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Warm-Mix Asphalt: Best Practices
3rd Edition

By

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Background

The United States Clean Air Act was passed into law in 1970. The first Earth Day was held that same year. Since that time, U.S. industries have worked to become better environmental stewards. The asphalt pavement industry has proven to be a leader, not just in implementing government-mandated technologies but also in seeking innovations to promote a cleaner planet and better working conditions for employees.

Members of the National Asphalt Pavement Association (NAPA) have taken the lead in a number of initiatives that have made asphalt plants better neighbors and enhanced working conditions for those involved in the production and construction of asphalt pavements. The asphalt industry has responded to a variety of government regulations, economic factors and changes in public attitudes. For example,

- Responding to the Clean Air Act of 1970, improvements in emission control technologies were developed. Wet scrubbers were developed first. The currently favored technology, baghouse filtration, has greatly reduced particulate emissions from asphalt plants.
- Rising oil prices and tightened supply during the two oil shortages of the 1970s spurred the development of new methods for reclaiming and recycling asphalt pavements. Improvements in milling machines and new methodologies for incorporating reclaimed asphalt pavement (RAP) and reclaimed asphalt shingles (RAS) have made recycling an industry standard, and asphalt is now the most recycled material in the U.S.
- Concerns about working conditions for paver operators have led to the development of engineering controls for highway-class asphalt pavers and best-practices guidance.
- Concerns about working conditions for crews involved in milling operations have led to the successful Silica/Milling Machine Partnership.
- Questions from the public about the impact of asphalt plants on communities provided the impetus for development of NAPA’s Diamond Achievement Commendation.

In 2002, NAPA identified new technologies in Europe that held the promise of reducing production and construction temperatures. Research at the National Center for Asphalt Technology (NCAT) and elsewhere had previously shown that lowering the plant mix temperature even by 10 °F (6 °C) can markedly reduce the production of emissions from asphalt mixtures (Lange and Stroup-Gardiner 2007). A study tour of NAPA leaders was quickly put together. Following the study tour, NAPA and its partners in agencies and academia began to pursue the research and development work necessary for implementation.

Warm-mix asphalt (WMA) represents a group of technologies which allow a reduction in the temperatures at which asphalt mixes are produced and placed. These technologies tend to provide complete aggregate coating at lower temperatures and act as compaction aids. The mechanisms which allow better coating and compaction vary from one technology to another.

Conventional hot-mix asphalt (HMA) is typically produced at temperatures from 280 °F to 320 °F (140 °C to 160 °C). WMA is produced at 212 °F to 280 °F (100 °C to 140 °C).

So what is significant about WMA? Improvements in coating and compaction provide a number of potential paving benefits for asphalt contractors and their agency partners. Reduction in production temperatures provides a number of benefits related to sustainable development and improved working conditions. The range of potential benefits includes:

- Paving benefits
  - Compaction aid,
  - Ability to pave in cool ambient temperatures without sacrificing quality,
  - Ability to haul asphalt pavement mixtures longer distances and/or durations and still have the necessary workability to place and compact the mix,
  - Ability to incorporate higher percentages of RAP, while producing the mixture at reasonable temperatures, and facilitating placement and compaction,
— Minimizing or eliminating bumps and cracks when placing asphalt over crack sealant
■ Reduced fuel consumption
■ Reduced plant emissions, including greenhouse gas emissions
■ Better working conditions

A Short History of WMA

In the fall of 1996, the German Ministry of Labor and Social Affairs was considering exposure limits for workers exposed to asphalt fumes. Certain types of asphalt mixtures used in Germany are produced at significantly higher temperatures than those typically used in the U.S. The German Bitumen Forum was founded in response to this consideration. The German Bitumen Forum is a partnership of government, industry, and labor. During this same time frame, WMA was under development in Europe in response to the need for greenhouse gas reduction. Each country within the European Union was faced with greenhouse gas reduction targets as a result of the 1997 Kyoto treaty on climate change. The benefits of reducing application temperatures were obvious. The German Bitumen Forum proposed the concept of reducing the temperatures at which asphalt mixtures were produced in order to reduce worker exposure.

The first WMA pavements were constructed in Europe. MHI (Mitteldeutsche Hartstein-Industrie AG) began experimenting with Aspha-min zeolite in 1995. Shell Bitumen and a contractor, Kolo Veidekke, began experimenting with a WAM (Warm Asphalt Mix) Emulsion, the precursor to WAM Foam in Norway in 1996. In 1997, the first pavements were constructed with Sasobit, a Fischer-Tropsch wax, in Hamburg, Germany. The first WAM Foam trial in Norway by Kolo Veidekke and the earliest Aspha-min zeolite trials on public roads in Germany were placed in 1999. In 2002, a NAPA study tour introduced WMA technology to the U.S. Figure 1 shows a timeline for the introduction of WMA into the U.S. and subsequent developments.

In 2005, NAPA and the Federal Highway Administration (FHWA) formed the WMA Technical Working Group (WMA TWG). If WMA was to be used on a wide-spread basis, agencies needed confidence in the performance of WMA pavements and a generic method of specification. With many new technologies, individual agencies perform their own evaluations. Often, different agencies collect different data sets on their trial sections during and after construction. One primary goal of the WMA TWG was the development of a data collection framework for WMA trials. The framework, available at www.warmmixasphalt.com, covers various engineering, environmental, and worker health and safety aspects of WMA. One important element of the framework is the inclusion of a hot-mix asphalt (HMA) control section along with any WMA trials to facilitate side-by-side comparisons. The framework allows data from various trials to be shared among the different WMA stakeholders.

The WMA TWG assimilated the data and short-term field performance collected from the various early trials. The use of a standard data collection protocol provides for a more robust data set from a broader range of geographic locations. The collected data were used to develop a generic guide specification for WMA, such that agencies do not need to specify a particular technology. Guidelines for appropriate use were also developed.

In 2006, FHWA, in conjunction with the American Association of State Highway and Transportation Officials (AASHTO) and the National Cooperative Highway Research Program (NCHRP), began planning an International Technology Scanning Tour on WMA. The purpose of the scan tour was to gather additional information on WMA technologies which would aid in implementation, with particular emphasis on long-term performance. The scan team traveled to Europe in May 2007. One of the team’s findings was that although some WMA technologies originated in Europe, the U.S. has made greater strides in evaluating and implementing WMA, thanks in part to industry-agency partnerships like the WMA TWG. The first National Cooperative Highway Research Project (NCHRP) 9-43 on WMA began in 2007 and was completed in 2011 to develop mix design methods for WMA (Bonaquist 2011).

In 2008, the WMA TWG developed a Warm-Mix Asphalt (WMA) Guide Specification for Highway Construction in AASHTO format. The Texas Department of Transportation (TxDOT) developed a specification which allowed contractors statewide to use WMA in lieu of HMA. Another NCHRP research project, dubbed NCHRP 9-47, was initiated to document the engineering properties, emissions, and field performance of WMA. Strong interest in WMA was demonstrated at the first International Conference on WMA held in Nashville, Tennessee in November 2008. The sold-out conference was attended by over 750 individuals. The presentations were webcast worldwide.
### FIGURE 1
Timeline for introduction of WMA into the U.S.

<table>
<thead>
<tr>
<th>Year</th>
<th>Events</th>
</tr>
</thead>
</table>
| 2002 | - European scan tour to Denmark, Germany, and Norway for NAPA leaders to examine warm-mix technologies including Aspha-min, WAM Foam, and Sasobit.  
| 2003 | - WMA featured in major international presentation at NAPA’s Annual Convention.  
|      | - Research sponsored by NAPA, FHWA, Eurovia, and Sasol on Aspha-min (Eurovia) and Sasobit (Sasol) begins at NCAT. |
|      | - WMA demonstration featured at World of Asphalt using Aspha-min zeolite.  
|      | - First field trials constructed in Florida and North Carolina. |
| 2005 | - NAPA-FHWA Warm-Mix Asphalt Technical Working Group (WMA TG) formed. Primary focus is proper implementation through data gathering and analysis to develop a generic method of specification.  
|      | - Research problem statement submitted for AASHTO consideration.  
|      | - Field trials in Florida, Indiana, Maryland, New Hampshire, Ohio, and Texas; and in Ontario and Quebec, Canada.  
|      | - NCAT reports published on Sasobit and Aspha-min. |
| 2006 | - Asphalt Pavement Conference at World of Asphalt features a half-day session on WMA.  
|      | - WMA TG publishes guidelines on performance and environmental testing.  
|      | - Based on research problem statement submitted in 2005, AASHTO gives top priority to funding WMA research.  
|      | - TWG submits two more research problem statements for AASHTO consideration.  
|      | - Field trials in California (asphalt rubber mix), Michigan, New York (new process — Low Energy Asphalt), Ohio (open house with 225 people), Missouri (new application to avoid temperature-caused bumps in road), South Carolina, Texas, Virginia, and Wisconsin (open house).  
|      | - Missouri contractor converts production paving jobs to warm mix based on success of trial.  
|      | - NCAT report published on Evotherm ET.  
|      | - Numerous NAPA presentations offered. |
| 2007 | - TRB session on WMA.  
|      | - AASHTO-FHWA Scan Tour conducted. Visits included Belgium, France, Germany, and Norway.  
|      | - NCHRP 9–43 research on WMA mix design initiated  
|      | - Five new WMA technologies including first U.S.-based foamed asphalt technology introduced by Astec.  
|      | - City street demo in San Antonio for APWA’s Annual Meeting.  
|      | - 20,000 tons of two WMA technologies placed near Yellowstone in August.  
|      | - Numerous field trials conducted. |
| 2008 | - Documented WMA trials conducted in 32 U.S. states to date  
|      | - Texas introduces first WMA specification which allows the use of WMA statewide  
|      | - WMA TG develops a Guide Specification for construction of WMA in AASHTO format  
|      | - Thirteen WMA technologies marketed in U.S.; more available worldwide  
|      | - 1st International Conference on Warm-Mix Asphalt held in Nashville with over 750 attendees and a worldwide webcast. |
| 2010 | - Documented WMA trials in 45 U.S. States and all 10 Canadian provinces  
|      | - 30 U.S. States and Canadian Provinces have specifications for WMA  
|      | - Over 20 WMA technologies marketed in the U.S., more available worldwide. |
| 2011 | - 2nd International Conference on Warm-Mix Asphalt attracted 550 people from 45 states and 24 countries to St. Louis. Overviews of practice in the U.S., South Africa, and Europe were given. More than 45 technical papers were presented.  
|      | - By year’s end, all 50 states had conducted trials of WMA.  
|      | - A survey conducted for FHWA in 2011 found that WMA usage was 17 million tons in 2009 and 47 million tons in 2010. |
FIGURE 2
State usage of WMA, circa December 2011

FIGURE 3
States with WMA specifications, circa December 2011
Between 2008 and 2010 there was a significant increase in the number of WMA technologies marketed in the U.S., particularly mechanical (non-additive) foaming technologies.

In 2010, FHWA made WMA one of its five “Every Day Counts” initiatives. Every Day Counts initiatives are designed to identify and deploy innovations with the potential to shorten project delivery, enhance the safety of our roadways, and protect the environment. Certainly WMA’s reduced fuel usage, emissions and fumes contribute to protecting the environment, but WMA can also help to shorten project delivery by facilitating longer paving seasons and longer haul distances. FHWA developed performance measures to track the success of deploying the Every Day Counts initiatives. For WMA, these measures include targets for agencies developing specifications and for tons of WMA produced.

All the U.S. states and the majority of Canadian provinces have some experience with WMA (Figure 2). Over 80 percent of U.S. states have a specification for WMA and a number of states have allowed WMA as an alternative to HMA (Figure 3). NAPA conducted a survey of reclaimed asphalt pavement (RAP), reclaimed asphalt shingles (RAS), and WMA usage in 2009 and 2010 (NAPA 2011). The survey estimated that the use of WMA in the United States increased from 19.2 million tons in 2009 to 47.6 million tons in 2010, representing approximately 13 percent of total asphalt production in 2010. The majority of the WMA was produced using mechanical foaming devices.

**Purpose and Methodology**

The purpose of this document is to present the state of the practice for WMA in the U.S. in early 2012 with the understanding that this is a rapidly changing field. Included are an overview of the various WMA technologies currently in use or under evaluation in the U.S., an overview of the benefits of WMA (including both engineering advantages and improvements in environmental factors and working conditions), and a description of best practices for the production and construction of WMA pavements. This document is designed to be used by both agency and contractor personnel.
WMA technologies are commonly classified as those that use chemical additives or surfactants (often liquids), foaming processes that use water, and those that use other non-foaming additives (often pellets). Some technologies fall into more than one category. Processes that introduce small amounts of water to hot asphalt, either via a foaming nozzle, damp aggregate, or a mineral filler such as zeolite, rely on the fact that when a given volume of water turns to steam at atmospheric pressure, it expands by a factor of approximately 1,700 (Yunus and Boles 1994). When the water is dispersed in hot asphalt and turns to steam, it results in an expansion of the binder phase of approximately 5 to 10 times. This increase in fluids content improves coating and compaction. The slower release rate of zeolite materials results in smaller expansion. For mechanical or free-water foaming systems, the water required to foam the asphalt is about one quart per ton of mix. Thus, 500,000 tons of mix requires approximately the same amount of water as that used by an average household on a yearly basis (American Water Works Association 2010).

The WMA processes that use organic additives or waxes show a decrease in viscosity above the melting point of the wax. The type of organic additive or wax must be selected carefully, such that the melting point of the additive is higher than the expected in-service temperatures to reduce the risk of permanent deformation. The type of organic additive or wax can also affect the low-temperature properties of the binder. This effect seems to be mitigated, in part, in the WMA by reduced production temperatures. Warm-mix processes involving the use of chemical additives or surfactants rely on a variety of different mechanisms to help the asphalt cement coat the aggregate at lower temperatures and a lubricity effect to improve compaction. Some technologies combine different classifications, for instance surfactant and wax or surfactant and water.

In practice, it has been the authors’ as well as numerous contractors’ experience that mechanical foaming systems allow the smallest amount of temperature reduction. The temperature reduction afforded by additive technologies varies widely depending on the product and the dosage. Systems such as Low Emission Asphalt and WAM Foam, which essentially require the final mix temperature to be below the temperature at which water boils, afford the greatest reductions in mixing and compaction temperatures. The actual temperature reduction will be determined by a number of factors, including mix type, binder grades, content of recycled mix and/or shingles, weather conditions, and haul distance.

The remainder of Chapter 2 presents each WMA technology which has been used or is scheduled to be used in the United States. Among the information given is contact information for each product, a description of the technology, any mix design modifications needed, any plant modifications needed, and information on usage in the United States. The technologies are subdivided by process type — chemical, foaming, and organic — and then listed in alphabetical order by technology name. The products are also listed in the table of contents for the reader’s convenience.

**Chemical Additives or Surfactants**

**CECABASE RT**

**WMA Technology Category:** Chemical Additive

**WMA Product Name:** CECABASE RT

**WMA Supplier Information:**
Arkema Group
Contact Person: Jonathan Weaver
Phone: (610) 205-7245
e-mail: jonathan.weaver@arkema.com

**WMA Technology Description:** Cecabase RT is a water-free (non-aqueous) surfactant package that is added to the asphalt binder to reduce production and placement temperatures. The product was developed in France in the early 2000s and the first test strip was placed in 2004. The blend of surfactants in Cecabase
RT works in two manners. First, the surfactant reduces surface tension at the aggregate interface to improve coating at lower temperatures. This also is thought to improve stripping resistance. Second, at temperatures higher than 190 °F (90 °C) it acts as a lubricant at the binder aggregate interface, making lay-down and compaction easier. Standard dosage rate is between 0.3 and 0.5 percent by weight of binder.

**Mix Design Modifications:** At standard addition rates, Cecabase RT does not change the PG grade of the binder (Jorda, N.D.). The mix design addition method should match the intended field addition method. Cecabase RT must be pre-blended with the binder prior to mixing. Quick blending with the binder a few seconds before mixing with aggregates can be used to simulate in-line injection. Mixing and compaction temperatures should match anticipated field mixing and compaction temperatures. On average, Cecabase RT reportedly allows production temperatures to be reduced by about 70 °F (40 °C).

**Plant Modifications:** Cecabase RT is a liquid at ambient temperatures. It is readily soluble in asphalt binder. It can be added to the asphalt binder at the terminal, in the storage tank at the mixing plant, or through in-line injection in the same manner as a conventional liquid anti-stripping agent.

**WMA Technology Experience/Usage:** Since 2004, over 2.0 million tons of WMA have been produced worldwide with Cecabase RT. Cecabase RT has been marketed in the U.S. since the summer of 2009. Table 1 presents data for some of the sections constructed.

