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16. Abstract Warm Mix Asphalt (WMA) technology, recently developed in Europe, is gaining strong interest in the US. By lowering the viscosity of asphalt binder and/or increasing the workability of mixture using minimal heat, WMA technology allows the mixing, transporting, and paving process at significantly lower temperature. Using this new technology, asphalt mix can be produced as much as 100°F lower than traditional hot mix asphalt (HMA). Several benefits of lower mixing and compaction temperature include: less emission, savings in energy cost, longer construction season, less odor, and construction during non-peak periods. Despite the apparent benefits, some researchers are concerned about the long-term performance of this new mixture. In last few years, dozens of field test sections have been constructed thorough out the USA using different WMA technologies. It is too early to report the performance; but so far, no negative performance has been reported in the literature. In the last few years, several large national and state level research projects have been initiated to evaluate, validate, and implement this new technology. This report documents the results of a comprehensive review of worldwide information dealing with the following issues as related to warm mix asphalt: Current state of the art/practice of WMA; cost and benefits of WMA technology; plant modifications to accommodate WMA; mixture design; durability and performance; performance related testing; quality control; specifications; and construction guidelines.					
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A REVIEW OF WARM MIX ASPHALT

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This report is not intended for construction, bidding, or permits purposes. The engineer in charge of the project was Arif Chowdhury, P.E. # 90891.

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EXECUTIVE SUMMARY

Warm Mix Asphalt (WMA) technology recently developed in Europe is gaining strong interest in the US. By lowering the viscosity of asphalt binder and/or increasing the workability of mixture using minimal heat, WMA technology allows the mixing, transporting, and paving process at significantly lower temperature compare to the conventional hot mix asphalt (HMA). Typically, WMA is defined as the asphalt mixture where the plant mixing temperature range is from 212°F to 275°F.

Type of WMA Technologies

The research team identified as many as fifteen different WMA technologies currently available. Eight of them are available in the USA. They are: Synthetic Zeolite, Double Barrel Green®, Low Energy Asphalt, WAM Foam, Evotherm®, Rediset™ WMX, REVIX™, and Sasobit®. The first four technologies are foaming based WMA, and the second four are based on chemical or organic additive(s). Foaming based WMA introduces a small amount of water into hot asphalt. This water turns into steam dispersed in hot binder which results in a huge and rapid expansion of asphalt binder. Foaming or expansion of binder helps coat the aggregate and increase mixture workability. The introduction of this small amount of water can be done by either a foaming nozzle (Double Barrel Green), or adding a hydrate (Synthetic Zeolite), or using moist aggregate (Low Energy Asphalt). In most cases, additive-based WMA lowers the binder viscosity that enables relatively low mixing temperature and hence increases the mixture workability.

Benefit and Comparative Cost of WMA

There are numerous benefits of WMA identified by several researchers. The potential benefits of WMA products/process, in general, over HMA are tremendous. The specific benefits and the degree of the benefits depend upon which specific WMA process is used. However, some of the important potential benefits include:

- significantly lower production and placement temperatures;
- less fuel/energy consumption, thus lowering fuel/energy costs;

- less aging of binder during plant mixing and placement, thus improving longevity of pavement service life;
- reduced thermal segregation in the mat;
- 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;
- facilitates compaction, which is beneficial for stiff mixes, RAP mixes, low-temperature paving, and reducing compaction effort;
- improved working conditions for plant/paving crew;
- diminished consternation of public over emissions; and
- easier permitting for plant site in urban areas.

The main economic benefit of WMA comes from the energy savings. 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 level of this economic benefit depends on the type and cost of energy. For example, if energy cost is high, the benefit, of course, is greater. Again, some WMA technologies require only initial investment for plant modification, some require continuous additional cost for the additives, and some require both form of additional cost.

Current Research and National Activities

Several initiatives have been undertaken by federal and state agencies, universities, and industries to evaluate, validate, and implement this new technology. Warm Mix Asphalt Technical Working Group (WMA TWG) initiated by Federal Highways Administration (FHWA) and National Asphalt Pavement Association (NAPA) is in the forefront of these

activates in the USA. The objectives of WMA-TWG are 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.

National Cooperative Highway Research Program has currently two major ongoing research projects that are evaluating different aspects of WMA technology. These two projects are Project 09-43, “Mix Design Practices for Warm-Mix Asphalt Technologies,” and Project 09-47, “Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies.” NAPA in cooperation with 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 US through a cooperative agreement between the National Center for Asphalt Technology (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.

Besides the above research projects several other research projects funded by different state highway agencies and private industries have recently been completed or are still ongoing. Most of these projects are evaluating different aspects of this new technology. In the last few years, almost seventy field test sections have been constructed throughout the USA using different types of WMA technologies.

Mixture Design and Construction

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, it appears that standard mix design procedures for HMA must be modified slightly to accommodate WMA. This report discusses some specific elements of WMA mixture design. These issues are: selection of binder grade, optimum binder content, aggregate gradation, specimen compaction, specimen curing time, and mixture evaluation.

Based on the findings during this review of current literature, the authors currently believe that WMA should provide the same structural values as HMA. Some researchers 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 QC/QA of the mix. The

suitability of WMA for the high production rates of asphalt plants in the US needs to be examined. There is concern by some engineers that those WMA products which 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.

Findings and Recommendation

Although WMA was introduced in the USA only few years ago, it is gaining tremendous attention from industries, agencies, and academia. From the extensive literature review the authors identified numerous engineering, economic, and environmental benefits of WMA over traditional HMA. At the same time, many researchers and users are skeptical about the long-term performance of WMA. There are lots of questions regarding the implementation of this technology; especially the specifications and quality control need to be answered. Since the field test sections constructed, so far, are less than five years old, it is too early to comment on long-term performance. To date, no notable negative performance has been reported.

The authors recommend that more nationally coordinated research is needed to answer the following questions that remain when one carefully considers the WMA mixture design, mixture evaluation, construction, and performance issues as compared to traditional HMA.

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CHAPTER 1

INTRODUCTION

Background

Warm Mix Asphalt (WMA) technology, recently developed in Europe, is gaining strong interest in the US. By lowering the viscosity of asphalt binder and/or increasing the workability of mixture using minimal heat, WMA technology allows the mixing, transporting, and paving process at significantly lower temperature. Using this new technology, asphalt mix can be produced as much as 100°F lower than traditional hot mix asphalt (HMA). Several benefits of lower mixing and compaction temperature include: lower emissions, savings in energy cost, longer construction season, less odor, and construction during non-peak periods.

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. One category of current promising products is termed warm mix asphalt. Although WMA technology 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 agencies and the industries 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 workability of the mix, they should reduce (or, at least, certainly not increase) compaction energy requirements and thus enhance in-place density (Prowell and Hurley, 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 (Barthe and Von Devivere, 2003). In the U.S., these technologies are being tried in an attempt to realize these potential benefits (Kuennen, 2004). 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 interstate highways 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 indicate that, compared to standard HMA, reductions of about 30 percent in energy consumption (APAO, 2003; Stroup-Gardiner and Lange, 2002) and CO₂ 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 CO₂, 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 – 60 percent decrease in dust generation by some technologies.

