an HMA control section.” The article indicated that the daily high temperatures during the first part of the test were initially in the 70°F to 80°F range but then “lowered somewhat after that.” Prowell also said, “The traffic was returned within an hour after construction—and few sites in the U.S. receive as high a loading rate as the NCAT test track, but just because the sections gave an excellent performance in that weather doesn’t guarantee that they would perform as well in the heat of the summer” (McKenzie, 2006).

At the 2007 Annual Meeting of the Transportation Research Board, Prowell et al. (2007) reported, “The WMA produced using the Evotherm process was successfully compacted after being stored in a silo for 17 hours. In-place densities of the WMA surface layers were equal to or better than the HMA surface layers even when compaction temperatures were reduced by

15°F to 75°F. Significantly improved in-place densities were observed for the WMA base and binder layer; however, the asphalt contents were also higher than expected for these sections. Laboratory rutting susceptibility tests conducted in the APA indicated similar performance for the WMA and HMA surface mixes using the PG 67-22 base asphalt. The two WMA sections and HMA section showed excellent field performance in terms of rutting after the application of 515,333 ESALs in a 43-day period. The WMA in section N1 showed good rutting performance even though traffic was returned to the sections 1.75 hours after paving commenced. Laboratory tests indicated increased potential for moisture damage with the WMA mixes. Field cores have been taken to corroborate this result after trafficking." The report indicated that the measured rut depths after 513,333 ESALs ranged from 0.8 mm to 1.1 mm.

**Indiana.** In July 2005, Evotherm was first used in the U.S. to produce 660 tons of WMA for a county road near Indianapolis, Indiana. The mixture was produced in a hybrid batch/drum plant and operated in the drum plant mode. Evotherm was used with a 12.5 mm nominal maximum aggregate size coarse-graded Superpave mix with crushed dolomite and 15 percent RAP. Discharge temperature from the drum was approximately 200°F. The mix was placed at an average depth of 50 mm and temperatures behind the screed were between 160°F and 200°F. The mix did not appear to be tender (Prowell and Hurley, 2005)

**Canada.** J.K. Davidson with McAsphalt (based in Toronto, Ontario) produced three reports concerning Evotherm trials in Canada.

The first trial involved paving a parking lot and a mainlane truck exit for the Miller Paving marketing office in Aurora in August 2005. Two different mixes were used—a 19 mm maximum aggregate size base course compacted to a thickness of 60 mm and a 13.2 mm maximum aggregate size surface course compacted to a thickness of 40 mm (Davidson, 2005a).

The second trial involved paving residential streets in Northeast Calgary in September 2005 using a 16 mm maximum aggregate size surface course compacted to a thickness of approximately 50 mm (Davidson, 2006).

The third trial involved overlaying Road #46 in the Ramara Township in October 2005 using a 16 mm maximum aggregate size surface course compacted to a thickness of 60 mm. An HMA control section was also placed in October (Davidson, 2005b).

Davidson reported that for the Aurora and Calgary projects the mix appeared to stay tender for an extended period of time. He reported the following for all three trials:

- Evotherm emulsion was slightly slower to pump up to the asphalt weight hopper than normal asphalt cement, which slightly slowed production.
- Batch size had to be reduced due to limitations in the capacity of the asphalt weigh hopper.
- Because the Evotherm emulsion is only 68 to 70 percent residue, the quantity of emulsion needed for the mix is 45 percent higher.
- Evotherm mix flowed under the paver screed without any evidence of tearing behind the screed.
- The breakdown roller could travel right up to the back of the paving machine with no evidence of pushing or shoving of the pavement mat.
- Using the vibratory mode on the breakdown roller showed no evidence of cracking in the mat.
- The longitudinal joint between lanes appeared to be very tight.
- The Evotherm mix generally had the appearance of HMA.

**San Antonio, Texas.** TxDOT placed their first warm-mix asphalt trial using the Evotherm process on Loop 368 in the San Antonio District in August/September 2006. All test sections are performing well at this time. TxDOT is still in the process of evaluating the short- and long-term performance of this field trial through field cores and performance monitoring. Documentation of this field trial is presented in Appendix A. Preliminary findings based on information documented thus far include the following:

***Mixture Design***

Both warm mix and control mixes were designed according to Item 341, Type C dense-graded mixes, which employ the use of the Texas gyratory compactor. Both mixes were designed to a target density of 96.5 percent. The control hot mix asphalt concrete (HMAC) had an optimum asphalt content of 4.8 percent, and the warm-mix optimum asphalt content (residual binder) was 4.2 percent. The control mix was produced with a PG 76-22 binder, and the warm mix (after the Evotherm modification) was also a PG 76-22. Both warm mix and control mix used the same aggregate source (predominately crushed limestone) and gradation. Also, both warm and control mixes were produced in the same asphalt plant.

***Production***

- The warm mix was produced at a temperature of 220°F, and the control was produced at 320°F.
- No reduction in fuel consumption was observed for the warm-mix production, and this observation is attributed to a heavy rain prior to production, which caused the aggregate stockpiles to be excessively wet, requiring more energy for plant operation.
- Warm mix was stored in silos for a maximum of 2 hours prior to load out.

***Quality Control***

WMA samples were compacted in the field laboratory to densities averaging 97 percent, which was the same as the control HMAC compacted densities. To evaluate the effect of laboratory curing on the warm mix, samples were compacted after three curing conditions: no cure, cure for 2 hours at 200°F, and cure for 2 hours at 240°F. The different curing conditions had no effect on compacted density.

***Placement and Compaction***

- The warm mix and control mixes were placed over the course of three nights. The warm mix was placed at a temperature ranging from 170°F to 210°F. Nuclear density tests on the warm mix ranged from 92.1 to 95 percent. The control mix was placed at 305°F, and nuclear density tests averaged 94.2.
- The same rolling patterns were used for both control and warm mixes.
- No problems were observed with the placement and compaction operation.
- Traffic was allowed on to the warm mix in some areas as soon as 2 hours after placement.

***Laboratory Testing on Lab-Molded Samples and Roadway Cores***

- Density of roadway cores taken after 1 month of traffic showed an overall average density of the warm mix (based on 26 cores) of 93.3 percent. Average density of the roadway cores from the control mix (based on four cores) was 92.6 percent.
- Density of warm-mix roadway cores taken in the wheel paths were compared with those taken between the wheel paths. There is no indication that the warm mix is densifying further under the action of traffic (after 1 month).
- For laboratory testing in the Hamburg and Texas Transportation Institute (TTI) Overlay Tester, warm-mix samples were compacted at two different temperatures: 240°F and 300°F. The warm-mix samples compacted at 300°F performed better in the Hamburg than those compacted at 240°F. All of the warm-mix samples failed the Hamburg test requirements (of no more than 12.5 mm rut depth at 20,000 passes) with the exception of the samples compacted at 300°F from the second night of warm-mix production. The warm-mix cores taken at 1 month also failed the

Hamburg requirements. The control mix generally passed the Hamburg test with the exception of one set of field cores.

- Indirect tensile strength tests were performed during the mix design and on roadway cores for both warm and control mixes. The control mix had tensile strengths of around 170 psi (both mix design and roadway cores). During the mix design process, the warm mix only had a tensile strength of 60 psi; however, the warm-mix roadway core tensile strengths ranged from 121 to 178 psi.
- Overlay test results for the roadway cores were compared to the lab-molded plant mix samples. All of the lab-molded warm-mix and control HMAC specimens performed poorly in the overlay test. However, there was a significant improvement seen in some of the cores taken at 1 month from the warm-mix sections.

**Laboratory Study.** Wasiuddin et al. (2007) conducted a laboratory study on Aspha-Min and reported that the rheological properties of two commonly used binders (PG 64-22 and PG 70-28) were evaluated, with and without Sasobit and Aspha-Min. No significant decrease in mixing temperature due to Aspha-Min was observed when using the rotational viscometer. No significant changes in binder grading were observed with the addition of Aspha-Min.

**Sasobit**

Sasol Wax maintains a list of projects on its web site that utilize Sasobit in asphalt paving (Sasol Wax, 2005). As of October 2005, Sasol Wax listed 235 projects and trials in many countries, including Germany, Denmark, France, the Czech Republic, Hungary, Italy, the Netherlands, New Zealand, Norway, Russia, the United Kingdom, South Africa, Sweden, and Switzerland. The projects and trials mainly involved various dense-graded mixes, SMA, and gussasphalt. For the projects on the list where Sasobit addition rates were indicated, many projects reported using a 3 percent rate, but the rates on other projects varied from 1 to 4.5 percent.

The authors could not find any reports on the field performance of WMA mixtures containing Sasobit. Findings of two laboratory studies are discussed below.

Kanitpong et al. (2007) conducted a laboratory study on Sasobit and reported that Sasobit modification can improve the workability and the fundamental properties of asphalt binders as indicated by improved rutting and fatigue resistance and higher complex shear modulus. Measurement of compactability showed that less energy is required to compact the Sasobit-modified mixes to the desired density even at 68°F to 104°F below compaction temperature.

Sasobit-modified mixtures demonstrate greater resistance to densification under traffic or higher potential to resist permanent deformation. However, there is no effect of Sasobit on the resistance of asphalt mixtures to moisture damage, but the reduction of mixing and compaction temperatures can cause detrimental effects on moisture sensitivity.

Wasiuddin et al. (2007) conducted a laboratory study on Sasobit and reported that rheological properties of two commonly used binders (PG 64-22 and PG 70-28) were evaluated, with and without additives (Sasobit and Aspha-Min). For PG 64-22, 2, 3, and 4 percent Sasobit reduced the mixing temperature of the pure binder from 325°F to 297°F (i.e., by 28ºF). For the PG 70-28, the reductions are 50ºF, 53ºF, and 55ºF, respectively, for 2, 3, and 4 percent Sasobit. Addition of 3 percent Sasobit increased the high-temperature binder grading of PG 64 (actually PG 65) to PG 68, while 4 percent Sasobit improves the PG 70 (actually PG 75) to PG 80. Reduction in binder viscosity and improvement in binder grading without increasing the viscosity indicated a two-way reduction (both direct and indirect) in production temperatures by Sasobit. Finally, Sasobit decreased the APA rut depths significantly, and these rut depths correlate well with the rutting factor $G^*/\sin(\delta)$. Wasiuddin et al. (2007) observed that rutting potential decreased with decreasing mixing and compaction temperatures.

**Low-Energy Asphalt**

Romier et al. (2006) reported the following concerning the production and placement of an LEA mix in November 2003: A total of 150 tons of LEA was produced using a batch plant modified for the sequential introduction of the two parts of the aggregates into the weighing system ahead of the mixer. The mixes were stored in the finished product storage hopper for more than 1 hour. They were placed using a paver-finisher and compacted using a double-drum vibrating compactor following the usual application procedures. The climatic conditions corresponded to normal seasonal values, with air temperatures a few degrees above freezing in the morning. Placement temperature was of the order of 140°F to 160°F. Residual water content in the mixes was near 0.5 percent. As the difference with the ambient temperature is smaller for LEA mixes than for their high-temperature counterparts, the rate of drop in temperature with time is less significant. The LEA mix exhibited a surface appearance comparable to that of HMA, including at joint locations.

**WAM-Foam**

Figure 3, from Larsen et al. (2004), shows rut depth measurements on a roadway project (RV 120) in Norway where WAM-Foam WMA was placed in September 2000 along with a regular HMA section. The report did not state the compacted thickness of the WMA mat. Rut depth measurements for the WMA and HMA are similar, as shown in Figure 3. The report states, “The mixture was a dense asphalt concrete Ab11 with an 85 pen (final) binder. The asphalt concrete was produced in a batch plant (7260 lb/batch). The first set of data for September 5, 2000 was the condition of the road before the paving of the new one-lift wearing course. The large increase after the first winter period is due to studded tires that wear off the mortar on the surface. This is typically observed on all Norwegian roads where the percentage of studded tires on cars in the winter period is close to 60 percent. The road has now gone through three winters.”

Figures 4 and 5, also from Larsen et al. (2004), show rut depths and international roughness index (IRI) measurements on FV 82 in Norway that involved the placement of WAM-Foam mix and an HMA control section. Again, the report did not state the compacted thickness of the WMA mat. Rut depths and IRI measurements for the WMA and HMA are similar as shown in Figures 4 and 5. The report concludes that the FV 82 road provides another example of a WMA wearing course for which it is possible to show the behavior of the road after a number of years. A section was placed on this road with a dense asphalt concrete WAgb11 using 180-pen binder (160/220 grade). The asphalt concrete mixture was produced in a batch plant (7260 lb/batch). Rut depths were measured on both the WAM-Foam and reference hot mix sections. These measurements cover a period from October 2000 to June 2003. The results associated with October 2000 were obtained before placing the new layers. The results for September 2001 were obtained after placing a leveling course (mixture prepared using cold recycling foam technique with 100 percent RAP). The results obtained in October 2001 were after paving with the WAM-Foam mixture (WAgb11) and the corresponding hot mixture (Agb11). Subsequent measurements were recorded to monitor the development of the rut depths.

