WARM - MIX ASPHALT
STATE OF THE ART AND BEST PRACTICES

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ABSTRACT

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Warm-mix asphalt (WMA), an up and coming technology in the pavement industry, permits the lowering of production and placement temperatures by 35°F to 100°F less than traditional hot-mix asphalt (HMA). The reduction in temperature provides various benefits such as decreased fuel consumption, improved compaction, extended paving seasons, longer haul distances, incorporation of greater percentages of recycled asphalt pavement (RAP), improved working conditions, and a reduction in the production of greenhouse gases.

Since the late 1980s when the National Asphalt Pavement Association (NAPA) partnered with the EPA to study air emissions, which included greenhouse gases, from asphalt plants and the primary introduction of WMA in the United States in 2002, there has been increased focus placed on the environment. In addition to the above benefits, research has shown that lowering the production temperature of warm-mix asphalt can lead to a significant reduction in the production of emissions.

Multiple technologies have been developed to allow asphalt mixtures to be placed at significantly lower temperatures. These technologies can be classified in many different ways either by temperature reduction, technologies that use water, technologies that use either an organic additive or wax, those that use chemical additives or surfactants.

Material testing is important for WMA just as it is for HMA. The Warm Mix Technical Working Group recommends two forms of testing for WMA: laboratory testing and field testing. These tests determine moisture content, specific gravity, tensile strength ratio, compaction, temperature cracking, fatigue life, density, bond strength, smoothness, and indirect tensile strength in addition to other testing techniques.

Current standards and specifications for WMA are being developed by states. The common practice presently is for WMA to meet the specifications and requirements of HMA. However, some states have already developed WMA specifications for the specific state. The Warm Mix Technical Working Group is working to determine a generic specification that may be implemented by government agencies.

Best practices are critical to the production and placement of warm-mix asphalt. These practices which include reduction of moisture content in stockpiles, burner adjustment to ensure complete fuel combustion, drying of aggregate and maintaining sufficient baghouse temperatures, and changes in placement are crucial to saving energy and the reduction of emissions.

Because warm-mix asphalt is a relatively new technology in the United States, research is needed. The industry, academia, and various agencies have made great strides in the area of warm-mix asphalt technology; however, additional research in mix design is crucial to the success of WMA. In addition to mix design, additional research is needed in the collection of data to determine the long-term performance of WMA specifically in the areas of rutting and moisture damage. Additional research in the area of the development of a product approval system for new technologies is needed along with quantifying the benefits of WMA. Applied research in the area of determining the environmental benefits of increased RAP use will lead to

the increased rate of recycling thus providing a reduction in emissions of greenhouse gases. Finally, further investigation into the production equipment for WMA is also needed.

This paper provides an overview of the current technologies, benefits and disadvantages, material testing procedures, current standards and specifications, present best practices, and areas of research needed in the production and placement of warm-mix asphalt.

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I. INTRODUCTION

A. BACKGROUND

Environmental awareness, such as reduction in air pollution targets, reduction of carbon dioxide (CO_2) emissions, sustainable development, and energy cost savings, is a growing concern for the hot mix asphalt industry. Traditionally, hot mix asphalt (HMA) is produced in either batch or drum plants at a discharge temperature between 280°F (138°C) and 320°F (160°C) (Goh, et al, 2007). It is necessary to use such elevated temperatures to dry and coat the aggregates with asphalt binder, achieve the desired workability, and provide sufficient time to compact the HMA mat. Research has been trying to reduce the mixing and compaction temperature of HMA since the 1970s by using the moisture in the aggregates, foaming the binder, and using emulsified asphalts (Button, et al, 2007). The reduction in production and placement temperature of HMA could result in several economical, environmental, and performance benefits. One technology under evaluation of promising products is warm mix asphalt (WMA). WMA represents a group of technologies that allow a reduction in the temperatures at which asphalt mixes are produced and placed. These technologies tend to reduce the viscosity of the asphalt binder to provide completed aggregate coating at lower temperatures. Warm mix asphalt is produced at temperatures 20 to 55°C (35 to 100°F) lower than typical hot-mix asphalt (HMA). The same mechanisms that allow WMA to improve workability at lower temperatures also allow WMA technologies to act as compaction aids. Improved compaction or in-place density tends to reduce permeability and binder hardening due to aging, which tends to improved performance in terms of cracking resistance and moisture susceptibility (D' Angelo, et al, 2008).

There are many potential benefits with lowering temperatures during production and paving using WMA instead of HMA particularly, reducing the energy consumed to produce HMA which leads to fuel savings. Lowering temperatures also allows for decreased potential emissions such as greenhouse gasses and odors from plants. The reduction in emissions is crucial near non-attainment areas such as large urban areas and cities that have strict air quality regulations (Button, et al, 2007). It has been reported that manufactures and materials suppliers have achieved energy savings on the order of 30%, with a corresponding reduction in CO2 emission of 30% (Goh, et al, 2007).

Technologies that permit reduced HMA production temperatures may demonstrate positive impacts on pavement performance. Due to improved workability of the mix, WMA allows for reduced effort to compact the mixture under typical conditions. Warm mix asphalt also allows for longer haul distances and extended paving seasons in cool weather while maintaining the ability to achieve required density. The warm mix technology allows for integration of higher percentages of reclaimed asphalt pavement (RAP) and the placement of thick lifts with minimal delays to traffic (D' Angelo, et al, 2008).

The lower production temperature of WMA reduces the oxidation of the asphalt binder. This should improve pavement performance with respect to aging, thermal and block cracking, and compaction characteristics when placed. However, less hardening may increase the potential for early rutting until the pavement has oxidized to some extent in service.

The reduction in temperature also allows for improved working conditions and reduced worker exposure. Tests for asphalt aerosols/fumes and polycyclic aromatic hydrocarbons (PAHs) indicated significant reductions compared to HMA, with results showing a 30 to 50 percent reduction (D' Angelo, et al, 2008).

Various WMA methodologies have been developed to date and can be categorized as those using an organic additive or wax, a chemical additive or surfactant, and those which use water for foaming. Those methods which use an organic additive or wax produce a decrease in viscosity when heated higher than the melting point of the wax which allows for mixing and coating of the aggregate. The method which uses surfactants works using a range of different chemical mechanisms. The process which uses water for foaming uses volume expansion from the conversion of liquid to gas/steam which causes an increase of the asphalt binder and therefore decreasing the mix viscosity. The water may be introduced either through a foaming operation, or by a material which contains internal water, or from a moist aggregate.

Selection of a WMA process is based multiple considerations. Perhaps the main factor in the selection of a WMA process is the desired amount of temperature reduction. Some of the technologies allow for a greater reduction in temperature than others. Also, some additives may have an impact on the final PG binder grades which can influence the process selection. Finally, the initial cost of production equipment and additives is another factor to consider when selecting a WMA process. Ultimately the performance of pavements constructed with each technology must be considered.

B. HISTORY OF WARM MIX ASPHALT

The process of lowering temperatures to produce asphalt paving mixes is not new. In fact, the idea of saving energy and reducing emissions in the asphalt industry has been debated for decades.

In 1956, Dr. Ladis H. Csanyi, a professor at 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 a steam into hot bitumen. In 1968, Mobil Oil Australia, which had acquired the patent rights for Csanyi's invention, modified the original process to add cold water rather than steam. This change made the bitumen foaming process more practical (Kristjansdottir, 2006).

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" as a practical guideline, which contains valuable information for specifying, designing, and producing emulsion-stabilized mixtures. Tom Kuennen, Contributing Editor for Better Roads Magazine, 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 (68 °F to 120°F) plants have a lower initial cost than conventional HMA plants, are more easily transported, and may be situated anywhere without Environmental Protection Agency (EPA) permits due to their lack of emissions. Furthermore, they are amenable to mixes with high percentages of reclaimed asphalt pavement (Button, et al, 2007).

In 1994, Maccarone examined developments in cold mixed asphalt based on the use of foamed bitumen and very high binder content emulsions. He wrote that around the world the use of cold mixes for use on roadworks are gaining greater acceptance. Such systems are energy efficient and environmentally friendly. Production of cold mixes does not emit hydrocarbons and use less fuel in manufacturing (Kristjansdottir, 2006).

Despite many good properties, cold mixes have not affected hot mix asphalt's position as the primary road surfacing material. Cold mixes cannot achieve the same long-term performance as hot mixes.

In 1995, Shell Bitumen filed a patent to cover a warm-mix asphalt technique that used a two-component technique. B.G. Koenders, of Shell Global Solutions, described an innovative WMA process that was tested in the laboratory and evaluated in large-scale field trials (in Norway, the United Kingdom, and the Netherlands) with particular reference to the production and placement of dense-graded wearing courses. Shell's work resulted in the development of WAM-Foam® (Button, et al, 2007).

Sasobit® began to be marketed in Europe in 1997, as an asphalt mixture compaction aid by Sasol Wax International AG. The technology later grew into the WMA process.

In 1999, Jenkins et al. introduced a new process, "half-warm" foamed bitumen treatment. Their paper explored the considerations and possible benefits of heating a wide variety of aggregates to temperatures above ambient but below 212°F (100°C) before the application of foamed bitumen (Kristjansdottir, 2006). 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 (Button, et al, 2007).

Since 2000, warm mixes have received attention in Europe, South Africa and Australia by asphalt pavement associations possibly due to the relatively higher prices of fossil fuels and asphalt. These associations began early to examine the benefits and performance of WMA (Button, et al, 2007).

At the Eurobitume congress in 2004, Barthel et al. introduced the use of a synthetic zeolite additive to produce warm mix asphalt. The zeolite creates a foaming effect that results in a higher workability of the mix (Kristjansdottir, 2006).

The pavement industry in North America started to give attention to warm mixes and in June 2005 the National Center for Asphalt Technology (NCAT) published two reports about the use of Sasobit, a synthetic wax, and Aspha-min, a synthetic zeolite, in warm mix asphalt (Kristjansdottir, 2006).

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. However, the potential for significant impact is now in view. WMAs have been used in the U.S. for several years. As of 2007, WMA paving projects were constructed in Alabama, Florida, Indiana, Kansas, Maryland, Missouri, Ohio, Vermont, North Carolina, New York, Tennessee, Texas, Wisconsin, Ontario, Alberta, and Washington, D.C. Additionally, several municipalities have conducted test of WMA. Most, if not all of the tests involve overlays on existing pavements (Button, et al, 2007).

Most of the work on WMA has involved dense-graded mixtures; however, Koenders et al., 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 (Button, et al, 2007).

C. PURPOSE

The purpose of this report is to examine the current warm mix technologies as well as the benefits and disadvantages of warm mix asphalt. The report will examine the laboratory and field techniques for evaluation of warm mix asphalt. A review of the current standards and specifications as well as the best practices for the production and placement of warm mix asphalt are also included. Finally, the report assesses the current research needs and makes recommendations accordingly.

II. WARM MIX TECHNOLOGIES

Several new technologies have been developed that allow asphalt mixtures to be produced and placed at significantly lower temperatures than HMA. With these technologies, temperatures can be reduced by as much as 30 percent while allowing the asphalt binder to adequately coat the aggregate during mixing at the plant and achieve the desired workability for placement and compaction (Buncher, 2007).

Current warm mix asphalt technologies can be classified in various ways. One method is to classify technologies based on the degree of temperature reduction. Figure 1 shows the classification of various application temperatures for asphalt concrete, ranging from cold mix to conventional hot mix. The range of production temperatures within warm mix asphalt is wide, from mixes that are 20 to 30°C (36 to 54°F) below HMA temperatures slightly above 100°C (212°F). Warm mix asphalt mixes are separated from half-warm asphalt mixtures by the resulting mix temperature. If the resulting temperature of the mix at the plant is less than 100°C (212°F), the mix is considered a half-warm mix (D' Angelo, Harm, et al, 2008).

Table 1 shows the method for classifying warm mix asphalt technologies by type. There are two major types of technologies those that use water and those that either an organic additive, or wax to affect the temperature reduction. Processes that introduce small amounts of water to hot asphalt, either by a foaming nozzle or a hydrophilic mater such as zeolite, or damp aggregate, rely on the fact that when a given volume of water turns to steam at atmospheric pressure, it expands by a factor of 1,673. When the water is dispersed in hot asphalt and turns to steam, it results in an expansion of the binder phase and corresponding reduction in the mix viscosity. The amount of expansion depends on a multiple factors, which include the amount of water added and the temperature of the binder (D' Angelo, et al, 2008).

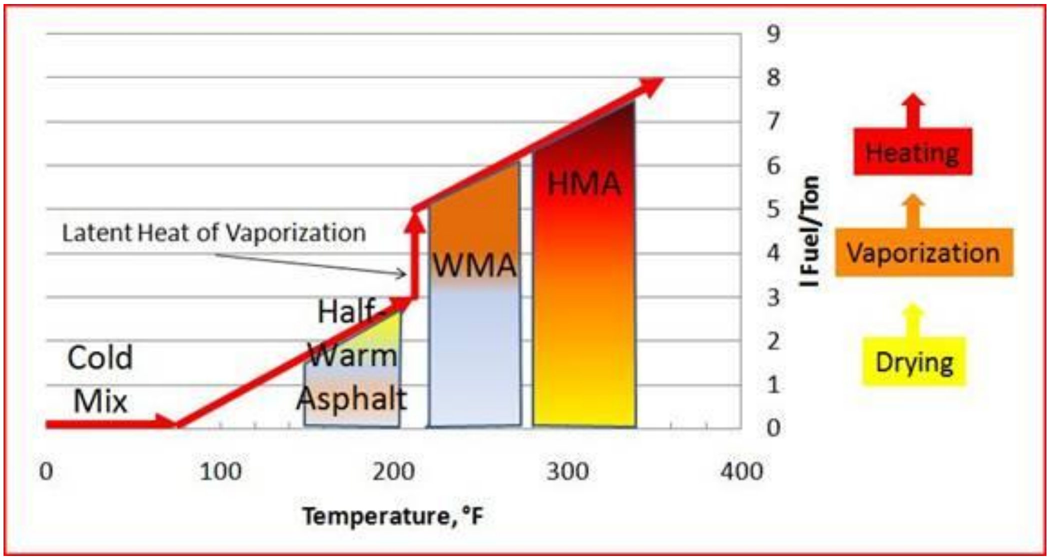

Figure 1 Asphalt Classification by Production Temperature

Table 1 Warm Mix Asphalt Technologies

Chemical Binder Additives	**Chemical Mixture Additives**	**Foaming Admixtures**	**Plant Modification**
Cecabase RT®	Asphaltan®	Advera®	Double-Barrel® Green
Evotherm™	Sasobit®	Aspha-Min®	Terex® WMA System
Rediset™ WMX		Suit-Kote Low Emission Asphalt	WAM - Foam
REVIX™			

A. CHEMICAL BINDER ADDITIVES

Chemical additives modify the viscosity temperature characteristics of the binder. In general they are proprietary chemicals so the exact mechanism and chemical process of how the product works is not available in the literature.