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 they listed include paving in ozone non-attainment 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 and Muthen, 1998). Conoco was later licensed to market foamed asphalt in the USA and further advanced the technology and evaluated the product as a base stabilizer both in the laboratory and in the field (Ruckel et al., 1979 and 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; 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 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 2-component technique (Harrison and Christodoulaki, 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 UK, 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 Australia (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 USA for less than five years, they are being evaluated at a rapidly increasing rate. For example, WMA paving projects in North America have been or are being constructed in Alabama, California, Colorado, Florida, Indiana, Kansas, Louisiana, Maryland, Missouri, Minnesota, Mississippi, Michigan, Ohio, Vermont, Virginia, South Carolina, North Carolina, New York, Tennessee, Texas, Wisconsin, Washington, D.C., Alberta, and Ontario. 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.

WMA TECHNOLOGIES IN THE USA

Prowell and Hurley (2007b) documented timeline for introduction of WMA into the USA. It began with a scanning tour of NAPA leaders in Europe to examine selected WMA technologies in 2002. In the following year, WMA was featured at NAPA's annual convention, and NCAT started their first research study on WMA. The first field trial with WMA in the US took place in North Carolina and Florida in 2004. Since then, several research studies have been undertaken by different agencies, and numerous field trials have been conducted with various WMA technologies throughout the USA. Prowell and Hurley (2007b) identified eight different types WMA technologies already introduced in the USA: Synthetic Zeolite, Sasobit[®], Evotherm[®], WAM-Foam[®], Double Barrel Green[®], REVIX[™], Rediset[™] WMX, and Low Energy Asphalt (LEA[®]). Others include (see Cindy) Terex[™], ...

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 and used in Europe, is Asphaltan B. All these 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 Prowell and Hurley, 2007b; 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.

All known WMA products and/or processes used in the north America, to date, are described in the following subsections.

Synthetic Zeolite

There are two synthetic zeolite based WMA processes available in the USA: Aspha-Min[®] and Advera[®]. In the USA, Aspha-Min[®] and Advera[®] technology are supplied by The Hubbard Group and PQ Corporation, respectively. Both of these two processes work in a similar way. In this report, the description of synthetic zeolite WMA is based on Aspha-Min[®]. Aspha-Min[®] is originally supplied by Eurovia Services GmbH, Bottrop in Germany (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 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 as a very fine white powdered form in 50-pound or 100-pound bags or in bulk for silos

(Kuennen, 2004). 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 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 (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 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 SBS modifier using a special cross-linking agent and is

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 produced.

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 ranges 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 (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 to 54°F and improves compactibility. 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 are reported to exhibit increased resistance to rutting.

Since 1997, over 142 projects have been paved using Sasobit, which total more than 2,716,254 square yards of pavement (Hurley and Prowell, 2005b). Projects were constructed in Austria, Belgium, China, Czech Republic, Denmark, France, Germany, Hungary, Italy, Macau, Malaysia, 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 USA by MeadWestvaco Asphalt Innovations, Charleston, South Carolina (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% 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), the 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 occurs 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, which promotes 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 CO₂ and

SO₂ 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 at more than 25 locations the USA.

Add new Evotherm see Cindy.

Double Barrel Green®

Developed by Astec Industries, Inc. in the USA, the Double Barrel Green® WMA technology was introduced couple of years ago. It is a foaming based WMA technology. In this process, a small amount of water is added to the mix using multi-nozzle foaming device in order to microscopically foam the asphalt. The Double Barrel Green® device is basically composed of manifold with system of valves, mixing chamber, and nozzles. The nozzles are computer controlled to adjust the foaming rate. The entire system is surrounded by a jacket with circulation of hot oil. Application of water through the nozzles creates steam which, in turn, is encapsulated in binder resulting in foaming and a huge volume increase of the binder. This technology provides a reduction of up to 50°F for mixing and compaction temperatures.

Typically, this process does not require any change in mixture design process. But Prowell and Hurley (2007b) suggested the use of a laboratory foaming device to simulate the plant mixing. As previously discussed, a significant plant modification is required for this process. Prowell and Hurley (2007b) reported that ten field test sections were constructed in 2007 using this WMA technology.

Rediset™ WMX

Rediset™ WMX is a chemical additive based WMA Technology from Akzo Nobel. It is a combination of cationic surfactants and organic additive based rheology modifier. Rediset™ WMX does not contain water; instead, the surfactants improve the wetting of aggregate surfaces with binder by “active adhesion,” and the other components the additive reduce the viscosity of the binder (Prowell and Hurley, 2007b).

A reduction of about 60°F mixing and compaction temperatures has been reported. The recommended rate is typically 1.5 to 2.0 percent by weight of asphalt binder. Using Rediset™ WMX does not require any modification in mixture design process except the mixing and compaction temperature. Rediset™ WMX WMA usually does not require any additional anti-stripping agent in the mixture as this product provides anti-stripping properties. This product

can be blended with binder or can be added to the mixture right after the addition of binder. If it is directly blended with binder at the refinery, it does not require any modification at the plant. Otherwise, minimal plant modification is required to add this product in the mixing drum close to where the asphalt binder is added to the aggregate. So far, only a few field trials of Rediset™ WMX have been conducted in the USA. Recently, a major asphalt paving project using Rediset™ WMX (40,000 tons) has been undertaken in Texas. This project will be completed in the spring of 2009.

Revix™

Revix™ is a chemical additive based WMA. Mathy Technology and Engineering Services, Inc. and Paragon Technical Services, Inc. developed Revix™ WMA in the USA. Prowell and Hurley (2007b) reported that Revix™ technology dose not depend on foaming or viscosity reduction for reducing mixing and compaction temperatures. Instead, a variety of surface-active agents or surfactants, waxes, processing aids, polymers, and other materials is used for this WMA technology. Revix™ WMA employs about 60 to 80°F reduction of mixing and compaction temperatures compared to similar PG graded binder.

Revix™ does not require any modification in the mixture design process except the mixing and compaction temperature. Typically Revix™ is blended with asphalt binder at the terminal; so plant modification is not required. But it is possible to add with the binder at the plant with minor modification. About nine field test sections with Revix™ WMA have been successfully constructed in the USA until the end of 2007.

WAM-Foam®

WAM-Foam® is a product of a joint venture between Shell International Petroleum Company Ltd., London, UK and Kolo-Veidekke, Olso, Norway (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 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 175-195°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 airgun is then used to blow the foaming chamber and pipes clean after each foam injection (Kristjansdottir, 2006 and Koenders, 2002). In their field trials in Norway, the dryer was operated at about 250 – 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 (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 pug mill.

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 CO₂ emissions. Independent testing has confirmed Shell's earlier findings (Larsen et al., 2004).

When RAP was used at levels from 15 percent 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 with RAP. (Larsen et al., 2004)

Low-Energy Asphalt[®]

Low-Energy Asphalt[®] (LEA) was developed by Fairco of Zozay, France (Romier et al., 2004 and Romier et al., 2006). 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 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° to 180°F). This (212°F) is a critical temperature, 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, 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 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. Approximately 40,000 tons of LEA have been placed in USA until the end of 2007. After additional laboratory and field evaluations, Gaudefroy et al. (2007) still hold that this is a viable WMA process.