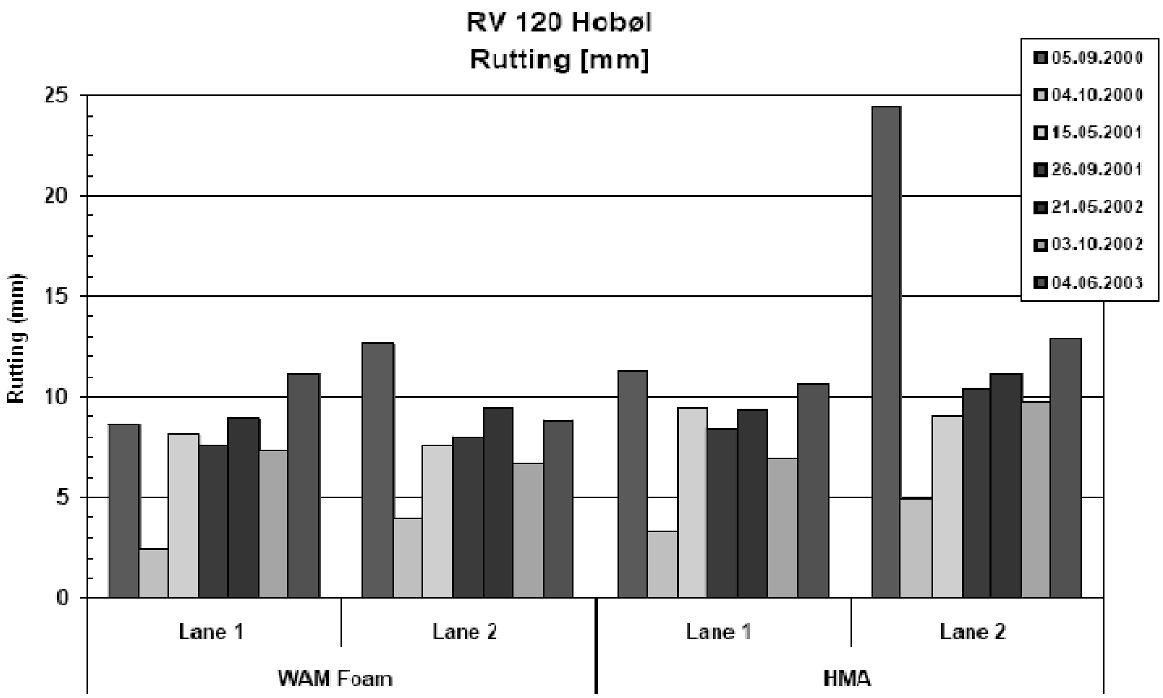


**Figure 3. Rut Depth Measurements on RV 120 in Norway (after Larsen et al., 2004).**

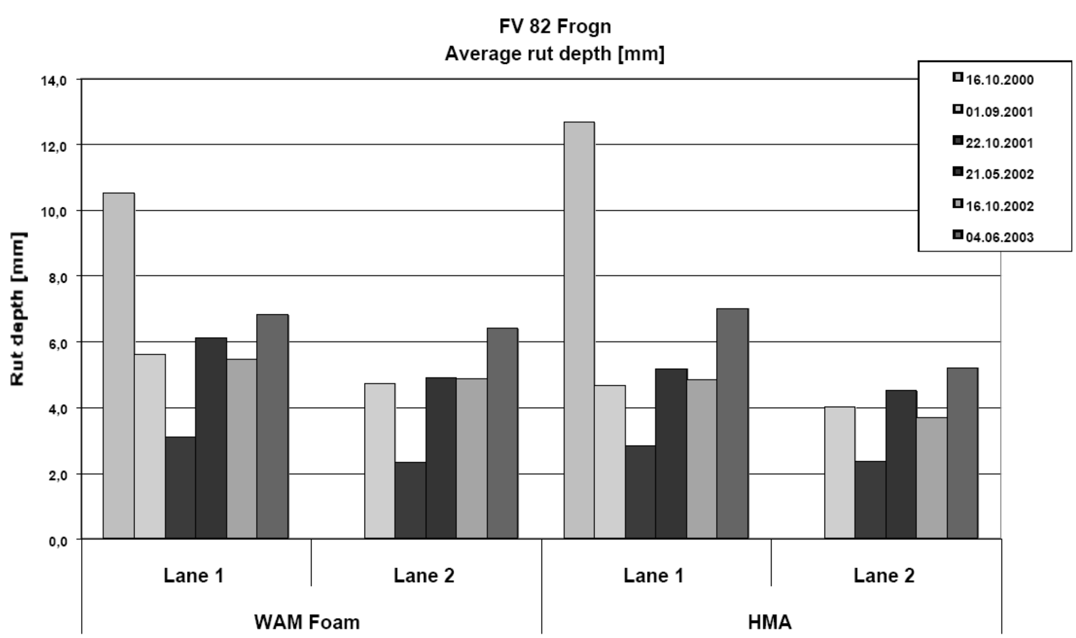


**Figure 4. Rut Depth Measurements on FV 82 in Norway (after Larsen et al., 2004).**

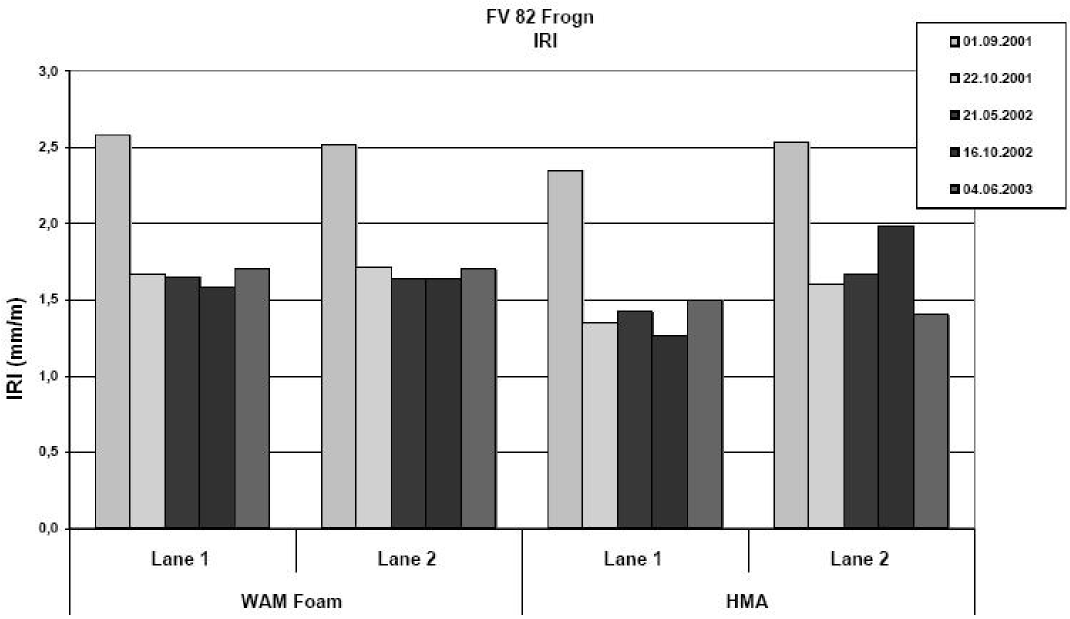


**Figure 5. IRI Measurements on FV 82 in Norway (after Larsen et al., 2004).**

### General Discussion of WMA Properties

Roadway sections using WMA appear to be performing well in the field according to the limited number of reports that address field performance, but in general, those sections have been in place for less than 5 years. In the authors' experience, asphalt pavement sections that fail prematurely will typically exhibit signs of distress within less than 5 years after construction. In addition, only a few studies appear to be addressing laboratory testing and applying the results to field performance, and these are mainly those studies conducted by NCAT.

## OTHER WARM-MIX ASPHALT APPLICATIONS

### Warm Open-Graded Mixes for Patching Permeable Friction Courses

Patching a permeable friction course (PFC) to maintain its permeability and noise abatement qualities has proven to be difficult. The use of hot PFC for patching often results in wasting large quantities of expensive material because the open-graded mix cools so rapidly. Patching with standard dense-graded cold mix destroys permeability and, thus, creates impediments to the designed flow patterns.

Soto and Blanco (2004a) have proposed a solution to this problem. This potential solution is a mixture combining the cohesion of HMA with the sustained workability of cold mix. They used a polymer-modified cationic medium setting emulsion as binder in a mix manufactured at a hot-mix plant but at temperatures not higher than 175°F. The mix can easily be stored for 24 hours. Several successful applications of this product have been demonstrated in Spain.

Why warm mixtures? They report that warm emulsion allows the use of aggregates that, considering their quality, gradation, and moisture conditions, could not be utilized in a continuous mixing system. The polymer-modified emulsion provides total aggregate coating and film uniformity. Placement and compaction is enhanced while the mix is warm. No blinding (sanding) is necessary before trafficking, which would be obligatory with cold mixes. Curing of the mix is fast, as the warm emulsion cures rapidly.

**Warm In-Plant Recycling**

Soto and Blanco (2004b) report that warm recycling can be used to produce and place up to 100 percent RAP using either a batch or drum mixing plant. The process heats the RAP to about 195°F and mixes it with an appropriate grade of asphalt emulsion. The mix can be stored in a silo for 24 hours to accommodate placing at above 140°F. This process allows the resulting pavement to be opened to traffic immediately, thus eliminating the curing period necessary in cold recycling.

Their laboratory investigation revealed the following advantages/improvements over cold recycled mixes: improved resistance to moisture damage (based on immersion-compression tests), increased density under similar compaction (3 percent lower air voids), and dynamic modulus was similar to that for conventional HMA.

Soto and Blanco (2004b) reported on field trials conducted in Spain and Portugal using conventional methods and equipment. Workability of the mixture was reportedly similar to that for HMA. They reported the following two advantages over cold in-place recycled RAP. Quality control is significantly improved since the warm mix is produced in a plant. Since most of the water was eliminated during production, a curing period is not necessary for the warm recycled mix before trafficking.

Mallick et al. (2007) evaluated two methods for using 100 percent RAP in warm applications for construction of pavement base layers: They heated the RAP to 230°F

- then added PG 64-28 at 300°F,
- then added 140°F emulsified asphalt (MS-2) in an asphalt plant, and
- then added Sasobit (at 1 and 1.5 percent) with PG 64-28 to permit a lower mixing temperature (255°F) than a typical hot plant operation.

Technicians compared workability, compactability, stiffness, and resistance to moisture damage of several types of mixes. They prepared slabs approximately 3 feet by 3 feet by 5 inches thick and tested cores from the slabs. Heating the RAP significantly improved dispersion of the binder as well as slab densification. Sasobit seemed to improve dispersion of the asphalt binder at the lower temperature. The use of Sasobit achieved almost similar workabilities, compactabilities, and moduli as the HMA specimens but at a lower temperature. For this RAP mix, 1 percent Sasobit yielded better results than 1.5 percent Sasobit.

## CURRENT NATIONAL ACTIVITIES RELATED TO WARM-MIX ASPHALT

### National Asphalt Pavement Association (NAPA) Research

According to Corrigan (2006), NAPA in cooperation with the FHWA proposed a research program to investigate the performance of WMA products. Initial research was conducted on the feasibility of using these technologies in the U.S. through a cooperative agreement between NCAT and FHWA. These studies included additional monetary support from NAPA and the individual WMA technology providers. NCAT has completed the research and published the findings in three reports that are available on their website (http://www.eng.auburn.edu/center/ncat/):

- Report 05-04—"Evaluation of Aspha-Min Zeolite for Use in Warm-Mix Asphalt," Hurley and Prowell (2005a)
- Report 05-06—"Evaluation of Sasobit for Use in Warm-Mix Asphalt," Hurley and Prowell (2005b)
- Report 06-02—"Evaluation of Evotherm for Use in Warm-Mix Asphalt," Hurley and Prowell (2006b)

**NCAT Laboratory Findings.** Although the initial research focused on Aspha-Min, Sasobit, and Evotherm, future research in this area is rapidly expanding to include other WMA technologies. The objectives of these laboratory studies were to determine the applicability of the three products to paving operations and environmental conditions commonly found in the United States, including the performance of the mixes in high-temperature conditions and situations that must be quickly returned to traffic. The findings of these three studies at NCAT are summarized in Hurley and Prowell (2006a). Tables 1, 2, 4, and 5 highlight their experiment and selected findings.

**Table 4. Tensile Strengths for Granite and Limestone (after Hurley and Prowell, 2006a).**

| Aggregate | Mix Type | Indirect Tensile Strength Unsaturated, psi | Indirect Tensile Strength Saturated, psi | TSR, % |
|---|---|---|---|---|
| Granite | Control | 126.6 | 123.4 | 0.97* |
| Granite | Zeolite | 155.0 | 126.3 | 0.81* |
| Granite | Sasobit | 59.5 | 40.6 | 0.68** |
| Granite | Zeolite | 67.2 | 40.4 | 0.60** |
| Granite | Control | 75.9 | 88.3 | 1.16 |
| Granite | Zeolite | 72.5 | 48.7 | 0.67 |
| Granite | Sasobit | 53.2 | 38.0 | 0.71 |
| Granite | Evotherm | 70.8 | 67.7 | 0.96 |
| Limestone | Control | 109.5 | 71.2 | 0.65 |
| Limestone | Zeolite | 86.6 | 44.2 | 0.51 |
| Limestone | Sasobit | 53.9 | 49.1 | 0.91 |
| Limestone | Evotherm | 75.0 | 46.8 | 0.62 |

Note: * Indicates samples were prepared in SGC in accordance with American Society for Testing and Materials (ASTM) D 4867.

Note: ** Indicates samples were prepared in SGC in accordance with ASTM D 4867 with 250°F compaction temperature.

**Table 5. Results from Hamburg Test (modified after Hurley and Prowell, 2006a).**

| Aggregate | Mix Type | Treatment | Stripping Inflection Point, cycles | Rutting Rate, mm/hr | Tensile Strength Ratio (TSR) | Total Rutting @ 10,000 cycles |
|---|---|---|---|---|---|---|
| Granite | Control | None | 6500[1] | 1.841 | 1.16 | 7.31 |
| Granite | Sasobit | None | 3975 | 2.961 | 0.71 | 11.75 |
| Granite | Aspha-Min | None | 3450 | 5.139 | 0.67 | 20.39 |
| Granite | Evotherm | None | > 10,000 | 1.708 | 0.96 | 6.78 |
| Granite | Aspha-Min | 1.5% Hydrated Lime 2-Stage Addition | 8500[1] | 1.912 | 0.87 | 7.59 |
| Granite | Aspha-Min | 1.5% Hydrated Lime - Added Dry | > 10,000 | 0.687 | 0.75 | 2.73 |
| Granite | Sasobit | 0.4% Magnabond | > 10,000 | 0.164 | 0.94 | 0.65 |
| Limestone | Control | None | 2500 | 4.284 | 0.65 | 17.00 |
| Limestone | Aspha-Min | None | 1700 | 2.835 | 0.51 | 11.25 |
| Limestone | Sasobit | None | 2900 | 3.976 | 0.91 | 15.78 |
| Limestone | Evotherm | None | 2550 | 3.178 | 0.62 | 12.61 |

[1] Only one of two specimens exhibited a stripping inflection point; reported value is average of 10,000 cycles and recorded stripping inflection point of second specimen.
[2] NA = No stripping inflection point observed.