Chemical binder additives are added directly to the asphalt binder. These additives make the asphalt “wetter,” so it more readily coats and lubricates the aggregate particles.

1. CECABASE RT®

CECABASE RT, a liquid additive, from CECA, a subsidiary of the Arkema Group, is a chemical additive that provides workability to the asphalt mixtures at lower temperatures using 0.3 to 0.5 percent of CECABASE per unit weight in asphalt. CECABSE allows reductions in fabrication temperature up to 113°F (45°C) (Jorda, et al, 2008). CECABASE is blended with the asphalt binder by the binder supplier. The modified binder is supplied to the HMA producer. No modification is required for mix production other than a reduction in temperature.

2. Evotherm^{TM}

Evotherm is a product developed by MeadWestvaco Asphalt Innovations, Charleston, South Carolina. In the original process, an emulsion is mixed with hot aggregates to produce a resulting mix temperature between 85 and 115°C (185 and 240°F). It uses a chemical additive technology and a “Dispersed Asphalt Technology” delivery system that is injected at the mixing plant or at the asphalt terminal. The chemistry is customized for aggregate compatibility and is delivered as a dispersed asphalt phase (emulsion). During WMA production, the asphalt emulsion with Evotherm chemical package is used in place of the traditional asphalt binder (D' Angelo, et al, 2008). The emulsion is mixed with the aggregate in the HMA plant. MeadWestvaco reports that this chemistry provides aggregate coating, workability, adhesion, and improved compaction with no change in materials or job mix formula required (FHWA, 2008).

Evotherm’s technology enables asphalt mixes to be produced at temperatures more than 100°F lower than hot mix asphalt applications (Walker, 2009). MeadWestvaco also reports that the decreased production temperatures of the Evotherm process can lead to plant energy savings of 55 percent; which results in a 45 percent reduction in CO_2 and SO_2 emissions, a 60 % reduction in NOX, a 41% reduction in total organic material, and benzene soluble fractions below detectable limits (FHWA, 2008). In addition the lower production temperatures provide for up to 75 percent reduction in photochemical smog emissions, improved worker safety due to the handling of cooler temperature materials, as well as reduced odor and fumes associated with hot mix asphalt (Walker, 2009).

Paving with Evotherm can allow increases in RAP utilization, haul distances, paving seasons, and pavement life. Evotherm performance has been used in over 300 projects in over 25 states, as well as in France, Spain, Canada, Mexico, South Africa, and China. Since 2005, Evotherm has been evaluated using accelerated testing at the NCAT test track (Walker, 2009).

3. Rediset^{TM} WMX

Rediset WMX is a WMA process that uses additives made to reduce mixing and paving temperatures and provide moisture resistance properties. The Rediset system enables the production of hot mix at up to 60°F (33°C) lower temperature versus normal hot mix. This can reduce fuel consumption by at least 20 percent and lower CO_2 emissions. The lower temperature during mixing and paving also reduces smoke and fumes from the mix (Walker, 2009).

Rediset comes in a free-flowing, pellet form. It is added to the asphalt binder at a rate of 1.5 to 2 percent of the binder, prior to mixing or directly to the mixing unit. The mixing plant does not have to be modified. It does not require modification of the mix design and does not change the PG grading of the asphalt binder (Walker, 2009).

Rediset improves the cohesive strength of the asphalt and reduces rutting and moisture sensitivity of the mix and in the final pavement. The underwater Hamburg Wheel Tracking test shows that Rediset will improve the pavement cohesive strength or par with or better than lime or cement (Walker, 2009).

4. REVIX^{TM}

MeadWestvaco has introduced its third generation of the technology co-developed by Paragon Technical Services, Inc. & Mathy Technology and Engineering Services. The technology called Evotherm 3G and also branded as REVIX^{TM} Reduced Temperature Asphalt is water free and does not rely on the principles of asphalt binder foaming or other methods of viscosity reduction. According to Mathy, the additive provides a reduction in the internal resistance between aggregate particles and the thin binder films to promote coating of the aggregate during production and performance densification during construction produce bituminous mixtures which when subjected to high shear rates during mixing. Rheological testing is used to determine the mix production and compaction temperatures (FHWA, 2008).

B. CHEMICAL MIXTURE ADDITIVES

Chemical mixture additives are waxes which provide workability above the melting point. These additives can be added either to the mixture or directly to the asphalt binder.

1. Asphaltan B®

Asphaltan B is produced by Romonta GmbH, Amsdorf, Germany. It is available in granular form in 25 kg bags (FHWA, 2008). Created specifically for "rolled asphalt," Asphaltan B is a refined Montan wax blended with a fatty acid amide (D' Angelo, et al, 2008).

Crude Montan Wax is a combination of nonglyceride long-chain carboxylic acid esters, free long-chain organic acids, long-chain alcohols, ketones, hydrocarbons, and resins (D' Angelo, et al, 2008). This wax is found in Germany, Eastern Europe and areas of the USA in certain types of lignite or brown coal deposits. 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 has survived over long geological 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 (FHWA, 2008).

Romonta recommends adding Asphaltan B at 2 to 4 percent by weight of the binder. It can be added to the asphalt mixing plant or directly at the binder producer tanks. It is compatible with polymer-modified binders. The melting point of Asphaltan B is approximately 210°F. Similar to Fisher-Tropsch waxes, it acts as an "asphalt flow improver" with associated reduced production temperatures. Romonta does not specify how much the production temperature can be lowered. Like Fisher-Tropsch waxes, Romonta also reports increased "compactibility" and resistance to rutting (FHWA, 2008).

2. Sasobit®

Sasobit, a long-chain aliphatic hydrocarbon, is produced by Sasol Wax in South Africa using a Fischer-Tropsch wax (Walker, 2009). Fischer-Tropsch paraffin waxes are produced by treating hot coal with steam in the present of a catalyst (D' Angelo, et al, 2008). Sasol Wax states that Sasobit has a melting point of approximately 210 °F and is completely soluble in asphalt binder at temperatures greater than 240°F (115°C) having a high viscosity at lower temperatures, and low viscosity at higher temperatures (FHWA, 2008). Sasobit forms a homogenous solution with the base asphalt upon stirring and produces a marked reduction in the asphalt's viscosity. This enables mixing and handling temperatures to be reduced by 20 to 55°F (10 to 30°C). During cooling, Sasobit crystallizes and forms a lattice structure in the asphalt increasing the asphalt stability (Walker, 2009).

Sasobit should be added to the asphalt binder either at the tank at the HMAC plant or by the binder supplier prior to shipping to the plant. The blended asphalt is stable and does not separate. Sasobit can be used with polymer-modified asphalts. The reduced viscosity provided by adding Sasobit improves the workability and compaction of modified binders (Walker, 2009).

Sasol Wax recommends adding Sasobit at 3 percent by weight of the mix to gain the desired reduction in viscosity and should not exceed 4 percent due to the possible impact on the binder’s low temperature properties (FHWA, 2008).

Hamburg Wheel Tracking tests have shown that Sasobit-modified binders display increased rutting resistance. In addition, Sasol Wax reports improved “compactibility” with an increase in the degree of compaction for the same roller loading as unmodified asphalt. Sasobit does not significantly affect the low temperature behavior of asphalts. The low temperature properties are determined by the base asphalt (Walker, 2009).

C. FOAMING ADMIXTURES

1. PQ Corporation Advera WMA

Advera WMA, a synthetic zeolite, is a warm mix asphalt technology first introduced in Europe over 10 years ago. It produces a sustained, time-release foaming of the asphalt binder at a true warm mix asphalt production temperature, 250°F, without modifying the PG grade of the binder (Walker, 2009). Advera has a finer gradation than Aspha-min, with 100 percent passing the 0.075 millimeter (No. 200) sieve (FHWA, 2008).

Advera WMA contains 20 percent moisture, which is structurally and chemically bound in the zeolite. The zeolite releases this moisture over a sustained period of time from the 4 Angstrom pore, causing micro-foaming. This small amount of micro-foam (0.05 percent water by the weight of mix) gives long lasting workability until the temperature drops below 212°F. The wider paving window allows for longer haul distances, cold weather paving, and the ability to pave over crack sealant successfully (Walker, 2009).

Advera has been tested with both dense and open graded mixes, in base and wearing courses throughout the USA and Canada. It can be used with any HMA plant, batch or drum.

Advera is introduced into the plant using a feeder, with minor modification to the plant – the addition of a port near the asphalt line in a drum plant and into the pug mill in a batch plant. One dosage level, 0.25 percent of the weight of the asphalt mix (5 pounds per ton) is used for all mixes (Walker, 2009).

2. Aspha-Min®

Aspha-Min is a synthetic zeolite product of Eurovia Services GmbH, Bottrop, Germany. Synthetic zeolite is composed of alumino-silicates of alkalimetals. The Aspha-Min is added at the plant at the same time as the binder (Buncher, 2007). Aspha-Min contains 21 percent water by mass of crystallization. The water is released in the temperature range of 185 to 360°F (FHWA, 2008). The zeolite releases internal water to microscopically foam the binder which increases binder volume resulting in decreasing binder viscosity (Buncher, 2007). Gradual release of water reportedly provides a 6 to 7 hour period of improved workability, which lasts until the temperature drops below 212°F (100°C) (D' Angelo, et al, 2008). Typically 0.3 percent zeolite by weight of mixture is added to the mixture shortly before or at the same time as the binder (D' Angelo, et al, 2008).

This can result in a 54°F reduction in typical HMA production temperatures. The reduction in temperatures is reported to lead to a 30 percent reduction in fuel energy consumption. Eurovia states that all commonly known asphalt and polymer-modified binders can be used as well as the addition of recycled asphalt (FHWA, 2008).

3. Suit-Kote Low Emission Asphalt

Low Emission Asphalt (LEA) is a warm mix technology that uses moisture contained in the aggregates to foam the asphalt. In the LEA process, the coarse aggregate is heated to 302°F(150°C) and mixed with the total binder required for the mixture at the normal binder temperature (appropriate for the particular grade). The liquid chemical additive rate is approximately 0.5 percent by weight of binder of a coating and adhesion additive is added to the binder just before mixing. After the coarse aggregate is coated, it is mixed with the cold, wet fine aggregate. Ideally, the fine aggregate, which could be as high was 40 percent of the total mixture, should contain 3 percent moisture (Walker, 2009). This moisture turns to steam and causes the asphalt on the coarse aggregate to foam, which in turn encapsulates the fine aggregate. The resulting (equilibrium) mix temperature is less than 212°F (100°C) and can be paved at temperatures as low as 170°F (Walker, 2009). In a drum plan, the fine aggregate is typically added through the reclaimed asphalt pavement (RAP) collar. If the fine aggregate is too wet, a portion of the fine aggregate can be dried with the coarse aggregate (FHWA, 2008).

New York has used low emission asphalt on multiple projects across the state since 2006. It is based on the Low Energy Process developed in France and relies on a chemical additive and sequential mixing to yield a 35 to 50 percent reduction in energy consumption over HMA. LEA also reduces greenhouse gas emissions, uses existing HMA mix designs, improves working conditions, and minimizes plant modifications (Walker, 2009).

D. PLANT MODIFICATION

1. Astec Double Barrel Green®

Astec, Inc. launched the Double Barrel Green System in June of 2007 as an option that can be included with any new Astec Double Barrel drum mixer/dryer or added as a retrofit. The Double Barrel Green System does not require the addition of commercial additives. Instead, the system uses water to produce foamed warm mix asphalt by injecting it into the mix along with the asphalt cement (Walker, 2009). The injection of water causes the liquid asphalt to foam and expand. The foaming action helps the liquid asphalt coat the aggregate at a temperature that normally is in the range of 230 to 270°F versus traditional temperatures of 300 to 340°F (Astec Inc., 2009).

The key benefits of the Double Barrel Green System according to Astec Inc., include:

Improved workability - The foamed liquid asphalt coating has a lower viscosity

No smoke and no smell because the light oils in liquid asphalt never reach the boiling point.

The ability to run high percentages of recycle mix with a standard grade of asphalt.

Longer pavement life - Due to less oxidation of mix and more uniformity of compaction

Approximately 14 percent less fuel is used corresponding to a 14 percent increase in production (greater temperature reduction results in bigger fuel savings).

Astec has introduced the Green Pac™ warm mix system, which can be retrofitted to continuous mix and batch plants from any manufacturer. Figure 2 shows the Green Pac™ system that may be added to plants. By offering the Green Pac System, Astec expands the benefits of its Double Barrel Green warm mix system to any asphalt plant owner or operator (Walker, 2009).

Figure 2 Green Pac^{TM} Warm Mix System

2. *Terex® WMA System*

Terex WMA asphalt foam processing line (See Figure 3) uses Terex patented, field-proven foamed asphalt technology, originally pioneered in 1998 as a bond in the processing of asphalt mass. A single expansion chamber ensures consistent AC/water mix at any production rate. Producing foamed asphalt outside of the drum the system immediately injects it into the drum's mixing chamber, evenly coating the aggregate. This system reduces mix temperatures by up to 90°C without the use of additives. This increases pavement durability and reduces asphalt bond aging from oxidation, preserving asphalt pavements elastic response to fatigue (Terex Corporation, 2009).

The new WMA Foam technology can save asphalt producers 10 to 22 percent in fuel (Terex Corporation, 2009).