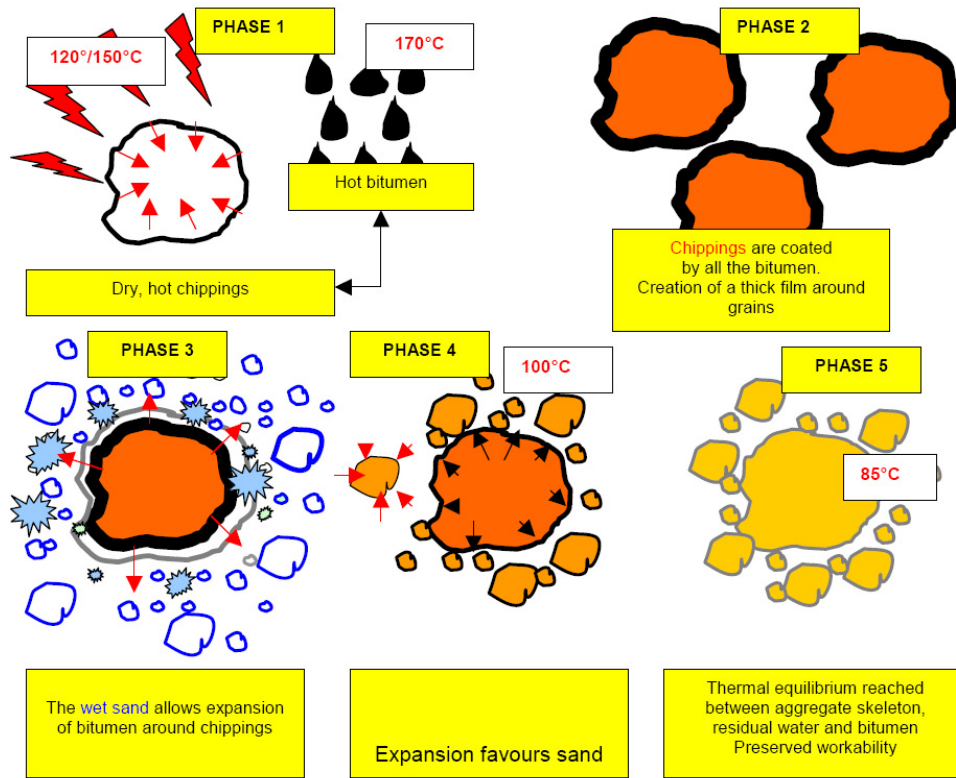


Figure 1. Functional Diagram Low-Energy Asphalt Technique (after Romier et al., 2006).

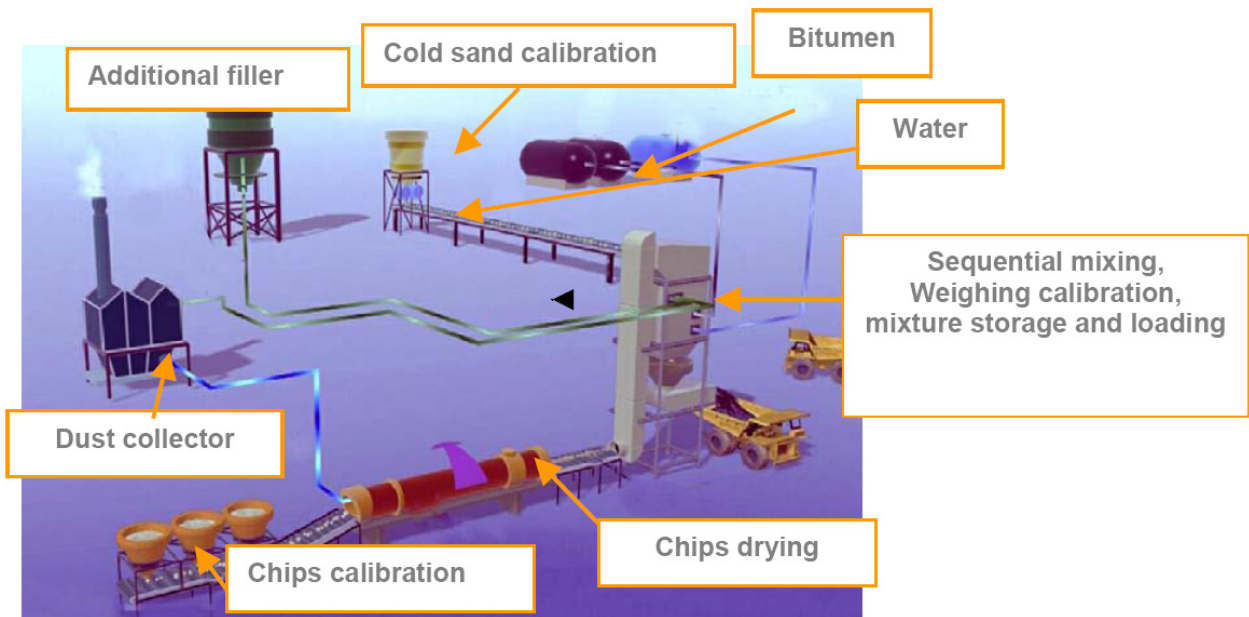


Figure 2. Batch-Plant Equipped for LEA Processing (after Romier et al., 2006).

OTHER WMA TECHNOLOGIES

In 2007, a group of US asphalt materials paving experts visited Belgium, France, Germany, and Norway to evaluate different WMA technologies. This scanning tour was administered through FHWA. During this scanning tour, D'Angelo et al. (2007) identified several more technologies available in Europe besides the above mentioned eight WMA technologies. They are: Asphaltan® B, ECOMAC, LEAB®, Licomont BS 100, 3E LT or Ecoflex, and LT asphalt. Details of these WMA technologies can be found in the summary report by D'Angelo et al. (2007). The following paragraphs describe Asphaltan® B process.

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 (2000), 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 USA 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 also 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 compactibility, 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 (2006), natural wax in straight run bitumen today is low in content and of a type which 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 ageing properties for the asphalts and test conditions used by Edwards (2006). They demonstrated that the effects due to wax content shown in DMA temperature sweeps (for HMA mixes) are well related to the corresponding effects shown in DSC thermograms (for asphalt binders).

In the case of blown bitumens and/or wax-modified bitumens in road construction, which are frequently used in the US 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.

CHAPTER 2

CURRENT NATIONAL ACTIVITIES RELATED TO WMA

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 Can be found at NAPA's webpage (<http://www.warmmixasphalt.com/>).

National Cooperative Highway Research Program (NCHRP) Projects

NCHRP currently has two major ongoing research projects that are evaluating different aspects of WMA technology. These two projects are Project 09-43, "Mix Design Practices for Warm-Mix Asphalt Technologies," and Project 09-47, "Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies."

NCHRP Project 09-43: This first study sponsored by NCHRP began in March 2007 and expected to be completed by March 2010. The objective of this research is to develop a mix design method for WMA in the form of an AASHTO-style manual of practice. According to NCHRP, 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://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=977>)

NCHRP Project 09-47: This study began in March 2008 and expected to be completed by September 2011. The objectives of this study are:

- establish relationships among mechanical properties of WMA binders and mixes and mixture field performance,
- compare different performances measures of WMA and conventional HMA pavements,
- compare production and laydown practices and costs between WMA and HMA pavements, and
- provide relative emissions measurement of WMA and conventional HMA technologies

Additional information on this project is available at the NCHRP webpage:

(<http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=1625>)

NAPA Research

According to Corrigan (2006), the National Asphalt Pavement Association (NAPA) in cooperation with the Federal Highway Administration (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 US through a cooperative agreement between the National Center for Asphalt Technology (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 the 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). Their experiment and selected findings are highlighted in Tables 1 through 4.

Their conclusions and recommendations are summarized below.

- 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 study.

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

Additive	Compaction Temperature, °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

Table 3: Tensile Strength Results for Granite and Limestone (after Hurley and Prowell (2006a)).