The bulleted list below summarizes their conclusions and recommendations.

- The gyratory compactor was not sensitive to the reduction in compaction temperature. Therefore, all test samples designed to simulate field compactability were compacted in the vibratory compactor.
- Use of any of the three warm-mix processes lowers the measured air voids in the gyratory compactor. While this may indicate a reduction in the optimum asphalt content, at this time, it is believed that additional research is required and that the optimum asphalt content of the mixture determined without any additives included should be used. The optimum asphalt content of the mixture without the addition of any additive was used for all of the testing in this project.
- All processes improved the compactability of the mixtures in both the SGC and vibratory compactor. Statistics indicated an average reduction in air voids up to 0.77 percent for the Aspha-Min, 0.89 percent for the Sasobit, and up to 1.53 percent for the Evotherm in the vibratory compactor. Improved compaction was noted at temperatures as low as 190°F for all three additives.

- None of the warm-mix processes affected resilient modulus of an asphalt mix when compared to control mixtures having the same Performance Grade (PG) binder. Higher density increased resilient modulus. Therefore, there is no effect on pavement thickness design when using these warm-mix processes.
- Addition of Sasobit, Aspha-Min, or Evotherm did not increase the rutting potential of the mix. Rutting potential increased with decreasing mixing and compaction temperatures; this may be related to the decreased aging of the binder. However, the mixes containing Sasobit were less sensitive (in terms of rutting) to the decreased production temperatures than the control mixes.
- Indirect tensile strengths for mixes containing Sasobit were lower, in some cases, as compared to the control mixes. This reduction in tensile strength is believed to be related to the ability of Sasobit to reduce binder aging.
- APA and Hamburg tests indicated good rutting resistance for the mixes containing Sasobit.
- Mixes containing WMA additives exhibited no difference in strength gain with time as compared to the control mixes. Addition of Aspha-Min or Evotherm may not require a cure time for the asphalt mixture prior to opening to traffic. Field data from Europe support this conclusion that addition of Sasobit does not require a cure time before opening trafficking.
- Lower mixing and compaction temperatures for warm mixes may increase the potential for moisture damage. Lower mixing/compaction temperatures can result in incomplete drying of the aggregate. Water trapped in the coated aggregate may enhance moisture damage. Reduced tensile strength and visual stripping were observed in both the control and warm asphalt mixes produced at 250°F.
- Various anti-stripping agents were evaluated to mitigate the potential for moisture damage. Hydrated lime with Aspha-Min was effective with the granite aggregate. Hydrated lime (1.5 percent) in the WMAs resulted in improved cohesion and moisture resistance. Addition of AKZO Nobel Magnabond (Kling Beta 2912) improved the tensile strength ratio values to acceptable levels for the Sasobit. An alternate Evotherm formulation provided good moisture resistance for the limestone aggregate.
- Hamburg wheel-tracking tests indicated good performance in terms of moisture susceptibility and rutting for the mixtures containing Sasobit and Magnabond.
- Hamburg results suggested that lime will augment rutting resistance of mixtures containing Aspha-Min compacted at lower temperatures due to the stiffening effects of lime.
- A binder modified with Sasobit needs to be engineered to meet the desired performance grade. For example, a PG 58-28 was used as the base asphalt with the addition of 2.5 percent Sasobit to produce a PG 64-22.
- Optimum asphalt content should be determined without the addition of any warm-mix additive. Additional samples should then be produced so the field target density can be

adjusted (e.g., if the laboratory air void content with any additive included was decreased in the lab by 0.5 percent, then the field target density should be increased by 0.5 percent).

- Based on the compaction and rutting results, a minimum field mixing temperature of 275°F and a minimum field compaction temperature of 250°F is recommended. If the mixing temperature is below 275°F, then the high-temperature grade should be bumped upward by one grade. Standard HMA performance testing should be conducted. Field compaction will dictate the true minimum compaction temperature depending on a number of factors.
- Tensile strength ratio testing should be conducted at the anticipated field production temperatures. If results are unfavorable, an anti-stripping agent should be incorporated to yield an acceptable tensile strength ratio.
- More research is needed to further evaluate field performance, the selection of the optimum asphalt content, and the selection of appropriate binder grades for lower production temperatures.

During the discussion of Hurley and Prowell (2006a) at the conference of the Association of Asphalt Paving Technologists, Mr. Gerald Reinke indicated a potential problem for WMA. He pointed out that, in Wisconsin, the climate calls for a PG 58-28. Further, if one uses a PG 64-22 in WMA, with the reduced binder aging, it would provide essentially the same rutting results as a PG 58-28 in HMA. This is fine for the high-temperature performance. The potential problem arises when the low-temperature specification properties of the WMA binder are measured. If one extracts and recovers the PG 64-22 from the WMA and performs the pressure aging vessel test, experience indicates that the resulting low-temperature properties typically miss the -28 grade by about 2 degrees. A modifier could be used to address this issue, but its cost would offset some of the economic benefits of the WMA. This needs to be addressed during future studies.

**NCAT Test Track Findings.** Prowell et al. (2007) reported findings from accelerated loading tests on WMA sections containing Evotherm at the NCAT Test Track. Evotherm was placed on three 200-foot test sections as rehabilitation layers in early November 2005. Figure 6 shows a section view of the layers. Sections N1 and N2 were milled to a depth of 5 inches to complete the structural rehabilitation of those sections. Two lifts of 19.0 mm nominal maximum aggregate size (NMAS) WMA were placed in Sections N1 and N2. The original track structure, 20 inches of HMA, 5 inches of asphalt-treated drainable base, and 6 inches of aggregate underlay the 1-inch Evotherm inlay placed in Section E9. The binder for the 9.5 mm NMAS surface mix was varied for each section (Figure 6). An HMA control containing a PG 67-22 binder (similar to AC-30) was placed in Section N2. All mixtures contained a blend of granite, limestone, and coarse sand.

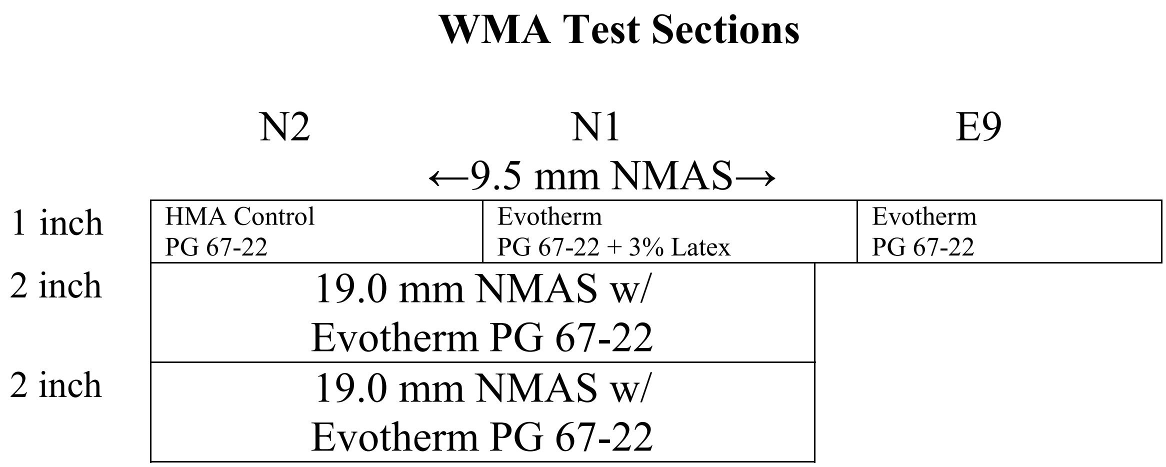


**Figure 6. Section View of Evotherm Layers at NCAT Test Track (after Prowell et al., 2007).**

In-place densities of the WMA surface layers were equal to or better than the corresponding HMA test sections, even though compaction temperatures were reduced by 15°F to 75°F. In fact, the Evotherm mixture was successfully compacted after storage in a silo for 17 hours. Laboratory rutting susceptibility tests conducted in the APA indicated similar performance for the WMA and HMA surface mixtures that contained PG 67-22 base asphalt. However, laboratory tests indicated an increased potential for moisture damage with the WMA mixtures. The two WMA sections and corresponding HMA section demonstrated excellent field performance in terms of rutting following application of >500,000 ESALs in a 43-day period. They turned over one of the WMA sections to traffic less than 2 hours after paving commenced and showed good results with pavement surface temperatures reaching about 90°F for the first 10 days after construction.

Prowell et al. (2007) used an infrared camera to monitor the thermal consistency of the mat behind the paving machine. Infrared images clearly demonstrated minimal thermal differential in the mat indicating no appreciable thermal segregation.

### Development of a Warm-Mix Asphalt Technical Working Group (TWG)

Corrigan (2006) notes that a WMA TWG was initiated by NAPA and FHWA with the mission to evaluate and validate WMA technologies and to implement proactive WMA policies, practices, and procedures that contribute to a high-quality, cost-effective transportation infrastructure. The WMA TWG will foster an environment where transportation officials from government and industry share information on new, innovative, or proven WMA technologies and validate those technologies, which will safeguard the transportation infrastructure of the U.S. and ensure that transportation funding and programs are efficiently and effectively utilized. The WMA TWG was developed to:

- provide national guidance in the investigation and implementation of WMA technologies;
- identify, review, validate, and provide technical guidance that will provide a WMA product with quality, cost-effectiveness, and performance equivalent to conventional HMA with the additional benefit of reduced emissions during production and placement; and
- discuss problems with WMA technology and develop solutions to such problems.

The WMA TWG is made up of representatives from the FHWA, NAPA, state highway agencies, state asphalt pavement associations, American Association of State Highway and Transportation Officials (AASHTO), NCAT, the hot mix asphalt industry, labor, and National Institute for Occupational Safety and Health (NIOSH). Further information on the WMA TWG is found at NAPA's webpage (http://www.warmmixasphalt.com/).

### National Cooperative Highway Research Program (NCHRP) Project 09-43

NCHRP has requested proposals on Project 09-43, "Mix Design Practices for Warm-Mix Asphalt Technologies," for fiscal year 2007. The objective of this research is to develop a mix design method for WMA in the form of an AASHTO-style manual of practice. This method shall:

- be based on Superpave mixture design methodology,
- include a suite of performance tests to assess whether a WMA mixture design will provide satisfactory field service, and
- apply to any WMA technology used to lower mixing and compaction temperatures.

Additional information on this project is available at the NCHRP webpage (http://www4.trb.org/trb/crp.nsf/All+Projects/NCHRP+9-43).

## ADVANTAGES AND DISADVANTAGES OF WARM-MIX ASPHALT

The benefits and limitations of WMA that were identified during review of the literature and through discussions with individuals having experience with WMA are listed in this subsection. The specific advantages and disadvantages of WMA are rather dependent on the specific WMA process being considered. Therefore, it may be somewhat misleading to assemble all the WMA processes into one group and elucidate their features that are superior or inferior to HMA. Nevertheless, the authors have attempted this in the following two subsections.

### Benefits of WMA as Compared to HMA

Some of the benefits of WMA have been discussed above where the individual WMA processes are discussed. The potential advantages of WMA products/processes, in general, over HMA are tremendous. The specific benefits and the degree of the benefits depend, of course, upon which WMA process is used. However, potential benefits include:

- significantly lower production and placement temperatures;
- less aging of binder during plant mixing and placement, thus improving longevity of pavement service life;
- reduced thermal segregation in the mat;
- less fuel/energy consumption, thus lowering fuel/energy costs;
- decreased emissions/odors from mixing plant and during placement;
- decreased dust production due to lower temperatures and shorter heating time;
- extended paving season (i.e., paving during cooler weather);
- extended mix haul distance (due to less difference between ambient temperature and mix temperature) and, thus providing expanded market areas;
- paving in non-attainment areas;
- more daylight paving (i.e., reduced requirements for night paving);
- facilitates compaction, which is beneficial for stiff mixes, RAP mixes, low-temperature paving, and reducing compaction effort;

- faster construction of pavements made of deep lifts of asphalt (e.g., intersections, which need to be opened as soon as possible; less time is required to cool the mix before the next lift is placed);
- improved working conditions for plant/paving crew;
- improved thin-lift capabilities (i.e., lower cooling rate from maximum temperature or lower compaction cessation temperature);
- quicker opening to traffic for some WMA products (a particularly important factor for some airports);
- diminished consternation of public over emissions; and
- easier permitting for plant site in urban areas.

A study of materials and pavements in Canada (Warm-Foam, similar to WAM-Foam) (Johnston et al., 2006) and Iceland (WAM-Foam, Aspha-Min, and Sasobit) (Kristjansdottir, 2006) indicated that WMA offers specific advantages for paving during cold weather when the WMA is placed at or near temperatures typically used for HMA. This offers a greater temperature gap between production and compaction cessation of the more easily compacted WMA and, incidentally, increases the allowable haul distance. This process is particularly beneficial for stiff mixes such as those containing hard binder and/or RAP.

Kristjansdottir et al. (2007) deduced that while lower emissions and reduced energy consumption are admirable benefits by themselves, they do not make a strong business case for adoption of WMA technology. Reduced viscosity by itself or in combination with other benefits appears to offer more potential for widespread WMA adoption, because these could allow owner agencies and contractors to:

- reduce compaction risks associated with cold weather,
- reduce compaction equipment needed on the jobsite, and
- lower the risk of poor compaction when working with stiff mixtures.

The extent of these potential benefits and how to optimize them needs to be studied in a strategic, nationally coordinated research program. In the U.S., several state DOTs, municipalities, and the NCHRP have initiated studies of WMA, but these are not coordinated and do not address all of the aspects of WMA. Studies should include long-term performance, life-cycle cost analyses, and a commitment by owner agencies (Kristjansdottir et al., 2007).