Figure 3 Terex® WMA System

3. WMA-Foam

WAM-Foam is a product of a joint venture between Shell International Petroleum Company Ltd., London, UK and Kolo-Veidekke, Oslo, Norway. The WAM-Foam process uses a two-stage addition of asphalt binder a soft and a hard. Lower asphalt mixture production temperatures can be achieved and the resulting blend of the binders is chosen to produce the desired performance grade. The soft binder typically representing 20 to 30 percent of the total binder content has a viscosity grade of 1,500 centistokes at 140°F (60°C) and is mixed with the aggregate in the first stage at approximately 230°F to achieve full aggregate coverage. The hard binder component mixed in a second stage into the pre-coated aggregates in the form of foam is typically a 70/100 penetration grade (pen), or about a PG 58/64-22. The aggregate, minus any filler, is heated to about 266°F (130°C) (D' Angelo, Harm, et al, 2008). Foaming of the hard binder is accomplished by adding ambient temperature water at a rate of 2 to 5 percent by mass of the hard binder into the heated hard binder at 330 to 356°F (175 to 180°C). The hard binder foam combines with the soft binder to achieve the required final composition and properties of the asphalt product (FHWA, 2008). This results in approximately 1.6 pounds (lb) of water per ton (0.8 kilogram (kg) per metric ton) of mix for a 5 percent asphalt content mixture (D' Angelo, et al, 2008). The water expands by a factor of approximately 1600 when it contacts the hot binder and turns to steam. This causes the resulting binder-water combination to expand to approximately 15 times its original volume. The resulting mix temperature is between 212 and 248°F (100 to 120°C) (Prowell and Hurley, 2007).

Shell states that WAM-Foam's success depends on careful selection of the soft and hard binder components. In some cases it is recommended to use an adhesion improver in the first mixing stage. Shell also states that initial coating of the aggregate in the first mixing stage is vital to prevent water from reaching the binder and aggregate interface and entering the aggregate and that water must be removed 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 results in a 30 percent reduction in CO_2 emissions (FHWA, 2008).

III. BENEFITS AND DISADVANTAGES OF WARM MIX ASPHALT

A. PAVING BENEFITS

1. Compaction

The decreased viscosity of WMA allows effective compaction at lower temperatures. The cool down rates at lower temperatures are slower which provides more time to complete compaction. Using WMA processes at HMA production temperatures facilitates compaction which is beneficial for stiff mixes and RAP, paving during extreme weather conditions and reduction in compaction effort (Kristjansdottir, 2006). Some WMA methodologies have been added to mixes containing highly modified binders (PG 82s, etc.) to facilitate compaction. Lab specimens of WMA routinely have less air voids and VMA than corresponding HMA specimens (Walker^2, 2009).

The grade of asphalt cement in HMA influences compaction such that lower viscosity (soft) grades are mixed, placed, and compacted at lower temperatures than harder grades. Soft grades are normally mixed at lower pugmill temperatures and have lower cessation temperatures. A mix made with softer grades than normal in order to improve compaction may be easier to compact at lower temperatures but it is likely to be unstable under summer traffic. Total compaction time between placement and cessation temperature for different grades is roughly the same. Asphalt modifiers such as hydrated lime, fibers, anti-oxidants, chemical anti-stripping agents, carbon black, rubber and polymers can each affect compaction in a different way. Cold weather compaction is not increased by the use of additives that increase viscosity. More viscous asphalt will probably have higher cessation temperatures (Kristjansdottir, 2006).

Compactibility is indeed well accounted for by the warm mix methods, since they all reduce the viscosity of the asphalt and have the capability on increasing compaction and thereby reducing permeability (Kristjansdottir, 2006). According to Warm-Mix Asphalt: European Practice; several studies have shown data that WMA technologies act as compaction aids allowing less compactive effort. Some of the technologies such as Sasobit were initially used for their stiffening effect at high in-service pavement temperatures. During this use it was observed that the materials reduced viscosity at compaction temperatures, particularly when compared to other types of modifiers (D' Angelo, et al, 2008).

2. Cold-Weather Paving

Compaction is especially important during cold weather paving. As ambient temperatures decrease, HMA cool down rates increase and the time available for compaction, before cessation temperature is reached, is reduced. 20 Pa-s (200 poises) is a reasonable lower viscosity limit for compactibility, i.e. cessation temperature. Dense, well compacted pavements have close aggregate-to-aggregate contact and will be more stable and have lower permeability. Achieving low permeability is especially important when compacting in cold weather (Kristjansdottir, 2006).

The mix design process does not need to be altered for cold weather conditions but particular care must be taken to ensure that mixtures are not overly susceptible to moisture damage. Surface water infiltration can cause rapid deterioration under traffic when pavement surfaces compacted in cold weather are more permeable (Kristjansdottir, 2006).

Achieving adequate moisture damage resistance may be a challenge when using warm mix methods. Since this is also a factor that needs special attention regarding cold weather conditions, it is very important for WMA in cold weather conditions. Therefore, for cold weather paving with WMA, use of anti-stripping agents is desirable, whether it is necessary depends on additional factors, such as aggregate quality and moisture content (Kristjansdottir, 2006).

Case studies have been presented in Germany in which paving was completed with various technologies when ambient temperatures were between -3 and 4°C (27 and 40°F). Base, binder, and an SMA surface course were placed using Aspha-min. The base course contained 45 percent RAP. Ambient temperatures during placement ranged from 30 to 37°F (-1 to 3°C). The mix temperatures for the WMA behind the paver ranged from 216 to 282°F (102 to 139°C). Better density results were obtained with the WMA than the HMA with the same or fewer roller passes. The ability to compact the mix at lower temperatures is achieved through reduction in viscosity of the binder. Data were presented using Licomont BS 100 on the viscosity reduction effect at lower temperatures; similar data were presented for Sasobit (D' Angelo, et al, 2008).

Actual production temperatures for WMA mixes produced during cool weather vary, depending on the WMA technology, ambient conditions, and haul distance. In most cases the production temperatures will most likely be reduced compared to HMA produced under the same conditions. In some cases, the production temperatures may be closer to that of HMA (D' Angelo, et al, 2008).

3. Longer Haul Distances

Using WMA processes at HMA production temperatures increases the temperature gap between production and cessation, allowing for increased haul distances (Kristjansdottir, 2006). HMA containing Sasobit reportedly was hauled up to 9 hours in Australia and the material was still able to be unloaded. The Department of Eure-et-Loir in France also believes that WMA technologies can be used for longer hauls while maintaining workability (D' Angelo, et al, 2008).

4. Use of Reclaimed Asphalt Pavements (RAP)

State Departments of Transportation (DOTs) are seriously considering the economic and environmental benefits of allowing high percentages of Reclaimed Asphalt Pavement (RAP) with WMA technologies (Copeland, et al, 2009). RAP primarily comes from milling of existing roadways or parking lots. Typically it is trucked from a milling machine to a stockpile at an asphalt plant. RAP helps reduce cost because the aggregates in the recycled material have already been coated with asphalt. Since 2007, 24 states have increased the allowable percentages of RAP in their asphalt pavements (Brown, 2010).

RAP rates between 10 and 30% are commonly used in bituminous mixes. According to several studies, with these rates bituminous mixtures perform similarly to conventional mixtures. However, environmental restrictions are causing an increase in RAP content added to recycled mixtures used in bituminous pavement construction and rehabilitation. This has a beneficial effect from the economic point of view and makes pavement construction sustainable over time due to lower energy and natural resource consumption (Valdés-Vidal, et al, 2010).

More than sixty percent of State DOTs permit high RAP percentages (i.e. more than 25% RAP by aggregate weight) to be used in asphalt bases. However, most projects do not routinely use high RAP percentages, in the surface and intermediate layers. Eleven states now have experience using high RAP combined with WMA. With this limited experience, State DOTs have expressed concern over the lack of guidance and information on the performance of high RAP mixtures and WMA (Copeland, et al, 2009).

WMA technologies may be beneficial with mixes containing high proportions of RAP in two ways: 1) the viscosity reduction will aid in compaction, and 2) the decreased aging of the binder as a result of the lower production temperatures may help compensate for the aged RAP binder, similar to using a softer binder grade (D' Angelo, et al, 2008). AASHTO M 323 *Standard Specification for Superpave Volumetric Mix Design* requires the use of blending charts to determine the proper virgin binder Performance Grade (PG) when using more than 25% RAP. In order to characterize the RAP binder for use in blending charts, the binder is extracted, recovered, and tested. It is assumed that the softer virgin binder and the stiff RAP binder blend producing a mix with a similar stiffness to virgin mix. However, if the binders do not properly blend, the mix may behave as mix with a lower grade of binder or lower effective asphalt content and may be susceptible to rutting (Copeland, et al, 2009).

In Germany, a case study was presented in which 45 percent RAP was used in the base course. In the Netherlands, both LEAB and HMA are routinely produced with 50 percent unfractionated RAP. Trials have been conducted in Germany with 90 to 100 percent RAP using Aspha-min zeolite and Sasobit (D' Angelo, et al, 2008).

According to the Warm-Mix Asphalt: European Practice; RAP usage in the United States appears to be higher than that in the countries visited during the scan. In Norway, Kolo Veidekke reported that it typically runs 7 to 8 percent RAP in all of its mixes. Milling is not used extensively in Norway, so its RAP supply is limited. Kolo Veidekke tries to run a consistent amount of RAP in all of its mixes. In its annual report, Colas reported that its U.S.-based operations average a recycling rate of 14 percent, compared to 3 percent in France. Colas' Northern Europe operations average an 11 percent recycling rate (D' Angelo, et al, 2008).

In June 2007, Astec and Southeastern Materials, a division of Talley Construction Company, collaborated to perform a 4,000-ton warm mix demonstration project for the city of Chattanooga, Tennessee. According to Don Brock, chairman of Astec Industries, "The city milled out 2 inches of pavement; we fractioned it back to its original sizes and ran it at 50 percent recycle" (Brown, 2010).

5. Increased Production in Non-attainment Areas

The ability to improve the environmental friendliness of asphalt paving creates opportunities to expand production. Current state and local regulations are such that in some ozone non-attainment areas, hot-mix plants are sometimes required to curtail operations in daylight hours during certain times of the year when ozone formation is problematic. Recently adopted new ozone standards will create additional ozone non-attainment areas, along with new, more stringent demands for emission reductions in the future and the demonstration that transportation plans and projects are in conformity with the Clean Air Act (Newcomb, 2006). WMA allows for paving in ozone nonattainment areas and/or more plant operation during daylight hours in these regions (Button, et al, 2007).

B. REDUCED FUEL AND ENERGY CONSUMPTION

The initial benefit of producing WMA is the reduction in energy consumption required to heat traditional hot mix asphalt (HMA) to temperatures in excess of 300°F. By reducing the temperature of asphalt mixtures WMA allows for reduced fuel consumption by 11 to 30 percent compared to HMA (Iowa Local Technical Assistance Program, 2009). Conventional high production temperatures are needed to reduce asphalt binder to become viscous enough to completely coat the aggregates in the HMA, provide good workability during lay down and compaction (Suttmeier, 2006).

Reports indicate that fuel savings with WMA typically range from 20 to 35 percent. These levels could be higher if burner tuning was completed to allow the burner to run at lower settings. Fuel savings could be higher (possibly 50 percent or more) with processes such as low-energy asphalt (LEA), in which the aggregates (or a portion of the aggregates) are not heated above the boiling point of water (D' Angelo, et al, 2008). According to the Warm-Mix Asphalt: European Practice; it does not appear that any change in electrical usage to mix and move the material through the plant has been considered in the analysis of potential fuel savings.

C. REDUCED EMISSIONS

Using WMA should result in reduced volatile organic compounds (VOCs), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), and particulates. There are two sources of reduced emissions, reduction in gas released by burning fuel and reduction in VOC from heating asphalt. Since most plant emissions result from burning fuel and WMA uses less fuel, there should be lower emissions. The amount of emissions reduction will depend on the temperature reduction, the type of fuel used, plant settings, moisture content of the aggregate, and RAP use (Walker[2], 2009).

According to Warm-Mix Asphalt: European Practice, multiple suppliers' presentations in Norway, Belgium, and France included data that indicated reduced plant emissions. Table 2 shows the ranges in reductions. Reduced emissions were reported in Germany, but no data were presented. Data from the Bitumen Forum relate emissions to temperature: "At temperatures below 80°C (176°F), there are virtually no emissions of bitumen; even at about 150°C (302°F), emissions are only about 1 mg/h. Significant emissions were recorded at 180°C (356°F) (D' Angelo, et al, 2008)."

Table 2 Reported Reductions in Plant Emissions (percent) with WMA

Emission	Norway	Italy	Netherlands	France
CO_2	31.5	30 - 40	15 – 30	23
SO_2	NA	35	NA	18
VOC	NA	50	NA	19
CO	28.5	10 – 30	NA	NA
NO_x	61.5	60 – 70	NA	18*
Dust	54.0	25 – 55	NA	NA

* Reported as NO_2

NA – not available

Problems observed in the United States with increased emissions – particularly CO and VOCs – potentially due to unburned fuel were not reported in Europe. The smaller plants used in most cases in Europe have correspondingly smaller burners, making it easier to adjust the burner to run at lower temperatures (D' Angelo, et al, 2008).

D. IMPROVED WORKING CONDITIONS

Working conditions in the production and placement of HMA are also important to the industry as improvements lead to an enhanced work environment, higher-quality work, and better employee and workforce retention. An important innovation regarding this was the implementation of engineering controls on pavers for fume reduction in 1997. These devices removed fumes from the immediate area of paver and screed operators. Significant HMA temperature reduction would have two benefits for the workforce: it would further reduce fumes in the vicinity of all paving workers and it would make for a cooler work environment (Newcomb, 2006, Walker 2009).

Enforcement of a new European Union regulation called Registration, Evaluation, Authorization, and Restriction of Chemicals (REACH) was implemented in June 2007. It requires chemical suppliers to provide information to workers on potential exposure and to set derived non-effect levels (DNEL). Asphalt binders are included under these regulations. Research has shown a strong correlation between production temperatures and asphalt fume production. It is anticipated the DNEL levels will set asphalt application temperatures at less than 200°C (392°F). While this is well above the temperature at which HMA is placed, particularly in the United States, it is lower than temperatures used for the production of mastic asphalt. Although mastic usage is relatively small, it is a technology that European agencies want to continue to specify. This seems to be a driving force toward WMA in areas where mastic asphalt is routinely used (D' Angelo, et al, 2008).