Aggregate	Mix Type	Indirect Tensile Strength		TSR, %
		Unsaturated, psi	Saturated, psi	
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 i.a.w. ASTM D 4867

Note: ** Indicates Samples were prepared in SGC i.a.w. ASTM D 4867 with 250°F compaction temperature

- 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.
- Application of either warm mix process did not affect the resilient modulus of an asphalt mix compared to control mixtures having the same PG binder. Higher density increased resilient modulus. Therefore, there would not be any 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.

Table 4: Results from Hamburg Wheel Tracking Test (Mod after Hurley and Prowell, 2006a)

Aggregate	Mix Type	Treatment	Stripping Inflection Point, cycles	Rutting Rate, mm/hr	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.

- 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 supports 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 TSR 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 PG58-28 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 PAV test, his experience indicates that the resulting low-temperature properties typically miss the -28 grade by about two 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 of 2005. Figure 3 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 one-inch Evotherm inlay placed in Section E9. The binder for the 9.5-mm NMAS surface mix was varied for each section (Figure 3). 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.

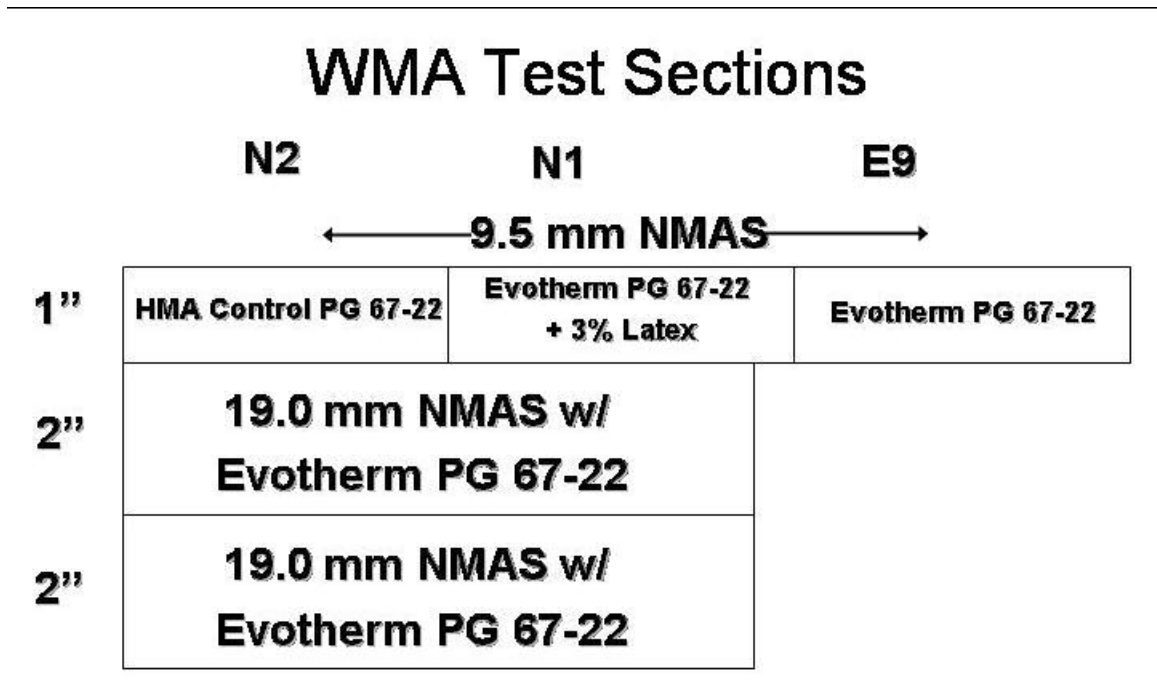


Figure 3: Section View of Evotherm Layers at NCAT Test Track (after Prowell et al., 2007).

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 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 Asphalt Pavement Analyzer (APA) indicated similar performance for the WMA and HMA surface mixtures which 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 ten 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.

State DOT Approval

Slowly but surely some state departments of transportation are accepting WMA technologies. Recently Texas Department of Transportation (TxDOT) included five different WMA technologies in their list of pre-approved materials. Table 5 present the WMA technologies pre-approved for use on department projects.

Table 5: TxDOT's Pre-approved List of WMA Technologies

WMA Technology	Process Type	WMA Supplier
Advera	Foaming Process	PQ Corporation
Double Barrel Green	Foaming Process	Astec Industries, Inc.
Evotherm	Chemical Additive	MeadWestvaco Asphalt Innovations
Redi-Set WMX	Chemical Additive	Akzo Nobel Surfactants
Sasobit	Organic Additive	Sasol Wax Americas, Inc.

CHAPTER 3

MIXTURE DESIGN AND CONSTRUCTION

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. Specific elements in the mixture design process are discussed below.

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 and 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 US. 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, water susceptibility of the resulting paving mixture.

When describing the LEA method, Romier et al. (2006) states 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, 2004; Romier et al., 2006). This is true even for asphalt mixtures produced at ambient temperature using foamed or emulsified asphalt (Maccarone, 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 dense-graded mixtures in Germany but also in stone mastic asphalt (SMA) and gussasphalt.

Several WMA processes (e.g., WAM-Foam, LEA) have demonstrated success in mixtures containing recycled asphalt pavement (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 a HMA mixture using the same aggregate type and gradation. They pointed out that earlier work (Bahia and Hanson, 2000; Huner, M.H. and E.R. 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, Asphaltan B). However, for those products that incorporate moisture to promote aggregate coating, workability, and compaction (e.g., Evotherm, Aspha-Min, 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 three 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.

Mixture Evaluation

Mechanical characterization of mixtures should be performed using standard volumetric analyses and laboratory specimen testing. State 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, 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).

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 of HMA mixtures. Others (Mallick et al., 2007; Kanitpong et al., 2007; 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. 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 five 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 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 which 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. (2001) 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.

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 five years. In the authors' experience, asphalt pavement sections that fail prematurely will typically exhibit signs of distress within less than five years after construction. In addition, only a few formal research projects appear to be addressing laboratory testing and tying the results to field performance, and these are mainly those studies conducted by NCAT.

WMA PROPERTIES AND PERFORMANCE

NCAT Laboratory Results for WMA

The National Center for Asphalt Technology (NCAT) has probably conducted more studies of WMA than any other agency in the USA (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 (SGC) 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 antistripping agents were effective in addressing this in the laboratory. Their results suggested that, when hydrated lime is used as antistrip, it will stiffen the WMA and assist rutting resistance.

For all three WMA products, NCAT personnel aged the densification samples for two 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 three-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 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, 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 SCG 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 one 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. Volumetric properties are shown in Table 6.

Table 6: 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 (lbs)	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 (22°C) lower. The gyratory air voids for the unaged warm mix was slightly higher than the control, but this also corresponds to a slightly higher 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. Bartel et al. (2005) reported that, three years after construction of the first WMA test section using zeolite, measurements indicated no significant changes in the surface characteristic. 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 one 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 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, “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 to 75°F (8 to 42°C). 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 little over half a million 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 little over half a million 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 (93°C). The mix was placed at an average depth of 50 mm (2 inches) and temperatures behind the screed were between 160 and 200°F (71 and 93°C). The mix did not appear to be tender (Prowell, 2005)

Canada. J.K Davidson with McAsphalt (based on 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. A HMA control section was also placed in October (Davidson, 2005b).

Davidson reported that, for the Aurora and Calgary projects that 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 weigh 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 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 of 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 HMA mix were designed according to Item 341, Type C dense graded mixes which employs the use of the Texas Gyrotory Compactor. Both mixes were designed to a target density of 96.5 percent. The control HMA 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 using 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, and both 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 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 loading out.