**Environmental Benefits of WMA**

To maximize our survival time on this planet, society must develop ways to reduce consumption of energy and fossil fuel, generation of heat, and greenhouse gas emissions. Scientists must conduct the required research, and then agencies must enact incentives, when necessary, to implement those ideas that make sense. Research needs to determine if WMA is logical, environmentally beneficial, and cost effective, and if so, engineers must develop the tools that will bring it into common use.

Jenkins et al. (1999) stated that the WAM-Foam process can be performed with 40 percent less energy consumption during plant processing than HMA. McKenzie (2006) describes how lower WMA production temperatures could lead to fuel savings that outweigh the additional cost of \$3.60/ton of mix for the Aspha-Min additive.

According to Barthel and Von Devivere (2003) when using Aspha-Min, measurements conducted for Eurovia indicated a 30 percent reduction in energy consumption because of a 54°F to 63°F reduction in mix temperature and a 75 percent reduction in fume emissions resulting from a 47°F reduction in production temperature. Measurements at the application site indicate a reduction in fume emissions of more than 90 percent, when the mix temperature was reduced from 345°F to 285°F and, in all cases, when Aspha-Min has been added and temperatures reduced, odor has decreased, and crew members have confirmed improved working conditions.

When using WAM-Foam, Shell reported plant fuel savings and $CO_2$ reductions of 30 percent. Measurements from a drum plant in Norway showed that WAM-Foam production yielded the following reductions, as compared to HMA at identical production rates: 40 percent in diesel consumption, 31 percent in $CO_2$ emissions, 29 percent in CO emissions, and 62 percent in $NO_X$ emissions (Larsen et al., 2004).

Based on simple heat balance calculations, Romier et al. (2006) report that the heating energy required for LEA is less than 50 percent of a similar HMA. Based on those calculations, they further report that LEA can reduce greenhouse gas ($CO_2$, $N_2O$, and $CH_4$) emissions by 50 percent.

If WMA technologies, in general, decrease heat of the mixture and emissions of volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs), they will certainly improve safety and working conditions for production workers and paving crews.

### Benefits of WMA as Compared to Cold Mix

In summary, Soto and Blanco (2004a) and Els (2004) offer the following advantages of WMA over cold mixtures for paving and patching, particularly for patching permeable friction courses.

- For WMA, essentially no curing time is necessary before trafficking.
- WMA allows use of higher quality aggregates that cannot be used in cold mixes.
- WMA provides better quality mixes due to the total coating of aggregates and binder film uniformity.
- WMA offers improved handling and compaction over cold mix.

### Hindrances to WMA Implementation

Even with the demonstrated benefits of WMA, particularly for large urban (non-attainment) areas along with and encouraging performance results, the new product still has significant hurdles to overcome before widespread acceptance in the U.S. (Zettler, 2006). Generally speaking, the paving industry, as a whole, is slow to accept new technologies. For example, Superpave has been around for 11 years, and it is still not universally accepted by all state DOTs.

Since WMA technologies are new, and most are proprietary, they will likely increase initial production costs. For mix production in Iceland, Kristjansdottir (2006) estimated per-ton premiums of $0.30 for WAM-Foam, $3.50 for Sasobit, and $4.00 for Aspha-Min. These costs were offset by reductions in fuel costs such that the percentage increase in mix production were -1.5 percent, 2.1 percent, and +2.7 percent, respectively. Some WMA additives can be added to the pugmill or blown into the mixing plant at the same point where the asphalt is injected into the drum (or the RAP collar), while others require additional equipment at the plant.

The diminished tensile strength reported by NCAT (Hurley and Prowell, 2005a, 2005b) is an indicator that more water remains in WMA than in HMA. However, to date, researchers are getting mixed signals on this issue, since field cores obtained from WMA test pavements indicate no damage. If findings from the laboratory and the field conflict, then, clearly, the laboratory procedures for evaluating WMA will need to be modified.

Koenders et al. (2000) asserted that WMA products that use emulsions (and possibly others that use water) might cause problems in the weighing system and the dust collection system of the mixing plant. They further indicated that, in their trials, this was not a major problem, but in routine operations, one should be aware of this possibility.

Hadley et al. (1969) associated lower HMA mixing temperatures with decreased tensile strength. Later, Kennedy et al. (1984) showed that increasing mixture temperature will enhance moisture susceptibility of HMA. They both associated higher mixing temperatures with lower viscosity of the asphalt and, thus, better wetting of the aggregate surface along with slightly more asphalt absorption into the aggregate surface which results in maximizing adhesion at the asphalt-aggregate interface. WMA research should include comparative evaluations of moisture susceptibility of similar WMA and HMA paving mixtures.

Research is needed to answer questions that remain when one carefully considers the WMA mixture design, mixture evaluation, construction, and performance issues as compared to traditional HMA.

- Because of the lower mixing temperature, does WMA yield less binder absorption into the aggregates? If so, how will lower absorption affect mixture design (optimum asphalt content) and long-term performance (e.g., moisture susceptibility)?
- Some WMA products have significantly lowered air voids during standard Superpave gyratory compaction as compared to similar HMA, which indicates reduced optimum asphalt content. Will the reduced asphalt content lead to problems related to durability (e.g., cracking, oxidative aging, and/or moisture susceptibility)?
- For testing HMA in the laboratory, there are essentially no cure time requirements for specimens. Are these procedures acceptable for WMA specimens, or is some cure time needed to expel the moisture for certain WMA products to yield realistic predictions of performance?
- Less heat energy for WMA processes likely leaves more moisture in the aggregates and, thus, in the compacted mat. How will this potential moisture affect short-term pavement performance?
- With less oxidative aging in the plant, should one start with a harder asphalt binder than typically used for HMA? If not, will the less aged, softer binder combined with the potential moisture in some WMA mixtures lead to premature permanent deformation?
- Will some cure time be required for WMA products containing moisture before traffic can be allowed on it without concern about permanent deformation?

In the survey conducted by Kristjansdottir et al. (2007), several respondents indicated that WMA will only be an option if it cost the same or less than HMA, unless (1) environmental regulations are made stricter or (2) it provides some quality or construction benefit (then a moderate increase in cost would be acceptable).

## COMPARATIVE COSTS OF PRODUCING WMA

Kristjansdottir et al. (2007) reported that, on the few WMA jobs where energy consumption was measured, there was typically a 20 to 75 percent reduction as compared to HMA, depending on how much the production temperature was lowered. The level of this benefit depends on the type and cost of energy. For example, if energy cost is high, the benefit, of course, is greater. Whether the power comes from fossil fuel or electricity, it requires roughly 300,000 BTUs to produce a ton of HMA, which is equivalent to about 2 to 3 gallons of fuel oil or diesel or about 2.5 to 3.5 therms of natural gas. Table 6 shows general costs for producing HMA and estimated savings from WMA technologies based on selected local energy costs. Costs for specific plants and materials (e.g., aggregate moisture content) will vary.

**Table 6. Cost Savings of WMA at Selected sites (after Kristjansdottir et al., 2007).**

| Location | Iceland | Honolulu, HI | Joliet, IL |
|---|---|---|---|
| Fuel Source | No. 2 fuel oil | Diesel | Natural gas |
| Amount to make 1 ton of $HMA_a$ | 2 - 3 gallons (7.6 - 11.4 L) | 2 - 3 gallons (7.6 - 11.4 L) | 2.5 - 3.5 therms |
| Fuel $cost_b$ | $2.50/gallon ($0.66/L) | $2.20 - $3.00/gallon ($0.58 - $0.79/L) | $0.70 - $0.80/therm |
| Fuel cost to make 1 ton of $HMA_c$ | $5.00 - $7.50 | $4.40 - $9.00 | $1.75 - $2.80 |
| Electricity to make 1 ton of $HMA_d$ | 8 - 14 kWh | 8 - 14 kWh | 8 - 14 kWh |
| Industrial electricity $cost_e$ | $0.02/kWh | $0.1805/kWh | $0.0445/kWh |
| Electricity cost to make 1 ton of $HMA_f$ | $0.16 - $0.28 | $1.44 - $2.53 | $0.36 - $0.64 |
| Total energy cost to make 1 ton of $HMA_g$ | $5.16 - $7.78 | $5.84 - $11.53 | $2.11 - $3.44 |
| 20% savings with $WMA_h$ | $1.00 - $1.50 | $0.88 - $1.80 | $0.35 - $0.56 |
| 50% savings with $WMA_i$ | $2.50 - $3.75 | $2.20 - $4.50 | $0.88 - $1.40 |

a. Aggregate moisture content assumed typical at 2 – 4 percent. Amounts of fuel are general averages.
b. Numbers taken from personal correspondence with a producer in each area.
c. Range shown is the low end amount of fuel multiplied by the low end fuel cost and the high end amount of fuel multiplied by the high end fuel cost. In general, this constitutes the cost to dry and heat aggregate.
d. Taken as the average of 8 to 14 kWh range obtained from (EFAI 2006). This constitutes other power requirements not furnished by the aggregate dryer or drum plant burner.
e. Taken as the average industrial retail price for the particular region either from the web page of Reykjavik Energy, www.or.is (Iceland) or from Table 5.6A of the Energy Information Administration's July 2006 *Electric Power Monthly*.
f. Range shown is the low electricity requirement multiplied by the low end electricity cost and the high end electricity requirement multiplied by the high end electricity cost.
g. Fuel cost added to electricity cost.
h. A rough estimate of the low end of expected savings from WMA technology. Range shown is the low end and high end of the fuel cost each multiplied by 20 percent.
i. A rough estimate of the low end of expected savings from WMA technology. Range shown is the low end and high end of the fuel cost each multiplied by 50 percent.

Use of WMA increases costs associated with various aspects of the technology. Kristjansdottir et al. (2007) tabulated costs for some of the leading WMA technologies (Table 7). They added that the purpose of Table 7 is not to compare costs of WMA technologies, but rather to show that WMA technologies have associated costs that must be at least matched by their perceived benefits. Since these technologies are relatively new, their costs fluctuate and will, with increasing use, likely decrease with time.

**Table 7. Costs of Various WMA Technologies (after Kristjansdottir et al., 2007).**

| WMA Technology | WAM-Foam[a] | Aspha-Min | Sasobit | Evotherm[b] |
|---|---|---|---|---|
| Equipment modification or installation costs | \$30,000-\$70,000 | \$0-\$40,000 | \$0-\$40,000 | minimal |
| Royalties | \$15,000 first yr<br>\$5,000/plant/yr<br>\$0.30/ton | None | None | None |
| Cost of material | NA | \$0.60/lb[c] | \$0.80/lb[d] | 7%-10% more than asphalt binder |
| Recommended dosage rate | NA | 0.3% by weight of mix | 1.5% to 3% by weight of binder | Use in place of asphalt binder |
| Approximate cost per ton of mix (per tonne of mix) | \$0.30[e]<br>(\$0.33) | \$3.60[e]<br>(\$3.96) | \$1.30 - \$2.60<br>(\$1.43 - \$2.86) | \$3.50 - \$4.00<br>(\$3.85 - \$4.40) |

a. According to electronic mail from Øyvind Moen, Kolo Veidekke, Norway. February 10, and January 19, 2006. The high end estimate of equipment cost comes from a Prowell and Hurley presentation accessible at: http://www.pavementpreservation.org/library/getfile.php?journal_id=735.
b. According to phone conversation with Johathan MacIver, Business Development Manager, Asphalt Innovations, MeadWestvaco. July 28, 2006.
c. According to electronic mail from Barry McKeon, Technical Manager at Hubbard Construction Company in Orlando, Florida. February 6, 2006.
d. According to electronic mail from Matthias Nolting, Business Unit Manager, Sasol Wax. January 19, 2006.
e. Not including first-year and royalty costs.
f. From Brown (2006).

Contractors perceive risk with new processes and materials and, as a result, increase their bid prices. Kristjansdottir et al. (2007) suggested that risks associated with WMA can be broadly classified into long-term performance and uncertainty. WMA is relatively new with the oldest sections being about 10 years old. While performance has generally been good, substantial empirical evidence of pavement life equivalent to HMA is needed to reduce perceived risk.

## SUMMARY OF FINDINGS AND RECOMMENDATIONS

WMA is distinguished from other asphalt mixtures by the temperature regimes at which it is produced along with the strength and durability of the final product. Cold asphalt mixtures are typically manufactured at ambient temperature (e.g., 68°F to 120°F), while hot mix is typically produced in the range of 285°F to 340°F. Warm mixes are those generally produced in the temperature range of 200°F to 275°F. The goal with warm mix is to obtain a level of strength and durability that is equivalent to HMA.

### Findings

Based on a review and synthesis of all known literature from worldwide sources, the findings are highlighted.

- WMA is not a new process; however, there are significant new technologies which deserve exploration and are being studied by a number of state agencies and municipalities.
- Six new WMA technologies appear to deserve further investigation: Aspha-Min, WAM-Foam, Low-Energy Asphalt, Sasobit, Evotherm, and Asphaltan B. Aspha-Min, Sasobit, and Evotherm are most likely to be available in Texas. Only Evotherm requires no plant modifications. A brief history leading up to the current technologies and detailed descriptions of each are provided.
- Benefits and limitations of WMA as compared to HMA are listed in this synthesis in a section dedicated to these issues. Specific advantages and disadvantages of WMA are dependent on the specific WMA process being utilized.
- Advantages of WMA over cold asphalt mixtures for paving and patching, particularly for patching permeable friction courses, may include: no curing time before trafficking, use of higher quality aggregates that cannot be used in cold mixes, better quality mixes due to the total coating of aggregates and binder film uniformity, and improved handling and compaction.
- Reducing production (mixing) and paving (compaction) temperatures by using WMA in place of HMA will yield beneficial environmental effects: decreased fuel or energy consumption (with consequential decreased cost); reduced emissions and odors from plants; reduced smoke and, thus, consternation from the public; and improved working conditions at the paving site. Generally, findings indicate the potential for 30 to 50 percent reduction in energy/fuel, 30 percent reduction in $CO_2$, 40 percent less fumes at the paving machine, and 50 to 60 percent reduction in dust generation.
- On the few WMA jobs where energy consumption has been measured, a 20 to 75 percent reduction was shown as compared to HMA. This depended on how much the production temperature was lowered, as well as the type and cost of the fuel used (higher energy cost

yields greater savings). Contractors perceive risk with new processes and materials and, as a result, increase their bid prices.