According to the European Scan Team; French, German, and Italian data has been presented that indicated reduced worker exposure when placing WMA. Direct comparisons of measurements of fumes and aerosols are difficult since different testing protocols and sampling periods are used in different countries. However, all of the exposure data for HMA was below the acceptable exposure limits. Tests for asphalt aerosols/fumes and polycyclic aromatic hydrocarbons (PAHs) indicated significant reductions compared to HMA. Data presented by the Bitumen Forum appear to result in a 30 to 50 percent reduction. Preliminary data from an impending Italian study indicates even greater reductions (D' Angelo, et al, 2008).

E. DISADVANTAGES

1. Increased Initial Production Cost

The factors affecting the economic viability of WMA need to be identified and tracked. Potential factors include: additive costs, plant modifications, asphalt costs, fuel costs, costs of emissions compliance equipment such as low NO_X burners and fugitive emissions containment systems, and costs related to worker exposure (Prowell, 2007).

Use of WMA increases costs associated with various aspects of the technology. Table 2 shows tabulated costs for some of the leading WMA technologies. Since these technologies are relatively new, their costs fluctuate and will, with increasing use, likely decrease with time (Chowdhury and Button, 2008).

One consideration for WMA is how many tons will be produced. Some of the methodologies have higher initial equipment costs. Others using additives have higher costs per ton produced. Typically warm mix additives cost between $2.50 and $3 per ton of mix (Brown, 2008). Another consideration is how much temperature reduction is desired. Some technologies offer more temperature reduction than others. Some WMA additives can affect the final PG binder grades. Typically both the high-temperature and low-temperature grades are raised slightly (Walker[2], 2009).

2. Moisture Susceptibility

Since binders in WMA mixtures may be softer than expected and because some WMA technologies use water as a workability aid, WMA mixtures may be susceptible to moisture damage. This is an issue with some HMA mixtures, of course, but with WMA mixtures there is the possibility of inadequately dried aggregates at the lower production temperatures and/or the introduction of additional moisture to the mix from the WMA technology/process, and this may affect the binder to aggregate adhesion, moisture susceptibility, and performance. The extent to which each of the different types of WMA technologies will impact moisture sensitivity needs to be established in order to provide unbiased moisture performance data and WMA usage guidance to state DOTs, contractors, and asphalt pavement producers (Harrigan, 2009).

Regarding moisture damage, the tensile strength ratio (TSR) of some tests performed on plant-produced WMA has been lower than comparable HMA samples. This lower TSR has been attributed to the reduction in binder aging at the lower production temperatures. Cores taken from WMA pavements after some service time have shown an increase in TSR and have not shown any moisture damage/stripping. European practice is to use anti-stripping agents in WMA (Walker, 2009).

3. Binder Absorption

Lower HMA mixing temperatures can be associated with decreased tensile strength. While increasing mixture temperature will enhance moisture susceptibility of HMA. Higher mixing temperatures can also contribute to 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 (Chowdhury and Button, 2008).

Coating the coarse aggregate with softer binder acts to satisfy the asphalt absorption of the coarse aggregate that may not otherwise occur with a stiffer binder at low temperature (D' Angelo, et al, 2008).

Table 3 Cost of Producing HMA and Savings from WMA for Selected Locations

Location	Iceland	Honolulu, HI	Joliet, IL
Fuel Source[a]	No. 2 fuel oil	Diesel	Natural Gas
Amount to make 1 ton of HMA[b]	2 – 3 gallons (7.6 - 11.4L)	2 – 3 gallons (7.6 - 11.4 L)	2.5 – 3.5 therms.
Fuel cost[c]	$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[d]	$5.00 - $7.50	$4.40 - $9.00	$1.75 –$2.80
Electricity to make 1 ton of HMA[e]	8 – 14 kWh	8 – 14 kWh	8 – 14 kWh
Industrial electricity cost[f]	$0.02/kWh	$0.1805/kWh	$0.0445/kWh
Electricity cost to make 1 ton of HMA[g]	$0.16 – $0.28	$1.44 – $2.53	$0.36 – $0.64
Total energy cost to make 1 ton of HMA[h]	$5.16 – $7.78	$5.84 – $11.53	$2.11 – $3.44
20% savings with WMA[i]	$1.00 – $1.50	$0.88 – $1.80	$0.35 – $0.56
50% savings with WMA[j]	$2.50 – $3.75	$2.20 – $4.50	$0.88 – $1.40

Footnotes to Table 3.

a. Aggregate moisture content assumed typical at 2 – 4%. Amounts of fuel are general averages.

b. Numbers taken from personal correspondence with a producer in each area.

c. Range shown is the low end amount of fuel multiplied by the low end fuel cost and the high end amount of fuel multiplied by the high end fuel cost. In general, this constitutes the cost to dry and heat aggregate.

d. Taken as the average of 8 to 14 kWh range obtained from (21). This constitutes other power requirements not furnished by the aggregate dryer or drum plant burner.

e. Taken as the average industrial retail price for the particular region either from the web page of Reykjavik Energy, www.or.is (Iceland) or from Table 5.6A of the Energy Information Administration's July 2006 Electric Power Monthly.

f. Range shown is the low electricity requirement multiplied by the low end electricity cost and the high end electricity requirement multiplied by the high end electricity cost.

g. Fuel cost added to electricity cost.

h. A rough estimate of the low end of expected savings from WMA technology. Range shown is the low end and high end of the fuel cost each multiplied by 20%.

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%.

The soft binder typically represents 20 to 30 percent of the total binder content. The resulting binder grade, assuming 20 percent of a V1500 and 80 percent of a 70/100 pen binder, would be a 70/100 pen binder, un-aged. If the resultant binder grade needs to be altered, this should be done by varying the component binder grades because a minimum percentage of the soft binder is required to coat the coarse aggregate. Coating the coarse aggregate with the soft binder should also satisfy the demand of any asphalt absorption of the coarse aggregate that may not otherwise occur with a stiffer binder at low temperature. Anti-stripping agents could also be added to the soft binder (D' Angelo, et al, 2008).

According to the Texas Department of Transportation; better densities, less oxidation of asphalt, and less asphalt absorption, generally produces a more durable pavement (Gaetano, 2009).

IV. MATERIAL TEST FOR WARM MIX ASPHALT

When considering a WMA trial, a minimum desired test section would be 800 - 1000 tons of WMA. This will allow a plant run of approximately four hours at reasonable production rates. Further, it is desirable to have a hot mix control section to be produced using the same mix design (without the WMA additives) (Warm Mix Asphalt Technical Working Group (WMA TWG), 2006).

A. LABORATORY TECHNIQUES FOR EVALUATION OF WARM MIX ASPHALT

The following are laboratory mix tests (field mixed/laboratory compacted) to be performed on both WMA and control sections (Warm Mix Asphalt Technical Working Group (WMA TWG), 2006).

Moisture Content of Mix at Load Out (Sampled from Truck) – AASHTO T329

Gyratory compaction of six pills for each sample to specified Ndesign compaction effort <u>without reheating mix other than to desired compaction temperature</u>. Record time needed to reheat samples (if any). After the volumetric properties are measured, the samples may be tested in the Asphalt Pavement Analyzer (APA) for rutting potential at the recommended climatic high temperature for the site.

Maximum Specific Gravity

Tensile Strength Ratio (TSR) Testing should be completed using 6 to 8, samples to 7 ± 0.5 percent air voids and a height of 95 mm; without reheating mix other than to desired compaction temperature. Record time needed to reheat samples (if any). The following equation has been used to estimate TSR sample weight in order to obtain 7 percent voids:

$M = (0.915)(G_{mm})(\pi)(56.25)(9.5) = 1536.11(G_{mm})$

The 150 mm diameter samples should be compacted to a constant height of 95 mm. Typically the National Center for Asphalt Technology (NCAT) will compact two trial samples first, allow to cool, bulk, and adjust the mass as necessary to obtain 7 percent voids for an additional six samples.

Compact three samples in the gyratory compactor to a height of 170 mm at the anticipated in-place (field) density for simple performance testing (SPT). The following equation has been used to estimate the target sample weight for 150 mm diameter samples compacted to a height of 170 mm. The first factor, 0.895, is the anticipated in-place density (93 percent of G_{mm}) minus 4.5 percent. The adjustment to the anticipated in-place density is necessary to correct for surface texture and the fact that the center of the sample is denser than the total samples (100 mm diameter samples, 150 mm tall, will be cored from the oversize SGC samples).

$M = (0.895)(G_{mm})(\pi)(56.25)(17.0) = 2688.7(G_{mm})$

Low Temperature Cracking – comparisons can be made between the low temperature cracking potential using the IDT test (AASHTO T322).

Additional Performance Testing specified by the Warm Mix Asphalt Technical Working Group which should be considered desirable but not mandatory include:

The Hamburg Wheel Test – AASHTO T324 measures the combined effects of rutting and moisture damage by rolling a steel wheel across the surface of an asphalt concrete slab that is immersed in hot water (FHWA, 2006). It also has been found to be sensitive to several factors, including asphalt cement stiffness, length of short-term aging, compaction temperature, and anti-stripping treatments. All these factors have previously been observed as possible areas in the evaluation of warm asphalt mixes, so the test results from the Hamburg wheel-tracking device may be vital in accurately establishing a good performing asphalt mix (Hurley and Prowell, 2006).

Test specimens must be conditioned under water for at least 30 minutes, once conditioned, the specimens are subjected to a wheel load of 157 -159 lb. This load is passed over the specimens up to 20,000 times. One cycle back and forth is considered two passes. The 20,000 pass mark indicates completion of the test as does a rut depth in excess of 40.9 mm. Once one of these criteria is met, the test is stopped automatically (Mahoney and Zinke, 2008).

Fatigue Life - Standard Method of Test for Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending – AASHTO T 321 subjects HMA beams to repeated loading in a 4 point loading machine. These tests can be run at a constant strain or constant stress level. Samples for beam fatigue testing should be prepared, preferably without reheating, to the anticipated in-place air void content. Improved densification tends to improve fatigue life. Thus, every effort should be made to capture the effect of improved compaction obtained within WMA.

Fracture Energy Testing - ASTM D7313 - 07a is an alternative method to assessing resistance to cracking

Texas Transportation Institute (TTI) Overlay Tester simulates the opening and closing of joints or cracks, which are the main driving force inducing reflective crack initiation and propagation (Zhou and Scullion, 2004).

Thermal Stress Restrained Specimen Test (TSRST) - AASHTO TP10 is used to evaluate the low-temperature cracking susceptibility of asphalt paving mixtures. The test is designed to measure the tensile stress in a beam specimen that is cooled at a constant rate while being restrained from contracting. As the temperature drops, thermal stresses build up until the specimen fractures (FHWA, 2006).

B. FIELD TECHNIQUES FOR EVALUATION OF WARM MIX ASPHALT

The following are field mix tests (field mixed/field compacted) to be performed on both WMA and control sections (Warm Mix Asphalt Technical Working Group (WMA TWG), 2006).

Density Tests – in place density should be determined based on cores. A minimum of nine cores should be taken from stratified random locations from each section. The cores should be sawed and measured for thickness. After density testing, the indirect tensile strength of three of the cores should be determined at 77°F. Loading rate for the indirect tensile strength shall be 2 inches/minute (same rate as for TSR).

Bond Strength Between Layers – three remaining cores should be used to determine bond strength between layers. There is some concern that the reduced mixture temperatures for WMA may fail to adequately bond to the underlying layer, particularly when PG binders are used as tack coat.

Aging During Construction – should be assessed by performing recoveries on the cores and the recovered binder graded. Extractions and recoveries should be performed according to AASHTO T319 or AASHTO T164 Method A with Rotovap recovery. The extraction solvent should be toluene and 95% ethanol mixed at a ratio of 85:15. The 95% ethanol contains 5 percent water. A maximum Rotovap temperature of 140°C should be used, lower if reduced pressures are utilized.

Indirect Tensile Strength – an additional six cores should be taken, three in and three between the wheel paths at three months, one and two years after construction and be tested at 77°F. The same should be done to test the density. The additional coring with time serves two purposes: 1) WMA additives have indicated reduced asphalt contents during design, the cores will be used to assess the in-place densification under traffic. These data should be related back to the QC air voids; 2) indirect tensile strength will be used to assess binder aging.

Smoothness Testing should be conducted prior to opening to traffic. AASHTO MP 17 provides guidance for developing specifications when an inertial profiling system is used for measurement and evaluation of ride quality and compliance.

Rut Depth Profiles should be conducted prior to opening to traffic (locations should be marked for future testing). AASHTO PP 38 is the Standard Practice for Determining Maximum Rut Depth in Asphalt Pavements.

V. PERFORMANCE OBSERVATIONS

The first pavements incorporating WMA additives were constructed in Europe in 1997; the oldest true WMA pavements were constructed in 1999. The FHWA International Scanning Tour team collected laboratory and short-term field performance data from some of the oldest WMA pavements in Europe in 2007. Based on the data collected by the scan team, performance of WMA mixes appears to be the same as or better than the performance of conventional HMA. The oldest sections in the U.S. were constructed in 2004 (Prowell and Hurley, 2007).

The two most prevalent concerns regarding the long-term performance of WMA have been increased potential for rutting and moisture damage. A number of projects have been constructed at the entrances to asphalt plants and exposed to heavy traffic. Some sections include the use of Aspha-min® at the Nashville, Tennessee World of Asphalt demonstration in 2004, Aspha-min® synthetic zeolite (referred to as U.S. zeolite at the time) at one of Pike Industries' plants in New Hampshire in 2005, and the use of LEA at Suit-Kote's Cortland, New York asphalt terminal in 2006. All of these pavements are reportedly performing well. The use of Evotherm^{TM} on two sections of the NCAT Test Track in 2005 (Evotherm^{TM} was also used for two lower lifts of a third section) is a better documented test. The average rut depth for the two Evotherm^{TM} sections, after 516,000 equivalent single axle loads (ESALs) were applied in a 43-day period (occurring at the end of the trafficking period for the remainder of the track) was 0.9 mm while the HMA control section, constructed at the same time, averaged 1.1 mm (Prowell and Hurley, 2007).

Short-term rutting data are also available for the St. Louis WMA trials constructed in May 2006. The sections were constructed on Hall Street, a four-lane roadway through a heavy industrial area. After six months of traffic, the maximum rutting observed was 1.1 mm in all three of the WMA section and there was no evidence of reflective bumps from the underlying crack sealant. Based on the performance of these sections, the short-term rutting performance of WMA appears to be good. Stiffness at in-service pavement temperatures and therefore their resistance to rutting has been reported (Prowell and Hurley, 2007).