Quality Control

- Warm mix samples were compacted in the field laboratory to densities averaging 97 percent, which was the same as the control HMA compacted densities. To evaluate the effect of laboratory curing on the warm mix, samples were compacted after 3 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.

Laydown and Compaction

- The WMA and HMA were placed over the course of 3 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 laydown 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 one 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 4 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 one 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 one 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 in some of the cores taken at one month from the warm mix sections.

Laboratory Study. Wasiuddin (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 additives (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,

Netherlands, New Zealand, Norway, Russia, the United Kingdom, South Africa, Sweden and Switzerland. The projects and trials mainly involved various dense-graded mixes, stone matrix asphalt (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 one percent to 4.5 percent.

The authors could not find any reports on the field performance of WMA mixtures with 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 20°C to 40°C 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 163°C to 147°C (i.e., by 16°C). For the PG 70-28, the reductions are 10°C, 12°C and 13°C, 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 $G^*/\sin(\delta)$. They 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 one 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 140/160°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 4, 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 4. The report states, “The mixture was a dense asphalt concrete Ab11 with a 85 pen (final) binder. The asphalt concrete was produced in a batch plant (3300 kg/batch)...The first set of data for 5 September 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.”

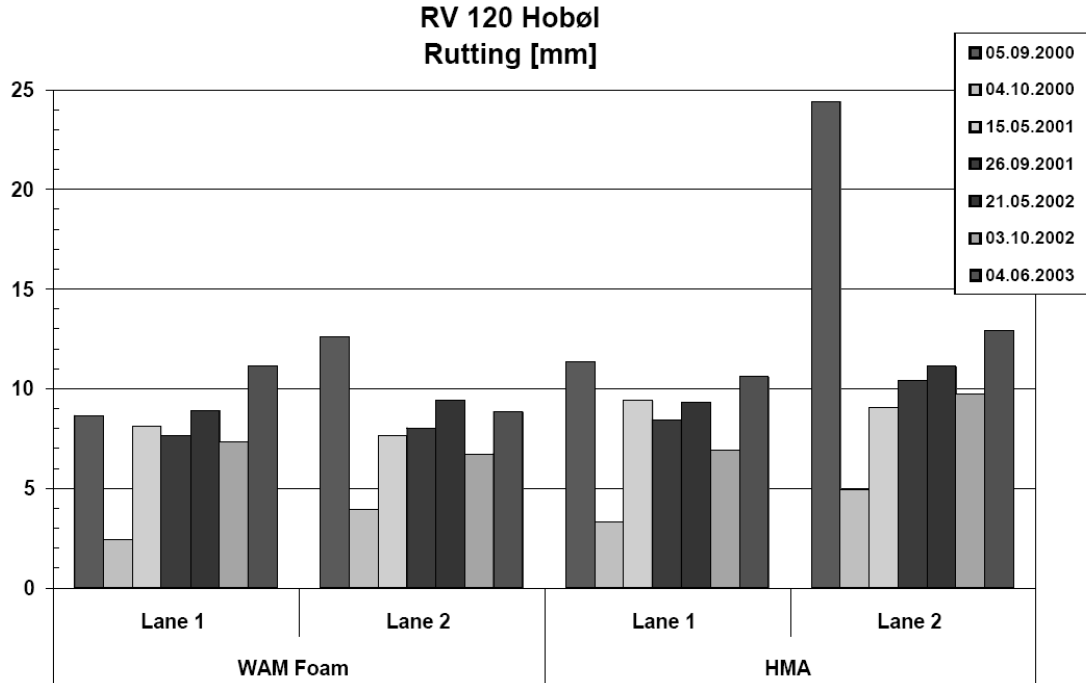


Figure 4: Rut Depth Measurements on RV 120 in Norway (after Larsen et al., 2004)

Figures 5 and 6, from Larsen et al. (2004), show rut depths and IRI measurements on FV 82 in Norway that involved the placement of WAM Foam mix and a 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 the Figures. The report concludes that the FV82 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 (3300 kg/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.

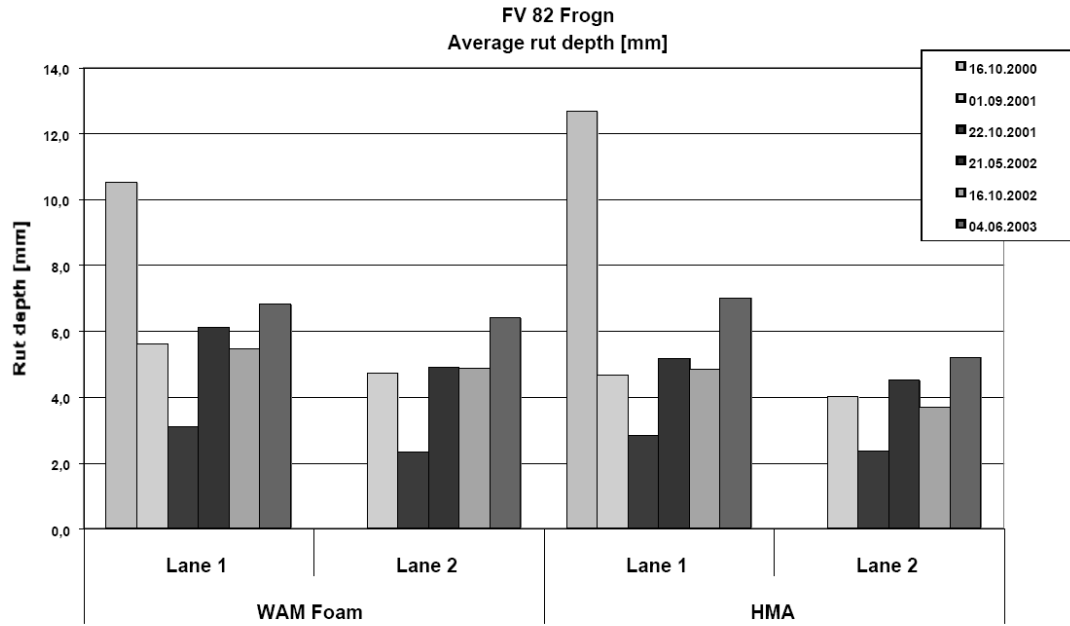


Figure 5: Rut Depth Measurements on FV 82 in Norway (after Larsen et al., 2004).