- The National Center for Asphalt Technology has conducted more research on WMA than anyone else in the U.S. Their findings from several reports are summarized herein. They recommended that the optimum asphalt content of WMA should be determined in the usual fashion for HMA and then be used in the WMA. Laboratory and field performance of WMA was generally similar to that for HMA.
- Lower mixing and compaction temperatures for WMA as compared to HMA may contribute to incomplete drying of the aggregate and thus increase the potential for moisture damage in the resultant pavement layer.
- Standard mix design procedures for HMA must be modified to accommodate WMA. Aggregate gradations typically used for HMA are acceptable for WMA. WMA technologies aid compaction, thus compactive effort must be reduced to prepare realistic laboratory specimens.
- For testing HMA in the laboratory, there is no cure time requirement for compacted specimens. They are often tested as soon as they reach the specified test temperature. This is probably acceptable for those WMA products that do not depend on moisture to enhance workability and compaction. However, for those products that incorporate moisture to promote aggregate coating, workability, and compaction, some cure time may be needed to expel the moisture and yield realistic predictions of performance. If this moisture is not expelled, laboratory tests to evaluate long-term performance may be negatively impacted (i.e., falsely predict unacceptable performance).
- Mechanical characterization of mixtures should be performed using standard volumetric analyses and laboratory specimen testing. WMA mixtures should be held to the same standards as HMA mixtures; however, proper curing methods for those WMA specimens that initially incorporate water must be determined.
- Regarding structural design, WMA should be given the same value as HMA.
- Compaction temperature of a WMA mat is apparently less critical than that of HMA, but it is still important to complete compaction while the mat temperature is within the appropriate window for the specific WMA product.
- Time to traffic after placing WMA is not a significant issue.
- Based on a limited number of reports that address field performance of WMA, pavements are performing well, but, typically, the sections reported had been in place for less than 5 years.
- WMA processes can incorporate RAP. In fact, some have reported the use of 100 percent RAP in certain WMA processes.
- NCHRP has implemented Project 09-43, “Mix Design Practices for Warm-Mix Asphalt Technologies.” The objective is to develop a mix design method for WMA which shall be based on Superpave mixture design methodology, include a suite of performance tests, and apply to any WMA technology.

- A WMA Technical Working Group was initiated by NAPA and FHWA with the missions to provide national guidance; evaluate and validate WMA technologies; and implement proactive WMA policies, practices, and procedures that contribute to a high-quality, cost-effective transportation infrastructure.

**Recommendations**

The preceding findings appear to support these recommendations.

- Research is needed to answer questions that remain when one carefully considers the WMA mixture design, mixture evaluation, construction, and performance issues as compared to traditional HMA.
    - Because of the lower mixing temperature, does WMA yield less binder absorption into the aggregates? If so, how will lower absorption affect mixture design (optimum asphalt content) and long-term performance (e.g., moisture susceptibility)?
    - Some WMA products have significantly lowered air voids during standard Superpave gyratory compaction as compared to similar HMA, which indicates reduced optimum asphalt content. Will the reduced asphalt content lead to problems related to durability (e.g., cracking, oxidative aging, and/or moisture susceptibility)?
    - For testing HMA in the laboratory, there are essentially no cure time requirements for specimens. Are these procedures acceptable for WMA specimens, or is some cure time needed to expel the moisture for certain WMA products to yield realistic predictions of performance?
    - Less heat energy for WMA processes likely leaves more moisture in the aggregates and, thus, in the compacted mat. How will this potential moisture affect short-term pavement performance?
    - With less oxidative aging in the plant, should one start with a harder asphalt binder than typically used for HMA? If not, will the less aged, softer binder combined with the potential moisture in some WMA mixtures lead to premature permanent deformation?
    - Will some cure time be required for WMA products containing moisture before traffic can be allowed on it without concern about permanent deformation?
- If a northern climate calls for a PG 58-28 and, because of reduced binder aging in WMA, one decides to use a PG 64-22, it would provide essentially the same high-temperature performance (rutting) as a PG 58-28 in HMA. However, if one extracts and recovers the PG 64-22 from the WMA and performs the pressure aging vessel test, one may find that the resulting low-temperature properties will be inadequate to meet specified values. A modifier could be used to address this issue, but its cost would offset some of the economic benefits of the WMA. This issue needs to be addressed during future studies.

- Nationally coordinated research is needed to further evaluate field performance, the selection of the optimum asphalt content, and the selection of appropriate binder grades for lower production temperatures.

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# APPENDIX A

# TxDOT EVOTHERM WARM-MIX TRIAL

# SAN ANTONIO DISTRICT—2006

# TxDOT EVOTHERM WARM-MIX TRIAL ON LOOP 368, SAN ANTONIO DISTRICT—2006

## Background

This project represents the first warm-mix asphalt trial placed by the Texas Department of Transportation. Evotherm, developed by MeadWestvaco Asphalt Innovations, Charleston, South Carolina, uses a non-proprietary technology that is based on a chemical package that includes emulsification agents; additives to improve aggregate coating, mixture workability, and compaction; as well as adhesion promoters (anti-stripping agents). The product enhances mixture workability, while lowering mixing temperatures to as low as 200°F. No plant modifications are required; the mix can be stored in silos and may be utilized with or without polymer modifier.

## Objectives

The objectives of TxDOT in conducting this field trial include the following:

- to evaluate the production, placement, and compaction of warm mix as compared with a conventional hot mix control using a standard TxDOT mixture design, and
- to evaluate the short- and long-term performance of the warm mix versus a control hot mix.

## Project Description

This project was in Bexar County within the city limits of San Antonio as shown in Figure A1. The project is located on Loop 368 (Old Austin Highway) and is a four-lane roadway divided by a median with curb and gutter and many businesses along each side.

The existing pavement (prior to placement of the warm mix and control) consisted of a cold-milled asphalt surface that had been seal coated with AC-15P and a Grade 4 precoated aggregate. The seal coat had been under traffic for about a month prior to the overlay.

All of the paving for this project was conducted at night, and a description of the paving sequence and locations is described in the following sections.

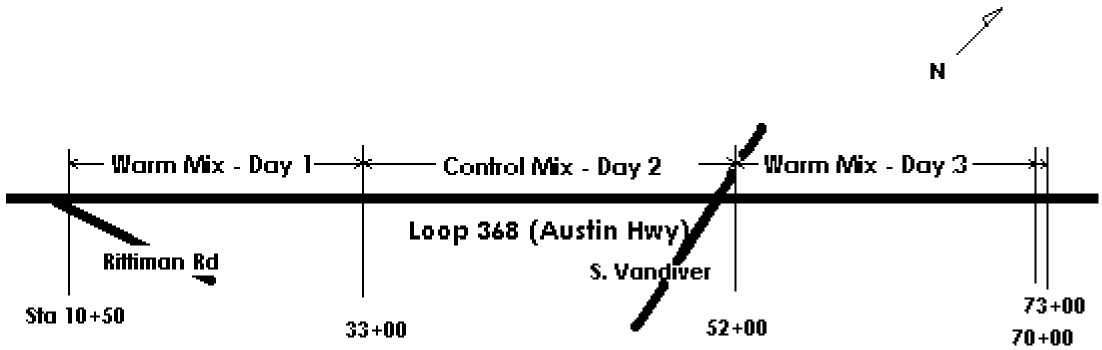


**Figure A1. San Antonio Evotherm Field Trial Location and Layout.**

***Day 1 of Field Trial (Warm Mix)***

*Mixture*: Warm Mix (produced by Vulcan Materials)

*Placed:* Began PM of Aug 30, 2006, and ended in the AM of Aug 31, 2006

*Quantity*: 1202.81 tons

*Limits*: Northbound and Southbound, 2 lanes in each direction,
Station 10+50 to Station 33+00

***Day 2 of Field Trial (Control)***

*Mixture:* Control Mix (produced by Vulcan Materials)

*Placed*: Began and ended in the PM of Aug 31, 2006

*Limits*: Northbound and Southbound, 2 lanes in each direction,
Station 33+00 to Station 52+00

***Day 3 of Field Trial (Warm Mix)***

*Mixture*: Warm Mix (produced by Vulcan Materials)

*Placed:* Began PM of Aug 30, 2006, and ended in the AM of Aug 31, 2006

*Quantity*: 697.81 tons

*Limits*: Southbound Inside Lane, Begin Station 73+00, End Station 52+00
Northbound Inside Lane, Begin Station 52+00, End Station 70+00

The warm and control mixes were produced by Vulcan Materials of San Antonio and placed by Dean Word Company of New Braunfels. Researchers also noted that the field trials were placed within the limits of a much larger HMAC paving project (CSJ 0016-08-027) that was both produced and placed by Dean Word Company.

**Mixture Design**

The control and warm mixtures met the gradation requirements of a TxDOT Item 341, Type C, dense-graded HMAC. The mixture designs were performed by Vulcan Materials laboratory. The asphalt used for the control HMAC was Valero PG 76-22. The base asphalt for the warm mix started as a Valero PG 64-22 prior to modification. Ergon modified and emulsified the asphalt using chemistry supplied by MeadWestvaco. Once modified, the warm-mix binder met the specifications of PG 76-22 (see Table A1). The modified asphalt was then emulsified and provided to Vulcan Materials laboratory to perform the mixture design. Two aggregate sources were used for the mixtures: Vulcan's Helotes Pit limestone and the Harris Pit field sand. Aggregate properties are as shown in Table A2. Note that the same aggregate sources and gradations were used for both the warm mix and the control.

Both warm and control mixtures were designed using a Texas gyratory compactor with a target density of 96.5 percent. Tables A3 and A4 present mixture design information.

**Table A1. Valero PG 76-22 Base Asphalt Superpave Grading Information.**

## SUPERPAVE BINDER SPECIFICATION M-320

**Customer Information:** | **Paragon Information:**

| Customer Information | | Paragon Information | |
|---|---|---|---|
| Company Name: | Mead Westvaco | Project Number: | 2006-21 |
| Address: | | Sample Identification: | |
| City/State/Zip: | | Technician Identification: | AGW |
| Contact Person: | TOM GIRARDEAU | Report Number: | |
| Sample Description: | 2% NX-1181 LATEX | Date Tested: | 5/11/06 |
| Sample Identification: | ZW361095 | Date Issued: | |
| Sample Condition: | | Notes: | 24 hour 80C Evap. Residue |
| Date Received: | | | |

| ORIGINAL BINDER | | T240 RESIDUE |
|---|---|---|
| Phase Angle: | | |
| T 28 Flash: | | |
| T 316 @135C | 1460.00 | |
| T 316 @163C | | Wt. Loss, % |
| T 316 @190C | | |

| ORIGINAL BINDER | | T240 RESIDUE | R 28 RESIDUE | | | | | |
|---|---|---|---|---|---|---|---|---|
| | T 315 | T 315 | | T 315 | | T 313 | T 313 | T 314 |
| Temp. °C | G*/sin δ 1.00 kPa min. | G*/sin δ 2.20 kPa min. | Temp. °C | G* sin δ 5.00 MPa max. | Temp. °C | Stiffness, S 300 MPa max | Slope, m 0.300 min. | Strain, % 1.0% min. |
| 40.00 | | | 37.00 | | 12.00 | | | |
| 46.00 | | | 34.00 | | 6.00 | | | |
| 52.00 | | | 31.00 | 1.843 | 0.00 | | | |
| 58.00 | | | 28.00 | | -6.00 | | | |
| 64.00 | | | 26.50 | | -12.00 | 126.0 | 0.312 | |
| 67.00 | | | 25.00 | | -18.00 | | | |
| 70.00 | | | 22.00 | | -24.00 | | | |
| 76.00 | 1.210 | 2.735 | 19.00 | | -30.00 | | | |
| 82.00 | 0.638 | | 16.00 | | -36.00 | | | |
| 88.00 | | | 13.00 | | -42.00 | | | |
| P/F | 77.80 | | P/F | | P/F | | | |
| TG | | | TG | | TG | | | |

Perf. Grade: **76-22** Certified by Andrew Menapace, Group Leader, Asphalt and Testing

True Grade:

## Table A2. Aggregate Properties (from Mix Design Reports).

| ***Property*** | ***Test*** | ***Spec Reqmt.*** | ***VMC - Helotes*** | ***VMC – Helotes*** | ***VMC – Helotes*** | ***VMC – Helotes*** | ***F. Harris*** |
|---|---|---|---|---|---|---|---|
| | | | ***"C" Rock*** | ***"D" Rock*** | ***"F" Rock*** | ***Mfg Sand*** | ***Field Sand*** |
| Decantation, % | Tex-217-F | 1.5 max | 0.2 | 0.4 | 0.1 | 0.3 | 0.2 |
| Deleterious Material, % | Tex-217-F | 1.5 max | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Surface Agg. Class | Tex-438-A Tex-612-J | B min | B | B | B | B | n/a |
| Magnesium Sulfate Soundness, % | Tex-411-A | 30 max | 7.7 | 10.2 | 10.2 | n/a | n/a |
| LA Abrasion, % | Tex-410-A | 40 max | 25.3 | 26.8 | 26.8 | n/a | n/a |
| Crushed Face Count | Tex-460-A | 85 min | 100 | 100 | 100 | 100 | n/a |
| Micro Deval, % | | Information Only | 19.6 | 18.7 | 19.6 | 29.9 | n/a |
| *Combined Aggregate* | | | | | | | |
| Sand Equivalent, % | Tex-203-F | 45 min | 91 | 91 | 91 | 80 | 82 |

## Table A3. Mix Design Information for Evotherm Warm Mix.

| | Bin No. 1 | Bin No. 2 | Bin No. 3 | Bin No. 4 | Bin No. 5 | |
|---|---|---|---|---|---|---|
| Aggregate Source | VMC - Helotes | VMC – Helotes | VMC – Helotes | VMC – Helotes | F. Harris | |
| Aggregate Description | "C" Rock | "D" Rock | "F" Rock | Manufactured Sand | Field Sand | |
| Individual Bin Percentage | 21% | 11.0% | 28.0% | 28.0% | 12.0% | Total |
| Sieve Size | % Passing | % Passing | % Passing | % Passing | % Passing | % Passing |
| 1" | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| ¾" | 99.9 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/8" | 20.6 | 64.6 | 99.9 | 100.0 | 100.0 | 79.4 |
| No. 4 | 6.5 | 26.0 | 44.6 | 99.0 | 100.0 | 56.4 |
| No. 8 | 0.9 | 6.3 | 10.3 | 79.0 | 99.9 | 37.9 |
| No. 30 | 0.7 | 0.5 | 0.4 | 44.2 | 95.1 | 24.1 |
| No. 50 | 0.6 | 0.5 | 0.3 | 20.5 | 71.4 | 14.6 |
| No. 200 | 0.3 | 0.4 | 0.3 | 2.9 | 8.5 | 2.0 |

| | | | | | |
|---|---|---|---|---|---|
| Asphalt Source & Grade: | Valero PG 76-22 * | Residual Binder Percent, (%): | 4.2 | Asphalt Spec. Grav.: | 1.043 |

*Note the base asphalt was Valero PG 64-22 but was modified by MeadWestvaco to a PG 76-22 prior to emulsification.

| | | | |
|---|---|---|---|
| Antistripping Agent: | - | Percent, (%): | - |

| | |
|---|---|
| VMA at Optimum | 13.0 |

| Mixture Evaluation @ Optimum Asphalt Content | | |
|---|---|---|
| Indirect Tensile Strength (psi) | Hamburg Wheel Tracking Test | |
| | Number of Cycles | Rut Depth (mm) |
| 60.4 | 5000<br>6577 | 7.86<br>12.5 |

Remarks: Mixed at 240°F. Cured for 2 hours and compacted at 240°F. Hamburg specimens remained at room temperature overnight prior to testing.