There has been a concern that the aggregates in WMA mixes may not be completely dry due to lower production temperatures. WMA production temperatures are all high enough to dry the moisture on the outside of the aggregates; however, at lower temperatures, the dwell time in the drum may not be long enough to completely remove the internal moisture. Laboratory tensile strength ratio (TSR) test have, in some cases, indicated lower TSR values as compared to HMA. The reduction in TSR could also be related to the reduced aging of the binder due to the lower production temperatures. Cores have been taken from a number of projects after a period of time to evaluate the change in tensile strength with time and examined for visual evidence of stripping. The tensile strength of the roadway cores increased with age, as expected. There has not been any visual evidence of stripping observed in any of the projects tested to date.

It is expected that the reduced aging of the binder at the time of construction may be beneficial in terms of reduced cracking in the pavement. As the binder ages it becomes more brittle. Cracking potential can increase with age. Reduced aging at the time of construction may improve the long-term durability of WMA pavements. However, some of the WMA technologies, particularly the organic additives, may have the potential to increase the likelihood of low temperature cracking (Prowell and Hurley, 2007).

In order to validate long-term performance continued monitoring of WMA projects is a necessity. The long-term performance of WMA must be as good as HMA if benefits are to be realized in the long term. The objectives of NCHRP Project 09-47 is to establish relationships among engineering properties of WMA binders and mixes and the field performance of pavements constructed with WMA technologies; determine relative measures of performance between WMA and conventional HMA pavements; compare production and laydown practices and costs between WMA and HMA pavements; and provide relative emissions measurement of WMA technologies as compared to conventional HMA technologies (Transportation Research Board of the National Academies, 2010).

NCHRP Project 9-49, “Long Term Field Performance of Warm Mix Asphalt Technologies,” assesses whether WMA technologies adversely affect the moisture susceptibility of flexible pavements and develops guidelines for identifying and limiting moisture susceptibility in WMA pavements. Close coordination with NCHRP Projects 9-43, “Mix Design Practices for Warm Mix Asphalt,” and 9-47A, “Properties and Performance of Warm Mix Asphalt Technologies,” is required in all phases of this project (Transportation Research Board of the National Academies, 2010).

VI. STANDARDS AND SPECIFICATIONS

A. CURRENT WARM MIX ASPHALT SPECIFICATIONS

According to a survey conducted by the Montana Department of Transportation, Office of Research Programs, twelve states currently have Warm Mix Asphalt Specifications in use. An additional 12 states responded to the survey by saying that the current Hot Mix Asphalt specification was viewed as sufficient for WMA.

The Warm Mix Asphalt Technical Working Group prepared a generic specification that may be adopted by states, which is presented in the Appendix. This is a preliminary specification because additional information is needed from NCHRP 9-43 before the mixture design section can be finalized.

A summary of the current state specifications being used is provided below (Perkins, 2009).

The Alabama DOT specification states that all procedures in the specification are applicable to both hot and warm mix asphalt. WMA is defined as mix temperatures between 215 and 280°F. For WMA, an approved list of processes is given. The specification requires an anti-stripping agent for all warm mix processes. Greater percentages of RAP (up to 35%) are allowed with WMA (Perkins, 2009).

The specification used by California DOT is based on their HMA specification. It allows three technologies for WMA; Advera, Evotherm, and Sasobit. The specification contains languages that provides for test to ensure the correct dosage rate of these additives at the plant (Perkins, 2009).

Florida has issued an interim specification for WMA. The specification allows for paving under cooler conditions than specified for HMA. The specification currently has an approved list of four technologies: Aspha-Min, Double Barrel Green, Evotherm, and Aqua Foam system. The specification requires the technology be a “recognized process with successful projects demonstrated nationally or internationally” (Perkins, 2009).

The Idaho specification recognizes that a lower air void content may be obtained with field produced loose mixes and suggests that this material be allowed to cool and be reheated prior to laboratory compaction. The specification does not allow technologies that alter the performance grade of the binder (Perkins, 2009).

Indiana provided provisions for an HMA specification that allows for use of WMA by inclusion of the following passages:

> QC/QA HMA may be produced as warm-mix asphalt, WMA, by using a water-injection foaming device for ESAL category 1, 2, and 3 mixtures. The DMF shall list the minimum plant discharge temperature for HMA and WMA as applicable to the mixture.

When RAP is used, the following provision was added for WMA:

> A maximum of 25.0% RAP or 5.0% ARS by weight (mass) of the total mixture may be used in WMA for ESAL category 1, 2, and 3 mixtures except ESAL category 3 surface mixtures (Perkins, 2009).

The Iowa DOT currently uses project specific contract modification to allow WMA. The modification specifies the type of technology. The modification states that the manufacturer's recommendations shall be followed for incorporating the technology. Laboratory compaction and placement temperatures are specified (Perkins, 2009).

A special provision (Special Provision Section 401.031) is used by the Maine DOT to address the use of WMA. The specification acknowledges the possible use of WMA by including WMA additive as a possible material in the composition of mixtures. The specification states that WMA additive should be added in a manner and rate according to the manufacturer's recommendations. The specification describes four possible options for additives, consisting of organic, synthetic zeolite, chemical and other products/processes approved by the department. Foaming technologies fall in the last option (Perkins, 2009).

Ohio DOT allows for the use of water-based foaming technologies by specifying a list of requirements for the equipment used at the plant to provide this technology (Supplemental Specification 800). The specification further requires that this equipment has been demonstrated to be stable and effective by use on non-Ohio DOT projects. The specification also allows increased RAP percentages by incorporating WMA technologies (Perkins, 2009).

The Pennsylvania DOT has a special provision specification for both base and surface course WMA. The specification contains a list of approved technologies including Advera, Double Barrel Green, Evotherm, Green Machine, Low Energy Asphalt, Rediset WMX, Sasobit, and Warm Mix Asphalt System. A Paving Operation Quality Control (QC) Plan is required, which includes details on construction equipment and methods. A technical representative from the specified WMA manufacture is required to be present during production and placement of WMA (Perkins, 2009).

The Texas DOT developed a traditional specification for dense-graded hot-mix asphalt that was amended by adding the following paragraph to allow WMA.

Warm Mix Asphalt (WMA) is defined as additives or processes that allow a reduction in the temperature at which asphalt mixtures are produced and placed. WMA is allowed for use at the Contractor’s option unless otherwise shown on the plans. The use of WMA is required when shown on plans. When WMA is required by the plans, produce an asphalt mixture within the temperature range of 215°F and 275°F. When WMA is not required as shown on plans, produce an asphalt mixture within the temperature range of 215°F and 350°F. Unless otherwise directed, use only WMA additives or processes listed on the Department’s approved list maintained by the Construction Division (Perkins, 2009).

Virginia DOT provides for the use of WMA through a special provision in Section 211 of their specifications. The department maintains an approved list of products that may be used. This list currently (as of August 2009) includes AQUABlack, Double Barrel Green, Evotherm ET, Sasobit, and Ultrafoam GX. New products are added as they are evaluated. Evaluation includes development of independent test data to support the product, mix design submittals and a trial section.

For conformance testing, Superpave properties are determined on WMA that has been allowed to cool to 100°F or less and then reheated. The specification addresses the issue of stripping by requiring that the tensile strength ratio (TSR) be greater than or equal to 0.6 according to AASHTO T283 test procedure. The specification limits the initial production to 500 tons per day in order to allow the engineer to examine the process control of the mixing plant, placement procedures, surface appearance of the mix, compaction patterns, and correlation to nuclear density tests (Perkins, 2009).

Washington State has amended their standard specification by including langue that acknowledges WMA technologies. If the contractor proposes to use this technology, then they are required to submit for approval the process they will use (Perkins, 2009).

VII. BEST PRACTICES FOR THE PRODUCTION AND PLACEMENT OF WARM MIX ASPHALT

A. REDUCING STOCKPILE MOISTURE CONTENT

Substantial energy is required to dry aggregate. Thus, reducing the moisture content of aggregate stockpiles produces a number of benefits. Reduced moisture contents results in fuel savings, increased production capacity, and better performance. Aggregates must be dry prior to coating with asphalt to reduce the potential for moisture damage. There is concern that reduced production temperatures may not allow for the complete drying of the aggregate. Reducing the moisture content of the aggregate when it enters the plant will increase the chance that the coated aggregate in WMA is dry (Prowell and Hurley, 2007).

Based on the findings of the FHWA International Scanning Tour on WMA in 2007, aggregate moisture contents may be less of a concern in Europe where WMA originated because the aggregates used there tend to have low water absorption. In France, it was reported that all of the aggregates used had water absorptions less than 1 percent.

Two primary methods that reduce aggregate moisture contents include loading aggregate from the high side of a sloped, paved area under the stockpile, or by covering the aggregate storage areas (Prowell and Hurley, 2007).

A number of best practices were routinely observed in Europe. In Norway, the contractor covered the RAP stockpiles to minimize moisture content even though only 7 to 8 percent RAP was typically incorporated into their mixes (this level of RAP addition, added to all of their mixes, used up the available quantity of RAP). Aggregate transfer belts were covered at the majority of the plants visited to minimize blowing dust and to keep the belts dry in case of rain (Prowell and Hurley, 2007).

The moisture content of a stockpile varies with elevation; the highest moisture contents being at the lowest elevation. Water in the stockpile drains to the lowest elevation and eventually out of the pile. The loader loads from the high side of the pile, which allows it to access the drier material. Astec Industries recommends a 4-foot drop across the stockpile (3 percent grade across 133 feet) (Prowell and West, 2005). It is also important that there is sufficient space between the stockpiles so that cross-contamination between stockpiles does not occur. Stockpiles should also be built to be free draining, to ensure that the moisture content within the stockpile stays as low and consistent as possible (St. Martin, Cooley, et al, 2004). Paving under the stockpile prevents the stockpile from settling into the ground with time and creating a bathtub, which will trap water. It also prevents the loss of aggregate inventory and reduces the potential for contamination if the stockpiles are moved or changed at a later date (Prowell and Hurley, 2007).

Granite Construction Company won a 2004 NAPA Quality in Construction Award for Non-Typical Applications for paving under the sand stockpiles at their Tracy Aggregate Facility. A 75,000 square-foot area was paved with a 3 percent slope for dewatering washed sand. By loading aggregate from the high side, the moisture content of the sand was reduced from 10 to 6 percent. The drier sand resulted in a 9.2 percent fuel savings which typically makes up about 35 percent of the Tracy Asphalt Plant mix (Prowell and West, 2005). Astec reported data from a contractor in North Carolina which indicated an average reduction in moisture content between non-sloped, unpaved stockpiles and sloped, paved stockpiles of 26.6 percent, which resulted in a decrease in the average composite moisture content of 2.3 percent water (Prowell and Hurley, 2007).

An alternate to paving under stockpiles is covered aggregate storage. Either portable or permanent structures may be used. Figure 3 shows a portable enclosure used by Kolo Veidekke, a Norwegian contractor, to cover their RAP stockpile. Permanent structures can also be built to cover all of a plant’s stockpiles, or more critical materials like fine aggregate and RAP. Cover the collecting conveyor belts helps to keep aggregates entering the plant dry in case of rain. Covered belts also reduce wind-blow dust (Prowell and Hurley, 2007).

Introducing drier aggregate into the production plant presents a number of benefits. For both WMA and HMA, drier aggregate results in fuel savings for a given discharge temperature. Gencor Industries estimates that a 2 percent reduction in aggregate moisture content (from 6 to 4 percent) would result in a saving of 0.48 gallons of No. 2 fuel oil per ton (a 25 percent savings) with a 310°F (154°C) discharge temperature. Plant emissions track fuel usage, so less fuel usage results in less plant emissions (Prowell and Hurley, 2007). Astec indicates that for the same 2 percent reduction in moisture content, the production rate for an 8-foot-diameter counter-flow drum would increase from 288 to 390 tons per hour (Prowell and West, 2005).

Figure 3 Kolo Veidekke Covered RAP Storage

Industry experience has varied. Average savings associated with paved stockpile yards have been on the order of $0.12 to $0.14 per ton depending on fuel price. The cost for grading and paving under aggregate stockpiles will vary, but ranges of $80,000 to $120,000 may be expected (Prowell and West, 2005).

Drier aggregate entering the plant may result in drier aggregate in the resulting mix. This may be the most important aspect of reducing aggregate stockpile moisture contents when producing WMA, particularly with aggregates with higher water absorptions (Prowell and Hurley, 2007).

B. BURNER ADJUSTMENT TO ENSURE COMPLETE FUEL COMBUSTION

Difficulty in adjusting burners to sufficiently low levels to reach the desired production temperatures for WMA has been reported by contractors. This has generally been exacerbated by the fact that the plant has been running at a very slow production rate for a small WMA trial. At normal production rates, most burners should be able to be readily adjusted to produce the lower production temperatures required for WMA. Regardless, a contractor may want to have an experienced burner technician available when attempting their first WMA trial to inspect the burner and aid with adjustments. A properly maintained burner with properly preheated fuel (if necessary) will provide the most economical plant operation regardless of whether WMA or HMA is being produced (Prowell and Hurley, 2007).

Lower burner settings result in the baghouse exhaust fan running at a lower speed (assuming a variable speed drive). Reduction in the exhaust fan speed may lower the static pressure or suction. This can reduce the quantity of dust pulled in the baghouse, and may necessitate an increase in the time between cleaning cycles in the baghouse (Prowell and Hurley, 2007).

One symptom of improper burner adjustment is uncombusted fuel. Incomplete fuel combustion wastes fuel and can contaminate the asphalt binder, leading to a binder which is less stiff than desired. Fuel savings when producing WMA will be higher if the burner is properly adjusted to ensure complete combustion. The potential for damage to the mix from uncombusted fuel is probably greater for WMA than for HMA. Because HMA production temperatures are higher, uncombusted fuel may be drive out of the mix more readily with HMA than with WMA. Uncombusted fuel was observed in at least one WMA trail to date, and suspected in another. WMA contaminated with fuel can be detected by the brown coloration of the coated aggregate. Performance tests on the affected mix indicated increased rutting susceptibility and lower dynamic modulus (stiffness) values. Stack emissions tests indicated higher levels of carbon monoxide (CO) than for the control mix, another indication of uncombusted fuel (Prowell and Hurley, 2007).