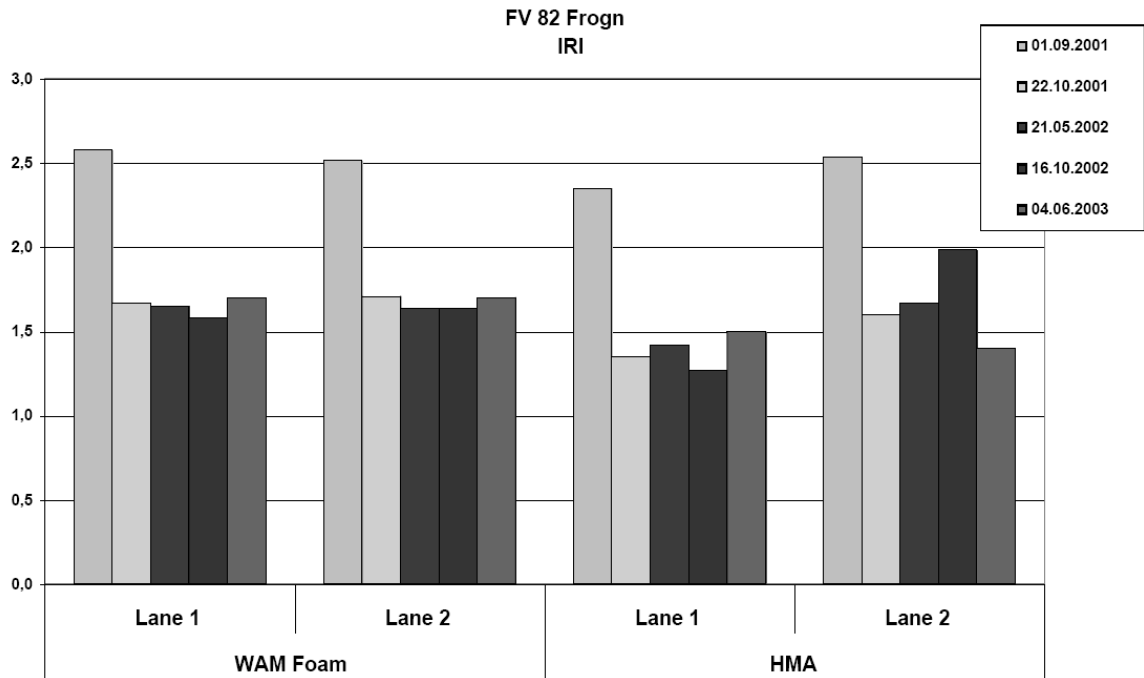


Figure 6: IRI Measurements on FV 82 in Norway (after Larsen et al., 2004)

CHAPTER 4

COMPARATIVE COST AND BENEFIT OF WMA

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 7 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.

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 8). They added that the purpose of Table 6 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.

The authors personally contacted several WMA technology providers. WAM-Foam requires plant modification to accommodate foaming, which is estimated to cost \$50,000 to \$70,000. The approximate cost of plant modification required for Double Barrel Green WMA technology was quoted as \$75,000 and no other materials costs are involved. Approximate reduction of production temperature is 50°F. So, the cost savings compared to conventional HMA depends on mostly the base cost of the fuel. The capital recovery period will depend on the production rate and cost of fuel. At the current level of high energy cost, the payback period will be shorter. On the other hand, none of Rediset WMX and REVIX WMA technologies require plant modification. In some cases, minor modification may be required for blending the additives with liquid binder at the plant. Compared to conventional HMA, the additional cost for these latter two processes are mainly associated with the cost of additives.

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 12 years old in Europe and less than five years old in the USA. While performance has generally been good, substantial empirical evidence of pavement life equivalent to HMA is needed to reduce perceived risk.

Table 7: Cost of Producing HMA and Savings from WMA for Selected Locations (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
<p>a. Aggregate moisture content assumed typical at 2 – 4%. Amounts of fuel are general averages.</p> <p>b. Numbers taken from personal correspondence with a producer in each area.</p> <p>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.</p> <p>d. Taken as the average of 8 to 14 kWh range obtained from (21). This constitutes other power requirements not furnished by the aggregate dryer or drum plant burner.</p> <p>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 <i>Electric Power Monthly</i>.</p> <p>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.</p> <p>g. Fuel cost added to electricity cost.</p> <p>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%.</p> <p>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%.</p>			

Table 8: 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 \$5,000/plant/yr \$0.30/ton	None	None	None
Cost of material	N/A	\$0.60/lb ^c	\$0.80/lb ^d	7-10% more than asphalt binder
Recommended dosage rate	N/A	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 ton ^e of mix)	\$0.30 ^c (\$0.33)	\$3.60 ^e (\$3.96)	\$1.30 – \$2.60 (\$1.43 – \$2.86)	\$3.50 – \$4.00 (\$3.85 – \$4.40)
<p>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.</p> <p>b. According to phone conversation with Johathan MacIver, Business Development Manager, Asphalt Innovations, MeadWestvaco. July 28, 2006.</p> <p>c. According to electronic mail from Barry McKeon, Technical Manager at Hubbard Construction Company in Orlando, Florida. February 6, 2006.</p> <p>d. According to electronic mail from Matthias Nolting, Business Unit Manager, Sasol Wax. January 19, 2006.</p> <p>e. Not including first-year and royalty costs.</p> <p>f. From Brown (2006).</p>				

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. Generally, 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 and decreased mobilization cost;
- 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, lifecycle 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 CO₂ 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 CO₂ 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 (CO₂, N₂O, and CH₄) 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. They claim that WMA:

- requires essentially no curing time before trafficking,
- allows use of higher quality aggregates that cannot be used in cold mixes,
- provides better quality mixes due to the total coating of aggregates and binder film uniformity, and
- 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 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 12 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, particularly in damp, cool weather, 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 small cure time (2 to 4 hours) 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).

OTHER WARM MIX ASPHALT APPLICATIONS

Warm Open-Graded Mixes for Patching Permeable Friction Courses

Patching a permeable friction courses (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 (1) then added PG 64-28 at 300°F, (2) then added 140°F emulsified asphalt (MS-2) in an asphalt plant, and (3) 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, compactibilities, 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.

Crumb Rubber Asphalt Mixture

Rubberized asphalt mix, sometimes known as crumb rubber asphalt mix (CRM), is produced and compacted at significantly higher temperature than conventional HMA. Due to low workability of CRM, it requires a higher mixing and compaction temperature. Akishetty et al. (2007) indicated that, using WMA technology, it is possible to lower the mixing and compaction temperature of CRM mixture. They conducted some laboratory testing with CRM mixtures with Sasobit and Aspha-Min additives along with control CRM. They did not find any significant difference in rutting, and moisture resistance properties between the control CRM and CRM with WMA additives.

These authors believe that WMA technology can be extended to minimize the field compaction problem for some 'harsh' types of mixtures. Field personnel sometimes experience difficulties achieving required density for certain type of mixtures. It is possible to use a smaller percentage of WMA additive, which can aid in achieving mat density. Probably, it is safer than arbitrarily raising binder content or production temperature. Again, the use of WMA additives may require checking job-mix formula.

CHAPTER 5

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 completely new process; however, there are significant new technologies which deserve exploration and are being studied by a number of state agencies and municipalities.

- Nine new WMA technologies eight of which already introduced in the USA appear to deserve further investigation: Double Barrel Green, Aspha-Min, WAM Foam, Low-Energy Asphalt, Sasobit, Evotherm, Rediset WMX, REVIX, and Asphaltan B. Some of these technologies are more promising than the others. 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 separate chapter 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 CO₂, 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 (and should be required to attain) 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 opening traffic after placing WMA is not a significant issue.
- Based on a limited number of reports that address field performance of WMA in the USA, pavements are performing well, but, typically, the sections reported had been in place for less than 5 years.
- WMA processes can successfully incorporate RAP. In fact, some have reported the use of 100 percent RAP in certain WMA processes.
- NCHRP has initiated two WMA related research project: NCHRP Project 09-43, and NCHRP Project 9-47. These two projects will evaluate different aspects of WMA including mixture design, performance testing, field construction, emission measurement, etc.
- 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 the following 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 small (2 to 4 hrs) 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.

- More 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.

REFERENCES

AAPA, *Warm Mix Asphalt – A-State-of-the-Art Review*, Advisory Note 17, Australian Asphalt Pavement Association, Kew, Victoria, Australia, 2001.

(<http://www.aapa.asn.au/content/aapa/download/AdvisoryNote17.pdf>)

AEMA, *Recommended Performance Guidelines*, Asphalt Emulsion Manufacturers Association (AEMA), Washington, D.C., 1981.