**Table A4. Mix Design Information for Control Hot Mix.**

| | Bin No. 1 | Bin No. 2 | Bin No. 3 | Bin No. 4 | Bin No. 5 | |
|---|---|---|---|---|---|---|
| Aggregate Source | VMC - Helotes | VMC – Helotes | VMC – Helotes | VMC – Helotes | F. Harris | |
| Aggregate Description | "C" Rock | "D" Rock | "F" Rock | Manufactured Sand | Field Sand | |
| Individual Bin Percentage | 21% | 11.0% | 28.0 | 28.0% | 12.0% | Total |
| Sieve Size | % Passing | % Passing | % Passing | % Passing | % Passing | % Passing |
| 1" | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| ¾" | 99.9 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 3/8" | 20.6 | 64.6 | 99.9 | 100.0 | 100.0 | 79.4 |
| No. 4 | 6.5 | 26.0 | 44.6 | 99.0 | 100.0 | 56.4 |
| No. 8 | 0.9 | 6.3 | 10.3 | 79.0 | 99.9 | 37.9 |
| No. 30 | 0.7 | 0.5 | 0.4 | 44.2 | 95.1 | 24.1 |
| No. 50 | 0.6 | 0.5 | 0.3 | 20.5 | 71.4 | 14.6 |
| No. 200 | 0.3 | 0.4 | 0.3 | 2.9 | 8.5 | 2.0 |

| | | | | | |
|---|---|---|---|---|---|
| Asphalt Source & Grade: | Valero 76-22 | Binder Percent, (%): | 4.8 | Asphalt Spec. Grav.: | 1.052 |

| | | | |
|---|---|---|---|
| Anti-stripping Agent: | Pre-Tech Pave Grip 400 | Percent, (%): | 0.75 |

| | |
|---|---|
| VMA at Optimum | 14.2% |

| **Mixture Evaluation @ Optimum Asphalt Content** | | |
|---|---|---|
| Indirect Tensile Strength (psi) | Hamburg Wheel Tracking Test | |
| | Number of Cycles | Rut Depth (mm) |
| 173 | 20,000 | 12.5 |

## Mixture Production

Both the warm mix and control were produced at Vulcan Materials plant located in San Antonio on Loop 1604. The plant was a parallel flow Astec with external coater.

The emulsion was pumped from the tanker trucks into the end of the drum through the regular plant metering system.

Production rate for the warm mix was about 190 tons per hour (conventional hot mix for this plant is around 250 tons per hour). The production rate was less than expected and was due to high moisture content in the aggregate stockpiles (primarily the field sand) from a rain that occurred the day prior to the first night of WMA production. The combined stockpile moisture content ranged from 4.8 to 5.2 percent. (Normal stockpile moisture content for these aggregates was between 3 and 4 percent). The limit on the production rate was due to problems with the external coater motor. It would have been desirable to have a mix discharge temperature of 200°F, but at temperatures below 220°F, the plant started having trouble with the coater (asphalt too viscous), causing the motor to trip. Amperages were about 20 percent higher with the warm mix. The drag chain, which transfers the mix up into the silos, was operating normally.

On the average, the fuel consumed was the same for the warm mix as for the hot mix. No reduction in fuel use was observed for the warm mix because of the high moisture content in the aggregates. There were no moisture problems in the baghouse—lots of steam was observed, but bags were not plugged up or caked over.

For the three nights that the test mixes were produced, the plant started producing mix around 7:00 pm and began shipping mix out at around 9:00 pm. About 180 tons of mix were stored during this first 2 hours of production but after the first 180 tons of mix, there was no need to silo mix.

Temperature of the warm mix at the time of loading into the haul trucks was 220°F.

Warm-mix plant samples were compacted in the laboratory under three different curing conditions:

- no cure,
- curing for 2 hours at 200°F, and
- curing for 2 hours at 240°F.

Table A5 shows these results. Averages of all sublots are summarized in Figure A2 for each curing condition. Based on these data, the density of the samples which were cured, whether at 200°F or 240°F, were no different than those that were not cured. The density of the compacted warm-mix specimens were comparable to the control. The control HMAC was compacted at 300°F, and all samples were compacted in the Texas gyratory compactor.

**Hamburg and Overlay Tests on Plant Produced/Lab Compacted Specimens**

Samples of the loose warm mix and hot mix were also sent to TxDOT's Construction Division Laboratory in Austin. These warm-mix samples were reheated and compacted to 93 percent density using the SGC at two different temperatures: 240°F and 300°F. The control samples were compacted to 93 percent density in the SGC at 300°F. These samples were subjected to Hamburg and overlay testing, and the results are shown in Tables A6 and A7.

The Hamburg test is used by TxDOT to measure the moisture susceptibility and rutting potential of HMA layers in Texas. During the test, two 2.5 inch high by 6-inch diameter HMA specimens are loaded at 122°F to characterize their rutting properties. The samples are submerged in a water bath and loaded with steel wheels.

The test loading parameters for the Hamburg test were as follows:

- Load: 705 N (158-lb force)
- Number of passes: 20,000
- Test condition/temperature: Under water at 122°F (50°C)
- Terminal rutting failure criterion: 0.5 inch (12.5 mm)
- HMAC specimen size: 6 inch diameter by 2.5 inch high

**Table A5. Plant-Produced Warm-Mix Samples Compacted after Different Curing Conditions Compared to the Plant-Produced Hot-Mix Compacted Specimens.**

| *Mixture* | *Sample Description* | *Asphalt Content (Ignition Method), %* | *Maximum Specific Gravity (Gr)* | *Bulk Specific Gravity (Ga)* | *Voids in Mineral Aggregate (VMA)* | *Density, %* |
|---|---|---|---|---|---|---|
| ***Warm Mix: No Cure*** | Start up sample (Day 1) | 4.6 | 2.408 | 2.359 | 12.5 | 98.0 |
| | Sampled at 250 tons (Day 1, Lot 1, Sublot 1) | 4.6 | 2.441 | 2.377 | 13.1 | 97.4 |
| | Sampled at 750 tons (Day 1, Lot 1, Sublot 2) | 4.6 | 2.423 | 2.368 | 13.3 | 97.7 |
| | Day 3, Lot 2, Sublot 1 | 4.6 | 2.439 | 2.321 | 15.1 | 95.1 |
| | ***Average*** | ***4.6*** | ***2.428*** | ***2.356*** | ***13.5*** | ***97.1*** |
| ***Warm Mix: Cured for 2 hours at 200°F*** | Start up sample (Day 1) | 4.6 | 2.419 | 2.349 | 13.3 | 97.1 |
| | Sampled at 250 tons (Day 1, Lot 1 Sublot 1) | 4.6 | 2.438 | 2.375 | 13.1 | 97.4 |
| | Sampled at 750 tons (Day 1, Lot 1 Sublot 2) | 4.6 | 2.430 | 2.371 | 12.9 | 97.6 |
| | Day 3, Lot 2 Sublot 1 | 4.6 | 2.442 | 2.325 | 15.0 | 95.2 |
| | ***Average*** | ***4.6*** | ***2.432*** | ***2.355*** | ***13.6*** | ***96.8*** |
| ***Warm Mix: Cured for 2 hours at 240°F*** | Start up sample (Day 1) | 4.6 | 2.423 | 2.346 | 13.5 | 96.8 |
| | Sampled at 250 tons (Day 1, Lot 1, Sublot 1) | 4.6 | 2.458 | 2.390 | 13.3 | 97.3 |
| | Sampled at 750 tons (Day 1, Lot 1, Sublot 2) | 4.6 | 2.432 | 2.365 | 13.2 | 97.2 |
| | Day 3, Lot 2, Sublot 1 | 4.6 | 2.440 | 2.334 | 14.6 | 95.7 |
| | ***Average*** | ***4.6*** | ***2.438*** | ***2.359*** | ***13.7*** | ***96.8*** |
| ***Control Hot Mix*** | Start up sample | 4.6 | 2.424 | 2.370 | 12.6 | 97.8 |
| | Day 2, Sublot 1 | 4.7 | 2.460 | 2.390 | 13.5 | 97.2 |
| | Day 2, Sublot 2 | 4.5 | 2.471 | 2.371 | 14.2 | 96.0 |
| | ***Average*** | ***4.6*** | ***2.452*** | ***2.377*** | ***13.4*** | ***97.0*** |

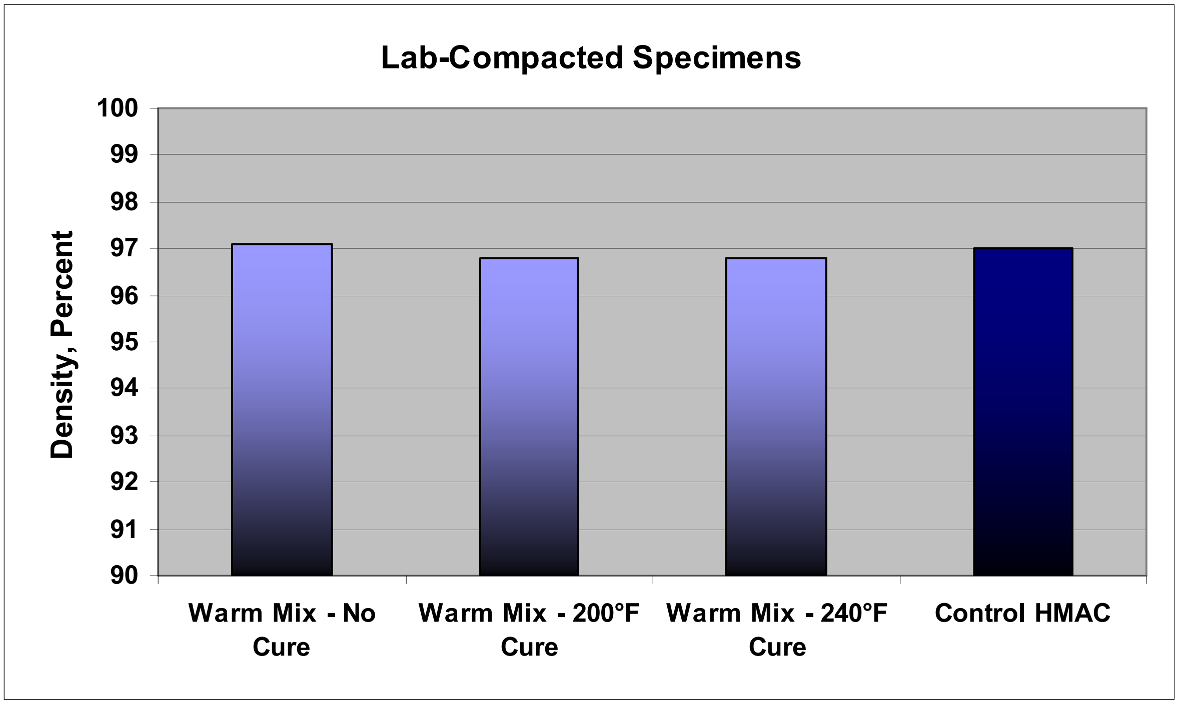


**Figure A2. Compacted Laboratory Density after Different Curing Conditions for Warm Mix Compared to HMAC (Compacted in Texas Gyratory Compactor).**

Generally, the warm-mix samples compacted at 300°F performed better in the Hamburg than those compacted at 240°F. All of the warm-mix samples failed the Hamburg test with the exception of the samples compacted at 300°F from the second night of warm-mix production.

