State Agencies' Status of Warm Mix Asphalt Technologies: A Review

Sofia M. Vidalis, Penn State University-Harrisburg, svidalis@psu.edu; Rajarajan Subramanian, Maryland Department of Transportation, RSubramanian@sha.state.md.us

Abstract

Warm Mix Asphalt technology has recently been on the rise among European countries and the United States. It is gaining popularity because it has multifold advantages over the conventional Hot Mix Asphalt. Warm Mix Asphalt is produced by mixing additives and using new technologies such as Warm Asphalt Mix Foam, Aspha-Min or Advera Zeolite, Low Energy Asphalt, Double Barrel Green, or Sasobit Wax to the asphalt mixture to reduce the viscosity and take the benefits of low temperatures at the production level, and the advantages of placement levels. Temperatures can be reduced by as much as 30%, which allows for lower CO_2 emissions and fumes, lower fuel consumption, effortless compaction on stiff mixes, better workability, long overhaul distances and a longer paving season for the asphalt mixture. However, the major driving force behind today's Warm Mix Asphalt technology is emissions reductions, especially in large metropolitan areas with tight air-quality restrictions.

Drastic reductions in mixing and placing temperatures have the obvious benefits of cutting fuel consumption and decreasing the production of greenhouse gases. This study evaluated the current practices in Warm Mix Asphalt technologies from State Highway Agencies through a review of the literature and a survey that was sent out to all State Highway Agencies. The questionnaire evaluated the advantages and disadvantages in using the Warm Mix Asphalt mixture over the conventional Hot Mix Asphalt or Cold Weather Paving and their current practices. The major findings in this study showed that the Warm Mix Asphalt is going to make the future asphalt roads of America.

Review of Warm-Mix Technologies

New asphalt pavement technologies have been looked at recently in the U.S. because of increasing highway congestion, decreasing availability of materials, increasing costs in the economy, increasing environmental awareness, and a maturing infrastructure. Congestion has been increasing every year. From 1980 to 1999, there was an increase in road miles by 1.5%, vehicle miles by 76%, and 482,000,000 hours of delays each year in the United States alone. This means that by the year 2020, the United States will see double that if new technologies are not adopted. As the cost of crude oil increases, so does the cost of asphalt binder and, hence, the costs associated with asphalt pavement. Asphalt pavement uses a waste product of oil refining, which peaked in price in the summer of 2008, around the time gasoline prices reached four dollars per gallon in the United States. Since the increase of asphalt prices, it is now closer to the cost of concrete, approximately a $20/ton (€14.72/metric ton) difference. Concrete is sometimes preferred over asphalt because of not having a big difference in price and the fact that it lasts twice as long [1].

Natural aggregates are widely distributed throughout the United States and occur in a variety of geologic environments; however, they are not universally available. Some areas lack quality aggregates, or existing aggregate deposits cannot be mined for a multitude of reasons such as pits or quarries that are located near populated cities. These residential communities usually require that mining of aggregates be conducted far from their boundaries. Thus, competing land-use plans, zoning requirements, and various regulations frequently prohibit extraction of aggregates near populated areas. However, the areas that have quality aggregates are going fast because of their demand. And as it goes, the higher the demand, the more costly the material. Because the demand for aggregates will continue to grow in the future, provisions to assure adequate supplies will have to be made. Therefore, the production of reclaimed asphalt pavement removed, and/or reprocessed pavement materials containing asphalt and aggregates, have been increasing in recent years. Replaced and reconstructed old roads have become major sources of "recyclable materials." In some applications, recycled aggregate can compete with natural aggregates on price and quality. The increasing limitations imposed on the use of landfills, as well as the higher costs imposed on their use, are making the recycling of aggregates economically viable. It also saves money, resources, and landfill space.