APAO, “Warm Mix Asphalt Shows Promise for Cost Reduction, Environmental Benefit,” *Centerline*, Asphalt Pavement Association of Oregon, Salem, Oregon, Fall 2003.

Bahia, H.U. and Hanson, “A Project NCHRP 9-10 Superpave Protocols for Modified Asphalt Binders,” Draft Topical Report (Task 9), prepared for National Cooperative Highway Research Program, Transportation Research Board, National Research Council, 2000.

Barthel, W. and M. Von Devivere, “Warm Asphalt Mixes by Adding Aspha-Min, A Synthetic Zeolite,” Proceedings, 48th Annual Convention, National Asphalt Pavement Association, San Diego, January 2003.

Barthel, W., J.P. Marchand, M. Von Devivere. “Warm asphalt mixes by adding a synthetic zeolite.” Eurovia (www.asphamin.com). Accessed January 2007.

Brown, D.C., “Warm Mix: The Push Is On,” *Public Works Magazine*, May 2006.

Button, J.W., C. Estakhri, and A. Wimsatt, “A Synthesis of Warm-Mix Asphalt,” Report FHWA/TX-07/0-5597-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 2007.

Butz, T., I. Rahimian, and G. Hildebrand, “Modifications of Road Bitumens with the Fischer-Tropsch Paraffin Sasobit®, *Journal of Applied Asphalt Binder Technology*, October 2001, pp. 70-86.

Chevron, *Butumuls Mix Manual*, Chevron USA, Asphalt Division, California, 1977.

Corrigan, M. “Warm Mix Asphalt Technologies and Research,” Federal Highway Administration, Office of Pavement Technology, Washington, D.C, Accessed December 2006. (<http://www.fhwa.dot.gov/pavement/asphalt/wma.cfm>)

D’Angelo, J. and et. al. “Warm Mix asphalt European Practice.” Report No. FHWA-PL-08-007, Washington DC, February 2008.

Damm, K-W., J. Abraham, T. Butz, G. Hildebrand, and G. Riebeschl, “Asphalt Flow Improvers as Intelligent Fillers for Got Asp[h]alts – A New Chapter in Asphalt Technology, *Journal of Applied Asphalt Binder Technology*, 2002, pp. 36-69.

Davidson, J.K. Evotherm Trial, Aurora Ontario, August 8, 2005. McAsphalt Engineering Services, Ontario, August, 2005a.

Davidson, J.K. Evotherm Trial, City of Calgary, September 28, 2005. McAsphalt Engineering Services, Ontario, January, 2006.

Davidson, J.K. Evotherm Trial, Ramara Township, Road 46, October 4, 5, 2006. McAsphalt Engineering Services, Ontario, December, 2005b.

Dorchies, P.T., M. Chappat, and J. Bilal, "The Environmental Road of the Future: Analysis of Energy Consumption and Greenhouse Gas Emissions," Proceedings, Canadian Asphalt Technical Association, Volume L, Victoria, B.C., Canada, 2005, pp. 1-26.

Edwards, Y., and P. Redelius, "Rheological Effects of Waxes in Bitumen," Division of Highway Engineering, Royal Institute of Technology (KTH), S-100 44, Stockholm Sweden, 2002.

Edwards, Y., Y. Tasdemir, and U. Isacson, "Influence of Commercial Waxes and Polyphosphoric Acid on Bitumen and Asphalt Concrete Performance at Low and Medium Temperatures," *Journal of Materials and Structures*, Volume 39, No. 7, Springer Netherlands, August, 2006.

Els, H., "Cold/Warm Processes and Recycling Moderator's Report, Part 2A," Proceedings (CD), 3rd Eurasphalt & Eurobitume Congress, Vienna, Austria, 2004.

FHWA, "Warm Mix Technologies and Research," Federal Highway Administration, U.S. Department of Transportation, <http://www.fhwa.dot.gov/pavement/wma.html>, accessed February 2004.

FHWA, *A Basic Asphalt Emulsion Manual*, FHWA-IP-79-1, Volumes 1 and 2, prepared by The Asphalt Institute, Washington, D.C., 1979.

Gaudefroy, V., F. Olard, B. Cazacliu, C. de La Roche, E. Beduneau, and J.P. Antoine, "Laboratory Investigations on the Mechanical Performances of Foamed Bitumen Mixes Using Half-Warm Aggregates," Proceedings (CD), 86th Annual Meeting of the Transportation Research Board, National Academy of Sciences, Washington, D.C., 2007.

Hadley, W.O., W.R. Hudson, and T.W. Kennedy, "An Evaluation of Factors Affecting the Tensile Properties of Asphalt-Treated Materials," Research Report 98-2, Center for Transportation Research, University of Texas at Austin, 1969.

Hampton, T., "U.S. Studies 'Warm Mix' Asphalt Methods," Engineering News Record, McGraw-Hill Construction, (<http://www.enr.construction.com/products/newproducts/archives/030428.asp>), accessed January 2007.

Harrison, T., and Christodoulaki, "Innovative Processes in Asphalt Production and Application - Strengthening Asphalt's Position in Helping to Build a Better World," Proceedings, First International Conference, World of Asphalt Pavements, Australian Asphalt Pavement Association, Kew, Victoria, Australia, 2000.

Hesp, S., "Reversible Ageing in Asphalt at Low Temperatures - Final Report," Department of Chemistry, Queen's University, Kingston, Ontario, Canada, 2004.

Huner, M.H. and E.R. Brown, "Effects of Reheating and Compaction Temperature on Hot Mix Asphalt Volumetrics," NCAT Report No. 01-04, National Center for Asphalt Technology, Auburn, Alabama, 2001.

Hurley, G.C. and B.D. Prowell, "Evaluation of Aspha-Min® Zeolite for Use in Warm Mix Asphalt," Report NCAT 05-04, National Center for Asphalt Technology, Auburn University, Auburn, Alabama, 2005a.

Hurley, G.C. and B.D. Prowell, "Evaluation of Evotherm for Use in Warm Mix Asphalt," Report NCAT 06-02, National Center for Asphalt Technology, Auburn University, Auburn, Alabama, 2006b.

Hurley, G.C. and B.D. Prowell, "Evaluation of Potential Processes for Use in Warm Mix Asphalt," *Journal of the Association of Asphalt Paving Technologists*, Volume 75, Savannah, Georgia, 2006a.

Hurley, G.C. and B.D. Prowell, "Evaluation of Sasobit® for Use in Warm Mix Asphalt," Report NCAT 05-06, National Center for Asphalt Technology, Auburn University, Auburn, Alabama, 2005b.

Jenkins, K.J., A.A.A. Molenaar, J.L.A. de Groot, and M.F.C. van de Ven, "Foamed Asphalt Produced Using Warmed Aggregates," *Journal of the Association of Asphalt Paving Technologists*, Volume 71, Colorado Springs, Colorado, 2002.

Jenkins, K.J., J.L.A. de Groot, M.F.C. van de Ven, and A.A.A. Molenaar, "Half-Warm Foamed Bitumen Treatment, a New Process," 7th Conference on Asphalt Pavements for Southern Africa (CAPSA), Victoria Falls, South Africa, 1999.

Johnston, A., K. Yeung, J. Bird, and B. Forfylyow, "Initial Canadian Experience with Warm Mix Asphalt in Calgary, Alberta," *Proceedings, 51st Annual Conference of the Canadian Technical Asphalt Association*, Volume LI, 2006, pp. 369-386.