**Evotherm**

**WMA Technology Category:** Chemical Additive

**WMA Product Name:** Evotherm

**WMA Supplier Information:**
- MeadWestvaco Asphalt Innovations
- **Contact Person:** Jonathan MacIver
- **Phone:** (843) 746-8116
- **e-mail:** jonathan.maciver@meadwestvaco.com
- [www.evotherm.com](http://www.evotherm.com)

**WMA Technology Description:** Evotherm, which was developed in the United States, is a chemistry package designed to enhance coating, adhesion, and workability at reduced temperatures. The technology can be used in a number of processes. In the original Evotherm Emulsion Technology (ET), introduced in 2004, an emulsion is mixed with hot aggregates to produce a resulting mix temperature between 185 °F to 240 °F (85 ° to 115 °C). Evotherm Dispersed Asphalt Technology (DAT) was developed in 2005 and introduced in 2007. Evotherm DAT uses the same chemical additives as Evotherm ET. Evotherm DAT is diluted with a small amount of water. The level of dilution affects the degree of temperature reduction possible.

### TABLE 1
Partial List of Cecabase RT WMA Field Sections

<table>
<thead>
<tr>
<th>Project</th>
<th>Date</th>
<th>PG Grade</th>
<th>NMAS, mm</th>
<th>Aggregate</th>
<th>N&lt;sub&gt;design&lt;/sub&gt;</th>
<th>RAP, %</th>
<th>Tonnage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Le Poire-sur-Vie, France</td>
<td>2004</td>
<td>40 Pen (76-22)</td>
<td>10</td>
<td>Rhyolite</td>
<td>NA</td>
<td>0</td>
<td>300</td>
</tr>
<tr>
<td>River Rd., Belgium, NY</td>
<td>August 2008</td>
<td>64-22</td>
<td>12.5</td>
<td>Dolomite</td>
<td>50 blows</td>
<td>30</td>
<td>1,228</td>
</tr>
<tr>
<td>Davis Doolittle Rd., Paris, NY</td>
<td>August 2008</td>
<td>64-22</td>
<td>12.5</td>
<td>Dolomite</td>
<td>65 gyrations</td>
<td>0</td>
<td>779</td>
</tr>
<tr>
<td>SR 42, Bloomsburg, PA</td>
<td>July 2010</td>
<td>64-22</td>
<td>9.5</td>
<td>Siltstone</td>
<td>75 gyrations</td>
<td>10</td>
<td>6,000</td>
</tr>
<tr>
<td>Hwy 35 Meander River, AB, Canada</td>
<td>September 2009</td>
<td>240 Pen (52-28)</td>
<td>12.5</td>
<td>Gravel</td>
<td>75 blows</td>
<td>0</td>
<td>25,000</td>
</tr>
<tr>
<td>SR 42, Forsyth, GA</td>
<td>November 2009</td>
<td>67-22</td>
<td>9.5</td>
<td>Granite (+1% lime)</td>
<td>65 gyrations</td>
<td>15</td>
<td>1,000</td>
</tr>
<tr>
<td>Little Neck Parkway, Queens, NY</td>
<td>October 2010</td>
<td>64-22</td>
<td>12.5</td>
<td>Trap rock</td>
<td>75 gyrations</td>
<td>20</td>
<td>1,000</td>
</tr>
<tr>
<td>Shakwak Hwy #3, Yukon, Canada</td>
<td>September 2011</td>
<td>150-200 Pen</td>
<td>12.5</td>
<td>Gravel</td>
<td>75 blows</td>
<td>0</td>
<td>40,000</td>
</tr>
</tbody>
</table>
The Evotherm DAT chemical solution is injected into the asphalt line just before the mixing chamber for drum plants, or directly into the pug mill for batch plants. Evotherm 3G (Third Generation), developed in partnership with Paragon Technical Services and Mathy Technology and Engineering, does not contain water and may be added at the binder terminal or mix plant. Evotherm 3G was initially marketed under the brand name ReviX by Paragon Technical Services and Mathy Technology and Engineering. Evotherm DAT and Evotherm 3G have replaced Evotherm ET. Evotherm DAT tends to allow slightly greater temperature reductions as compared to Evotherm 3G.

**Mix Design Modifications:** Mix design modifications vary, depending on whether the DAT or 3G process is being replicated. To reproduce the DAT process in the lab, the asphalt binder would be heated to the normal temperature to produce a viscosity of 170 centistokes (0.17 Pascal-seconds) as determined with the rotational viscometer (normal mixing temperature). The aggregate should be heated to a temperature approximately 27 °F (15 °C) greater than the intended mixing temperature. The aggregate should be added to the mixing bowl and a crater formed. The appropriate mass of binder should be added into the crater as for a normal mix design. Finally, the diluted Evotherm DAT chemistry package is added at a rate of about 5 percent by weight of binder and the mixer should be started immediately. For pre-blended Evotherm 3G, no changes are necessary to the mix design process.

**Plant Modifications:** For terminally blended Evotherm 3G, no plant modifications are required. The asphalt tank should be emptied as much as practical prior to introducing the binder containing Evotherm 3G. For non-aqueous plant additions of Evotherm 3G, the chemical may need to be pre-warmed to facilitate pumping. For the Evotherm DAT process, an injection point is needed on the existing asphalt line. Figure 4 shows the injection point and DAT volumetric pump used to feed the Evotherm chemistry. Evotherm DAT has been added in tandem with the water used by mechanical foaming systems.

**WMA Technology Experience/Usage:** A laboratory evaluation of Evotherm ET was conducted at NCAT in 2006. The finished report (NCAT 06-02) can be viewed on their Web site, www.ncat.us. Worldwide, Evotherm has been used to produce approximately 7.5 million tons of WMA.

**HyperTherm/QualiTherm**

**WMA Technology Category:** Chemical Additive

**WMA Product Name:** HyperTherm/QualiTherm

**WMA Supplier Information:**

**Canada:**
Coco Asphalt Engineering
Contact Person: Steve Manolis
Phone: (416) 633-9670
e-mail: smanolis@cocogroup.com
www.cocoasphaltengineering.com/warm_mix.aspx

---

**FIGURE 4**

Evotherm DAT Injection Point and Volumetric Pump
HyperTherm was developed in Canada and is currently marketed in the U.S. as QualiTherm. HyperTherm is a non-aqueous, fatty-acid based chemical additive. It is designed to reduce mixing and compaction temperatures for WMA applications and to improve workability with HMA applications.

Mix Design Modifications: If the binder is not available in a pre-blended form for laboratory use, the appropriate amount can be added to the hot binder using a low shear mixer/stirring device. Typical addition rates are 0.2 to 0.3 percent by weight of the total binder. At these addition rates, the additive is reported to have only minor effects on the rheological properties of the binder. Samples should be mixed and compacted at anticipated field temperatures. Mixing temperatures as low as 248 °F (120 °C) with compaction temperatures as low as 194 °F (90 °C) are reported.

Plant Modification: HyperTherm/QualiTherm can be added to the liquid asphalt at the binder terminal or in-line injected at the asphalt plant. Plant addition requirements are similar to that described for Evotherm DAT. HyperTherm/QualiTherm is supplied in 55-gallon drums or 330-gallon totes.

WMA Technology Experience/Usage: HyperTherm was initially used by Lafarge in Canada. It is estimated that 100,000 tons of WMA have been produced with HyperTherm/QualiTherm to date. Table 2 documents some of the field trials.

Rediset

WMA Technology Category: Chemical Additive
WMA Product Name: Rediset
WMA Supplier Information: AkzoNobel Surfactants
Contact Person: Dr. Sundaram Logaraj
Phone: (312) 544-7046
http://sc.akzonobel.com/en/asphalt/Pages/home.aspx

Rediset combines cationic surface-active agents and rheology modifiers. Rediset was initially introduced in a solid form (WMX) (Figure 5). In 2011, a liquid form, Rediset LQ, was

| TABLE 2
HyperTherm/QualiTherm field test sections |
<table>
<thead>
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<tbody>
<tr>
<td>Project</td>
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<tr>
<td>Oxford Rd. 4</td>
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<tr>
<td>Highway 401 Ramps Ontario Ministry of Transportation (MTO)</td>
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<tr>
<td>Garth Street, City of Hamilton, Ontario</td>
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<tr>
<td>MTO Patrol Yard</td>
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<tr>
<td>Highway 11, MTO</td>
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<tr>
<td>Highway 10, MTO</td>
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<tr>
<td>City of Hamilton, Ontario</td>
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*MSM is Manufactured Shingle Modifier
introduced. Neither product contains water. Rediset modifies the asphalt binder such that it reduces the surface tension of asphalt, which enhances its ability to coat the aggregate surface and increases the workability of the mix. Rediset's components allow coating and compaction at temperatures to be reduced by up to 60 °F (33 °C). The active adhesion agents promote bonding between the asphalt binder and aggregate surface, reportedly even if there is residual water present on the surface of the aggregate.

Mix Design Modifications: Recommended dosing rates vary depending on the desired outcome. Rediset WMX can be used as a compaction aid at dosages ranging from 0.5 to 1.0 percent; a warm-mix additive for unmodified binders at 1.0 to 1.5 percent; and a warm-mix additive for modified binders at 1.5 to 2.0 percent. The recommended dosage rate for Rediset LQ is 0.4 to 0.75 percent by weight of binder. The PG grading of the asphalt typically is not affected at the recommended addition. Because of the anti-stripping effect provided by the Rediset products, additional liquid anti-stripping agents are not normally required.

Rediset additives are added to the asphalt mixture with no changes to the mix design procedure except for the mixing and compaction temperatures. In most cases Rediset will be pre-mixed with the binder. Alternatively, Rediset WMX may be added directly to the mixture, preferably just after addition of the binder.

Plant Modification: Rediset can be added to the asphalt mixture via several different methods. It can be blended directly into the asphalt binder, with or without high-shear blending, at the refinery, asphalt terminal, or hot-mix plant. The use of pre-blended binder does not require modifications to the hot-mix plant itself. In commercial applications, Rediset WMX-treated binder has been shown to be stable for at least two weeks at asphalt storage temperatures. Rediset WMX can also be stored as a liquid in a small heated tank and then injected into the asphalt binder line; Rediset LQ can be added in-line without pre-heating. The free-flowing pastillated (bead) form of the product also allows the possibility of being added directly into the mixing drum close to where the asphalt is introduced using equipment similar to that shown in Figures 26 and 27. The Rediset LQ liquid can also be metered into a plant's binder line using equipment similar to that used to introduce liquid anti-stripping agents.

WMA Technology Experience/Usage: Since the introduction of Rediset WMX in 2007, many successful field trials and larger-scale projects have been completed throughout the United States as well as in Europe, Canada, Brazil, Argentina, South Africa and China. Table 3 presents project information for example projects.

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**Foaming Processes**

**Accu-Shear**

**WMA Technology Category:** Foaming Process  
**WMA Product Names:** Accu-Shear  
**WMA Supplier Information:**  
Stansteel Asphalt Plant Products  
Contact Person: Tom McCune  
Phone: (502) 245-1977 or (800) 826-0223  
e-mail: tmccune@stansteel.com  
http://www.stansteel.com/accushear.asp

**WMA Technology Description:** The Accu-Shear assembly allows water, WMA chemical additives, other liquid additives, or a combination of liquids to be simultaneously injected into the asphalt line (Figure 6). The Accu-Shear assembly utilizes a variable speed colloidal mill to blend the water or other additives. The colloidal mill's shearing process mechanically blends the liquids, similar to an emulsion process. The variable speed drive allows the rate of shear to be adjusted to dynamically foam the asphalt. The manufacturer believes that this should increase the life of the foam. The Accu-Shear operates over the
Mix Design Modifications: Mix design modifications will depend on whether the Accu-Shear is used to add water, a chemical WMA additive, or a combination thereof. Mix designs using WMA chemical additives should be completed as described for that additive. For simple water additions, it is not expected that a standard laboratory foaming device will replicate Accu-Shear's process. In this case, the design may need to be produced with non-foamed asphalt at a reduced temperature and then verified with plant-produced material.

Plant Modifications: The Accu-Shear is tied into the plant’s asphalt line and controls. As noted previously, a number of compatible liquids can be blended simultaneously (Figure 7). The system can also be used for binder modification.

WMA Technology Experience/Usage: Stansteel reports successful placement of Accu-Shear units that are used daily and perform in a dependable manner throughout the U.S. and Canada.
**Advera WMA**

**WMA Technology Category:** Foaming Process with Synthetic Zeolite  
**WMA Product Names:** Advera WMA  
**WMA Supplier Information:**  
- PQ Corporation (Advera WMA)  
- Contact Person: Annette G. Smith  
- Phone: (610) 651-4469  
- e-mail: annette.smith@pqcorp.com  
- www.adverawma.com  

**WMA Technology Description:** Advera WMA (Figure 8) is a synthetic zeolite, passing the No. 200 (0.075 mm) sieve, composed of aluminosilicates and alkali-metals. It contains approximately 20 percent water of crystallization which is released by increasing temperature above the boiling point of water. The zeolite time-releases a very small amount of water, creating a controlled, prolonged foaming effect, leading to a slight increase in binder volume, and improving the workability of the mix.
Mix Design Modifications: Advera WMA is typically added at 0.20 to 0.25 percent (with a recommended min/max rate of 0.10 to 0.30 percent) by total weight of mix. Lower dosages are recommended when Advera WMA is used as a compaction aid; higher dosages are recommended for mixtures with binder contents in excess of 7 percent. If Advera WMA is to be included in the mix design, the Draft Appendix to AASHTO R35 recommends adding it on top of the binder in a crater of aggregate formed in the mixing bowl (Bonaquist, 2011). Alternatively, Advera WMA should be thoroughly pre-blended with the asphalt binder shortly prior to mixing using a mechanical mixing device. Advera WMA should not be heated in an oven prior to mixing. Mix designs should be prepared at the anticipated field mixing and compaction temperatures, typically 50 °F (28 °C) less than comparable HMA.

Plant Modifications: Advera WMA can be added using a number of feed systems. Permanent mineral filler-type silos with screw conveyors may be used similar to those which would be used to introduce hydrated lime (Figure 9). Different portable feeders are used for drum plants (Figure 10) and batch plants (Figure 11). For a drum plant, the material can be added using a 4-inch (100 mm) diameter port, close to the point at which the asphalt binder is added. It is important to direct the additive into the asphalt binder for thorough blending to occur. For batch plants, a 2-inch (50 mm) steel or plastic pipe should be installed from the feeder to as close as possible to the center of the pug mill. Advera WMA may also be pre-blended with RAP or recycled asphalt shingles (RAS), acting both as an anti-clumping flow aid for the recycled-material stockpile and as a WMA additive. Advera WMA may also be added in tandem with mechanical foam systems for a synergistic benefit.

Advera WMA is supplied in 1,000-pound (455 kg) bags, two bags per pallet. The material needs to be kept dry in order to properly feed. For large projects or for a permanent installation, siloed bulk material is recommended.

WMA Technology Experience/Usage: Advera WMA has been used in the United States since 2006. Over 1 million tons of Advera WMA has been placed in the U.S. and Canada. Advera WMA has also been used in Europe and Asia.

**FIGURE 9**
Example of mineral silo utilized for batch or drum plant addition

**FIGURE 10**
Portable pneumatic feeder for drum plant addition of Advera WMA
FIGURE 11
Portable batch plant feeder for addition of Advera WMA

FIGURE 12
Maxam AQUABlack WMA System

AQUABlack WMA System

WMA Technology Category: Foaming Process
WMA Product Name: AQUABlack Solutions
WMA Supplier Information:
Maxam Equipment, Inc.
Contact Person: Roger Sandberg
Phone: (800) 292-6070
e-mail: rsandberghma@gmail.com

WMA Technology Description: The AQUABlack Solutions WMA System, developed by Maxam Equipment Inc., uses a patented, stainless-steel foaming gun in conjunction with a center convergence nozzle to produce foaming. Maxam has developed the MicroBubble foaming technology to produce microbubbles, which are reported to remain in the asphalt mixture longer than with a foaming system that does not use high pressure, increasing mixture workability. The MicroBubble foaming technology uses water pressure up to 1,000 pounds per square inch (psi) (6895 kPa) to atomize the water and reportedly create greater expansion of the foam with microbubbles that are retained through mixing, storage, and placement.

Plant Modifications: The AQUABlack WMA System can be installed on any existing asphalt plant. The system is installed to the asphalt binder line just before entering the drying drum. A control panel installed inside the asphalt plant control tower regulates the appropriate amount of water needed based on the asphalt binder flow rate. A mass flow meter monitors the flow rate, signaling if the rate goes out of the specified range. Figure 12 shows the unit installed on a drum mix plant.

WMA Technology Experience/Usage: To date, around 250 AQUA-Black units are in operation at drum plants and approximately 25 units are on batch plants. The National Center for Asphalt Technology conducted an evaluation of field mix produced using the Maxam AQUABlack System collected from one site. The finished report (NCAT 11-06) can be viewed on their Web site, www.ncat.us.
AquaFoam
WMA Technology Category: Foaming Process
WMA Product Name: AquaFoam
WMA Supplier Information: AquaFoam, LLC
Contact Person: Paul Schwan
Phone: (513) 874-0201
e-mail: paulschwan@fuse.net

WMA Technology Description: The AquaFoam foaming system includes two fan nozzles mounted 180 degrees to one another. The nozzles are mounted perpendicular to the asphalt stream. A one-way check valve prevents asphalt from back-flowing into the water system. The water is delivered to the nozzles using a variable-frequency-drive pump. The controls, the pump, and a 65-gallon tank are mounted on a skid unit. A high-resolution pulse counter is used to meter the water flow. The system is tied into the plant’s blending system in a manner similar to liquid anti-stripping agent addition. The water tank includes a water-level switch.