There can be a number of causes for uncombusted fuel with both WMA and HMA. The burner nozzles may be worn or clogged with yard dust or sludge from improperly filtered reclaimed oil, or the fuel may be improperly preheated. Many plants now fire their burners with reclaimed oil. Heavier grades of fuel oil, such as many reclaimed oils, require preheating to reduce their viscosity in order to ensure complete atomization. No. 2 fuel oil (diesel) has a viscosity of approximately 40 Saybolt Seconds Universal (SSU). No. 2 fuel oil does not require preheating to ensure combustion. Most manufactures recommend pre-heating heavier oils to 70 to 90 SSU (Prowell and Hurley, 2007).

The viscosity of reclaimed oil can vary from load to load. Ideally, the viscosity of each load should be tested. However, since most plants have a 20,000 to 30,000 gallon storage tank, unless multiple loads arrive at the same time, the other oil in the tank should help to buffer or reduce load to load variation. To test the Saybolt viscosity, a sample of the oil is heated and then its viscosity tested over a range of temperatures. The Saybolt viscosity is the time it takes in seconds for the oil to drain from the Saybolt viscometer at a given temperature. By testing the viscosity over a range of temperatures, the required preheating temperature corresponding to the target viscosity can be determined.

Another option is in-line viscometers. In-line viscometers can be used to measure the viscosity of the oil flow feeding the burner. Such viscometers could be tied directly into the temperature controller for preheating the fuel. However, in-line viscometers can be expensive and need to be calibrated to be effective. Regardless of the method used to measure the viscosity of reclaimed oil, the controls for the preheated are best installed in the control tower so that they can be readily monitored by the plant operator (Prowell and Hurley, 2007).

C. DRYING AGGREGATE AND MAINTAINING ADEQUATE BAGHOUSE TEMPERATURES

One of the biggest challenges in the production of WMA may be the balance between adequately drying the aggregate and maintaining a baghouse temperature high enough to prevent condensation. With baghouses, temperatures at the dryer exit are usually controlled at about 240° F. This prevents condensation of water or acids in the baghouse. When using natural gas or low sulphur fuel oils, exit temperatures can be lowered to 220° F. Lower temperatures allow higher production rates while using less fuel, a more efficient plant operation (Brock, 2001).

Complete drying of the surface moisture of the aggregate has been shown to occur with aggregate bed temperatures as low as approximately 180°F (82°C). The aggregate bed is the aggregate at the bottom of the drum, waiting to be picked up by the flights and showered. This temperature represents the average temperature of the aggregate; variation in temperature may be expected with aggregate size. Higher temperatures aid in drying internal moisture. Internal moisture will vary widely, depending on the water absorption of the aggregate. With low-absorption materials (less than 1 percent water absorption), it may not be much of a concern. Some high-absorption limestone and gravel aggregates may not be completely dry even at normal HMA production temperatures (Prowell and Hurley, 2007).

There are several indicators of incomplete drying of the aggregate. One is the difference in the exhaust gas temperatures from one side of the drum to the other where they enter the breach or ductwork at the exit of the drum. If this differential exceeds approximately 60°F (33°C), incomplete drying is most likely occurring. Second, if the mix temperature drops more than 20°F (11°C) from discharge to load-out, moisture is most likely present. Finally, the moisture content of the mixture can be measured, but there is concern that it is difficult to drive internal moisture from coated aggregate in order to obtain an accurate measurement with simple oven drying (Prowell and Hurley, 2007).

T. J. Young provides best practice guidelines for minimizing condensation in the baghouse and preventing damage from corrosion, when running at normal HMA production temperatures. These guidelines are even more important when running large quantities of WMA. First, any air leaks should be sealed, particularly the seals on the baghouse top doors. Air leaks cause two problems: first, cooler ambient air can reduce the overall temperature of the exhaust stream, leading to condensation, and second, air leaks waste fan capacity, thereby lowering the maximum production rate. Condensation can occur in a limited portion of the baghouse, such as the windward side. In this case, a periodic painting of the interior surfaces of the clean air plenum (the portion of the baghouse above where the bags are collected to the tube sheets and below the top doors) with epoxy based paint would help prevent corrosion (Prowell and Hurley, 2007).

According to Astec Inc., the Double Barrel mixer plant gives an important secondary benefit. It allows bags in the baghouse to have much longer life. Because no oil from a Double Barrel mixer reaches the baghouse, bags last 700,000 to 1,000,000 tons of mix (Brock, 2001).

The Double Barrel mixer has another advantage over conventional drum mixers. On the Double Barrel mixer, fines are returned to the mixer from the baghouse via a rotary air lock and screw conveyor. The pressure drop between the baghouse and the Double Barrel mixer is very low. As a result, the airlock will last up to ten times longer than the air lock and blower system typically used on a conventional drum mixer (Brock, 2001).

A contractor in the Netherlands produces WMA in a batch plant using a foaming process with a discharge temperature of 194°F (90°C). They added a secondary burner in the exhaust ducts, after the dryer drum, to increase the temperature of the exhaust gases entering the baghouse. This method is considered a last resort due to the initial cost of the extra burner and associated controls and the additional fuel consumption and resulting emissions. It should be noted that the contractor reports significant fuel savings, 40 percent with virgin mixes and 30 percent with recycled mixes, even with the additional burner (Prowell and Hurley, 2007).

Some general best practices for baghouse operations when producing WMA include:

Preheat the baghouse for 15 to 20 minutes to remove condensation.

Monitor pressure drops across the bags. Condensation can cause caking of the bags. A pressure drop greater than 4 to 5 inches of water column can signal build-up, necessitating increasing the baghouse temperature or adjusting the cleaning system.

Inspect fines return lines more frequently to ensure no build-up due to moisture. Typically, fines at lower temperatures are more susceptible to moisture, affecting flow back into the mix.

The following presents some options for balancing aggregate drying and baghouse temperatures. Their effectiveness will vary depending on the plant configuration. With a parallel flow drum plant, there is probably less of a concern than with a counter-flow dryer drum or drum plant. The difference between the discharge temperature of the mix and the temperature of the exhaust gases prior to entering the baghouse for an efficiently adjusted parallel flow drum plant is approximately 20°F (11°C). Thus, WMA could be produced with high-sulfur fuels down to a discharge temperature of approximately 260°F (127°C) and down to approximately 240°F (116°C) with low-sulfur fuels without concern. Since the exhaust gases are moving counter to the direction of aggregate flow with a counter-flow drum plant or dryer drum, the temperature profile of the exhaust gases is less clear (Prowell and Hurley, 2007).

1. Reducing Drum Slope

Reducing the slope of the drum or installing a donut or other types of flights which retard the flow of aggregate through the drum increase the dwell time in the drum thus allowing more time for the aggregate to dry. Reducing the slope of the drum should have a minimal, if any, effect on production capacity. More aggregate will be retained in the drum at a given time. This increases the weight of the drum and therefore increases the electrical consumption of the motor turning the drum. The additional aggregate in the drum increases the veil of aggregate and increases heat transfer efficiency. This, however, will have the consequences of reducing the temperature of the exhaust gases going to the baghouse, which may exacerbate condensation problems (Prowell and Hurley, 2007).

A minimum slope of 2.5 percent is recommended to help avoid accumulation of aggregate on the bottom of the drum. However, the actual minimum slope is dependent on the specific drum, diameter, flighting, presence of donuts, and other factors. Plant operators should refer to the manufacturer's recommendations. There should be no detrimental effects from reducing the slope of the drum when producing asphalt concrete, other than that the burner settings may need to be recalibrated to produce the desired discharge setting (Prowell and Hurley, 2007).

2. Removing Flights to Increase Heat Penetration

Flights are the metal elements welded or bolted to the inside circumference of the drum that are designed to control the movement of the aggregates as they pass through the drum. Manufactures use various patterns, shapes, numbers, and locations of flights in drum facilities however, all flights are designed in an attempt to get the aggregates heated and dried, using the minimum amount of fuel, and to efficiently coat the aggregate with asphalt cement (Roberts, et al, 1996).

Due to lower temperatures of WMA and the addition of RAP, buildup on the flights and in the drum can occur more rapidly. In addition, frequent starts and stops can be more of a problem with warm mix due to cooler temperatures. Excessive buildup on the flights can affect mix quality (Garrett and Bartoszek, 2008).

One way to increase the temperature of the exhaust gases going to the baghouse is to remove some of the flights closest to the burner to allow better heat penetration into the drum, thereby raising the temperature of the exhaust gases. Some plant types have door flights which can be closed to prevent the material from being picked up. This reduces some of the heat transfer to the aggregate and therefore may result in incomplete drying. Further, changes to the flighting are time consuming. If a contractor will be regularly producing both WMA and HMA, with varying percentages of RAP, flighting changes need to be carefully balanced so that baghouse temperature are not too hot when producing HMA with a high RAP content versus temperatures for a virgin WMA (Prowell and Hurley, 2007).

3. Increasing Combustion Air

Increasing the baghouse temperature is relatively easy to accomplish. One way is to increase the amount of combustion air provided to the burner for a given setting. A minimum amount of air (really oxygen) is required for combustion. Excess air will need to be heated, requiring a slight increase in fuel consumption. However, the increased heated burner air and therefore increased exhaust air will be greater than that required to dry the aggregate for a given burner setting, and will increase the temperature to the baghouse. This can be accomplished by adjusting the damper on a combined induced-and forced-draft burner. Some total forced-draft burners allow the burner profile to be adjusted in the control tower to increase air flow through the burner. In some cases, the plant controls can store multiple burner profiles, allowing the contractor to rapidly change between an optimum profile for producing WMA and HMA or even varying amounts of RAP. Periodic burner tuning according to manufacturer recommendations can help to ensure that effective combustion profiles are maintained. When making adjustments to the burner, operators must also take into consideration the impact on plant emissions of carbon monoxide and nitrogen oxides, as permit limitations may apply. Small changes in burner tuning may result in consequential changes in individual pollutant emission rates (Prowell and Hurley, 2007).

4. Adding RAP to WMA

One of the unique qualities of asphalt cement is that it is rejuvenated when RAP is blended with virgin materials. The binder in the RAP when softened by heating will blend with virgin binder resulting in an integrated binder. Through proper selection of the virgin binder type and proportions the resultant blend is functionally equivalent to asphalt concrete made with 100% virgin materials. This is referred to as the highest and best use (NAPA, 2009).

The addition of even a relatively small amount of RAP to WMA can greatly aid in drying the virgin aggregate and increasing the baghouse temperature with no detrimental consequences. This is the “green-on-green,” WMA combined with recycling solution. For a discharge temperature of 220°F (104°C), the virgin aggregate must be heated to 280°F (138°C) for a batch plant running a mixture with 10 percent RAP with a moisture content of 3 percent. Heating the virgin aggregate to 280°F is sufficient to remove the internal moisture. Heating the virgin aggregate to 280 °F provides sufficient temperature for the exhaust gases going to the baghouse.

Therefore, the addition of a small amount of RAP helps to satisfy both needs (Prowell and Hurley, 2007).

When a conventional hot mix plant runs RAP, the virgin aggregate are heated to 500 or 600°F to heat the RAP. But WMA technology uses lower temperatures as a result the light oils are not removed from the virgin binder or the RAP. Using warm mix technologies provides a better film thickness of binder on the aggregate, and the RAP is not scorched in the process (Brown, 2010). Film thickness of WMA has not been discussed except for the foaming process where the film thickness is only thicker until the steam cools below 212°F.

One problem with HMA recycling with RAP is the need to use "softer" virgin asphalt to adjust the viscosity of the RAP. With WAM it may not be necessary to use"softer" asphalt since the asphalt doesn't go through as much hardening during curing.

On the performance side, one benefit of WMA is the reduced oxidative aging of the binder. This has the potential to improve long-term cracking resistance and to help rejuvenate the aged binder in any RAP. One potential concern regarding the reduced aging is the possibility that the initial in-place stiffness of the binder in a WMA pavement may be slightly less than expected, or slightly less than that predicted by the rolling thin-film oven (RTFO) test. This could result in increased early rutting susceptibility. Although rutting has not been observed in any of the WMA trials to date, the inclusion of a small amount of RAP would tend to increase the composite binder stiffness, counteracting this tendency. Thus the addition of RAP to WMA mixes is a win-win situation (Prowell and Hurley, 2007).

D. PLACEMENT CHANGES

From a placement standpoint, U.S. experience and the findings of the FHWA International Scanning Tour in 2007 indicate that the placement of WMA is business as usual. Some European contractors have even commented that equipment remains cleaner with less asphalt buildup when placing WMA. In a few instants WMA has been observed not to flow as well as HMA. That is, it may not feed as quickly out of a truck and into a transfer vehicle or paver. A similar occurrence was observed on a project where the material exiting the coater was required to flow into a vertical bucket elevator while being transferred to a storage silo. It should be emphasized that there is no evidence that the material was sticking to the equipment, just that it did not flow as readily. Increasing the production temperature slightly resolved the problem (Prowell and Hurley, 2007).

From a compaction standpoint, WMA is not different from HMA mixes. In most cases, it has been easier to obtain density with WMA mixes as compared to HMA mixes, even with the reduced compaction temperatures. However, in a few cases, particularly when the production temperature has been pushed to its lowest extreme, WMA has required a greater compaction effort. Compaction should be monitored using a nondestructive device, calibrated to cores, to ensure that adequate density is consistently being achieved (Prowell and Hurley, 2007).

VIII. ADDITIONAL RESEARCH NEEDS

There has been considerable progress made in the evaluation of Warm Mix Asphalt. Thus far, the results are promising. The majority of the success comes from the efforts of the National Asphalt Pavement Association, the WMA Technical Working Group, the Federal Highway Administration, and the National Center for Asphalt Technology. However, additional research needs to be conducted in the evaluation, and development areas. Some of the research is currently under way or has been initiated. But further work is required in the areas below.