The TTI overlay tester shown in Figure A3 is used to measure the reflection cracking potential of HMA surface layers in Texas. The test loading parameters for the overlay tester were as follows:

- Loading: Cyclic triangular displacement-controlled waveform at 0.025 in (0.63 mm)
- Loading rate: 10 seconds per cycle
- Test temperature: 77°F (25°C)
- Terminal cracking failure criterion: 300 load cycles (for surface mixes)
- HMAC specimen size: 6 inch total length by 3 inch width by 1.5 inch

**Table A6. Hamburg Test Results from Laboratory-Molded Samples.**

| Hamburg Results, Lab Molded Samples | | | | | | | |
|---|---|---|---|---|---|---|---|
| *Plant Mix Description* | *Sample* | *Molding Temp, °F* | *Rut at 5K, mm* | *Rut at 10K, mm* | *Rut at 15K, mm* | *Rut at 20K, mm* | *Passes* |
| **Day 1 Warm Mix Sampled at 750 Tons, Lot 1, Sublot 2** | **1** | 240 | 7.8 | | | | 7400 |
| | **2** | | | | | | |
| | **3** | | 6.4 | | | | 9700 |
| | **4** | | | | | | |
| | **1** | 300 | 5.9 | 12.2 | | | 10,500 |
| | **2** | | | | | | |
| | **3** | | 9.1 | | | | 8700 |
| | **4** | | | | | | |
| **Day 1 Warm Mix Sampled at 250 Tons, Lot 1, Sublot 1** | **1** | 240 | 9.6 | | | | 6500 |
| | **3** | | | | | | |
| | **2** | | 9.7 | | | | 6600 |
| | **4** | | | | | | |
| | **1** | 300 | 4.2 | 10.7 | | | 11,300 |
| | **2** | | | | | | |
| | **3** | | 4.3 | 8.1 | | | 14,700 |
| | **4** | | | | | | |
| **Day 2 Control Mix** | **2** | 300 | 2.3 | 3.6 | 5.1 | 7.0 | 20,000 |
| | **3** | | | | | | |
| | **4** | | 3.3 | 5.5 | 7.8 | 10.3 | 20,000 |
| | **5** | | | | | | |
| **Day 3 Warm Mix Sampled at 250 Tons, Lot 2** | **1** | 240 | 3.7 | 9.2 | | | 13,001 |
| | **2** | | | | | | |
| | **3** | | 5.2 | 10.7 | | | 10,701 |
| | **7** | | | | | | |
| | **6** | 300 | 2.6 | 3.2 | 4.2 | 5.6 | 20,000 |
| | **7** | | | | | | |
| | **4** | | 1.5 | 2.8 | 4.1 | 5.2 | 20,000 |
| | **5** | | | | | | |

**Table A7. Overlay Test Results on Laboratory-Compacted Specimens.**

| Overlay Results | | | | | | |
|---|---|---|---|---|---|---|
| *Mix Description* | *Sample* | *Molding Temp* | *Max load (lbs)** | *Final** Load (lbs)* | *% Decline* | *Cycles* |
| Day 1 Warm Mix Sampled at 750 Tons, Lot 1 Sublot 2 | 1 | 240 | 582.9 | 39.8 | 93.2 | 12 |
| | 2 | | 577.2 | 30.9 | 94.6 | 21 |
| | 1 | 300 | 646.4 | 34.6 | 94.6 | 3 |
| | 2 | | 600.9 | 38.8 | 93.5 | 7 |
| Day 1 Warm Mix Sampled at 250 Tons, Lot 1 Sublot 1 | 1 | 240 | 575 | 38.1 | 93.4 | 21 |
| | 2 | | 631.3 | 43.5 | 93.1 | 21 |
| | 1 | 300 | 838.2 | 58.4 | 93 | 77 |
| | 2 | | 795.7 | 54.8 | 93.1 | 7 |
| Day 2 Control Mix | 1 | 300 | 877.1 | 59.7 | 93.2 | 8 |
| | 2 | | 851.6 | 57.4 | 93.3 | 12 |
| Day 3 Warm Mix Sampled at 250 Tons, Lot 2 | 1 | 240 | 627.7 | 43.5 | 93.1 | 11 |
| | 2 | | 646.2 | 44.6 | 93.1 | 36 |
| | 1 | 300 | 650.9 | 44.1 | 93.2 | 6 |
| | 2 | | 661.6 | 41.4 | 93.7 | 2 |
| | 3 | | 628.4 | 42.4 | 93.3 | 6 |

*   Max Load is the load associated with the initial test cycle.
** Final Load is the load associated with the last test cycle.

**Figure A3. TTI Overlay Tester.**

The overlay tester was developed to judge a mixture's resistance to thermally induced reflection cracking. However, mixes that pass this test will also have good fatigue resistance. The warm-mix laboratory-compacted mixes did poorly in this test, as did the control mix. Newly developed criteria for TxDOT mixes recommend that standard mixes should last a minimum of 300 cycles, whereas crack-resistant overlays should last more than 750 cycles.

The overlay test results seen here for both the warm mix and the control mix are typical of many current TxDOT dense-graded mixes. This has been a result of several factors including:

- the move to stiffer binders, and
- general reduction in asphalt concrete (AC) content.

This has been recognized by TxDOT, and the overlay tester described above has been proposed to address this issue.

**Placement and Compaction**

The mix was loaded into belly dump trucks, which were all tarped and insulated. The mix was hauled a distance of 20 miles (about 25 minutes) to the jobsite. A remixing windrow elevator (Lincoln model 660 AXL) was used to transfer the mix into a Barber Greene 260B paver.

The paver had a vibratory screed, which was on during the paving. One observation by the paving contractor was that "we normally heat the screed once about 20 minutes before starting, but for the warm mix, we had to relight the burners on the screed every 8 to 10 loads because the mat started to tear." Also, he observed that the angle of attack on the screed was doubled what is typically seen on hot mix.

The compacted mat thickness was about 2 inches. Both the control and warm mix were compacted using the same roller pattern: two passes with a vibratory roller, one pass in static mode, then between four and six passes with pneumatic roller.

The vibratory roller was a Hamm HD120 operated at low amplitude and a frequency of about 2500 Hz (midrange).

The pneumatic roller was Ingersall Rand, PT 240N, (24,000 lb, 8 wheels). The tires were bias ply with a tire pressure of 50 psi.

Portions of the overlay were opened to traffic within 2 hours of placement.

Asphalt concrete placement testing as reported by Arias and Associates is shown in Table A8.

**Table A8. Asphalt Concrete Placement Data.**

| Mixture | Mix Delivery Temperature | Placement Temperature | Average Nuclear Density, % |
|---|---|---|---|
| Warm Mix (Day 1 – Aug. 30, 2006 | 180°F to 200°F | 170°F to 180°F | 93.5 to 95.0 |
| Control Mix (Day 2 – Aug. 31, 2006) | 315°F | 305°F | 94.2 |
| Warm Mix (Day 3 – Sept. 7, 2006) | 220°F | 205°F to 210°F | 92.1 to 93.8 |

## Evaluation of 1-Month Road Cores

Cores were obtained 1 month after the warm and control mixes were placed and were sent to TxDOT's Construction Division in Austin for testing. Table A9 tabulates the results of these tests.

The Ga in Table A9 represents the bulk specific gravity of the mix, and the Gr represents the maximum specific gravity. The maximum specific gravity values shown in Table A9 are based on averages values associated with the respective production lot shown in Table A5.

Core samples taken for the indirect tensile strength tests included three samples taken from the wheel path and three samples taken from between the wheel paths for each lot. Averages of the densities of these cores are summarized in Figure A4. Indirect tensile strengths are summarized in Figure A5. Any mix tenderness, binder softening, or insufficient curing that one may expect to be associated with the warm mix could be reflected with increased densities in the wheel path after 1 month of trafficking. However, the densities in the wheel path are *less* than the densities between the wheel paths for both the warm mix and the control mix. Note in Table A9 (Indirect Tensile Strength Cores) that the cores taken in the wheel paths are generally thicker than the cores taken between the wheel path. This may be an indication that the wheel paths may have been rutted prior to overlay (although the surface had been cold milled). This variation in mat thickness will lead to a differential compaction effort resulting in the roller applying more effort on the higher points of the pavement or, in this case, between the wheel paths.

# Table A9. Test Results from Roadway Cores.

**Hamburg Results**

| Core | Description | Rut at 5K, mm | Rut at 10K, mm | Rut at 15K, mm | Rut at 20K, mm | Total Passes | Ga | Gr | Density, % |
|---|---|---|---|---|---|---|---|---|---|
| 1a | Warm Mix, Lot 1 sublot 1, 1st night (15+00 CL 6'offset CL) | 8.2 | | | | 6401 | 2.307 | | 94.3 |
| 1b | | | | | | | 2.313 | 2.446 | 94.6 |
| 2a | Warm Mix, Lot 1 sublot 2 (15+60 OL 7' Offset South Bond) | 7.3 | | | | 7901 | 2.236 | | 92.1 |
| 2b | | | | | | | 2.272 | 2.428 | 93.6 |
| 1a1 | Control Mix | 6.8 | 9.1 | | | 14601 | 2.306 | | 93.5 |
| 1a2 | | | | | | | 2.275 | | 92.3 |
| 1b1 | Control Mix | 4.5 | 5.7 | 7.5 | 10.7 | 20000 | 2.265 | | 91.8 |
| 1b2 | | | | | | | 2.287 | 2.466 | 92.7 |

**Overlay Results**

| Core | Description | Max load (lbs) | Final Load (lbs) | % Decline | Cycles | Ga | | Gr | Density, % |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Original | Trimmed | | |
| 2c | Warm Mix, Lot 1 sublot 2 (15+60 OL) (7'Offset South Bond) | 626.4 | 43.6 | 93.0 | 638 | 2.252 | 2.243 | | 92.4 |
| 2d | | 554.8 | 38.8 | 93.0 | 224 | 2.242 | 2.240 | 2.428 | 92.3 |
| 1c | Warm Mix, Lot 1 sublot 1 , 1st night | 696.0 | 47.9 | 93.1 | 41 | 2.317 | 2.317 | | 94.7 |
| 1d | | 783.0 | 52.6 | 93.3 | 118 | 2.312 | 2.313 | 2.446 | 94.6 |

**Indirect Tensile Strength**

| Core | Description | Diam (in) | Ht (in) | Load (lb) | Strength (psi) | Ga | Gr | Density, % |
|---|---|---|---|---|---|---|---|---|
| 1a | Day 1 Warm Mix | 5.9 | 1.9 | 2254 | 128.1 | 2.248 | 2.437 | 92.2 |
| 1b | | 5.9 | 1.8 | 2269 | 136.1 | 2.248 | | 92.2 |
| 1c | | 6.0 | 1.8 | 2085 | 123.0 | 2.255 | | 92.5 |
| 1a(wp) | | 6.0 | 2.0 | 2285 | 121.3 | 2.240 | | 91.9 |
| 1b(wp) | | 5.9 | 2.0 | 2247 | 122.5 | 2.247 | | 92.2 |
| 1c(wp) | | 5.9 | 2.0 | 2260 | 122.6 | 2.234 | | 91.7 |
| 2a1d | Day 3 Warm Mix | 5.9 | 2.0 | 2842 | 153.4 | 2.331 | 2.440 | 95.5 |
| 2b1e | | 5.9 | 2.0 | 3293 | 177.8 | 2.320 | | 95.1 |
| 2c1f | | 6.0 | 2.0 | 2874 | 152.5 | 2.331 | | 95.5 |
| 2a(wp) | | 6.0 | 2.4 | 3422 | 151.4 | 2.287 | | 93.7 |
| 2b(wp) | | 5.9 | 2.4 | 3433 | 154.4 | 2.284 | | 93.6 |
| 2c(wp) | | 5.9 | 2.5 | 3607 | 155.8 | 2.279 | | 93.4 |
| 3a | Day 2 Control Mix | 5.9 | 1.7 | 2266 | 143.9 | 2.258 | 2.466 | 91.6 |
| 3b | | 5.9 | 1.7 | 2420 | 153.7 | 2.273 | | 92.2 |
| 3c | | 5.9 | 1.7 | 2552 | 162.1 | 2.255 | | 91.4 |
| 3a(wp) | | 5.9 | 1.7 | 3079 | 195.5 | 2.322 | | 94.2 |
| 3b(wp) | | 5.9 | 1.8 | 3178 | 190.6 | 2.310 | | 93.7 |
| 3c(wp) | | 5.9 | 1.8 | 3031 | 181.8 | 2.319 | | 94.0 |