Plant Modifications: The foaming nozzle unit is mounted in the asphalt line just before it would enter the drum (Figure 13) and is connected to the hot-oil system. The skid can be placed at a convenient location nearby (Figure 14). The skid requires electrical (460-volt, 3-phase) and water connections.

Mix Design Modifications: A water addition of 1.5 percent by total weight of mix is adequate for most mixes. Stiffer mixes may require additional water. The mix should be produced at the anticipated field mixing and compaction temperatures. Specifications may require the use of a lab foaming device. Whether or not a laboratory foaming device is used, a plant-produced trial batch is recommended.

WMA Technology Experience/Usage: Over 65 units have been installed to date.

FIGURE 14
AquaFoam metering skid

Aspha-min
WMA Technology Category: Foaming Process with Synthetic Zeolite
WMA Product Name: Aspha-min
WMA Supplier Information: Aspha-min GmbH
Contact Person: Christian Hass
Phone: +49-6181-98-388-97
e-mail: c.hass@aspha-min.com
www.aspha-min.com

WMA Technology Description: Aspha-min was the first synthetic zeolite used in the U.S., but at this writing it is not being actively marketed here. Aspha-min is composed of aluminosilicates and alkalimetals that contain approximately 20 percent water of crystallization which is released by increasing temperature above the boiling point of water. The zeolite releases a very small amount of water, creating a controlled foaming effect, leading to a slight increase in binder volume, and reducing the viscosity of the binder. The
zeolite manufacturer reports that a gradual release of water from the zeolite provides a 6- to 7-hour period of improved workability, which lasts until the temperature drops below approximately 212 °F (100 °C), although material can be held in a silo for a longer period.

**Mix Design Modifications:** Typically, Aspha-min is added at a rate of 0.3 percent by total weight of mixture, and is normally added to the mixture at the same time as, or in a crater on top of, the liquid asphalt binder. The zeolite should not be heated in an oven prior to mixing. Aspha-min is coarser than Advera WMA, approximately a 50-mesh (0.300 mm) size (Figure 15).

**Plant Modifications:** Aspha-min can be added to the plant in a number of different methods. For a batch plant, it can be added manually to the pug mill using melt bags or automatically using a weigh bucket. For a drum plant, it can be added through the RAP collar or by using a specially built vane feeder that can control the quantity and can then pneumatically blow the synthetic zeolite into the binder stream of the mixing drum.

**WMA Technology Experience/Usage:** A laboratory evaluation of Aspha-min zeolite was conducted at NCAT in 2005. The finished report (NCAT 05-04) can be viewed on their Web site, www.ncat.us. Approximately 1.3 million tons of WMA have been produced world-wide with Aspha-min to date.

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**Astec Green Systems**

**WMA Technology Category:** Foaming Process

**WMA Product Names:** Double Barrel Green, Green Pac for Continuous, Green Pac for Batch

**WMA Supplier Information:**
- Astec Industries Inc.
- Contact Person: Mike Varner
- Phone: (423) 867-4210
- e-mail: mvarner@astecinc.com
- www.astecinc.com

**WMA Technology Description:** The Astec Green Systems use a multi-nozzle device to microscopically foam the asphalt binder with water. These devices consist of a manifold with a system of valves, mixing chambers, and nozzles, water skid with pump, and control system integrated with the plant controls. Figure 16 illustrates a typical nozzle in the system. The manifold includes either a hot oil or electric heating system. Each nozzle injects water into a separate mixing/foaming chamber. All nozzles open and close at the same time. Consistent foaming is achieved by splitting the flow of the liquid asphalt binder into separate flows and then foaming each binder independently. The water is regulated by a positive displacement pump and water flow meter controlled by feedback from the asphalt flow. Typically, 2 percent water is injected based on the mass flow rate of the virgin asphalt binder (approximately 1.0 pound of water per ton of mix). A small percentage of this water is encapsulated in the binder as steam, increasing the binder volume.

**FIGURE 15**

Aspha-min zeolite

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**FIGURE 16**

Schematic of Astec Green System's nozzle
Mix Design Modifications: To date, the Astec Green process has used standard HMA mix designs. The Draft Appendix for AASHTO R35 recommends that a laboratory foaming device be used to better replicate field conditions for performance testing of laboratory-produced material (Bonaquist 2011). A laboratory mixing temperature of 250 °F to 275 °F (121 °C to 135 °C) is recommended.

Plant Modifications: Figure 17 shows the multi-nozzle foaming manifold on an Astec Double Barrel plant. The only plant modification involves the installation of the foaming manifold, water, air, power, and control lines. Astec’s Green Pac Warm Mix System allows the same technology to be used on plants of any type or manufacture.

WMA Technology Experience/Usage: Since 2007, a total of 453 Astec warm mix systems (Double Barrel Green and Green Pac) have been installed worldwide. Of these, 211 units are Generation 1 (G1) systems, and 242 units are Generation 2 (G2). Five units of the G2 systems in use are the Green Pac for Batch.

WMA Technology Description: The AESCO/MADSEN Static Inline Vortex Mixer, also known as the Eco-Foam II, uses the principle of shear zone turbulence to enhance the mixing/foaming process. This process also uses vortex shedding, which happens when a specific fluid produces oscillations after it passes an obstruction. These oscillations create alternating low-pressure zones, also aiding in the mixing process.

To begin the foaming process, liquid asphalt binder is delivered to the Vortex mixer and is forced through the mixer restriction, creating a high-speed flow. Water or other liquid (additive, liquid anti-stripping agent) is injected downstream from the mixer tabs and into the low-speed, reversed flow region at a rate of 1 to 2 percent of the liquid asphalt flow rate. This difference in addition rates speeds the mixing of the asphalt binder and additive/water by increasing the contact area between the high- and low-speed fluids. Once the asphalt and water/additive becomes a single fluid, it passes over obstructions, creating oscillations that enhance the foaming process. Once the fluid leaves the Vortex mixer, the foamed asphalt can then enter the mixing drum.

Plant Modifications: As with other mechanical foaming systems, the Eco-Foam II WMA System can be easily installed onto any new or existing asphalt plant. The unit is installed just outside the dryer drum, and a separate variable-speed high-pressure water pumping and metering system with computerized controls is included. The control system can be attached to existing plant controls to produce a fully automatic or manual operation of the system. The Vortex mixer is shown in Figure 18.

Eco-Foam II

WMA Technology Category: Foaming Process
WMA Product Name: Eco-Foam II
WMA Supplier Information:
AESCO/MADSEN
Contact Person: Steve Malloy
Phone: (253) 939-4150 ext. 232
e-mail: smalloy@aescomadsen.com
www.aescomadsen.com
**WMA Technology Experience/Usage:** Since 2007, approximately 100 Eco-Foam II units are in operation.

**LEA (Low Emission Asphalt)**  
[known as Low Energy Asphalt outside the United States]

**WMA Technology Category:** Foaming Process  
**WMA Product Name:** LEA (Low Emission Asphalt)  
**WMA Supplier Information:**  
McConnaughay Technologies  
Contact Person: Mike Murphy  
Phone: (607) 753-1100, Ext. 332  
e-mail: mmurphy@suit-kote.com  
www.mcconnaughay.com

**WMA Technology Description:** In the LEA (Low Emission Asphalt) process, the coarse aggregate is heated to approximately 302 °F (150 °C) and is then mixed with the total binder required for the mixture at the normal binder temperature (appropriate for the particular grade). Approximately 0.4 percent by weight of binder of a coating and adhesion additive is added to the binder just prior to mixing. After the coarse aggregate is coated, it is mixed with the cold, wet fine aggregate or blend of fine aggregate and RAP. Ideally, the fine aggregate should contain approximately 3 to 4 percent moisture. 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). Figure 19 illustrates the LEA process. A second technology, LEA Lite, uses the same basic chemistry as LEA without the addition of wet fine aggregate. LEA Lite would be classified as a chemical additive.

**Mix Design Modifications:** Typically, aggregate used in the mix design process is void of any moisture. In the LEA process, the aggregate used is separated into a coarse (dry) portion and fine (wet) portion. The coarse/dry portion is generally 60 to 70 percent of the total aggregate and may include some fines. For the coarse aggregate portion, it is recommended that the temperature of the coarse aggregate be approximately 36 °F (20 °C) cooler than when designing standard HMA. For the fine portion, an appropriate amount of water (3 to 4 percent) should be added prior to mixing.

---

**FIGURE 19**  
LEA sequential mixing process
with the dry, coarse aggregate and asphalt binder. The coating and adhesion additive is recommended to be blended with the binder during the mix-design process. Mix designs using LEA Lite would be performed similar to those described for other chemical additives. It may be pre-blended with the binder or added directly into the mixing bowl on top of the binder.

**Plant Modifications:** Several minor modifications are needed when using a drum plant to produce LEA. First, a volumetric pump, similar to that which would be used for a liquid anti-stripping agent, is needed to add the coating and adhesion additive to the binder. An injection port is added to the asphalt line going to the drum, or to the pug mill if using a batch plant. Also, an additional cold feed bin going to the RAP collar is necessary so addition of the cold, wet fine aggregate can occur if the WMA contains RAP. A third modification is the movement of the asphalt line going into the drum. This is necessary to make sure the coarse aggregate is fully coated with asphalt before the wet, fine aggregate is introduced. For a batch plant, a separate cold-feed bin (Figure 20) for the addition of the wet fine aggregate is needed. A moisture monitoring system is required to monitor the moisture content of the wet fine aggregate. It is also possible that, for dry areas, additional moisture may need to be added to the fine aggregate; shower-head type moisture addition methods on the cold feed conveyor have been used successfully. LEA Lite may be pre-blended at the asphalt terminal or added using an in-line injection process in a manner similar to that described for other chemical additives.

**WMA Technology Experience/Usage:** Approximately 140,000 tons of WMA have been produced with LEA in the United States, with additional tonnage worldwide.

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**FIGURE 20**

Separate cold-feed bin and elevator for addition of wet fines
Meeker Warm Mix

WMA Technology Category: Foaming Process
WMA Product Name: Meeker Warm Mix
WMA Supplier Information: Meeker Equipment
  Contact Person: Bill Garrett
  Phone: (717) 667-6000, Ext. 6
  e-mail: bill@meekerequipment.com

WMA Technology Description: Meeker Warm Mix is a simple design with no moving parts in the foamer, it was originally designed for the many batch plants in the northeastern U.S. Meeker foaming technology maintains constant high-pressure water injection into the pressurized asphalt binder as it is piped to the pug mill or other types of mixers. A fully heated static mixing device follows the water injection point, completely foaming all the liquid binder at varying binder weights and/or flow rates.

Plant Modifications: Meeker's foamer can be installed on both batch and drum plants. For a batch plant, Meeker's foamer (Figure 21a) is added to the binder piping on the tower platform just before the binder enters the pug mill (Figure 21b). On a drum plant, it is installed just before entering the mixing chamber. The water metering skid can be placed anywhere on the site (Figure 22). Power and water need to be supplied to the metering skid and a water line is needed from the metering skid to the foamer.

FIGURE 21 a, b
Meeker Warm Mix (left), batch plant installation (right)

FIGURE 22
Meeker foaming skid at base of batch tower
WMA Technology Experience/Usage: There are currently eight Meeker Warm Mix units installed and operational on batch plants both domestically and internationally, and over 50 units installed on drum plants.

Terex WMA System
WMA Technology Category: Foaming Process
WMA Product Name: Terex WMA System
WMA Supplier Information: Terex Roadbuilding
   Contact Person: Tim Owens
   Phone: (405) 491-2126
   e-mail: tim.owens@terex.com
   www.terexrb.com
WMA Technology Description: The Terex WMA System uses a patented, single expansion chamber that will reportedly provide consistent asphalt binder/water mixing at any desired production rate. The system is a complete package that only requires a jacketed asphalt binder line and water feed pipes to be supplied by the contractor. The Terex WMA System produces foam just outside the drying drum, then immediately injects the foamed asphalt into the mixing drum, evenly coating the aggregate.

Plant Modifications: The Terex WMA System fits any unitized counterflow mixing drum and can be easily installed onto an existing drum (Figure 23). The system has no moving parts aside from the water pump and the meter. The system comes complete except for the contractor-supplied jacketed asphalt binder and water feed.

FIGURE 23
Terex WMA System

Tri-Mix Warm Mix Injection System
WMA Technology Category: Foaming Process or Chemical Injection
WMA Product Name: Tri-Mix Warm Mix Injection System
WMA Supplier Information: Tarmac International, Inc.
   Contact Person: Ron Heap
   Phone: (816) 220-0700
   e-mail: info@tarmacinc.com
   web site: http://tarmacinc.com
WMA Technology Description: The Tri-Mix Warm Mix Injection System uses two opposed high-pressure injection nozzles (Figure 24) followed by a downstream static mixer to foam the asphalt or add a water-based chemical additive such as Evotherm DAT. The 24-inch-long foaming unit is hot-oil jacketed (Figure 25).

   The variable-frequency drive pump and controls are mounted on a separate pumping skid (Figure 25). A heating package is available for the skid for cold-weather operation. Three levels of controls are available: manual solid-state (rate manually set at skid, self-adjusts with changes in production rate), PLC with Internet control and printing capability (rate can be set over Internet), and full computer control tied in with the plant’s blending system (replacement blending system for plant).

Plant Modifications: The water injection unit is installed in the asphalt line with jumpers for the hot-oil

FIGURE 24
Tri-Mix injection nozzles
The pump skid requires water, compressed air, and electrical connections. Compressed air is used to prevent clogging of the nozzles when water or chemicals are not being added. The pump can be located at a convenient place nearby.

**Mix Design Modifications:** The unit is capable of water variable addition rates up to 4.0 percent by total weight of binder. The mix should be produced at the anticipated field mixing and compaction temperatures. Specifications may require the use of a lab foaming device. Whether or not a laboratory foaming device is used, a plant-produced trial batch is recommended. If a chemical additive is used, the additive should be added as described for that technology diluted with the same amount of water used in the field addition.

**WMA Technology Experience/Usage:** To date, 17 Tarmac Tri-Mix Warm Mix injection systems have been installed and are operational.

**Ultrafoam GX2 System**

**WMA Technology Category:** Foaming Process

**WMA Product Name:** Ultrafoam GX2 System

**WMA Supplier Information:**
- Gencor Industries, Inc.
- Contact Person: Dennis B. Hunt
- Phone: (407) 290-6000
- e-mail: dhunt@gencor.com
- http://gencorgreenmachine.com/ultrafoam.html

**WMA Technology Description:** Sometimes called the Green Machine, the Ultrafoam GX2 warm-mix asphalt system is the second generation of the Ultrafoam GX WMA System and, similar to the first-generation unit, uses only the energy supplied by the pump or head supplying the asphalt binder to achieve the foaming process. This eliminates the need for a powered mixing device, allowing the asphalt binder to be introduced at various flow rates, temperatures, and pressures, resulting in more consistent asphalt foaming at different production rates.

The Ultrafoam GX2 system uses approximately 1.25 to 2 percent water by weight of total asphalt binder to achieve adequate foaming. The added water is injected into the center of the asphalt flow. A centrally located spring-loaded water valve is opened when water pressure is applied. A diaphragm plate, located external to the nozzle, allows the asphalt binder to flow at varying rate while keeping the fluid pressure constant. This results in a well-maintained ratio of asphalt binder and water and reportedly creates smaller steam bubbles for more consistent asphalt foaming.

**Plant Modifications:** As with most other foaming devices, the only plant modifications are associated with the installation of the foaming system. The Ultrafoam GX2 foaming generator is presented in Figure 26. A separate unitized skid houses all other needed equipment (water pump, inlet strainer, gauge, pressure switch, pressure relief valve, water flow meter).

**WMA Technology Experience/Usage:** A laboratory evaluation of mix produced with the Ultrafoam GX was conducted at NCAT in 2010. The report (NCAT 10-03)
can be viewed on their Web site, www.ncat.us. To date, approximately 200 first- and second-generation Ultra-foam GX units have been installed and are in use.

**WAM* Foam**

**WMA Technology Category:** Foaming Process  
**WMA Product Name:** WAM* Foam  
**WMA Supplier Information:** Shell Bitumen  
- Contact Person: Karel Poncelet  
- Phone: +32-54-32-87-31  
- e-mail: karel.poncelet@shell.com  
- www.shell.com/bitumen  

*WAM is a trademark of the Shell Group.

**WMA Technology Description:** The WAM Foam process uses a two-stage addition of asphalt binder, one nominally soft and the other nominally hard. The resulting blend of the two binders is selected to produce the desired PG (performance grade). The soft binder typically represents 20 to 30 percent of the total binder content. If the resultant binder grade needs to be altered, this should be done by varying the component binder grades, as a minimum percentage of the soft binder is required to coat the coarse aggregate. Coating the coarse aggregate with the soft binder also satisfies the demand of any asphalt absorption by the coarse aggregate that may not otherwise occur with a stiffer binder at low temperatures. Anti-stripping agents could also be added to the soft binder. 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 asphalt fraction (approximately 1.6 pounds of water per ton of mix assuming 5 percent total asphalt content, 80 percent of which is hard binder) at approximately 347 °F to 356 °F (175 °C to 180 °C).