A. MIX DESIGN

The reduction of field compaction temperatures is permitted by WMA. The reduced temperatures should also be used in the laboratory. A method for determining the minimum field compaction temperature is needed. Multiple studies have indicated that WMA can improve compaction in the laboratory as well as in the field. Laboratory compaction should be conducted at the anticipated field compaction temperature. Even at reduced temperatures, lower air voids have been noted with WMA technologies, particularly with the gyrator compaction. Although this would tend to indicate a reduction in the optimum binder content, to date, most projects have been constructed using the same optimum asphalt content as would be used to produce the same mix as HMA. This is partially due to concerns over the potential for reducing long-term durability by reducing optimum asphalt content (Prowell and Hurley, 2007).

The binder selection is another design concern. The reduced production temperatures used with WMA would tend to reduce the aging of the binder. PG binders are specified based on two criteria for rutting resistance, the stiffness of the original binder and the stiffness of the binder after aging in the rolling thin-film oven (RTFO). RTFO aging is supposed to simulate the aging that occurs during production and laydown. If this aging is reduced in the field due to reduced production temperatures, the in-place binder may not be as stiff as anticipated. This could possibly result in increased rutting susceptibility. However, field trials conducted to date, including several at heavily trafficked plant entrances and the National Center for Asphalt Technology Test Track, have proved very rut resistant. The criteria for laboratory performance tests, especially those for moisture damage and the associated aging protocols, are an additional concern (Prowell and Hurley, 2007).

The National Cooperative Highway Research Program (NCHRP) funded NCHRP Project 09-43, “Mix Design Practices for Warm Mix Asphalt,” to develop a mix design method for warm mix asphalt (WMA) in the form of a draft AASHTO-recommended practice. This method is based on Superpave mix design methodology; it includes a suite of performance tests to assess whether a WMA mix design will provide satisfactory field service, and be applicable to any WMA technology used to lower mixing and compaction temperatures (Transportation Research Board of the National Academies, 2010).

Can WMA mixes be prepared in the lab? Are any lab procedures able to foam the asphalt similar to Astec Green PAC?

B. NEW PRODUCT APPROVAL

An approval system needs to be developed for new WMA technologies. The system must be based on performance testing and supplemented by field trials (D' Angelo, et al, 2008). As interest in WMA increases, new WMA technologies will continue to enter the market. This is good in that additional competition may help to reduce cost. However, it is important that the various technologies provide performance which is as good as or better than HMA. Previously, new technologies of various kinds have often been evaluated individually by agencies. In some cases, the sections were not well documented, or their long-term performance was not monitored. Protocol for product approval should include initial laboratory screening and well-documented field trials. Approval protocols for new products are needed not just for WMA, but for other modifiers and mixes.

The FHWA International Scanning Tour team recognized that two of the countries visited, France and Germany, had well-developed systems for evaluating new products. Both were done in partnership between the agency and the contractor. In Germany, trials begin with laboratory testing. Then multiple field trials are placed. The field trials must be placed under high traffic, in the right-hand or travel lane, and must have a minimum length of 1,640 ft (500 m). The contractual conditions for field trials are altered to reduce the contractor’s risk. In France, the Service of Technical Studies of the Roads and Expressways (SETRA) has a certification process for new materials. Certifications are confidential and are conducted in a partnership between the contractor and the agency. A panel of at least three people oversees the evaluation. The conditions of the field trials dictate the usage conditions for which the project is approved. Projects are monitored for a three-year period. Many European countries include three-to five-year materials and workmanship warranties. Norway allows the use of WAM-Foam in lieu of HMA, but the contractor is required to meet all of the performance criteria for HMA. Performance tests, particularly for rutting potential and moisture susceptibility, are routinely utilized in European mix design procedures. Tests for mixture stiffness (modulus) and fatigue are also conducted for higher level designs (Prowell and Hurley, 2007).

A key element of new-product evaluations, whether they are for WMA or other modifiers of mix innovations, is the development and acceptance of laboratory performance tests. Tests for rutting resistance, moisture damage susceptibility, and cracking potential are required. Rutting resistance is often the primary concern of agencies, as rutting failures can occur early in the service life of the pavement. The performance tests do not have to be perfect predictors of performance. However, they do need to be able to identify the potential for an early or catastrophic failure (Prowell and Hurley, 2007).

C. QUANTIFICATION OF BENEFITS

WMA technologies may increase cost, either because of initial plant modifications, additive costs, or both. Although the use of WMA has the potential to result in fuel savings, and with some processes these may be significant, these savings may not offset the increased material costs. If fuel savings are to be considered to offset costs, a total energy audit should be conducted to measure both fuel and electrical consumption. There is evidence that WMA mixes may be more difficult, in some cases, to move in the plant, possibly increasing electrical use (Prowell and Hurley, 2007).

Reductions in emissions and improvements in working conditions should also be quantified. This is particularly important if a goal is to increase production tonnage in non-attainment areas or to sell emission credits (Prowell and Hurley, 2007).

The purpose of NCHRP Project 09 – 47A is to establish relationships among engineering properties of WMA binders and mixes and the field performance of pavements constructed with WMA technologies; determine relative measures of performance between WMA and conventional HMA pavements; compare production and laydown practices and costs between WMA and HMA pavements (including necessary plant adjustments to optimize plant operations when producing WMA); and provide relative emissions measurement of WMA technologies as compared to conventional HMA technologies (Transportation Research Board of the National Academies, 2010).

D. RAP AND WMA

There are also opportunities for applied research, including quantifying the environmental benefits of increased RAP use, developing technologies and procedures to recycle high percentages of reclaimed material, developing technologies and procedures to better preserve the aggregate gradation in RAP, and improving performance testing methods and specifications for use of RAP and roofing shingle mixtures. All of these activities would contribute to increasing the overall rate of recycling and therefore provide reductions in emissions of greenhouse gases (National Asphalt Pavement Association, 2009).

Many areas of the country have excess RAP. WMA has the potential to greatly increase RAP usage in a symbiotic manner:

WMA reduces the viscosity of the mix, improving the workability and the ability to compact mixes containing higher percentages of RAP.

The reduced production temperatures used for WMA may decrease the aging of the virgin binder. The softer virgin binder might help rejuvenate the aged binder in the RAP.

The use of RAP requires the virgin aggregate to be heated. Sufficient heating will dry the internal moisture out of the virgin aggregate, even if the overall mix temperature is lower.

The aggregate veil will not be as dense if a portion of the aggregate comes from RAP. This, combined with the fact that the virgin aggregate is sufficiently heated, will increase the temperature of exhaust gases introduced into the baghouse.

The combined benefits of WMA and RAP require further exploration and documentation. Field projects were constructed in Maryland in 2005 using Sasobit® and high percentages of RAP. Several projects were constructed in 2007 using the Double Barrel® Green process and high percentages of RAP (Prowell and Hurley, 2007).

E. PRODUCTION EQUIPMENT

Equipment manufacturers are already investigating plant modifications to better accommodate WMA and to allow contractors to more readily switch between WMA and HMA.

Options like readily adjustable flighting, adjustable barrel lengths, slingers, and even smaller burners may provide solutions in the future. Placement and compaction equipment should require no changes (Prowell and Hurley, 2007).

IX. CONCLUSION

Warm-mix asphalt is a relatively new concept in the American paving industry that shows much potential to transform the production and placement of asphalt mixtures. After first gaining attention from the National Asphalt Pavement Association in 2002; warm-mix asphalt represents a collection of technologies that permits a reduction in the temperatures at which asphalt mixes are produced and placed. The response to warm-mix asphalt from agencies and contractors has been impressive with over 20 states implementing the construction of WMA sections.

There are many ways to classify the types of WMA technologies however; there are two major types of technologies; those that use water and those that use either an organic additive or wax to influence the temperature reduction. Current technologies being used to date include chemical binder additives such as Cecabase RT®, Evotherm^{TM}, Rediset^{TM} WMX, and REVIX^{TM}; chemical mixture additives such as Asphaltan® and Sasobit®; and foaming admixtures such as Advera®, Aspha-Min®, and Low Energy Asphalt. Contractors may also choose to modify existing HMA facilities using the Double-Barrel® Green System, Terex® WMA System, or by using the WAM-Foam process. These technologies allow temperatures to be reduced by as much as 30 percent while allowing the asphalt binder to adequately coat the aggregate during the mixing at the plant in order to attain the desired workability of a given binder and a given temperature.

Potential paving benefits associated with warm-mix asphalt include improved compaction, extended paving season for cold-weather paving, longer haul distances and increased production in non-attainment areas, and reduced fuel consumption. WMA allows for the increased use of RAP into the mix to improve compaction and reduce aging of the virgin binder. However, the inclusion of RAP will require improved drying and increased baghouse temperatures.

WMA is considered more environmentally friendly than traditional HMA. The use of WMA allows for decreased production temperatures and reduced fuel consumption resulting in lower emissions at the plant and paving site. Greenhouse gases, fugitive emissions, and fumes are decreased by using WMA. In addition to the improved environmental conditions working conditions at the plant and paving site are improved through the use of WMA.

Along with the improved paving and environmental benefits as well as improved working conditions there are factors which affect the economic practicality of WMA. These potential factors include increased initial production costs in the form of additive costs, asphalt costs, fuel costs, and plant modifications. The use of WMA increases costs related to the various types of technologies. Given that binders in WMA mixtures may be softer than expected and because some WMA technologies use water as a workability aid, another disadvantage is that WMA mixtures may be susceptible to moisture damage. Moisture susceptibility is also an issue with HMA however, with WMA the possibility of inadequately dried aggregates at the lower production temperatures and/or the introduction of additional moisture to the mix from the technology may affect the binder to aggregate adhesion and performance. As lower mixing temperatures may cause issue with moisture susceptibility, higher mixing temperatures can lead to lower asphalt viscosity therefore, 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.

The material testing for Warm Mix Asphalt consists of two parts laboratory techniques and field techniques. When considering a warm-mix asphalt trial, a minimum section should be in the range of 800 – 1000 tons of WMA. This allows the plant to run around four hours at reasonable production rates. It is desirable to produce a hot mix control section using the same mix design without the WMA additives. A large variety of test methods are available including laboratory determining the moisture content of the mix at load out, gyratory compaction of pills for each sample, maximum specific gravity testing, tensile strength ratio testing, compaction testing, low temperature cracking, Hamburg test, beam fatigue tests, measuring the fracture energy, using the TTI overlay tester, and thermal stress restrained specimen test. The density protocol developed for laboratory characteristics of WMA should be tailored to meet specific research goals. The field techniques may include performing density tests, determining the bond strength between layers, measuring the aging during construction, measuring the indirect tensile strength, smoothness testing, and developing rut depth profiles. Since the majority of asphalt construction is rehabilitation using overlays an important aspect of quantifying the performance of WMA projects is to thoroughly document the condition of the existing pavement.

Those states which do not have specifications for warm-mix asphalt are currently developing specifications. The common practice is for states to use the current hot-mix specification for the warm-mix production and placement. Twelve states currently have warm-mix specifications being used within the states. A generic preliminary specification which may be adopted by states has been prepared by The Warm Mix Technical Working Group.

The current best practices for the production and placement of WMA is intended to focus on both the potential and observed concerns related to warm-mix asphalt. The practices are planned to be used on existing HMA plants by contractors that will most probably be producing both WMA and HMA. The alternation between WMA and HMA requires plant modifications to be made considering both materials and a potential range of RAP levels. Best practices for the production of HMA, such as minimizing aggregate and RAP stockpile moisture contents, appropriate preheating of burner fuels, proper burner adjustment, eliminating air leaks in duct systems, and attention to baghouse design and operation. WMA best practices only focus on this because WMA is new, best practices are still important for HMA. Production best practices result in energy savings and therefore reduced emissions whether used with WMA or HMA.

There has already been significant research in the area of warm-mix asphalt and moving toward the future there will be more research. The industry, agency, and academia have formed partnerships such as the WMA Technical Working Group, which has accelerated the research process. Additional research needs in the areas of mix design, long-term performance, new product approval, quantification of benefits, recycled asphalt pavements, and production equipment is crucial to the growth of warm-mix asphalt. The need to evaluate new WMA technologies is possibly the most critical need. Laboratory performance tests are also an important requirement. The development of a generic specification for WMA that agencies can use to allow WMA in place of HMA is critical.

There is a need to continue to produce and place pavements that are environmentally friendly while being economical and safe. Extending the life of the pavement through enhanced materials, mix design, and best practices, the industry can lessen the environmental impact and reduce cost. The use of RAP provides for a reduced mix cost as well as reduced need for virgin materials. Therefore, the industry and its partners should strive to continue improvement in environmental performance and best practices of warm-mix asphalt.

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APPENDIX

Warm Mix Asphalt (WMA) Guide Specification for

Highway Construction

Division 400 – Asphalt Pavements and Surface Treatments

Section 4XX – Warm Mix Asphalt (WMA) Pavement

Warm mix asphalt (WMA) is the generic term used to describe the reduction in production, paving, and compaction temperatures achieved through the application of one of several WMA technologies.

Some modifications to HMA plants may be necessary to accommodate the WMA technologies as noted in Section 4XX.03 Construction.

Production and paving temperatures may need to be increased for higher reclaimed asphalt pavement (RAP) contents, increased haul distances, decreased ambient temperatures, or other WMA project specific conditions.

All provisions for the production and placement of conventional HMA mixtures as stipulated in [*applicable Agency specification*] are in force except as noted below.

4XX.01 Description

Construct one or more courses of plant produced warm mix asphalt (WMA) pavement on a prepared foundation, using virgin aggregate or a combination of virgin and/or reclaimed aggregate material (RAM) and prescribed manufactured WMA additives and/or WMA plant process modifications. Use of RAP materials, consisting of cold milled, crushed, or processed bituminous asphalt mixture; and reclaimed asphalt shingles (RAS) are permitted at the current [*Agency specified*] percentages, provided that the mixture meets all the requirements of these specifications.

4XX.02 Material

WMA may be produced by one or a combination of several technologies involving HMA plant foaming processes and equipment, mineral additives, or chemicals that allow the reduction of mix production temperatures to within 185°F to 275°F. (*Note: The upper temperature range is* *appropriate for modified asphalt binders and WMA mixtures which include higher percentages of reclaimed asphalt pavement.*)

Provide materials as specified in:

Aggregate	Subsection XXX
Liquid Antistrips	Subsection XXX
Asphalt Binder	Subsection XXX
HMA Additives	Subsection XXX
Lime for Asphalt Mixtures	Subsection XXX
Mineral Filler	Subsection XXX
Reclaimed Asphalt Pavement	Subsection XXX
Reclaimed Aggregate Material	Subsection XXX
Reclaimed Asphalt Shingles	Subsection XXX

4XX.03 Construction

A. *Mix Design.* Develop and submit a job mix formula for each mixture according to AASHTO R 35 or [*Agency specified procedure*]. Each job mix formula must be capable of being produced, placed, and compacted as specified. Apply all mix design requirements for HMA to the development of the WMA mix design.