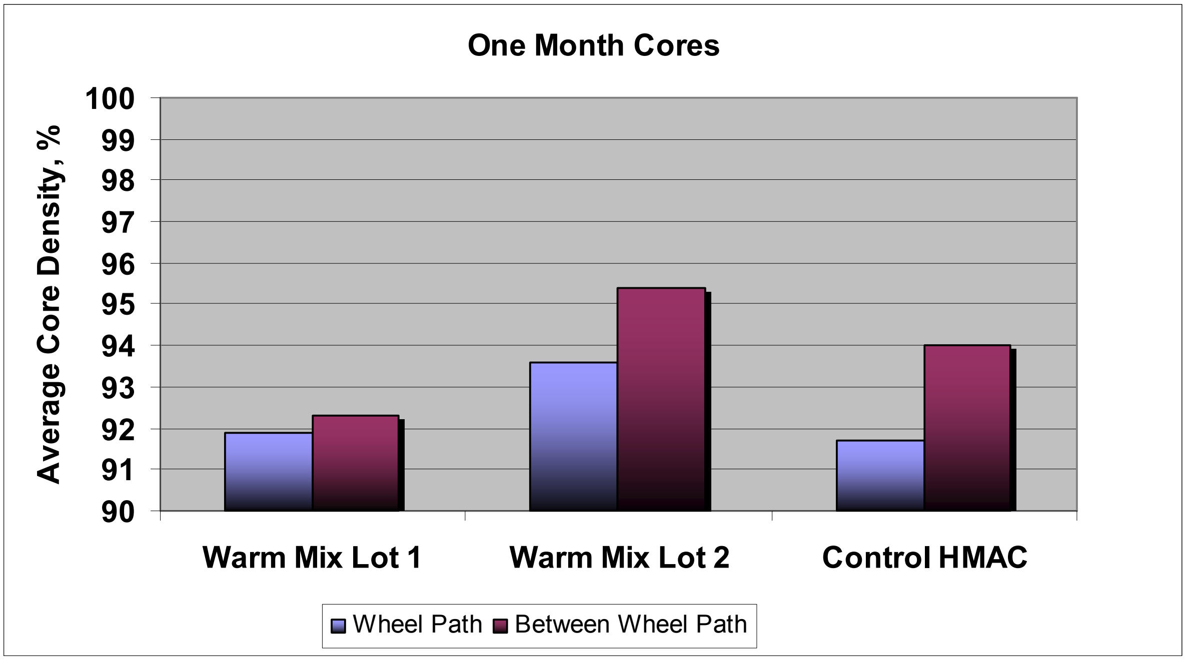


**Figure A4. Average Core Densities in the Wheel Paths and between the Wheel Paths for Warm and Control Mixes.**

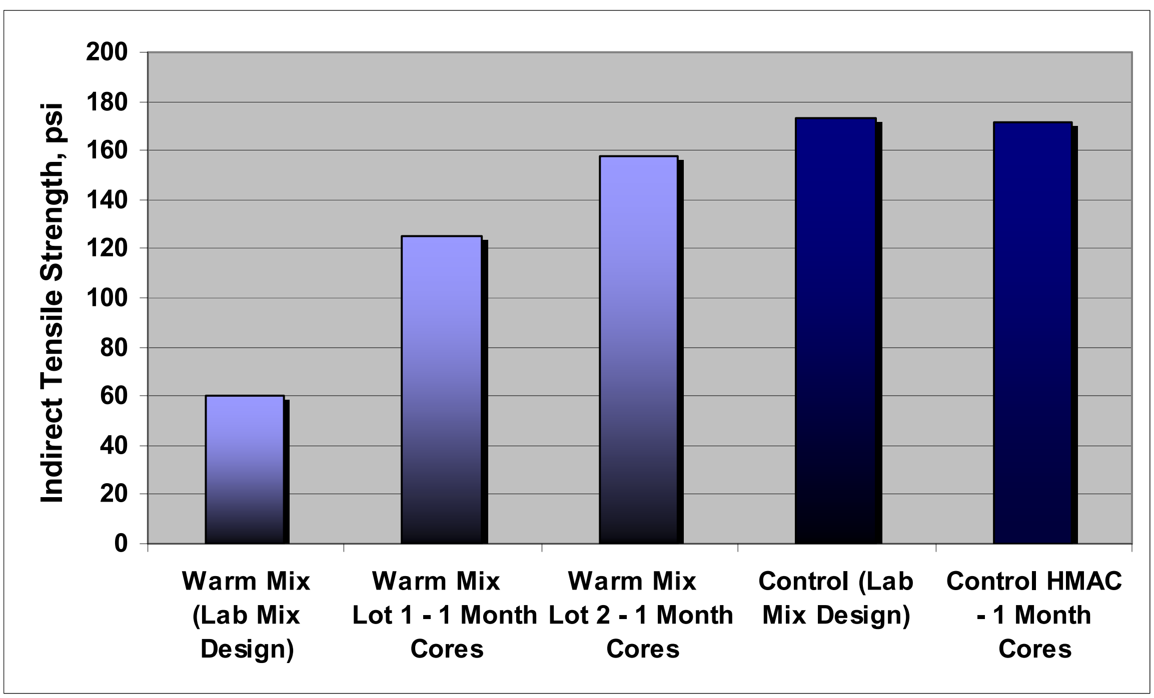


**Figure A5. Indirect Tensile Strength of Road Cores for Warm Mix and Control Mix Compared to Values Obtained from the Mixture Design.**

*Indirect Tensile Strength Test Results for Road Cores*

Results from the indirect tensile strength tests are shown in Table A9. Comparing the tensile strength of the cores in the wheel paths to those between the wheel paths indicate no significant difference. Average tensile strengths for each lot are shown in Figure A5 and are compared to the tensile strength of the lab-molded sample tested during the mix design process. The tensile strengths of the warm-mix cores taken at 1 month show a significant improvement over the tensile strength of the warm mix during the mix design process.

*Hamburg Test Results for Road Cores*

Hamburg test results for the roadway cores are compared to the lab-molded plant mix samples in Figure A6. As mentioned previously, some improvement is observed in the warm-mix samples compacted at 300°F versus those compacted at 240°F. However, the warm-mix cores taken at 1 month did not indicate that the mix improved with time (in terms of rut or moisture susceptibility resistance) compared to the lab-molded samples.

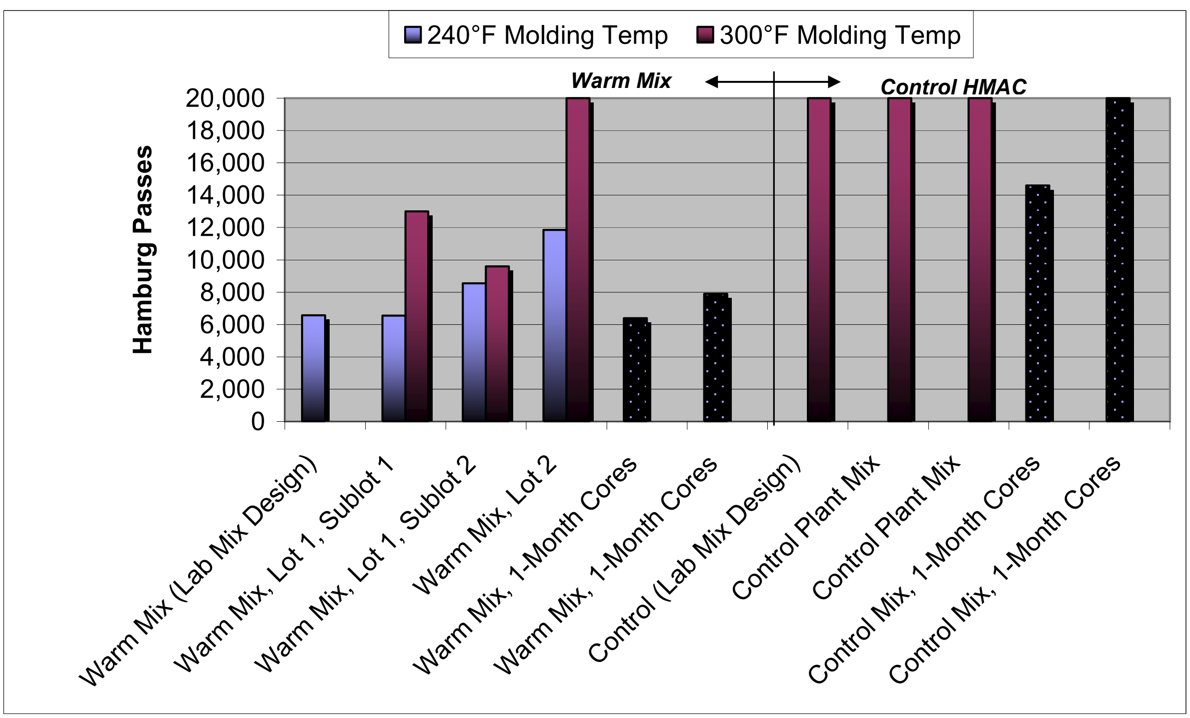


**Figure A6. Hamburg Wheel Tracking Test Results for Lab Molded Warm Mix and Control Mixes Compared to 1-Month Roadway Cores.**

*Overlay Test Results for Road Cores*

Overlay test results for the roadway cores are compared to the lab-molded plant mix samples in Figure A7. All of the lab-molded warm-mix and control HMAC specimens performed poorly in the overlay test. However, there was a significant improvement seen in some of the cores taken at 1 month from the warm-mix sections. There may be a difference in density associated with the cores as compared with the lab-compacted specimens. The lab specimens were compacted to 93 percent density, and the warm-mix road cores ranged from 92.3 to 94.6 percent density. This difference in density would not account for the improvement seen in the overlay test road cores. This difference would indicate there is a "curing" effect that is occurring with time, providing for improved cracking resistance.

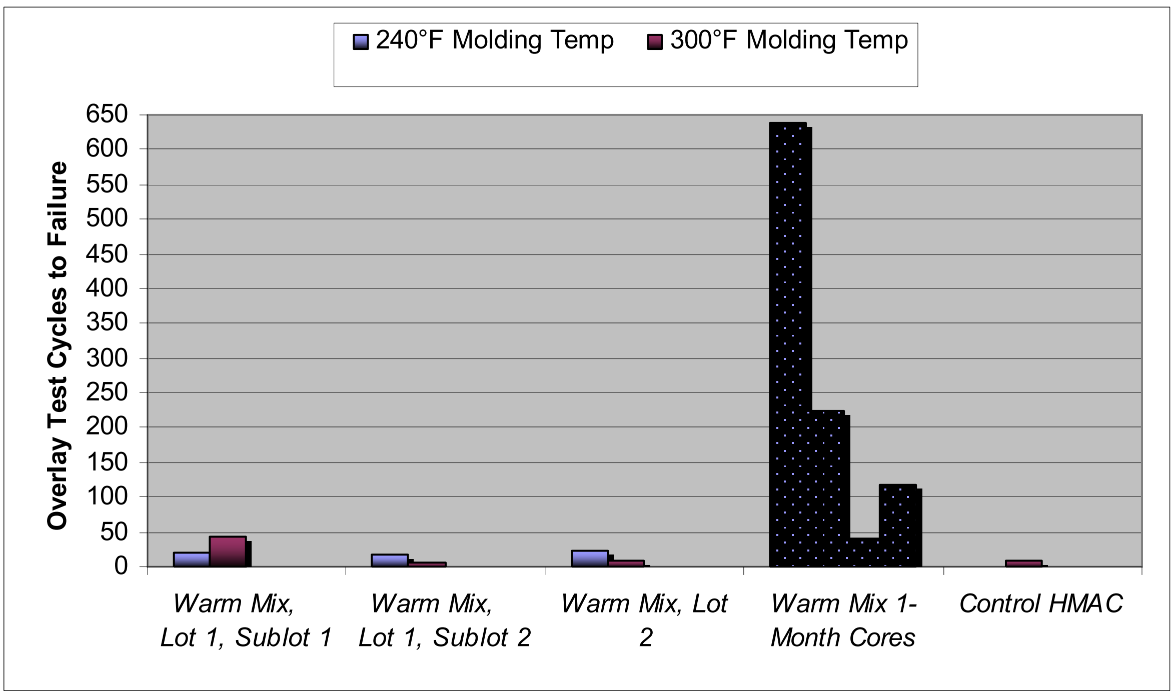


**Figure A7. Overlay Test Results for Lab-Molded Warm-Mix and Control Mixes Compared to 1-Month Roadway Cores.**

**Summary**

TxDOT placed their first warm-mix asphalt trial using the Evotherm process on Loop 368 in the San Antonio District in August/September 2006. All test sections are performing well at this time. TxDOT is still in the process of evaluating the short- and long-term performance of this field trial through field cores and performance monitoring. Preliminary findings based on information documented thus far include the following:

### *Mix Design*

Both warm and control mixes were designed according to Item 341, Type C dense-graded mixes, which employ the use of the Texas gyratory compactor. Both mixes were designed to a target density of 96.5 percent. The control HMAC had an optimum asphalt content of 4.8 percent, and the warm-mix optimum asphalt content (residual binder) was 4.2 percent. The control mix was produced with a PG 76-22 binder, and the warm mix (after the Evotherm modification) was also a PG 76-22. The same aggregate source (predominantly crushed limestone) and gradation was used for both warm and control mixes. Also, both warm and control mixes were produced in the same asphalt plant.

### *Production*

- The warm mix was produced at a temperature of 220°F, and the control mix was produced at 320°F.
- No reduction in fuel consumption was observed for the warm-mix production, which is attributed to a heavy rain prior to production that caused the aggregate stockpiles to be excessively wet requiring more energy for plant operation.
- Warm mix was stored in silos for a maximum of 2 hours prior to load out.

### *Quality Control*

WMA samples were compacted in the field laboratory to densities averaging 97 percent which was the same as the control HMAC compacted densities. To evaluate the effect of laboratory curing on the warm mix, samples were compacted after three curing conditions: no cure, cure for 2 hours at 200°F, and cure for 2 hours at 240°F. The different curing conditions had no effect on compacted density.

### *Placement and Compaction*

- The warm and control mixes were placed over the course of three nights. The warm mix was placed at a temperature ranging from 170°F to 210°F. Nuclear density tests on the warm mix ranged from 92.1 to 95 percent. The control mix was placed at 305°F, and nuclear density tests averaged 94.2 percent.
- The same roller pattern was used for both control and warm mixes.
- No problems were observed with the placement and compaction operation.

- Traffic was allowed onto the warm mix in some areas as soon as 2 hours after placement.

***Laboratory Testing on Lab-Molded Samples and Roadway Cores***

- Density of roadway cores taken after 1 month of traffic showed an overall average density of the warm mix (based on 26 cores) of 93.3 percent. Average density of the roadway cores from the control mix (based on four cores) was 92.6 percent.
- Density of WMA roadway cores taken in the wheel paths was compared with those taken between the wheel paths. There is no indication that the warm mix is densifying further under the action of traffic (after 1 month).
- For laboratory testing in the Hamburg and overlay tester, warm-mix samples were compacted at two different temperatures: 240°F and 300°F. The warm-mix samples compacted at 300°F performed better in the Hamburg than those compacted at 240°F. All of the warm-mix samples failed the Hamburg test requirements (of no more than 12.5 mm rut depth at 20,000 passes) with the exception of the samples compacted at 300°F from the second night of warm-mix production. The warm-mix cores taken at 1 month also failed the Hamburg requirements. The control mix generally passed the Hamburg test with the exception of one set of field cores. Although the test results indicate the potential for rutting or stripping, these problems have not yet been evident in the field.
- Indirect tensile strength tests were performed during the mix design and on roadway cores for both warm and control mixes. The control mix had tensile strengths of around 170 psi (both mix design and roadway cores). During the mix design process, the warm mix only had a tensile strength of 60 psi; however, the warm-mix roadway core tensile strengths ranged from 121 to 178 psi.
- Overlay test results for the roadway cores were compared to the lab-molded plant mix samples. All of the lab-molded warm-mix and control HMAC specimens performed poorly in the overlay test. However, there was a significant improvement seen in the some of the cores taken at 1 month from the warm-mix sections.

***Future Work***

- Cores were taken at 3 months and are in the process of being tested at TTI.
- The district also plans to take cores at 1 year.
- Performance monitoring will continue over the next year.