**Mix Design Modifications:** The production of WAM Foam in the laboratory requires a laboratory foaming device. Several models are commercially produced. A laboratory foaming device consists of a heated binder tank, a water reservoir, volumetric pumps or other means for controlling the binder and water flow rates, and a foaming nozzle. Compressed air is used to clean the foaming nozzle. Trials should first be performed to determine the optimum temperature for the hard binder to produce good foam using a laboratory foaming device. The aggregate is heated to the mixing temperature required by the soft binder. The aggregate is mixed with the soft binder using a bucket mixer or laboratory pug mill. A laboratory foaming device is used to foam the hard binder into the mixer while mixing.

**Plant Modifications:** WAM Foam can be produced using either a batch or drum plant with modifications. For a batch plant, the soft binder is added through the original asphalt line and weigh bucket. A second asphalt line is needed to supply the hard binder, the addition of which is regulated by a mass flow meter. A foaming nozzle and expansion chamber is also needed above the pug mill. Figure 27 shows the controls and expansion chamber for a batch plant. It is important that, after each foaming process, compressed air be introduced into the expansion chamber to remove any residual binder from the chamber after each batch to prevent clogging. Modifications on a drum plant are easier than those for a batch plant. Similar to the batch plant, the existing asphalt line on a drum plant supplies the soft binder. An additional line is needed for the addition of the hard binder, along with a well-insulated water line to foam the asphalt. The hard asphalt line and nozzle do not extend deep inside the drum, allowing the soft binder to first coat the aggregate. Since the drum plant is continuous, foaming is hence continuous, eliminating the need for compressed air to purge the foaming nozzle and expansion chamber during production.

**WMA Technology Experience/Usage:** Over 100,000 tons of WAM Foam have been produced, primarily in Europe and Australia. Two field trials have been conducted in North America using WAM Foam.

## Non-foaming Additives

**BituTech PER**

**WMA Technology Category:** Non-foaming Additive  
**WMA Product Name:** BituTech PER  
(Also branded as Hydrogreen and previously branded as Astech)  
**WMA Supplier Information:** Engineered Additives, LLC.  
- Contact Person: Allen Smith  
- Phone: (973) 216-3560  
- e-mail: asmith@engineeredadditives.com  
- http://www.engineeredadditives.com

**WMA Technology Description:** BituTech PER is formulated for high-RAP or RAS mixes and reportedly improves co-mingling of aged and virgin binders. It is a U.S.-based product produced entirely from renewable plant materials. The product was initially used as a rejuvenator for mixes containing RAP. BituTech PER is designed to mimic the malthenes phase of
the asphalt binder. In mixes containing RAP, it supplements the maltenes component, aids in dispersion of asphaltenes, and provides viscosity reduction. This improves the low-temperature properties of the combined virgin and RAP binder. Reduced binder viscosity and increased dispersion of asphaltenes facilitate complete coating of the aggregates and improved compaction at reduced temperatures. BituTech PER is added at 0.5 to 0.75 percent of the total weight of RAP plus RAS in the mix. BituTech PER should only be used in mixes with high levels of RAP/RAS that would normally require recycling agents to produce acceptable binder stiffness.

**Mix Design Modifications:** The first step is to determine the total RAP/RAS content of the mixture in order to determine the addition rate. Use a low-shear mixer to blend the appropriate amount of BituTech PER into hot binder or use pre-blended binder. Prepare samples at the anticipated field mixing and compaction temperatures.

**Plant Modifications:** BituTech PER may be pre-blended into the binder at the terminal or injected into the binder with a dosing pump before the binder enters the asphalt plant. BituTech PER is a liquid at ambient temperatures.

**WMA Technology Experience/Usage:** BituTech PER was first used in Florida by a major paving company as a replacement for petroleum aromatic oils (rejuvenators). Over 1 million tons of RAP mix containing BituTech PER have been placed since 2007. Table 4 describes the warm-mix projects constructed using BituTech PER to date.

### TABLE 4
**BituTech PER WMA Field Sections**

<table>
<thead>
<tr>
<th>Project</th>
<th>Date</th>
<th>PG Grade</th>
<th>NMAS, mm</th>
<th>RAP, %</th>
<th>Tonnage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Florida</td>
<td>October 2009</td>
<td>67-22</td>
<td>12.5</td>
<td>40</td>
<td>600</td>
</tr>
<tr>
<td>Little Neck Parkway, New York, NY</td>
<td>October 2010</td>
<td>64-22</td>
<td>12.5</td>
<td>20</td>
<td>1000</td>
</tr>
</tbody>
</table>
**LEADCAP**

**WMA Technology Category:** Non-foaming Additive  
**WMA Product Name:** LEADCAP  
**WMA Supplier Information:** Kumho Petrochemical Co.  
  Distributed in U.S. by Cook Chemical Company, Inc.  
  Contact Person: Michael Cook  
  Phone: (949) 275-8241  
  e-mail: mcook@cookchem.com  
  http://leadcapwma.com

**WMA Technology Description:** LEADCAP stands for Low Energy and Low Carbon-Dioxide Asphalt Pavement. LEADCAP is a wax-based additive with a crystal controller and adhesion promoter (Figure 28). The product was developed in 2008 by the Korea Institute of Construction Technology in conjunction with Kumho Petrochemical. The wax acts to reduce the viscosity of and provide a lubricating effect to the asphalt binder. The crystal controller prevents certain types of chemical bonds from forming between the wax molecules, reducing crystallization. This helps to prevent low-temperature cracking. The adhesion promoter acts as an anti-stripping agent. Combined, the additive allows warm-mix benefits with the ability to increase the high-temperature PG binder grade, depending on the dosage level, without impacting the low-temperature grade. LEADCAP allows mixing and compaction temperatures to be reduced by 54 °F (30 °C).

**Mix Design Modifications:** Recommended dosing rates vary depending on the desired effect to the high-temperature binder grade. Typically, an addition of 1.5 percent imparts WMA properties; 3.0 percent will increase one high-temperature PG binder grade (64 to 70); and 4.0 percent can increase two high-temperature grades (64 to 76). LEADCAP additives are added to the asphalt mixture with no changes to the mix design procedure except for the mixing and compaction temperatures. LEADCAP may be pre-mixed with the binder. Alternatively, LEADCAP can be added directly to the mixture, typically in a crater in the mixing bowl on top of the binder.

**Plant Modifications:** If LEADCAP is pre-blended with the binder, no plant modifications are necessary. LEADCAP does not require high-shear blending. It can be added to the plant’s tank and dispersed by circulation. Pre-measured bags of LEADCAP can be added directly to a batch plant’s pugmill.

**WMA Technology Experience/Usage:** LEADCAP was introduced in 2008 with nine trials in Korea between 2008 and 2010. Additional trials were constructed in Japan, Italy, and Portugal in 2010 and China, Thailand, and the United States in 2011. Table 5 presents project information for a U.S. project. Oliveira et al. (2011) document the Portuguese trial.

**Sasobit**

**WMA Technology Category:** Non-foaming Additive  
**WMA Product Name:** Sasobit  
**WMA Supplier Information:** Sasol Wax North America Corp.  
  Contact Person: Lisa Hunt  
  Phone: (510) 232-8704  
  e-mail: Lisa.Hunt@USSasol.com  
  www.sasolwax.US.com

**TABLE 5**  
**LEADCAP Field Test Sections**

<table>
<thead>
<tr>
<th>Project</th>
<th>Date</th>
<th>PG Grade</th>
<th>NMAS mm</th>
<th>$N_{\text{design}}$</th>
<th>RAP, %</th>
<th>Tonnage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capital Street, Iowa City, IA</td>
<td>August 2011</td>
<td>64-22</td>
<td>12.5</td>
<td>76</td>
<td>10</td>
<td>350</td>
</tr>
</tbody>
</table>
**WMA Technology Description:** Sasobit is a synthetic paraffin wax produced from the Fischer-Tropsch method, which involves treating hot coal or natural gas with steam in the presence of a catalyst. They are long-chain aliphatic hydrocarbon waxes with a congealing point of more than 212 °F (100 °C), with higher viscosity than asphalt below their melting point and lower viscosity than asphalt at temperatures above their melting point. They solidify in asphalt from between 149 °F to 239 °F (65 °C to 115 °C) into regularly distributed, microscopic stick-shaped particles.

A second form of Sasobit is available, and is known as Sasobit-LM. This form is identical to the original Sasobit, but has a lower congealing point (approximately 207 °F [97 °C]). Sasobit-LM is reported to enhance the workability of asphalt mixtures containing RAS (reclaimed asphalt shingles) due to its wider molecular weight distribution.

**Mix Design Modifications:** Sasobit is generally added at a rate of 1.5 percent by weight of the total (including RAP and RAS) binder, but addition rates of 0.8 to 4 percent have been used. If Sasobit is preblended with the binder, mix design proceeds without any changes, other than using the expected field mixing and compaction temperatures. If the Sasobit will be added at the plant in its pelletized form, after charging the mixing bowl with the aggregate, a crater is formed. The asphalt binder is added into the crater and the appropriate amount of Sasobit is added on top of the binder prior to mixing. The most common form of Sasobit is shown in Figure 29.

**Plant Modifications:** Sasobit can be added to the plant by a number of different methods. It can be blended directly into the asphalt binder, without high-shear blending. This means direct blending can occur either at the terminal or at the asphalt plant. For a drum plant, it can be added through the RAP collar, but the preferred method requires a specially built feeder (similar to a fiber feeder) that can control the quantity and then blow the organic additive into the drum. The Sasobit would be blown into the drum at approximately the same point where the asphalt binder is added. Existing fiber ports have been used. An example of this feeder is presented in Figure 30. The 4-inch-diameter hose in Figure 30 was supplying fibers and the 2-inch-diameter hose was supplying Sasobit. If the material is being blown into the drum, a
clear view port (Figure 31) is recommended to verify the feed. Sasobit can also be added in-line with the binder in a molten state.

**WMA Technology Experience/Usage:** A laboratory evaluation of Sasobit was conducted at NCAT in 2005. The finished report (NCAT 05-06) can be viewed on their Web site, www.ncat.us. Sasobit is commonly used today in both the United States and Canada. Approximately 2.5 to 3 million tons of Sasobit WMA have been placed in North America to date.

**FIGURE 31**
Clear view port to ensure Sasobit flow

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**SonneWarmix**

**WMA Technology Category:** Non-foaming Additive  
**WMA Product Name:** SonneWarmix  
**WMA Supplier Information:** Sonneborn, Inc.  
- Contact Person: Chris Strack  
- Phone: (203) 261-8582  
- e-mail: chris.strack@sonneborn.com  
- www.sonnewarmix.com  

**WMA Technology Description:** SonneWarmix is a high melt point, paraffinic hydrocarbon blend (wax). The product had been marketed originally under the names AD-RAP and Sonneborn AR. Binder modified with SonneWarmix has been marketed by All States Materials Group as ECOBIT. The melting point of SonneWarmix is 175 °F (79 °C) and it is a liquid between 195 °F to 200 °F (91 °C to 93 °C).

**Mix Design Modifications:** If the binder is not available in a pre-blended form for laboratory use, a sample of SonneWarmix could be heated to 200 °F to 250 °F (93 °C to 121 °C) and the appropriate amount added to the hot binder using a low shear mixer/stirring device. Typical addition rates 0.5 to 1.5 percent by weight of the total binder weight (including RAP/RAS), depending on the percentage of RAP, RAS, crumb rubber, or other polymer modifiers in the mix. The maximum recommended dosage for unmodified, virgin mixes is 0.75 percent. Samples should be mixed and compacted at anticipated field temperatures. A 50 °F (28 °C) reduction in compaction temperature is typical.

**Plant Modification:** SonneWarmix is added to the liquid asphalt at the terminal or refinery. No modifications at the hot-mix plant are required. The product must be heated to 200 °F to 250 °F (93 °C to 121 °C) in order to liquefy for the addition process. Either a warming box or heating bands (Figure 32) may be used to liquefy the product. It is added with a variable frequency drive, positive displacement pump capable of measuring 1.5 to 15 gpm. It may be added at the binder suction pump or prior to a static mixer to achieve proper mixing. SonneWarmix is supplied in 55-gallon drums, steel tight-head (FOH) drums, tank trucks, and rail cars.

**WMA Technology Experience/Usage:** SonneWarmix was introduced in 2008. As of November 2010, the product had been approved in four U.S. states and two Canadian cities. Example projects are shown in Table 6.

**FIGURE 32**
Heating Bands for liquefying SonneWarmix or similar products
Thiopave

**WMA Technology Category:** Non-foaming Additive  
**WMA Product Name:** Shell Thiopave  
**WMA Supplier Information:**  
- Shell Sulphur Solutions  
- Contact Person: Gary Fitts, P.E.  
- Phone: (210) 241-0195  
- e-mail: gary.fitts@shell.com  
- http://www.shell.com/home/content/sulphur/your_needs/products/in_roads/

**WMA Technology Description:** Shell Thiopave (previously known as SEAM – Sulfur Extended Asphalt Modifier) is based on the sulfur-extended asphalt technology. This technology combines sulfur and an WMA additive. The sulfur partially replaces some (typically 20 to 25 percent) of the asphalt binder volume needed to fully coat and bind the virgin aggregate. While some of the elemental sulfur is dispersed within the asphalt binder, the remainder provides a crystalline binder, resulting in increased mixture stiffness and resistance to permanent deformation. At elevated temperatures, sulfur-modified mixtures may produce harmful levels of hydrogen sulfide ($H_2S$) and sulfur dioxide ($SO_2$). The WMA additive allows reduced production and compaction temperatures critical to reducing these emissions. Future recycling of the pavement must also be done at reduced temperatures. Pelletized Thiopave is presented in Figure 33. The Thiopave system may also include an organic additive that performs as a coating and workability aid as well as other modifiers.

**Mix Design Modifications:** During the mix design process, small modifications are needed to ensure the correct amount of Thiopave is added to the asphalt binder. By using a simple mathematical calculation, shown in Equation 1, the amount of Thiopave needed for substitution in the asphalt binder can be determined.

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### TABLE 6  
**SonneWarmix field sections**

<table>
<thead>
<tr>
<th>Project</th>
<th>Date</th>
<th>PG Grade</th>
<th>NMAS, mm</th>
<th>$N_{\text{design}}$</th>
<th>RAP, %</th>
<th>Tonnage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sunderland, MA</td>
<td>May 2009</td>
<td>52-34</td>
<td>19.0</td>
<td>NA</td>
<td>40</td>
<td>200</td>
</tr>
<tr>
<td>Saratoga Springs, NY</td>
<td>Sept. 2009</td>
<td>64-22</td>
<td>19.0</td>
<td>75 gyrations</td>
<td>0</td>
<td>400</td>
</tr>
<tr>
<td>Route 3, Plymouth, MA</td>
<td>Oct. 2009</td>
<td>AR</td>
<td>12.5</td>
<td>100 gyrations</td>
<td>0</td>
<td>5,000</td>
</tr>
<tr>
<td>Sonneborn Gate 1 Petrolia, PA</td>
<td>Oct. 2009</td>
<td>64-22</td>
<td>9.5</td>
<td>25.0</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>I-95, Carmel, ME</td>
<td>Oct. 2010</td>
<td>64-28</td>
<td>12.5</td>
<td>75 gyrations</td>
<td>15</td>
<td>12,000</td>
</tr>
<tr>
<td>Little Neck Parkway New York, NY</td>
<td>Oct. 2010</td>
<td>64-22</td>
<td>12.5</td>
<td>75 gyrations</td>
<td>20</td>
<td>1,000</td>
</tr>
<tr>
<td>Route 146 Douglas, MA</td>
<td>Nov. 2010</td>
<td>AR</td>
<td>12.5</td>
<td>100 gyrations</td>
<td>0</td>
<td>14,000</td>
</tr>
</tbody>
</table>

---

**FIGURE 33**  
**Shell Thiopave pellets**

---
Equation 1

\[
\text{Thiopave + Binder Wt. \% = } A \frac{(100 \times R)}{100 \times R - P_s \times (R - G_b)}
\]

Where:
- \( A \) = Percent mass of asphalt binder in conventional mix design
- \( R \) = Thiopave to binder substitution ratio, or \( R = \frac{G_{\text{thio}}}{G_b} \)
- \( P_s \) = Percent mass of Thiopave in total binder
- \( G_b \) = Specific gravity of asphalt binder
- \( G_{\text{thio}} \) = Specific gravity of Thiopave = 2.07

**Plant Modifications:** In small trial or demonstration projects, Thiopave has been pneumatically added directly into the mixing drum toward the end of the mixing process, after the addition of the asphalt binder. For larger volume projects, Thiopave may be added with a conveyor belt system (Figure 34). This will allow Thiopave to melt quickly, using the shearing action inside the mixing drum to thoroughly disperse the sulfur into the asphalt mixture. During production, the mixing temperature should be closely controlled, targeting a discharge temperature of 266 °F ± 9 °F (130 °C ± 5 °C). Production temperatures must exceed 248 °F (120 °C) to ensure that the sulfur pellets melt and are distributed throughout the mix.