Increased public awareness of climate change and shifting political attitudes within the United States may lead to federal regulations on the emissions of greenhouse gases, such as carbon dioxide (CO_2). The transportation sector represents 27% of the total U.S. GHG emissions, with passenger cars and light-duty trucks accounting for 17% of the total. The production and placement of asphalt pavements consumes less fuel and produces lower levels of greenhouse gases compared to automobiles, according to a recent study. Asphalt pavements require about 20% less energy to produce and construct than other pavements. This means that less fuel consumption equals less production of carbon dioxide and other greenhouse gases. However, this does not mean that it does not emit any greenhouse gases. Even though it emits less gas, lowering the temperatures by 50ºF (27ºC) or more would save fuel and reduce the production of greenhouse gases and other emissions even further [2]. Total emissions from asphalt plants, including greenhouse gases and fumes, would be reduced by decreasing the temperature of asphalt production and placement. This technology and the reduction in fuel usage to produce the mix would have a significant impact on transportation construction projects in and around non-attainment areas such as large metropolitan areas that have air-quality restrictions.

Because of all these factors, recent research of new technologies has focused on Warm Mix Asphalt (WMA). Studies have shown that WMA processes can lower the temperatures at which the material is mixed and placed on the road by 50ºF to 100ºF (27ºC to 56ºC) compared to the conventional hot mix asphalt [2]. Such drastic reductions can cut fuel consumption, decrease the production of greenhouse gases, drastically reduce the production of emissions, and decrease the use of new aggregate materials being used. This paper evaluates the current practices in Warm Mix Asphalt technology through case studies done in Europe, South Africa, Asia, and the United States. A questionnaire was sent out to all State Highway Agencies to also evaluate their experiences using WMA and the type of technologies they found more useful. The advantages and disadvantages of using Warm Mix Asphalt instead of the conventional Hot Mix Asphalt or Cold Weather Paving was found through the State Highway Agencies' responses. There are many advantages and factors driving the development and implementation of WMA technologies globally. In order for WMA to succeed in the United States, WMA projects must have equal or better performance when compared to traditional HMA pavements in the U.S.

International and National Practices

Warm Mix Asphalt was first developed and used in Europe through four distinct technologies: Aspha-Min®, WAM Foam®, Sasobit® and Asphaltan B®. Aspha-Min®, also known as Zeolite, is a synthetic that is added at the plant at the same time as the binder during mixing. This binder decreases the viscosity of the binder and increases the workability of the mix. WAM Foam® is a two-component system that introduces a soft binder and hard foamed binder at different stages during plant production. Sasobit® and Asphaltan B® are organic-additive compounds such as small crystalline paraffin wax or low-molecular-weight-esterified wax. After the hype in Europe, WMA first came to the United States in 2002. It wasn't until 2004 that the first warm-mix section tests were built in the U.S. The Aspha-Min and Sasobit products have been used, as well as a fourth technology called Evotherm™. MeadWestvaco Asphalt Innovations, of Charleston, South Carolina, developed Evotherm, a non-proprietary technology, especially for WMA. This chemical package includes a dispersed asphalt (emulsion) technology that improves coating, workability and adhesion. No plant modifications were required for using Evotherm in the WMA. Improvements in the compactability of WMA mixes can facilitate an extension of the paving season and allow longer-haul distances. Welfare of workers was also considered, particularly with gussasphalt or mastic asphalt, which is produced at much higher temperatures than HMA [3].

Since 1997, over 142 projects were paved using Sasobit® totaling more than 2,716,254 square yards (2,271,499 m^2) of pavement. Projects were constructed in Austria, Belgium, China, Czech Republic, Denmark, France, Germany, Hungary, Italy, Macau, Malaysia, Netherlands, New Zealand, Norway, Russia, Slovenia, South Africa, Sweden, Switzerland, the United Kingdom, and the United States. The projects included a wide range of aggregate types and mix types, including: dense graded mixes, stone mastic asphalt and Gussaphalt. Sasobit® addition rates ranged from 0.8 to four percent by mass of binder [4].