(Note to Contracting Agency: Recommended mix design practices specific to WMA have not been established. Job mix formulas for WMA mixtures are currently developed with conventional HMA mix design practices and the WMA technology process or additives are included afterward. The Contracting Agency and WMA producer must ensure that WMA technology does not adversely affect the asphalt binder performance grade and WMA mixture performance during the development and verification of the WMA job mix formula. All acceptance and performance testing must be conducted wit hthe WMA technology added. A specific WMA mix design recommended practice is expected upon the completion of National Cooperative Highway Research Program (NCHRP) Project 09-43 “Mix Design Practices for Warm Mix Asphalt” detailed at *www.trb.org/TRBNet/Project/Display.asp?ProjectID=977*.)

Submit a written job mix formula for review and approval at least [XX] calendar days before production, or when sources of asphalt binder, aggregates, WMA additives, or other components of the mix change.

Submit the following information:

1. All information required in the report section of AASHTO R 35 or [*Agency specified procedure*].
2. WMA technology and/or WMA additives information.
3. WMA technology manufacturer's established recommendations for usage.
4. WMA technology manufacturer's established target rate for water and additives, the acceptable variation for production, and documentation showing the impact of excessive production variation.
5. WMA technology material safety data sheets (MSDS).
6. Documentation of past WMA technology field applications including project type, project owner, tonnage, location, mix design, mixture volumetric, field density, and performance; or documentation of WMA technology listing on [*Agency specified*] approved products list.
7. Temperature range for mixing.
8. Temperature range for compacting.
9. Asphalt binder performance grade test data over the range of WMA additive percentages proposed for use.
10. WMA mixture performance test results [*as required by the Contracting Agency*].
11. Laboratory test data, samples and sources of all mixture components, and asphalt binder viscosity-temperature relationships.

(Note to Contracting Agency: Some WMA technologies may alter the asphalt binder grade and conventional performance grading may not be suitable to quantify the WMA technology effects.)

B. *Additives.* Use anti-stripping additives, silicone additives, WMA additives, and WMA technologies as specified. Comply with approved mix design quantities. Confirm the addition rate through field tests performed during production.

(Note to Contracting Agency: Silicone additives are historically used as both an antifoam and defoamer to inhibit foaming in asphalt binder applications. Ensure silicon additive compatibility when asphalt binder foaming processes are used to produce WMA.)

Comply with the manufacturer’s recommendations for incorporating additives and WMA technologies into the mix. Comply with manufacturer’s recommendations regarding receiving, storage, and delivery of additives.

Maintain supplier recommendations on file at the asphalt mixing plant and make available for reference while producing WMA.

C. *Sampling.* Perform sampling according to the following standards:

1. Aggregate. AASHTO T2 or [Agency specified procedure].

2. Asphalt Binder. AASHTO T40 or [Agency specified procedure].

3. Warm Mix Asphalt (WMA) Plant Mix. AASHTO T 168 or [Agency specified procedure].

D. Weather Limitations.

1. Place WMA mixtures only on dry, unfrozen surfaces and only when weather conditions allow for proper production, placement, handling, and compacting.

2. Meet [*agency specified*] placement temperatures.

(Note to Contracting Agency: The minimum HMA delivery, placement, and compaction temperatures should be reviewed to accommodate the WMA reduced temperature and achieve workability and density requirements. Documentation that demonstrates a proven history of the WMA technology’s ability to be placed and compacted at the reduced temperatures may be required. A test strip or initial production verification requirement can be used to demonstrate placement and compaction at the reduced temperature. Minimum ambient paving temperature requirements may be lowered 20°F from normal temperature requirements. Do not lower ambient paving temperatures to below freezing.)

E. *Equipment*. Use equipment and WMA technologies capable of producing an asphalt mixture that meet specification requirements and is workable at the minimum placement and compaction temperature desired, regardless of storage or haul distance considerations.

1. Asphalt Mixing Plant. Meet AASHTO M 156 or [as further modified by the Agency].

Modify the asphalt mixing plant as required by the manufacture to introduce the WMA technology.

Plant modifications may include additional plant instrumentation, the installation of asphalt binder foaming systems and/or WMA additive delivery systems, tuning the plant burner and adjusting the flights in order to operate at lower production temperatures and/or reduced tonnage.

(Note: Implementation of best management practices in the control of aggregate moisture content prior to introduction to the drying or mixing drum is highly recommended in order to achieve the maximum benefit of WMA technology.)

(Note to Contracting Agency: It may be beneficial to produce an HMA mixture at conventional HMA temperatures immediately before WMA production at the lower temperatures in order to bring the plant up to temperature and ensure proper baghouse operating temperature. The following references published by the National Asphalt Pavement Association detail specifics related to plant modifications and operational changes in order to maximize the benefits of WMA production, especially regarding reduced fuel usage and reduced emissions:

Quality Improvement Series 125 (QIP 125, “Warm Mix Asphalt: Best Practices”, Quality Improvement Series 126 (QIP 126), “ Energy Conservation in Hot Mix Asphalt Production,” and Environmental Council 101 (EC-101), “ Best Management Practices to Minimize Emissions During HMA Construction”)

All metering devices will meet the current [*Agency specified*] requirement for liquid or mineral additives. Document the integration of plant control and interlocks when using WMA additive metering devices.

2. *Hauling Equipment.* Furnish equipment with tight, clean, smooth metal beds to haul WMA mixture. Keep beds free of petroleum oils, solvents, or other materials that would adversely affect the mixture. Apply a thin coat of approved release agent to beds as necessary to prevent

mixture sticking. Do not use petroleum derivatives or other coating material that contaminates or alters the characteristics of the mix.

Be prepared to cover and insulate hauling beds. Equip each truck with a waterproof and windproof cover of suitable material and sufficient size to protect the mix from the weather. Securely fasten covers when necessary to maintain temperature. Ensure that covers do not allow water to enter the bed, paver, or mix transfer device during mix unloading. Use insulated truck best when necessary to maintain temperature.

3. *Asphalt Pavers.* Provide self-propelled asphalt pavers with activated, heated, adjustable, vibratory screed assemblies to spread and finish to the specified section widths and thicknesses. Provide full width screw augers and provide auger extensions to ensure that paver’s distribution system places the mixture uniformly, maintaining a consistent head of material in front of the screed. Screed or strike-off the surface without segregating, tearing, shoving, or gouging the mixture.

Operate the paver at consistent speeds and in a manner that results in an even, continuous layer. Avoid and minimize stop and start operation or allowing the paver to remain stationary during operation.

Equip pavers with automatic screed controls with sensors capable of continuously sensing grade, sensing the transverse slope of the screed and providing the automatic signals that operate the screed to maintaining grade and transverse slope. Control the screed to maintain the grade and transverse slope according to plan.

The Contractor may operate equipment manually in irregularly shaped, narrow, and minor areas.

If automatic controls fail, operate equipment manually only for the remainder of the work day and only if specified results are obtained.

Suspend paving if the specified surface tolerances are not met. Resume only after correcting the situation.

4. *Rollers.* Use rollers as required to achieve [Agency specified] pavement density and capable of reversing direction without shoving or tearing the mixture.

Operate rollers according to manufacturer's recommendations. Only use vibratory rollers equipped with separate energy and propulsion controls. Select equipment that will not crush the aggregate or displace the mixture.

F. *Mixing and Holding.* Heat the asphalt binder within the specified temperature range. Ensure a continuous supply of heated asphalt binder to the mixer.

Heat and dry aggregates to the required temperature. Avoid damaging or contaminating the aggregate.

Combine and mix the dried aggregates and asphalt binder to meet the job mix formula. Ensure a minimum of 95 percent uniform coating of aggregates according to AASHTO T 195 or [*Agency specified procedure*].

Correct procedures if storing or holding causes segregation, excessive heat loss, or a reduced quality mixture. Properly dispose of mixture which does not meet specifications.

G. *Preparing Base or Existing Surface.* Clear surface of debris and deleterious material. Apply and cure tack coat before placing the WMA. Apply a tack coat on all surfaces, curbs, gutters, manholes, or other structure surfaces, that will be in contact with the WMA.

Repair damaged areas of the base or existing surface. Restore the existing surface or based to a uniform grade and cross section before placing the mix.

H. *Pre-paving Requirements*. Prior to placing any WMA mix, produce a sufficient amount of WMA mix to properly calibrate the plant and procedures using the mix design approved for mainline construction. The Engineer will sample and test the WMA mix thus produced for the following:

1. Voids in mineral aggregate (VMA);
2. Asphalt binder content;
3. Gradation;
4. Air voids; and
5. Tensile Strength Ratio (or Hamburg Wheel Tracking test for moisture damage)

Heat WMA filed samples, transported to the laboratory, to the field production temperature, or lower, when reheating is required for WMA mixture testing.

(Note: Field produced WMA loose mix samples which are immediately compacted and tested, without reheating, may produce lower voids in mineral aggregate and lower air voids test results when compacted to reheated samples. This should be validated during the test strip of initial production lot. One possible remedy is to cool the WMA sample to room temperature and reheat to a temperature that is less than or equal to the WMA filed production temperature before laboratory compaction. This will minimize the WMA technology's effects on the test result and ensure the sample is not excessively aged.)

Place no WMA mixture that fails to meet specification requirements. WMA mixture not meeting the requirements may be used in the construction of temporary facilities when approved by the Engineer.

Construct a control strip or initial production lot with production materials and equipment. Select compacting methods to meet the specified density. The Engineer will take random loose mix and core samples to verify compliance with job mix and specification requirements. Reconstruct the test strip of initial production lot if the job mix formula, the compacting method, or compacting equipment changes, or if results do not meet specifications.

I. *Spreading and Finishing.* Spread and finish the mixture with asphalt pavers to specified grade and thickness.

Hand place material in areas inaccessible to mechanical spreading and finishing equipment. Maintain a consistent supply of mixture to ensure uninterrupted paving.

Minimize inconvenience to traffic and protect existing and finished surfaces. Leave only short lane sections, normally less than [26 ft (8 m)], where the abutting lane is not placed the same day, or according to [*Agency specified*] traffic safety requirements.

J. *Compacting.* Compact immediately after spreading and before the WMA mixture falls below the minimum job mix design compaction temperature. Discontinue paving if unable to achieve the specified density before the mixture cools below the minimum recommended WMA job mix design compaction temperature.

Provide the number, weight type, and sequence of rollers necessary to compact the mixture without displacing, cracking, or shoving, Roll the WMA mixture parallel to the centerline. Begin rolling superelevated curves at the low side and continue to the high side, overlapping longitudinal passes parallel to the centerline.

Maintain a uniform roller speed with the drive wheels nearest the paver. Operate vibratory rollers uniformly at the manufacture's recommended speed and frequency.

Continue rolling to eliminate all roller marks and to achieve the minimum [*Agency specified*] percent of theoretical maximum density of the recommended [*Agency specified*] percent of laboratory density as determined according to [*Agency-specified method*].

(Note to Contracting Agency: Air void and density requirements are important to provide long term performance of asphalt pavements. Due to the potential for increased workability of WMA mixtures and therefore increased density, it is important to monitor rolling operations to ensure excessive compaction does not occur and minimum air void requirements and/or the upper limit on percent of maximum density are not exceeded.)

Maintain the line and grade of the edge during rolling.

Prevent the mixture from adhering to the rollers by using very small quantities of detergent or other approved release material.

Hand compact areas inaccessible to rollers.

The Engineer will take random tests of the compacted pavement to verify specification compliance. At no cost to the Agency, remove and replace mixture that does not meet specification requirements or that becomes contaminated with foreign materials. Remove defective materials for the full thickness of the course by saw cutting the sides perpendicular and parallel to the direction of traffic. Coat saw cut edges with bituminous materials and replace the defective material with specification materials.

K. *Joints*. Protect ends of a freshly laid mixture from damage by rollers. Form transverse joints to expose the full depth of the course. Apply a tack coat on transverse and longitudinal joint contact surfaces immediately before paving. Construct all longitudinal joints within 12 in. (300 mm) of the lane lines. Offset longitudinal and transverse joints on succeeding lifts 6 inches (150 mm) to 12 inches (300 mm) from the joint in the layer immediately below. Create the longitudinal joint in the top layer along the centerline of two-lane highways or at the lane lines of roadways with more than two lines.

L. *Surface Tests.* Then Engineer will test pavement surfaces to verify compliance with [*Agency specified*] smoothness and texture requirements.

Correct pavement surfaces that do not meet specification requirements by cold milling, diamond grinding, overlaying, or removing and replacing according to the following:

a. *Diamond Grinding.* Diamond grind final pavement surfaces exposed to vehicle traffic to the required surface tolerance and cross section. Remove and dispose of all waste material.

b. *Cold Milling.* Cold mill intermediate pavement surfaces to the required surface tolerance and cross section. Remove and dispose of all waste materials.

c. *Overlaying.* Use specification materials for overlays. Overlay the full width of the underlying pavement surface. Place a minimum recommended overlay thickness of [1.6 in. (40 mm)]. Use only one overlay.

d. *Removing and Replacing.* Replace rejected areas with WMA pavement materials that meet specification requirements. Test the corrected surface area. Complete all corrections before determining pavement thickness.

4XX.04 Measurement

The Engineer will measure work acceptably completed as specified in Subsection XXX and as follows:

A. The Engineer will base quantities of asphalt binder on the theoretical mass incorporated into accepted product as verified by samples taken according to Subsection XXX.

4XX.05 Payment

Include costs of plant startup operations, considering both labor and materials, in the price bid for the mixture in place.

The Agency will pay for accepted quantities at the contract unit process as follows:

Pay Item Pay Unit

(A) Asphalt Binder to (Mg), gal (L)

(B) WMA Plant Mix – Type_____ ton (Mg), yd^2 (m^2)

Such payment is full compensation for furnishing all materials, equipment, labor, and incidentals to complete the work as specified.