**WMA Technology Experience/Usage:** Molten liquid sulfur technology was originally developed during the late 1970s and early 1980s and referred to as sulfur extended asphalt. The solid pelletized “SEAM” or Thiopave technology has been used since 2000. NCAT has conducted several studies on Thiopave. The reports (NCAT 09-05, 10-05, 11-30, and 11-07) can be viewed on their Web site, www.ncat.us. To date, approximately 450,000 tons of mix modified with Thiopave have been produced worldwide. Table 7 presents project information on a select few of these projects.

**FIGURE 34**
Conveyor belt addition of Thiopave into drum plant
### TABLE 7
Shell Thiopave field sections

<table>
<thead>
<tr>
<th>Project</th>
<th>Date</th>
<th>Base PG Grade</th>
<th>NMAS, mm</th>
<th>N&lt;sub&gt;design&lt;/sub&gt;</th>
<th>RAP, %</th>
<th>Tonnage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southgate, CA</td>
<td>2002</td>
<td>AR 8000</td>
<td>12.5</td>
<td>75 blows</td>
<td>0</td>
<td>595</td>
</tr>
<tr>
<td>Port of Oakland, CA</td>
<td>2004</td>
<td>AR 8000</td>
<td>19.0</td>
<td>75 blows</td>
<td>0</td>
<td>200</td>
</tr>
<tr>
<td>US 71, Adrian, MO</td>
<td>2009</td>
<td>PG 64-22</td>
<td>9.5</td>
<td>75 blows</td>
<td>0</td>
<td>25,000</td>
</tr>
<tr>
<td>NCAT Test Track Sections N5 and N6, Auburn, AL</td>
<td>2009</td>
<td>PG 67-22</td>
<td>19.0</td>
<td>60 gyrations</td>
<td>0</td>
<td>1,400</td>
</tr>
<tr>
<td>Longview, TX</td>
<td>2009</td>
<td>PG 64-22</td>
<td>9.5</td>
<td>Texas Gyratory</td>
<td>0-15</td>
<td>1,100</td>
</tr>
<tr>
<td>US 71, Jasper, MO</td>
<td>2010</td>
<td>PG 64-22</td>
<td>19.0</td>
<td>NA</td>
<td>15</td>
<td>155,000</td>
</tr>
<tr>
<td>NCAT, Test Track Sections E9, W2, and W7, Auburn, AL</td>
<td>2010</td>
<td>PG 67-22</td>
<td>19.0</td>
<td>60 gyrations</td>
<td>0</td>
<td>600</td>
</tr>
<tr>
<td>US 183, Austin, TX</td>
<td>2010</td>
<td>PG 64-22</td>
<td>12.5</td>
<td>Texas Gyratory</td>
<td>20</td>
<td>2,000</td>
</tr>
<tr>
<td>Hwy 659, Bonnyville, AB, Canada</td>
<td>2011</td>
<td>200-300 Pen</td>
<td>12.5</td>
<td>75 blows</td>
<td>0</td>
<td>25,000</td>
</tr>
</tbody>
</table>
Compaction Aid

Asphalt mixtures that contain highly modified asphalt binders, those incorporating high percentages of RAP or RAS, or specialty mixtures such as stone-matrix asphalt (SMA) have been known to be stiff and fairly difficult to compact. This difficulty in compaction can lead to lower in-place densities and the possibility of penalties being assessed to the contractor. As a result, contractors may be tempted to increase placement temperatures to ensure adequate compaction. Even if adequate in-place density is achieved, the required effort may cause excessive aggregate breakdown or otherwise damage the asphalt mat. Using WMA technologies at “typical” compaction temperatures will aid in the compaction of these stiffer mixes. Some technologies were, in fact, initially used for their stiffening effect at high in-service temperatures, when it was observed that the materials aided compaction at standard paving temperatures.

Many instances of using WMA technologies as a compaction aid have been reported. Massachusetts Department of Transportation now specifies warm mix for all of its gap-graded asphalt rubber (AR) mixtures.

Warm Mix in Racetracks?

The first warm mix project in the United States was constructed by Hubbard Construction in Orlando, Florida in February 2004. However, a warm mix additive was actually used the previous year in the reconstruction of Homestead-Miami Speedway. At the time, the contractor didn’t know it was warm mix! The supplier included the additive to raise the softening point of the binder, a common specification for racetracks. Laboratory mixing and compaction temperatures were reduced compared to what would normally be expected for a PG 82-22. Since then, the same additive has been used in other tracks, such as Talladega Superspeedway and Phoenix International Raceway. Primarily, it was used as a compaction aid. In many cases, only a limited number of rollers can be utilized on banked ovals, since the equipment needs to be supported. In Talladega, a single roller was used, supported by a dozer (Figure 35). Production and laydown temperatures were lower than comparable projects where the additive wasn’t used. At Michigan International Speedway, mix was successfully hauled for 1½ hours and then placed on the track in cool weather. In Phoenix, track mix temperatures behind the screed were typically in the 275 °F (135 °C) range — truly warm mix!

FIGURE 35
Warm-mix technologies used as a compaction aid
Sasobit has been used in several high-performance commercial paving projects throughout the United States. These projects used highly modified PG 82-22 and PG 82-28 asphalt binders with approximately 1 percent Sasobit added. Aspha-min has been used to improve the workability of open-graded friction courses in areas requiring hand work (NAPA 2008). The mixture was placed at 320 °F (160 °C).

**Cold-weather Paving**

Warm-mix technologies offer the potential to extend the paving season in colder climates. This is possible because of three factors. First, WMA additives or processes improve compaction at a given temperature. Second, WMA is compactable at lower temperatures than HMA. Third, the rate of cooling is driven by the difference in temperature between the asphalt mixture and ambient air, so that a mixture produced at a lower temperature will cool at a slower rate.

Case studies were presented during the European scan tour of 2007 where, in Germany, paving was conducted with several different WMA technologies when ambient temperatures were between 27 and 40°F (−3 and 4 °C). Better density was achieved with the WMA compared to the HMA with the same or fewer roller passes (Harnischfeger 2007). Another example of cold-weather paving with WMA additives involved paving in November in New York state, where the temperature, with the wind chill, was in the 30s Fahrenheit. It was a high-performance paving operation using a PG 82-28 where compaction was crucial, and the addition of Sasobit allowed compaction to be achieved. A similar project was constructed in South Carolina during January and February using a PG 82-22 binder. Average core densities of 93.9 percent of theoretical maximum density (TMD) were achieved.

Jackson (2011) documented the use of WMA for non-typical paving projects. Included was an emergency repair to Interstate 70 placed when the temperature was 23 °F (−5 °C). The 12.5 mm NMAS mixture contained both RAP (10 percent) and RAS (3 percent). The mixture was produced at 305 °F (152 °C). After a 60-minute haul, average laydown temperatures were reported to be 256 °F (124 °C). An average of 94.2 percent of theoretical maximum density was obtained.

Care must be taken when selecting production and construction temperatures for cold-weather paving. Similar to HMA, temperatures will most likely need to be increased as the ambient temperature decreases. The half-life of foamed asphalt is generally related to the binder/mixture temperature, with higher temperatures resulting in a shorter half-life (Jenkins 2000). Half-life is defined as the time it takes for the volume of the foam to decrease by one-half. However, an experiment conducted for the Nippo Corporation, a large Japanese asphalt contractor, indicates that mechanical foaming systems provide compaction benefits over non-foamed HMA even at production temperatures typical of HMA (Prowell et al. 2010). Figure 36 shows a comparison between the densities...
achieved at various compaction temperatures for a foamed asphalt produced at 325 °F and 270 °F (165 °C and 132 °C) and HMA produced at 336 °F (169 °C). The figure indicates that even at elevated temperatures, the foamed mix provides improved compaction compared to the HMA.

The smaller temperature differential between WMA and ambient temperature reduces the rate of cooling. Thus WMA would provide additional time for compaction while cooling the same amount, e.g. WMA cooling from 250 °F to 175 °F compared to HMA cooling from 300 °F to 225 °F. Hand work may still be problematic. Field personnel reported warm mix placed in radiuses of cross-overs in cold weather did not “stick” or was not cohesive. The author observed raveling in these areas shortly after construction.

Longer Haul Distances

Similar to the potential for extending the paving season through the use of WMA technologies, longer haul distances may be facilitated by the reduced rate of cooling of WMA and the improved compaction at lower temperatures. An early example of the successful use of WMA with longer haul distances is the Ohio WMA open house in 2006. During this event, WMA produced with three different technologies was hauled an hour and then placed at Ohio University’s accelerated loading facility.

In 2008, the California Department of Transportation (Caltrans) used WMA on four paving projects in Northern California to deal with a combination of long haul distances, cool weather, and polymer-modified binders (Barros 2009). Mix was hauled for one to three hours. WMA was used in both dense-graded and open-graded mixtures. Because of the cool weather and long hauls, a crust formed on the asphalt in the haul trucks; this crust broke up into chunks as the mix was dumped. For the two projects where a materials transfer vehicle was not used, some material was wasted to eliminate the chunks. Adequate workability was still observed. Temperature reductions of up to 25 °F (14 °C) were still possible and compaction was improved. Field performance to date has been good.

Similarly, Lane Construction Corp.’s Texas Division placed 17,000 tons of WMA using Evotherm DAT in Lake Mineral Wells State Park, Texas, between November 2008 and March 2009. The project required a 60-mile haul. WMA was produced at 250 °F (121 °C) with compaction temperatures of approximately 225 °F (107 °C) with typical in-place densities in excess of 93.5 percent of TMD (Udelhofen 2009).

In 2010, Rhode Island Department of Transportation looked to warm mix to facilitate paving on Block Island. The project required a two-hour haul, one hour of which was on a ferry (Figure 37). Previously, T. Miozzi Inc. had dealt with the haul distance by moving an asphalt plant to the island. This time they produced WMA on the mainland using Advera WMA. In addition to the long haul, the pavement had recently been crack-sealed. The mix was reported to be very workable when it reached the site and in-place density exceeded compaction requirements (Fournier 2010).

Use of Higher Percentages of RAP

WMA technologies can be beneficial to asphalt mixtures containing high percentages of RAP in several ways. First, WMA will aid in pavement compaction. Second, the decreased aging of the asphalt binder, resulting from the lower production temperatures, may help to rejuvenate the RAP binder, particularly in regard to low-temperature cracking. In the Netherlands, both HMA and LEAB (a foamed asphalt process not used in the U.S.) are routinely produced with 50 percent RAP. Field trials have been conducted in Germany with 90 to 100 percent RAP using Aspha-min and Sasobit (Prowell 2007).

Field trials have been conducted in the U.S. using several WMA technologies where the RAP percentages ranged from 20 to 50 percent. Boggs Paving Inc. produced 15,000 tons of WMA containing 50 percent fractionated RAP for a demonstration project in York County, South Carolina. The mixture was produced using the Double Barrel Green system at production temperatures of 270 °F (132 °C) (NAPA 2008).

Research conducted as part of National Cooperative Highway Research Program (NCHRP) 9-43 indicates that aged RAP binder will blend with virgin aggregate as long as the WMA production temperatures exceed the recovered high-temperature PG grade of the binder. The study showed that high-temperature grade for RAP typically ranges from PG 82 to PG 94. Thus, minimum mixing temperatures would range from 180 °F to 200 °F (82 °C to 94 °C). Further, with typical WMA temperature reductions of approximately 50 °F (28 °C), the low-temperature grade is improved by approximately 0.6 °C, which equates to allowing an additional 10 percent RAP to be added to the mixture (from a binder grade standpoint) without having to change the virgin binder grade (Bonaquist 2011).
Less Restriction and Potentially More Paving Hours in Non-attainment Areas

Some areas of the U.S. struggle to achieve and maintain national air-quality standards set by the U.S. EPA for various pollutants such as fine particles (PM 2.5), nitrous oxides, ozone, and sulfur dioxide. These areas are referred to as non-attainment areas. Local agencies are required to develop plans to reduce emissions in general and particularly on non-attainment days. Although EPA does not consider asphalt plants major sources of air pollution and asphalt plants consistently produce lower levels of emissions than allowed by regulations, some agencies’ plans prevent paving on non-attainment days. Research has proven that plant and paving emissions are directly dependent upon temperature (Lange and Stroup-Gardiner 2007). Lower temperatures at the plant mean that less fuel is consumed and plant site emissions are accordingly reduced. These reductions can assist plant operators with permit compliance and may potentially allow for increased asphalt production in non-attainment areas. Allowing contractors to continue to work on non-attainment days was an incentive to Tennessee DOT to investigate WMA (NAPA 2008).

Specific Plant Concerns

Where possible, contractors return baghouse fines to the mix but, in some cases, contractors are forced to waste baghouse fines. If wasted fines are not mixed with water, they result in considerable dust at the plant site. However, it is difficult to mix the hot fines with water. Using WMA allowed one contractor to lower baghouse temperatures at their portable plant, which consequently allowed the cooler waste baghouse fines to be mixed with water, producing a more easily managed slurry (Figure 38).

Specific Pavement Rehabilitations

Lower mix temperatures can improve ride on some pavement rehabilitation projects. An example is the WMA field evaluation that took place in St. Louis, Missouri in May 2006. Figure 39 shows bumps that can form in the roadway surface when overlaying crack sealer. These bumps were believed to be caused either by expansion of the rubberized crack sealer material in the underlying surface, or by moisture in cracks in the underlying pavement turning to steam from the hot-mix asphalt overlay being placed and pushing the crack sealer upward.
Several WMA technologies were evaluated in an attempt to eliminate the bumps. It was believed that the lower WMA placement temperatures would minimize expansion of the sealant to expand or reduce the steam generated by heating water present in the pavement, thereby preventing the bumps from forming. After construction, it was determined that, when below 240 °F (116 °C), virtually no bumps formed. Adequate density was achieved with less effort than conventional hot mix (MacDonald 2006) for all WMA technologies used (Aspha-min, Evotherm ET, and Sasobit). Based on the success of this application, the contractor approached Missouri DOT to change other projects to WMA in order to improve the resulting pavement smoothness where similar circumstances existed. Another Missouri contractor utilized WMA in conjunction with a spray paver to ensure a good bond to a milled concrete pavement while avoiding reflective bumps from joint sealant (Jackson 2011). Texas DOT has successfully used WMA to eliminate the same type of problem.

Payne and Dolan Inc. proposed the use of WMA for the overlay on a runway at the West Bend Airport in
West Bend, Wisconsin. The existing runway had extensive cracking. The cracks had recently been sealed with a rubberized crack sealant (Figures 40a and b). The 75-foot-wide runway was paved in echelon with two 37.5-foot-wide passes (Figure 40b). The WMA compaction temperatures were approximately 235 °F (113 °C). The resulting pavement had excellent ride.

Reduced Fuel Usage

Theoretical calculations indicate that a temperature reduction of 50 °F (28 °C) should result in a fuel saving of 11 percent (Cervarich 2007). Fuel savings reported on various WMA projects constructed to date ranged from a 15.4 percent increase to a 77 percent reduction. The average fuel savings were 23 percent (Prowell et al. 2009). The increase occurred with an emulsion technology mixed at a high temperature. It is believed that the increase resulted from the energy required to vaporize the water in the emulsion and then heat the mixture to a high temperature. Figure 41 presents a summary of reported fuel savings based on literature reviewed as part of NCHRP research project 9-47A (Prowell et al. 2009). As expected, fuel savings are related to the degree of temperature reduction relative to HMA.

Fuel usage was monitored as part of the NCHRP 9-47A field trials. Table 8 shows data collected from five projects (Frank et al. 2011). Burner tuning was conducted prior to measurements at sites 2,
4, and 5. Stack emissions tests were conducted at these sites. In all cases, the use of WMA resulted in a reduction in fuel usage. Site 3 had the lowest stockpile moisture contents and the lowest fuel usage per ton. It was observed that after stack testing was completed, the plant operator increased the production temperature of WMA E to HMA temperatures while still producing WMA E. This accounts for the small reduction in fuel usage. Calculations based on sites 4 and 5 indicate that fuel savings are distributed as follows: 15 percent reduction in stack temperature, 56 percent reduction in mix temperature, and 41 percent reduction in casing loss. The high percentage attributed to casing loss, an inefficiency in heating, explains why in general reductions are larger than the theoretical 11 percent savings. The dryer drum at Site 4 was insulated, reducing casing losses.

It is important that burners be tuned to allow efficient firing across the revised range of settings. It should be noted that the level of fuel savings is dependent on several factors, such as the temperature reduction from the use of WMA, the moisture content of the aggregate, and details of the plant’s design and operation. Fuel usage reportedly increases approximately 10 percent for every 1 percent increase in aggregate moisture content (Prowell and West 2005). Fuel savings could be higher (possibly 50 percent or more) with processes such as LEAB and LEA where the aggregates, or a portion of the aggregates, are not heated above the boiling point of water.

The literature did not indicate that any consideration of increased electrical usage has been considered in the analysis of potential fuel savings. One example of possible electrical use increase is from higher drag chain amperage needed to move WMA to the silo for storage. Data collected as part of NCHRP 9-47A is still being analyzed. One site indicated slight increases in electrical usage with WMA, another site indicated no change.