Jones, W., "Warm Mix Asphalt Pavements: Technology of the Future," *Asphalt Magazine*, Asphalt Institute, Lexington, Kentucky, Fall 2004.

Kanitpong, K., Sonthong, S., Nam, K., Martono, W., and Bahia, H., "Laboratory Study on Warm Mix Asphalt Additives," *Proceedings, 86th Annual Meeting of the Transportation Research Board (CD)*, National Academy of Sciences, Washington, D.C., 2007.

Kennedy, T.W., F.L. Roberts, J.N. Anagnos, "Texas Boiling Test for Evaluating Moisture Susceptibility of Asphalt Mixtures," Research Report 253-5, Center for Transportation Research, University of Texas at Austin, 1984.

Koenders, B.G., D.A. Stoker, C. Bowen, P. de Groot, O. Larsen, D. Hardy, and K.P. Wilms, "Innovative Processes in Asphalt Production and Application to Obtain Lower Operating Temperatures," 2nd Eurasphalt & Eurobitume Congress, Barcelona, Spain, 2000.

Koenders, B.G., D.A. Stoker, C. Robertus, O. Larsen, J. Johansen, "WAM-Foam, Asphalt Production at Lower Operating Temperatures," *Proceedings, 9th Conference of International Society for Asphalt Pavements*, Copenhagen, Denmark, 2002.

Kristjansdottir, O., "Warm Mix Asphalt for Cold Weather Paving," Report No. WA-RD 650.1, A thesis for partial fulfillment of the degree of Master of Science in Civil Engineering, University of Washington, Seattle, Washington, 2006.

Kristjansdottir, O., L. Michael, S.T. Muench, and G. Burke, "Assessing the Potential for Warm Mix Asphalt Technology Adoption," *Proceedings (CD), 86th Annual Meeting of the Transportation Research Board*, National Academy of Sciences, Washington, D.C., 2007.

Kuennen, T., "Paths to Progress - 2005," *Better Roads*, James Informational Media, Inc., Des Plaines, Illinois, December 2004.

Kuennen, T., "Warm Mixes are a Hot Topic," *Better Roads*, James Informational Media, Inc., Des Plaines, Illinois, June 2004.

Larry Michaels, personal communication, engineering consultant, formerly state materials engineer for Maryland DOT, January, 2007.

Larsen, O.R., O. Moen, C. Robertus, B.G., Koenders, "WAM-Foam Asphalt Production at Lower Operating Temperatures as an Environmental Friendly Alternative to HMA," Proceedings, 3rd Eurasphalt & Eurobitume Congress, Vienna, 2004.

Little, D.N., J.W. Button, J.A. Epps, "Structural Properties of Laboratory Mixtures Containing Foamed Asphalt and Marginal Aggregates," *Transportation Research Record 911*, Transportation Research Board, National Academy of Sciences, Washington, D.C., 1983.

Maccarone, S., G. Holleran, and A. Ky, "Cold Asphalt Systems as an Alternative to Hot Mix," Proceedings, 9th International AAPA Conference, Surfers Paradise, Queensland, Australia, 1994. (<http://asphalt.csir.co.za/FArefs/>)

Mallick, R.B., J.E. Bradley, and R.L. Bradbury, "An Evaluation of Heated RAP Material and Wax Modified Asphalt for Use in Recycled Hot Mix Asphalt," Proceedings (CD), 86th Annual Meeting of the Transportation Research Board, National Academy of Sciences, Washington, D.C., 2007.

McKenzie, P. "Taking a Closer Look at Warm Mix," *Better Roads*, Volume 76, Number 6, June 2006, pp. 64-69.

Muthen, K. M., *Foamed Asphalt Mixes – Mix Design Procedure*, Report CR-98/077, Sabita Ltd. and CSIR Transportek, South Africa, 1998. (<http://asphalt.csir.co.za/foamasph/foamasph.pdf>)

NCAT, "NCAT Evaluates Warm Mix Asphalt," *Asphalt Technology News*, Volume 17, Number 2, Fall, 2005.

Newcomb, D., "An Introduction to Warm Mix Asphalt," National Asphalt Pavement Association, Lanham, Maryland, 2006. (http://fs1.hotmix.org/mbc/Introduction_to_Warm-mix_Aspphalt.pdf)

Prowell, B. and G. Hurley, "Warm-Mix Asphalt: best Practices" Quality Improvement Series, National Asphalt Pavement Association, December 2007b.

Prowell, B. and G. Hurley, "Expect Cooler Temperatures: Ongoing Research at NCAT Is Proving Warm-Mix Asphalt Is a Clear and Ongoing Option in the U.S.," *Roads and Bridges*, Volume 43, Number 2, February 2005, pp. 4.

Prowell, B., G.C. Hurley, and E. Crews, "Field Performance of Warm Mix Asphalt at the NCAT Test Track," Proceedings (CD), 86th Annual Meeting of the Transportation Research Board, National Academy of Sciences, Washington, D.C., 2007.

Prowell, B.D., G.C. Hurley. Starting to Warm. *Roads and Bridges*, Volume 42, Number 9, 2005.

Romier, A., M. Audeon, D. Jac, and Y. Martineau, "Low-Energy Asphalt (LEA) with the Performance of Hot Mix Asphalt," *Europeanroads Review*, ISSN 1763-3087, Paris, France, 2004, pp. 20-29 (<http://cat.inist.fr/?aModele=afficheN&cpsid=17303194>).

"Low-Energy Asphalt with Performance of Hot-Mix Asphalt", National Academy of Sciences, Washington, D.C., 2006

Ruckel, P.J., L.L. Kole, F. Abel, R.E. Zator, J.W. Button, and J.A. Epps, "Foamix Asphalt Advances," Asphalt Pavement Construction: New Materials and Techniques, *ASTM STP 724*, J.A. Scherocman, Ed., American Society for Testing and Materials, 1980, pp. 93-109.

Sasobit: Roads and Trials with Sasobit. Product information. Sasol Wax, Germany, 2005. (https://www.sasolwax.com/data/sasolwax_/Bitumen%20Modification/Roads%20and%20trials.pdf), accessed January, 2007.

Soto, J.A. and A. Blanco, "Maintenance of Porous Wearing Courses by Using Warm Open-Graded Mixes with Polymer-Modified Medium Setting Emulsions," Proceedings, 3rd Eurasphalt & Eurobitume Congress, Vienna, Austria, 2004a, pp. 560-567.

Soto, J.A. and A. Blanco, "Warm In-Plant Recycling with Bituminous Emulsions," Proceedings, 3rd Eurasphalt & Eurobitume Congress, Vienna, Austria, 2004b, pp. 651-656.

Stroup-Gardiner, M. and C. Lange, "Characterization of Asphalt Odors and Emissions," Proceedings, 9th International Conference on Asphalt Pavements, Copenhagen, Denmark, August 2002.

Takamura, K., "Binder Characterization for Latex Polymer-Modified Evotherm® Warm Mix," Charlotte Technical Center, BASF Corporation, Charlotte, North Carolina, 2005.

Wasiuddin, N., Selvaratnam, S., Zaman, M. and Guegan, M., "A Comparative Laboratory Study of Sasobit® and Aspha-Min® in Warm Mix Asphalt," Proceedings (CD), 86th Annual Meeting of the Transportation Research Board, National Academy of Sciences, Washington, D.C., 2007.

Zettler, R., "Warm Mix Stands Up to Its Trials," *Better Roads*, James Informational Media, Inc., Des Plaines, Illinois, February 2006.