### TABLE 8
Fuel usage measured as part of NCHRP 9-47A field projects (Frank et al. 2011)

<table>
<thead>
<tr>
<th>Site</th>
<th>Fuel</th>
<th>Mix</th>
<th>Stockpile Moisture, %</th>
<th>Production Rate, TPH</th>
<th>Production Temperature, °F</th>
<th>Fuel Usage MBTU₁/ton</th>
<th>Reduction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Natural Gas</td>
<td>HMA</td>
<td>2.6</td>
<td>316</td>
<td>325</td>
<td>0.278</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WMA A</td>
<td>3.0</td>
<td>310</td>
<td>285</td>
<td>0.218</td>
<td>21.6</td>
</tr>
<tr>
<td>2</td>
<td>Reclaimed Fuel Oil</td>
<td>HMA</td>
<td>3.6</td>
<td>310</td>
<td>300</td>
<td>0.271</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WMA B</td>
<td>3.9</td>
<td>323</td>
<td>269</td>
<td>0.225</td>
<td>13.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WMA C</td>
<td>4.1</td>
<td>320</td>
<td>269</td>
<td>0.187</td>
<td>17.0</td>
</tr>
<tr>
<td>3</td>
<td>Liquid Propane</td>
<td>HMA</td>
<td>1.3</td>
<td>370</td>
<td>298</td>
<td>0.157</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WMA D</td>
<td>1.5</td>
<td>378</td>
<td>252</td>
<td>0.137</td>
<td>12.7</td>
</tr>
<tr>
<td>4</td>
<td>Natural Gas</td>
<td>HMA</td>
<td>3.2</td>
<td>292</td>
<td>300</td>
<td>0.226</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WMA E</td>
<td>3.5</td>
<td>305</td>
<td>277</td>
<td>0.224</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WMA F</td>
<td>3.8</td>
<td>300</td>
<td>256</td>
<td>0.212</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WMA G</td>
<td>3.8</td>
<td>279</td>
<td>268</td>
<td>0.201</td>
<td>11.1</td>
</tr>
<tr>
<td>5</td>
<td>Natural Gas</td>
<td>HMA</td>
<td>3.1</td>
<td>271</td>
<td>332</td>
<td>0.260</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>WMA H</td>
<td>3.4</td>
<td>244</td>
<td>240</td>
<td>0.236</td>
<td>9.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WMA I</td>
<td>2.4</td>
<td>267</td>
<td>252</td>
<td>0.216</td>
<td>16.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>WMAJ</td>
<td>3.6</td>
<td>268</td>
<td>253</td>
<td>0.211</td>
<td>18.8</td>
</tr>
</tbody>
</table>

₁ Million British thermal unit
Reduced Emissions

As was pointed out in the introduction, the potential to reduce emissions of substances including greenhouse gases prompted the first experiments with WMA technology in Europe. The motivation was to meet stricter emissions regulations set forth by the Kyoto Protocol. The U.S. has significant regulations pertaining to emissions that must be followed under the provisions of the Clean Air Act of 1990. These provisions are largely administered through implementation plans drawn up by state and local air authorities under the auspices of the U.S. Environmental Protection Agency (EPA). Such restrictions often target volatile organic compounds (VOCs), nitrogen oxides (NOx), carbon monoxide (CO), small particulates (PM 2.5), carbon dioxide (CO2), sulfur dioxide (SO2), and various other pollutants, including those labeled as hazardous air pollutants (HAPs).

Reducing emissions through the use of WMA is dependent upon several factors. First, the type and level of emission reduction will vary according to the degree of temperature reduction and other operational factors such as type of fuel used, the plant's design and operation, aggregate moisture content, and RAP/RAS use. Generally speaking, less fuel use translates directly to lower emissions at the plant, since the largest part of gaseous emissions is the result of fuel combustion during the drying and heating processes. Research has also shown that increases in emissions at plant load-out and at the laydown site are exponentially related to increases in temperature. Figure 42 shows the reduction in load-out (fugitive) emissions produced by using WMA. A lower level of these plant emissions may reduce odors and otherwise improve conditions for workers and neighbors.

Table 9 presents emissions reductions with WMA from several countries. CO2 reductions were consistent across the board and correlated with the reduction in fuel combustion.

NCHRP project 9-47A collected stack emissions tests from 17 projects representing six technologies (Prowell et al. 2009). The data collected varied. The data quality also varied. Not all of the data was normalized for oxygen dilution to lbs/hr per the WMA TWG protocol. The data support the following:

- CO2 is generally reduced,
- NOx is reduced in all cases,
- SO2 and VOCs were below allowable levels.
Since stack emissions are largely the result of combusted fuel, reduced fuel usage combined with proper burner tuning should result in reduced CO$_2$ emissions. The data collected to date support this (Figure 43).

### FIGURE 43
Fuel usage versus CO$_2$ emissions for WMA projects (Frank et al. 2011)

---

### TABLE 9
Observed reduction (percent) in emissions with WMA (D’Angelo et al. 2007)

<table>
<thead>
<tr>
<th>Emission</th>
<th>Norway</th>
<th>Italy</th>
<th>Netherlands</th>
<th>France</th>
<th>Canada</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO$_2$</td>
<td>31.5</td>
<td>30 – 40</td>
<td>15 – 30</td>
<td>23</td>
<td>45.8</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>NA</td>
<td>35</td>
<td>NA</td>
<td>18</td>
<td>41.2</td>
</tr>
<tr>
<td>VOC</td>
<td>NA</td>
<td>50</td>
<td>NA</td>
<td>19</td>
<td>NA</td>
</tr>
<tr>
<td>CO</td>
<td>28.5</td>
<td>10 – 30</td>
<td>NA</td>
<td>NA</td>
<td>63.1</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>62.5</td>
<td>60 – 70</td>
<td>NA</td>
<td>18$^1$</td>
<td>58.0</td>
</tr>
<tr>
<td>Dust</td>
<td>54.0</td>
<td>25 – 55</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

$^1$ Reported as NO$_2$

Stack emissions were measured at three sites as part of NCHRP 9-47A, representing eight WMA mixes and three HMA control mixes (Frank et al. 2011). CO and VOC formation are affected by burner design, maintenance, and tuning. A burner that is not tuned properly or one that is not well maintained may result in elevated levels of CO and/or VOCs. These plant practices tend to overshadow potential WMA reductions. VOC emissions at a parallel-flow drum plant were significantly lower for WMA compared to HMA. WMA mixes at the site using recycled fuel oil resulted in a 50 percent reduction in SO$_2$ emissions. This is important because recycled fuel oil contains higher levels of sulfur than other fuel types. With the exception of one mix, NO$_x$ emissions from WMA were reduced compared to HMA.

### Greenhouse Gas Calculator
A Greenhouse Gas Calculator is offered on NAPA’s Web site at www.AsphaltPavement.org. This calculator gives asphalt plant operators a tool for determining the amount of greenhouse gases their facilities release. The user-friendly interface incorporates the look of input and output gauges. The calculator is built on a database that calculates CO$_2$-equivalent gases, based on total annual fuel consumed or on tons of mix produced. It also allows the user to compute reductions in emissions resulting from incorporating WMA, RAP, and RAS into mixes.

### Improved Working Conditions
Research has shown that the quantity and nature of fume to which workers may be exposed is impacted by temperature (Cavallari et al. 2011a, Cavallari et al. 2011b). Reduction of mix temperatures through the deployment of WMA will reduce exposures and improve working conditions.
The first data in the U.S. were collected and published using the framework for emissions assessment surrounding laydown operations (www.warmmixasphalt.com) that was developed by the FHWA/NAPA WMA Technical Working Group (WMA TWG) from two early multi-technology WMA projects (Chojnacki 2006, EES Group Inc. 2006). Industrial hygiene testing was conducted according to National Institute of Occupational Health and Safety (NIOSH) Method 5042. Area samplers were mounted at fixed points on the paver. While some of these points are not representative of actual worker exposure, the data can be used to provide emission comparisons between HMA and WMA. In addition, some crew members were outfitted with personal samplers. Three technologies were evaluated in the studies: Aspha-min zeolite, Evotherm, and Sasobit, two on the first project and all three on the second.

On the first project, WMA temperatures behind the screed were reduced by 30 °F to 80 °F (17 °C to 44 °C) compared to the HMA control. The asphalt fumes, measured as benzene-soluble matter (BSM), were reduced on average by 70 to 74 percent, with individual reductions at the six area sampling points indicating reductions of 22 to 91 percent (EES Group, Inc. 2006). Four sets of data were collected, one for each of the two WMA technologies and two sets of HMA control data. Each data set included results for two personal sampling devices worn by each of the screed operators. Seven of the eight personal sampler results were below detection limits. The eighth result, based on one screed operator’s sample for one of the HMA (not WMA) data sets, was 0.42 mg/m³, which was still below the American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value of 0.5 mg/m³.

For the second project, temperatures behind the screed were reduced between 52 °F and 77 °F (29 °C and 43 °C) compared to the HMA control mixture. Area samplers were mounted on the paver and data were collected as described above. Both total particulate matter (TPM) and BSM were reported. The WMA technologies resulted in average reductions in TPM between 67 and 77 percent. BSM was reduced by 72 to 81 percent as compared to the HMA control (EES Group, Inc. 2006).

Personal sampling devices were used on the paver and screed operators to monitor fume exposure for both a control (HMA) and a WMA section in a study conducted by Virginia Department of Transportation (Diefenderfer et al. 2007). Three of four samples for TPM were below detection limits; the fourth reading, 0.35 mg/m³, was well below the NIOSH recommended exposure value of 5 mg/m³. All four BSM readings, for both HMA and WMA, were below detection limits.

All of the early studies indicated WMA reduced fumes based on area samplers. In general, personal samplers worn by workers indicated lower exposure, but it was difficult to quantify improvements since most measurements for BSM were below detectable limits.

### TABLE 10
Comparison of total organic matter data (TOM) from NCHRP 9-47A sites (Kriech et al. 2011)

<table>
<thead>
<tr>
<th>Mix</th>
<th>Avg. Laydown Temp., °F</th>
<th>Avg. Laydown TOM mg/m³</th>
<th>Max. TOM mg/m³</th>
<th>Min. TOM mg/m³</th>
<th>Standard Deviation, mg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Indiana</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HMA</td>
<td>259</td>
<td>0.32</td>
<td>0.53</td>
<td>0.17</td>
<td>0.14</td>
</tr>
<tr>
<td>WMA A</td>
<td>237</td>
<td>0.12</td>
<td>0.25</td>
<td>0.05</td>
<td>0.07</td>
</tr>
<tr>
<td>WMA B</td>
<td>232</td>
<td>0.34</td>
<td>0.58</td>
<td>0.27</td>
<td>0.11</td>
</tr>
<tr>
<td>WMA C</td>
<td>241</td>
<td>0.15</td>
<td>0.30</td>
<td>0.04</td>
<td>0.09</td>
</tr>
<tr>
<td><strong>New York</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HMA</td>
<td>322</td>
<td>2.21</td>
<td>2.97</td>
<td>1.62</td>
<td>0.46</td>
</tr>
<tr>
<td>WMA D</td>
<td>223</td>
<td>1.17</td>
<td>1.78</td>
<td>0.58</td>
<td>0.37</td>
</tr>
<tr>
<td>WMA E</td>
<td>228</td>
<td>1.40</td>
<td>1.79</td>
<td>0.78</td>
<td>0.29</td>
</tr>
<tr>
<td>WMA F</td>
<td>243</td>
<td>1.48</td>
<td>2.14</td>
<td>1.33</td>
<td>0.24</td>
</tr>
</tbody>
</table>
NCHRP 9-47A collected extensive worker exposure data on multi-technology WMA projects with HMA control sections in New York and Indiana (Kriech et al. 2011). Four workers were recruited from each paving crew and monitored for four consecutive days. Positions included operator, screedman, raker, and laborer or foreman. Two samples were collected each day for each position, producing eight results per mix. All days excluded the use of diesel oil as a release/cleaning agent to focus assessment on asphalt emissions. Six WMA technologies were represented: BituTech PER, Cecabase RT, Evotherm DAT, SonneWarmix, Ultrafoam GX2, and wax. The temperatures immediately behind the screed of the HMA control mixes were markedly different between the two sites; Indiana HMA temperatures averaged 250 °F (121 °C) while New York HMA temperatures averaged 322 °F (161 °C).

This study used a more discriminative procedure, developed by Heritage Research Group, which measures total organic matter, or TOM (Kriech et al. 2002). The total organic matter data is summarized in Table 10. WMA resulted in a minimum of a 33 percent reduction in TOM compared to HMA with the exception of one WMA technology. Individual reductions ranged up to 60.9 percent. The average TOM data from the Indiana site and from previous studies (Kriech 2002) were lower than those measured for the New York HMA. HMA temperatures were higher in New York and TOM concentrations were seven times higher. Thermal gravimetric analyses were conducted to compare the base binder from Indiana and New York. The analyses indicated that the New York binder was more volatile, resulting in higher TOM concentrations.
Best practices for mix design, production, and placement of WMA are not very different from those that have long been advocated for HMA. While the recommendations in this chapter are intended to address specific concerns related to the design and production of WMA, they can also be utilized at HMA plants and by contractors who will be producing both WMA and HMA. Best practices for the production of WMA, such as minimizing stockpile moisture, tuning burners, good plant maintenance, and generous use of insulation, also generate cost savings for HMA production. Implementing the following best practices will result in energy savings, reduced emissions, and improved productivity whether they are used with WMA or HMA. There is no one best practice to address every situation. Instead, a variety of practices are offered for the user to consider. Other resources to consider include NAPA’s publication 101 Ideas to Reduce Costs and Enhance Revenue (order number QIP-127) and Energy Conservation in Hot-Mix Asphalt Production (order number QIP-126). Best Management Practices to Minimize Emissions During HMA Construction (EC-101), and The Fundamentals of the Operation and Maintenance of the Exhaust Gas System in a Hot Mix Asphalt Facility (IS-52).

Mix Design

NCHRP 9-43 developed mix design practices for WMA (Bonaquist 2011). Recommendations for WMA design differ from HMA in the following key areas:

- Selection of WMA technology,
- Determination of mixing and compaction temperatures,
- Maximum stiffness for aged RAP binder based on compaction temperature,
- Sample preparation, and
- Evaluation of rutting resistance.

The recommendations are presented in the Draft Appendix to AASHTO R35, Special Mixture Design Considerations and Methods for Warm Mix Asphalt (Bonaquist 2011) and briefly summarized below.

Selection of WMA technologies is a major focus of this publication. Some of the factors which should be considered include: cost; performance history/data; desired production and placement temperature, including factors such as expected ambient temperatures and haul time; expected tonnage of WMA to be produced now and in the future; and necessary plant modifications. New technologies continue to be introduced. Some agencies maintain formal lists of approved WMA technologies.

For HMA mixes using unmodified binder, equivalent mixing and compaction temperatures are determined using the rotational viscometer. Numerous research studies indicate that viscosity reduction does not explain the majority of WMA behavior. The Draft Appendix to AASHTO R35 recommends that mixing temperatures be determined based on coating. The selected or minimum mixing temperature should provide greater than 95 percent coating when tested according to AASHTO T195, the Ross Count procedure long used for determining wet-mix cycle times for batch plants.

The proposed compaction temperature is evaluated using the gyratory compactor. Research indicates that the number of gyrations to 92 percent theoretical maximum density (G_{mm}) was related to field compactability (Leiva and West, 2008). In the Draft Appendix to R36, duplicate samples are compacted at the proposed compaction temperature and 54 °F (30 °C) below the proposed compaction temperature. Using the recorded height data, the number of gyrations to 92 percent G_{mm} are determined for each sample. The ratio of the number of \( \left( \frac{N_{g2}}{N_{g2}} \right)_{T-30}/\left( \frac{N_{g2}}{N_{g2}} \right)_{T} \) should be less than or equal to 1.25. The gyratory compactor does seem to be sensitive to reductions in temperature at the low numbers of gyrations used in this evaluation.

Experiments conducted as part of NCHRP 9-43 indicate that blending does occur between virgin and aged RAP binder as long as the compaction temperature of the WMA exceeds the as-recovered high-temperature grade of the RAP binder. Therefore, for RAP having a recovered binder grade of PG 82-XX, the minimum compaction temperature of the WMA...
would be 180 °F (82 °C). Lower production temperatures utilized with WMA slightly reduce the aging of the virgin binder. The Draft Appendix for AASHTO R35 includes a table of improvements to the low-temperature continuous grade of the virgin binder which can be used when determining allowable RAP percentages based on blending charts. Although the reduction in aging/improvement in the continuous low-temperature grade appears small, the NCHRP 9-43 team estimates that improving the low-temperature properties of the virgin binder by 0.6 °C will allow 10 percent additional RAP binder to be added to the mixture.

The Draft Appendix for AASHTO R35 provides laboratory specimen fabrication procedures for four categories of WMA: 1) additives added to the binder, 2) additives added to the mixture, 3) wet aggregate mixtures, and 4) foamed asphalt mixtures. Low shear blending is used to introduce additives into the binder. Sampless for laboratory evaluation may be provided pre-mixed by the supplier or readily prepared in the lab (the author often uses a drill fitted with a piece of bent coat hanger). Mixture additives are introduced on top of the binder poured in a crater in the aggregate in the mixing bowl. Many additives can be introduced by both methods, depending on planned production as discussed in Chapter 2. Low Emission Asphalt (LEA) is the primary wet-aggregate mixture process used in the United States.

Unlike the other WMA technologies, foamed asphalt requires specialized equipment for laboratory production. Currently, there are at least three manufacturers producing laboratory foaming devices: D&H Equipment’s Hydro-Foamer, Pavement Technology’s The Foamer, and Wirtgen’s WLB 10 S laboratory-scale foamed bitumen plant. The WLB 10 S replaces Wirtgen’s older model foamer, which was primarily designed for full-depth reclamation and stabilization with foamed asphalt. The new model allows better control of the water flow to simulate WMA processes. Both The Foamer and the Hydro-Foamer were specifically designed to produce foam for WMA. The Foamer includes an innovative system for holding the liquid asphalt to minimize clean up.

While it may be difficult to simulate field-produced foamed mixtures in the laboratory without a laboratory foaming device, Sabita, the South African Bitumen Association, offers contractors an alternative in their Best Practice Guideline & Specification for Warm Mix Asphalt. Sabita recommends producing foamed asphalt mixtures through the plant to finish the design at the estimated optimum asphalt content and the estimated optimum ±0.3 percent.

The Draft Appendix for AASHTO R35 recommends the use of a planetary (bread) mixer for preparation of WMA. Samples are to be mixed for 90 seconds. WMA mix verifications performed as part of NCHRP 9-47A have successfully used a less expensive bucket mixer. The 90-second mixing time appears to be excessive in most cases but may aid in the distribution of aged RAP binder.

**FIGURE 44 a, b**
Wirtgen WLB 10 S (left) and Pavement Technology’s The Foamer (right)
The final difference between WMA and HMA designs is the requirement for rut testing for mixtures designed for over 3 million equivalent single-axle loads. The Draft Appendix for AASHTO R35 recommends the Flow Number Test be performed during WMA designs according to AASHTO TP 79. Gyratory samples are prepared at 7.0 ± 1.0 percent air voids according to AASHTO PP 60. Prepared samples 100 mm in diameter by 150 mm tall are tested unconfined, using a repeated load deviatoric stress of 600 kPa (87 psi) with a 30 kPa (4 psi) contact stress. Samples are tested at the 50 percent reliability temperature determined for the project site according to LTPP Bind Version 3.1. The proposed minimum flow numbers range from 30 for 3 to 10 million ESALs, 105 for 10 to 30 million ESALs, and 415 for over 30 million ESALs. Other rutting tests such as the asphalt pavement analyzer or Hamburg tests may also be appropriate, but minimum test criteria have not been developed.

Maintaining Adequate Baghouse Temperatures

One of the biggest challenges in the production of WMA may be keeping baghouse temperatures high enough to prevent condensation. Condensation causes two problems: corrosion of the baghouse and the formation of “mud” (damp baghouse fines). In well-maintained baghouses, inlet temperatures should be above 220 °F (104 °C) for low-sulfur fuels and 240 °F to 250 °F (116 °C to 121 °C) for high-sulfur fuels, such as reclaimed oils. High-sulfur fuels produce acidic gases that attack steel if they condense on cooler surfaces such as baghouse tube sheets. Low baghouse temperatures are less likely with parallel-flow plants than with more efficient counter-flow plants. Typically, exhaust gases for parallel-flow drum plants range between 20 °F (11 °C) cooler and 50 °F (28 °C) hotter than mix discharge temperatures. Thus, WMA could be produced without concern at 260 °F (127 °C) with high-sulfur fuels and down to 240 °F (116 °C) with low-sulfur fuels. Cooler exhaust temperatures on parallel-flow plants do not necessarily indicate a more efficient dryer. To the contrary, it means that air leakage at the discharge breech is cooling the exhaust gas even more.

Young (2007) provides several best practices for minimizing condensation in the baghouse and preventing damage from corrosion when running at normal HMA production temperatures. These best practices are even more important when running WMA on a regular basis.

- Seal air leaks, particularly the seals on the baghouse doors and around dryer breeching. Air leaks cause two problems: first, cooler ambient air can reduce the overall temperature of the exhaust stream, leading to condensation; second, air leaks waste fan capacity, thereby lowering the maximum production rate.
- Preheat the baghouse for 15 to 20 minutes to heat the steel housing completely.
- Inspect the fines return lines more frequently to ensure that no buildup due to moisture occurs. Typically, fines at lower temperatures are more susceptible to moisture, affecting flow back into the mix.
- Condensation may only occur in a limited portion of the baghouse, such as the windward side. In this case, a periodic painting of the interior surfaces with epoxy-based paint will minimize damage from corrosion.

The minimum exhaust temperature necessary to avoid problems with condensation and returning baghouse fines will vary from plant to plant and from mix to mix. Cold weather and high aggregate moisture can be a dangerous combination when it comes to condensation and dust problems. Tight, well-maintained plants can be more sensitive to condensation due to higher moisture concentrations in the exhaust gas.

FIGURE 44 c
D&H Equipment Hydro-Foamer
The following are several strategies suitable for increasing baghouse temperatures. Some are quick to implement while others are inexpensive. Some options require equipment upgrades that offer more benefits than simply raising stack temperatures.

**Remove Veiling Flights**

The most common practice to increase exhaust gas temperature is to remove flights. Removing flights reduces the dryer’s efficiency, and transfers less heat into the aggregate, resulting in higher gas temperatures. Taken to the extreme, this may result in incomplete drying; so remove only a few flights at a time. Since changes to flighting are time-consuming, it is not a viable strategy for tuning the plant every time mix and production rates change. If a contractor will be regularly producing both WMA and HMA, especially with varying percentages of RAP, one of the following strategies may prove to be more versatile.

**Increase Air Flow**

A much quicker fix to increasing the baghouse temperature (on a short-term basis) is to open the exhaust damper. This increases air velocity through the dryer and reduces dryer efficiency since the air has less time to transfer its heat to the aggregate. Many operators find this practice counterintuitive, since opening the damper cools the baghouse when preheating the plant. During preheating, that extra air flow is a much higher percentage of the total air and cools the air stream. However, during production it stills cools the air a little but speeds it up too. The combination is enough to slow down the heat transfer to the aggregate and raise exhaust temperatures.

**Duct Heaters**

While this method has high initial costs due to the added burner, fuel piping, and controls, it gives operators total control over their stack temperatures. The principle of operation is simple: Put as many flights in the dryer as possible to get exhaust temperatures as low as possible, then turn on the duct heater to maintain minimum baghouse temperatures at any production rate, mix temperature, or RAP percentage. While the duct heater burns fuel in addition to the main burner, the combined fuel use is less, due to reducing heat loss up the stack (Figure 45).

A contractor in the Netherlands produces WMA in a batch plant with a discharge temperature of 194 °F (90 °C). The company added a duct heater on the baghouse inlet duct to increase gas temperature independently of the mix temperature and reduced fuel use 40 percent with virgin mixes and 30 percent with recycled mixes compared to hot mix produced without a duct heater (D’Angelo et al. 2007).

**Install Variable Frequency Drive (VFD) on Drum Drive or Slinger**

Another option that gives operators the ability to control baghouse temperature independently from mix temperature is the installation of VFDs on drum drive motors and slinger feeds. Each effectively adds or removes flights as the motor speed changes. For drum drives, increasing rotational speed from 8 rpm to 9 rpm is roughly equivalent to adding three flights in every zone of the dryer. Slowing it down from 8 rpm to 7 rpm produces the same increase in baghouse temperature as taking out three flights in every zone. The slower the dryer turns, the less time aggregate spends falling through the hot gases (showering). This reduces heat transfer efficiency, since less heat is transferred from the hot gases to the aggregate. The hotter gases exiting the drum increase the baghouse temperature.

Variable speed slinger belts are not new. Along with indexing slingers, they have long been an option on...
many new plants. For slingers, the relationship between speed and gas temperature is opposite that for dryer speed. A faster slinger propels aggregate deep into the dryer, skipping over the top of veiling flights and raising gas temperatures. A slower slinger dumps aggregate into those same flights and reduces gas temperature. The cost in labor and lost productivity to clean a muddy baghouse hopper can pay for a slinger or VFD, avoiding the problem completely.

**Insulate Baghouse and Ductwork**

It is not typical for the entire baghouse to have a condensation problem when stack temperatures are borderline cool; rather, condensation almost always forms in the end of the baghouse farthest from the inlet duct. That end is coolest due to the cumulative effect of heat loss in the baghouse itself. Insulating the baghouse minimizes that heat loss and allows operators to put that heat into the aggregate by increasing the aggregate veil rather than allowing it to escape into the atmosphere.

The asphalt industry has moved away from insulating baghouses due to the initial cost and concerns with corrosion caused by moisture trapped between the insulation and the baghouse steel. One plant manager solved both problems by insulating the baghouse with rigid foil-faced foam panels purchased at the local home improvement center. Since the panels are open around the entire perimeter, they drain freely and corrosion has not been a problem (Figure 46).

**FIGURE 46**
Insulation panels on baghouse

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**Drying Aggregate**

Complete drying of the surface moisture of the virgin aggregate has been shown to occur with aggregate bed temperatures as low as approximately 180 °F (82 °C) (Brock no date). 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.

There are several good indicators of incomplete aggregate drying. The most sensitive indicator is a temperature differential greater than 20 °F (11 °C) between the dryer discharge and the truck after the plant has heated to mix temperatures. Water dripping from silos or excessive amounts of steam rising from drag conveyors and silo vents are readily observable indications that moisture is present in the mix. Finally, the moisture content of the mix can be determined by measuring weight loss after heating a loose sample of mix at compaction temperatures for two hours as described in AASHTO T329. That loss should be less than approximately 0.5 percent of the total mix weight for low-absorption aggregates.

**Increase Aggregate Retention Time**

Reducing drum slope, installing dams between zones of veiling flights, and installing flights that retard the flow of aggregate through the drum serve to increase aggregate retention time. This allows more time to drive off internal moisture before discharge. Increasing retention time should have a minimal effect on production capacity, provided that the dryer drives are not near motor capacity. Increasing retention time is accomplished by increasing the depth of the aggregate bed in the dryer and therefore increases motor load required to spin the dryer. Careful consideration of unintended consequences needs to be given before increasing aggregate retention time. The additional aggregate in the drum also increases the veil of aggregate and increases heat transfer efficiency. This will reduce exit gas temperatures, which may exacerbate baghouse condensation problems with WMA.
Insulate Dryer Shell

In the 1950s, the Barber-Greene Company did a study of aggregate dryers to understand how they worked. While it seemed to be a simple process — which could informally be described as dropping aggregate enough times through really hot air so that the aggregate heats as the air cools — they were surprised by the finer details of the process. They found that the fine aggregate gets hot as it veils through the hot gases, since it has a high surface area for its weight (specific surface). Coarse aggregate, on the other hand, is harder to heat and gets hot while lying in the bottom of the dryer next to the hot fine aggregate. This is why large stone mixes without any fine aggregate in the feed are hard to heat.

Since stone is heated in the bottom of the dryer, keeping the dryer shell hot with thermal insulation will improve aggregate heating and drying. Insulating a 40' x 9' diameter dryer can save up to 30,000 gallons of fuel per year, based on a dryer that operates 1,500 hours per year on fuel oil. (Here, savings are a function of time spent in production, not tons produced.) As noted in Chapter 3, an average of 41 percent of the fuel saving attributed to WMA resulted from reductions in casing losses. Some operators are concerned that dryer insulation can cause corrosion and increase stress in tire supports, resulting in premature dryer failures especially when running high percentages of RAP. The key to a successful insulation retrofit is to first evaluate the tire support design, shell construction, and, most importantly, the adequacy of the combustion flights to keep shell temperatures below 600 °F (316 °C). A dryer shell that operates at 900 °F (482 °C) without insulation will not last long with insulation!

Install VFD on Drum Drive

As discussed above, VFD drives give operators the ability to control gas temperatures independent of mix temperatures. Increasing drum speed also serves to increase aggregate retention time, since aggregate spends more time in flights waiting to be dumped back down to the dryer bed. This option alone facilitates gas temperature optimization, aggregate retention time, and motor load with a single technology. That does not mean all three objectives — gas temperature, aggregate moisture content, and motor load — can be optimized simultaneously, but rarely is it the case that all three are problematic.

Reduce Stockpile Moisture Content

Aggregate must be dry prior to coating with asphalt cement (AC) to reduce the potential for moisture damage in the mat. Many producers are concerned that reduced WMA temperatures may not allow for complete drying, especially with highly absorptive stone. If residual moisture is a concern, options include reducing stockpile moisture or modifying dryer...
operations. Reducing the moisture content of aggregate stockpiles provides multiple benefits. It takes a surprisingly large amount of energy to turn water into steam. It also takes a lot of air to burn the extra fuel. On average, reducing aggregate moisture 1 percent results in a 10 percent fuel saving and a 10 percent increase in production capacity. If a plant produces 200,000 tons per year and the drying cost is $4 per ton, reducing stockpile moisture by just 1 percent over the year will yield fuel savings of $80,000 per year.

One method of reducing stockpile moisture content is to cover stockpiles with portable or permanent structures. Several U.S. contractors, such as the Walker Company in Kentucky, have adopted this practice (Figure 47). When fine aggregate is quite dry, covering conveyors to minimize blowing dust and to keep material dry when it rains (Figure 48) is also an option.

In addition to covering stockpiles, there are three other options to reduce stockpile moisture: 1) Grade the stockpile area with a minimum 3 percent slope away from the plant, 2) Use air-classified (dry dusted) manufactured sand, and 3) Process RAP and RAS in small batches as needed for production.

1. **Grading stockpiles**

   The capillary strength of water is so great that it can climb three feet up from the bottom of an aggregate stockpile. That is why it is important to make sure loader operators keep the bucket three feet above the bottom of the pile, especially after a rain. Grading the stockpile area allows water to drain out the low side of the stockpile and away from the plant (Figure 49). Sloping the stockpile away from the plant is helpful, since loader operators will tend to feed the plant from the face closest to the hopper. Not every yard can be re-graded to drain away from the plant. If a yard is in a depression rather than on a hill, RAP and fine aggregate piles should be placed on the higher ground and coarse aggregate in the lower areas (Figure 50).
The reported reduction in aggregate moisture following re-grading stockpile areas varies. Granite Construction Co. reported a 4 percent decrease in fine aggregate moisture contents (from 10 to 6 percent) at one site. The drier sand, which made up 35 percent of the subject mix, resulted in a fuel saving of 9.2 percent (Prowell and West 2005). Astec Industries Inc. reports that a North Carolina plant realized a 2.3 percent decrease in average moisture content following the regrading of a stockpile area (Simmons no date).

2. Using air classifiers
Many producers are now using air classifiers to remove excess minus 200 fines from manufactured sand rather than a wet wash. An air classifier uses moving air, sometimes supplemented with inertial or centrifugal forces and direction change, to remove dust particles from crushed sand. The stripped fines can be sold for pipe bedding or stockpiled for use as mineral filler in SMA (stone-matrix asphalt) projects. Switching from washed sand to dry de-dusted sand produced using an air classifier decreased Tilcon New Jersey Inc.’s combined aggregate moisture by 2 percent and lowered drying costs 0.04 therms per ton. A therm is 100,000 BTU, or approximately the energy equivalent of burning 100 cubic feet of natural gas.

3. Processing RAP and RAS in small batches
When RAP or RAS contains too much moisture, it bridges in the cold feed bin, builds up in the RAP collar, and holds back production. With WMA there is the added concern that wet RAP will not dry fast enough to distribute the recycled binder uniformly through the mix. Karlsson and Isacsson (2006) report that incomplete mixing of virgin and RAP binders results in a soft mix, prone to over-compaction and deformation. When New York City DOT constructed an NCHRP 9-47A WMA demonstration with a mixture containing Superpave 20 percent RAP. The superheated aggregate was 100 °F (56 °C) cooler with WMA than with the HMA for the same mix. Lower superheated aggregate temperatures are more likely to lead to incomplete drying of the RAP and incomplete distribution of the aged binder. An indication of incomplete drying of the RAP prior to AC injection is water dripping from storage silos; this indicates that RAP did not dry sufficiently before AC injection. Also, if low laboratory-compacted air voids occur, dryer RAP may be the remedy.
The best way to get dry RAP is to crush it. Most producers and agencies prefer to build a large stock-
pile of processed RAP with known, tested properties. However, when those piles get rained on, they tend to hold moisture. Stockpiled RAP tends to have moisture content of 2 to 3 percent higher than freshly crushed RAP. If RAP cannot be processed on an as-needed basis, then covering the RAP stockpiles may be an attractive solution. New York City DOT keeps RAP under a shelter (Figure 51). This allows them to produce mixes with 40 percent RAP at their Queens’ batch plant in any weather. New York City DOT estimates that using dry RAP saves $0.16 per ton in heating cost and using 40 percent recycle content saves $20 per ton as compared to all-virgin mix.

Burner Performance

Most burners have one modulating actuator motor with mechanical linkage driving dampers and fuel valves. These burners have served the industry well for many years. They are relatively simple, easy to repair, and reliable. The challenge with a mechanical linkage is making sure that the air to fuel ratio is optimal through the full firing range. Some contractors have reported difficulties adjusting burners to sufficiently low levels to reach the desired production temperatures for WMA. This has generally been exacerbated when the plant runs at a very slow production rate for a small WMA trial. At normal production rates, most burners should be able to produce the lower temperatures required for WMA. In any case, a contractor should have an experienced burner technician available when attempting their first WMA trial to inspect the burner and aid with adjustments.

One symptom of improper burner adjustment and maintenance is unburned fuel. Adding raw fuel is not just expensive and potentially explosive, liquid fuels can also contaminate the mix, leading to a binder which is less stiff than desired. The potential for mix damage from uncombusted fuel is probably greater for WMA than for HMA, because unburned fuel is more likely to vaporize at HMA temperatures. Uncombusted fuel was observed in at least two WMA trials to date, and suspected in another. WMA contaminated with fuel oil 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) and total hydrocarbons (THC) than for the control mix, another indication of uncombusted fuel.

There can be a number of causes for uncombusted fuel with both WMA and HMA. Clogged burner nozzles and fuel filters are always a good place to start looking. When burning heavy or reclaimed oil, maintaining preheater temperatures and accelerated pump wear are frequent problem areas.

Sometimes the solution can be as simple as lowering the fuel pressure. In one case where the fuel pressure was too high, the burner only added enough air to burn 70 percent of the natural gas. The remainder went up the stack, unburned, for several years. The problem was finally fixed when the plant decided to try WMA and brought in a burner technician. In this case, drying costs when producing HMA dropped from 0.34 therms per ton to 0.23 therms per ton by lowering the fuel pressure. An additional drop from 0.23 therms per ton to 0.21 therms per ton was realized when producing WMA.

RAP and RAS Recycling

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. For a discharge temperature of 220 °F (104 °C), the virgin aggregate must be superheated to a temperature of 280 °F (138 °C) for a batch plant running a mixture with 10 percent RAP with a moisture content of 3 percent (Young 2007). Superheating the virgin aggregate will increase the likelihood that the internal moisture in the virgin aggregate is removed. Superheating the virgin aggregate will also increase the temperature of the exhaust gases going to the baghouse. Thus the addition of a small amount of RAP helps to satisfy both needs.

On the performance side, one benefit of WMA is the reduced aging of the fresh binder. This has the potential to improve long-term low-temperature cracking resistance of the blended virgin and RAP binders. 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 rutting susceptibility early in the life of a project. Although rutting has not been observed in any of the WMA projects to date, the inclusion of a small amount of RAP would tend to increase the composite binder stiffness, counteracting this effect. Thus the addition of RAP to WMA mixes is a win-win situation.
In order for RAP and RAS to make their intended contribution to the mechanical properties of recycle mixes, their aged binders must be dispersed through the fresh aggregate. This sharing of aged binder with fresh aggregate requires that the recycled products be dried, heated and mechanically mixed, ideally before being coated with fresh AC. Several producers have had problems accomplishing this with existing dryers due to the limited time the two products share together between the RAP collar and the AC injection point. This is particularly problematic with RAS and counterflow drum plants with late-entry RAP collars.

In batch plant recycling, the steam explosion in the pug mill does not occur until after AC is added. Some steam is created as soon as the superheated aggregate is mixed with the cold damp RAP, but at a considerably slower rate than when liquid AC acts as a heat transfer medium, making intimate contact with the damp RAP particles. Comparing this to drum plants, we cannot assume that the few feet of dryer dedicated to dry-mixing superheated aggregate with recycled materials is sufficient to completely disperse the recycled binder.

One recommended solution to improve RAP dispersion and drying is to convert late-entry RAP collars to early-entry by shortening the burner tube and AC injection pipe (if allowed by the plant design). Early-entry designs flash-dry damp recycled material by taking advantage of the intense radiant energy of the flame. The thermal mass of the stone and sand protect the aged binder from significant hardening during its brief time in front of the flame.

Placement Changes

From a placement standpoint, WMA best practices are much the same as for HMA. Several contractors have commented that equipment remains cleaner with less asphalt buildup when placing WMA. In a few instances, material flow issues have been observed at both asphalt plants and when dumping into transfer vehicles or pavers. Material flow issues were observed at one plant 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, but it did not move as readily. A slight increase in the production temperature resolved the problem. Similarly, WMA has been observed not to flow as well as HMA out of a truck and into a transfer vehicle or paver.

There has been one report that WMA affected the angle of attack of the paver screed. However, the WMA in this case was warmer than would typically be recommended for WMA. Initially, it was believed that WMA eliminated thermal segregation. Although uniformity appears to be generally improved, additional testing indicates thermal segregation can still occur. Hand work can be difficult at reduced temperatures, particularly in the urban environment where more hand work is required for manholes, grates, valves, and so forth.

Compaction

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 non-destructive device, calibrated to cores, to ensure that adequate density is consistently being achieved.
Summary of Experience and Future Research Needs

Significant progress has been made in evaluating and implementing WMA. A number of National Cooperative Highway Research Projects (NCHRP) were developed and initiated through the efforts of the WMA Technical Working Group and others (Table 11). Additional projects are under consideration for funding. The results to date are very positive. Contractors continue to find new benefits from the use of WMA. Agencies have cooperated with industry to create opportunities for demonstration projects and to develop specifications. Although much progress has been made since the first edition of this publication, there still remain a number of areas where additional evaluation, development, and research are required. Efforts are under way or have been initiated in all of these areas. Further consideration is required in such areas as

- Mix design
- Guidance for selection of production temperatures
- Long-term performance
- New-product approval
- Quantification of benefits
- RAP and WMA

### TABLE 11

<table>
<thead>
<tr>
<th>Project</th>
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<td>9-43</td>
<td>Mix Design Practices for Warm Mix Asphalt</td>
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<td>Properties and Performance of Warm Mix Asphalt Technologies</td>
<td>January 2013</td>
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<td>9-49</td>
<td>Performance of WMA Technologies: Stage I — Moisture Susceptibility</td>
<td>January 2013</td>
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<td>9-49A</td>
<td>Performance of WMA Technologies: Stage II — Long-Term Field Performance</td>
<td>July 2016</td>
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<tr>
<td>9-53</td>
<td>Properties of Foamed Asphalt for Warm Mix Asphalt Applications</td>
<td>Pending – Expected 2014</td>
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that changing optimum binder content, even slightly, may alter the performance of WMA in the field. Mix verifications are being performed using the NCHRP 9-43 procedure as part of NHRP 9-47A.

PG (performance graded) 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. Initially, there was concern that this could result in increased rutting susceptibility. However, field performance of pavements constructed to date, including at accelerated loading facilities such as the National Center for Asphalt Technology Test Track and the Caltrans heavy vehicles simulator, has indicated a high level of resistance to rutting. The same is true of projects on heavily trafficked roadways, such as I-70 in Colorado. As noted in Chapter 4, for design traffic levels in excess of 3 million ESALs (equivalent single axle loads), the flow number (FN) test, a repeated load deformation test, is recommended for WMA design, but not required for HMA.

Research is needed to determine whether laboratory foaming processes simulate field-produced mix. Additional research is required to verify the proper degree of laboratory aging for WMA. Laboratory aging affects the results of performance tests on the resulting samples. The criteria for laboratory performance tests, especially those for moisture damage and rutting, need to be verified. NCHRP 9-53 and NCHRP 9-52 should help to address these needs.

**Guidance for Selection of Production Temperatures**

WMA can be used to reduce production temperatures. WMA can be used to improve compaction in cold-weather paving and long hauls. WMA can be used to improve compaction with high percentages of RAP.

WMA may not, however, be able to do all of these things at once. Technology providers may suggest maximum temperature reduction in order to maximize fuel savings. Agencies may also set maximum temperatures for mixtures to be deemed WMA and reject mixes at higher temperatures. However, when dealing with adverse paving conditions, e.g. cold weather, long hauls, high RAP, or all of the above, the wise contractor will gradually reduce temperatures. Research indicates that even small reductions in production temperature provides environmental benefits (Lange and Stroup-Gardiner, 2007).

Conversely, production temperatures that are too high may cause WMA to be tender under the roller. Guidance needs to be developed to help contractors select realistic production and compaction temperatures for WMA.

**Long-term Performance**

To realize long-term reductions in emissions and fuel usage, the performance of WMA needs to be as good as HMA. Thus arises the need to document long-term performance. The first pavements incorporating WMA additives were constructed in Europe in 1997; the oldest true WMA pavements were constructed in 1999. The first WMA sections in the U.S. were constructed in 2004. Figure 52 shows Highway 115 in Charlotte, NC, 26 months after construction.

In 2007, the U.S. WMA Scan Team collected laboratory and short-term field performance data from some of the oldest WMA pavements in Europe. 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 (D’Angelo et al. 2007)

The two most prevalent early concerns regarding the long-term performance of WMA were increased potential for rutting and moisture damage. A number of projects have been constructed in areas exposed to heavy traffic. Evotherm ET was used on two sections of the NCAT Test Track in 2005 (Evotherm was also used for two lower lifts of a third section). After 515,333 ESALs applied in a 43-day period (occurring at the end of the trafficking period for the remainder of the track), the average rut depth for the two Evotherm sections was 0.035 in. (0.9 mm) while the HMA control section, constructed at the same time, averaged 0.043 in. (1.1 mm) (Prowell et al. 2007). One of these Evotherm sections (E10) remained in place for both the 2006 and 2009 Test Track Cycles. After an additional 20 million ESALs, the rut depth is less than 0.197 in. (5 mm) with only one transverse crack (NCAT 2011).

In 2007, Caltrans initiated WMA testing with their heavy vehicle simulator at the University of California Pavement Research Center. Three WMA technolo-
gies, Advera WMA, Evotherm DAT, and Sasobit, were included in the study as well as an HMA control. Based on the test results, WMA can provide similar rutting performance as HMA (Jones 2009).

Figure 53 shows Hall Street in St. Louis, Missouri, a heavy industrial area, 66 months after construction. The project was constructed in 2006. This pavement had been heavily crack-sealed, resulting in reflective cracking when an HMA overlay was initially placed. In the 2006 project was completed with three WMA technologies, Aspha-min, Evotherm, and Sasobit. In 2011, when the authors last visited, the WMA sections were still in good condition. Missouri DOT reported that the majority of the reflective cracks visible in the WMA sections did not propagate through the 2-inch overlay until the winter of 2010-2011, whereas portions of the HMA control section cracked immediately over the underlying crack sealant. After 26 months of traffic, the maximum rutting observed was 1.1 mm (Hurley et al. 2010); after 66 months it was 4.0 mm.

Based on the performance of these various sections, the rutting performance of WMA has been observed to be good. As noted previously, some of the WMA additives actually increase the binder stiffness at in-service pavement temperatures and therefore enhance resistance to rutting.

There has been a concern that the aggregates in WMA mixes may not be completely dry due to the 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. Testing conducted to date indicates that the aggregates in WMA are acceptably dry.

Laboratory tensile strength ratio (TSR) tests have, in some cases, indicated lower TSR values as com-
pared 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 to look for visual evidence of stripping. The tensile strength of the roadway cores has increased with age, as expected. An exception was noted for one technology on the Hall Street project in St. Louis (Hurley et al. 2010). Visual evidence of stripping has not been observed in any of the projects tested to date. Some raveling has been noted on the Ohio WMA Open House project constructed on SR 541 in 2006 (Hurley et al. 2009).

Continued monitoring of WMA projects is required to verify long-term performance. The data collection guidelines, presented at www.warmmixasphalt.com, are an important step in gathering this information. NCHRP Project 9-47A, Engineering Properties, Emissions and Field Performance of Warm Mix Asphalt Technologies, and NCHRP Project 9-49A, Performance of Warm Mix Technologies: Stage II—Long-Term Field Performance will assist in this effort. Verification of the long-term performance of WMA is important for two reasons. First, if the performance of WMA were found to be inferior to HMA (which seems unlikely), then the potential environmental benefits, such as reduced emissions, could be lost due to a
more frequent paving cycle. Second, if long-term performance is improved, for instance by reduced cracking, then additional costs for WMA may be more readily justified.

**New-product Approval**

A development that would be helpful to the future success of WMA is a product-approval system on a national or at least regional basis. While additional competition may help to reduce costs, it is important that the various technologies provide performance which is as good as or better than HMA.

A key element of new-product evaluations, be they for WMA or other asphalt modifiers or mix innovations, is the development and acceptance of laboratory performance tests with realistic criteria. Tests for rutting resistance, moisture damage susceptibility, and cracking potential are required. Rutting resistance is often the primary concern of agencies. The performance tests do not have to be perfect predictors of performance, capable of predicting rutting to the nearest 0.04 inch (1 mm) after a specific number of years. They do need to be able to identify the potential of an early or catastrophic failure.

As interest in WMA expanded over the three years between the first and second editions of this publication, at least 12 new technologies entered the U.S. market. In the past, 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. Product approval protocols should include both 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 U.S. WMA Scan Team recognized that two of the countries visited, France and Germany, had well-developed systems for evaluating new products (D’Angelo et al. 2007). 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.

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.

A number of state agencies have developed approval procedures; California, Colorado, New York, North Carolina, and Texas are examples. The Northeastern states, in conjunction with the Northeast Asphalt User Producer Group, have developed a warm-mix qualification process. Products are qualified by a host state in the region. Currently, there are seven approved WMA technologies. NCHRP Project 20-07, Task 311, Development of a Warm Mix Asphalt Technology Evaluation Program, is tasked with developing a framework for new-product approval for adoption by the National Transportation Product Evaluation Program.

**Quantification of Benefits**

WMA technologies may either increase or decrease costs. Factors determining cost increases include 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. As noted previously, there is evidence that WMA mixes may be more difficult, in some cases, to move in the plant, possibly increasing electrical use. Preliminary data from NCHRP 9-47A indicates slight increases in electrical consumption when producing WMA.

Some WMA technologies include anti-stripping agents. This may eliminate the need for adding additional anti-stripping agent to the mix, another opportunity for cost savings.

Reductions in emissions and improvements in working conditions are being quantified as part of NCHRP 9-47A.
The data collection guidelines presented at www.warmmixasphalt.com are designed to collect the necessary data to quantify the environmental benefits and long-term performance of WMA. Aside from the environmental benefits related to WMA, WMA technologies have the potential to provide valuable paving benefits to address problematic conditions, such as cold-weather paving. In these instances, the increased probability of success provided by WMA justifies the additional cost.

**RAP and WMA**

As discussed in Chapter 4, RAP has the potential to benefit WMA. In areas where RAP is in limited supply, adding a consistent, if minimal, amount of RAP to all WMA mixes can provide production benefits in terms of drying the virgin aggregate and increasing the baghouse temperature. A similar process was used by Kolo Veidekke, the Norwegian contractor who worked with Shell to develop WAM Foam, who routinely adds 7 to 8 percent RAP to all of their mixes.

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

- WMA improves the ability to compact mixes containing higher percentages of RAP.
- The reduced production temperatures used for WMA decreases the aging of the virgin binder. This slightly softer virgin binder improves the low-temperature properties of the blended binder.
- The use of RAP will require the virgin aggregate to be superheated. Superheating will help 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 superheated, will increase the temperature of exhaust gases introduced into the baghouse.

The combined benefits of WMA and RAP require further exploration and documentation. The interaction between WMA processes, production temperatures, RAP content, and their relationship to workability and compactability should be investigated. A number of field projects have been constructed using WMA and high percentages of RAP. These should be monitored to document rate of aging and long-term durability.

**Summary**

Warm-mix asphalt is a proven technology with the potential to revolutionize the production of asphalt mixtures. WMA first drew notice from hot-mix asphalt producers in the U.S. in 2002. By the end of 2011, 47 states had adopted specifications or contract language allowing WMA on projects and 20 states had set targets for future use of WMA. In 2010, the U.S. produced 47 million tons of WMA, up from 17 million tons in 2009. The response to these technologies among contractors and agencies is unprecedented. Why all of the interest? The answer probably lies in the fact that WMA can address such a wide variety of needs.

Potential paving benefits include lower production temperatures, reduced fuel consumption, the extension of the paving season in cold climates, longer haul distances, longer storage times, and enhanced compaction. There is the potential to increase the level of RAP that can be incorporated into mixes. The addition of RAP to WMA may benefit both processes; WMA improves compaction and results in less aging of the virgin binder and RAP will require superheating the virgin aggregates, improving drying and increasing baghouse temperatures.

On the environmental side, decreased production temperatures and reduced fuel consumption result in lower emissions at the plant and paving site. The decreased emissions include greenhouse gases, fugitive emissions, and fumes. In addition, working conditions at the plant and paving site are improved.

Significant research and evaluation has already been completed. Partnerships between agencies, industry, and academia, such as the WMA Technical Working Group, have accelerated this effort. Several research needs were identified and most of them are currently being addressed.


Udelhofen, G., “Park Road is Ideal Warm Mix Project.” Asphalt Contractor, March 10, 2009.


### APPROXIMATE CONVERSION TO SI UNITS

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**NOTE:** Volumes greater than 1000 L shall be shown in m³.

### APPROXIMATE CONVERSION FROM SI UNITS

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*SI is the symbol for the International System of Measurement.*

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