The first Evotherm construction project was conducted in South Africa in November, 2003. A liquid additive system was designed to integrate with existing plant equipment and materials called Evotherm which produces quality asphalt pavements at temperatures up to 100°F (55°C) lower than conventional hot mix asphalt. Another benefit is that Evotherm requires no equipment changes at the plant or job-site. The Evotherm mixes use the same aggregates, volumetrics and binder content as conventional HMA. Through research studies, Evotherm performance on highways has been proven in over 100 projects in 19 states in the U.S., as well as France, Spain, Canada, South Africa, Mexico and China. Accelerated testing results at the United States National Center for Asphalt Technology's Pavement Test Track showed that Evotherm pavements can stand up to the equivalent of more than 10 years of heavy truck traffic, performing exceptionally well with virtually no deformation. Evotherm sections have endured over 8 million ESALs with less than 0.15 inches (3.4 mm) of rutting [5].

According to Dr. Heinrich Els of DAV (German Asphalt Pavement Association) Bonn, Germany, the low-temperature asphalt mixes, with an emphasis on the use of organic additives, are used. Several methods for bringing down the mix temperatures are being developed in Germany. They include a method for adding aggregates in sequence, a two-phase bitumen mixing method and adding both organic and mineral additives. The two types of organic additives are synthetic paraffin waxes and low-molecular-weight ester compounds. The paraffins are long-chained aliphatic hydrocarbons derived from coal gasification using the Fischer-Tropsch process. The ester additives consist mainly of esters from fat acids and wax alcohols and are produced by toluene extraction of brown coal. These additives increase viscosity and penetration of the bitumen at low temperatures. These additives have been researched in the lab and in the field for about five years. The performance goals for low-temperature mixes include having the same (or better) resistance to fatigue and deformation, and comparable workability at the paving site. Field experience with Stone Matrix Asphalt has shown that compaction can begin between 215°F and 250°F (102°C and 121°C) [6].

Max von Devivere of Eurovia Services GmbH in Bottrop, Germany, discussed using a synthetic Zeolite that Eurovia has trade-named Aspha-min. He said that, in Germany, asphalt mixes are typically produced between 302°F and 482°F (150°C and 250°). With Aspha-min, production and placement temperatures can be reduced dramatically, to between 266°F and 293°F (130°C and 145°C). Zeolites—crystalline hydrated aluminum silicates—release water at different rates. In tests conducted by Eurovia, lowering the mix production temperature by 55°F (29ºC) reduced energy consumption by about 30%. It also reduced the production of asphalt fume by 75%. Measurements at the paving site, where the material had cooled even further, showed a 90% reduction in fume. Significant reductions in odor were also documented, said von Devivere. At least eight test sections have been constructed, and no difference in performance has been seen. Eurovia expects to build a 50,000 ton (45,359 metric ton) test section on the German motorway this spring. Shell Global Solutions in Petit Couronne, France, and Kolo-Veidekke ASA in Oslo, Norway, teamed up for the use of the WAM-Foam process in Asphalt Road Construction. WAM-Foam is the product of a joint venture between Shell and Kolo-Veidekke, which began in 1995. European companies are required to keep "accounts" of their CO_2 emissions. In addition, "green purchases" are required—that is, at an equal price, the most environmentally friendly solution must be chosen [7].

In the U.S., there have been over 200 WMA projects and/or test sections of pavement. Almost all states are researching and experimenting with WMA. A questionnaire was sent out to all of the State Highway Agency's in the United States to find out their experiences in using WMA in their projects and the advantages and disadvantages they faced. Out of the 50 states only 20 responded, with the majority having some or a lot of experience with WMA. Alabama, California, Florida, Idaho, Indiana, Iowa, Maine, Ohio, Pennsylvania, Texas, Virginia, and Washington have already begun actively adopting warm mix into their asphalt specification provisions [8]. Other states that have been using WMA for three years or more are Ohio and New York. Tables 1 and 2 show all the State Highway Agency's that participated in the survey. Since construction practices with WMA are not greatly different from those for HMA, the questionnaire focused more on their experiences in using WMA, the technology used, benefits, drawbacks, and any cost associated with the adoption of WMA technologies. There are a lot of factors considered in WMA such as temperature, haul distance, weather conditions, fuel consumption, environment, emissions, additives, viscosity, thickness, strength, and compaction. One of the questions on the survey was to rank the importance, from one to three (three being most important), of each factor in regards to cost savings. The State Agencies that did not have enough experience with WMA replied "not available" (NA). Temperature, fuel consumption, and compaction were found to be the top three factors that play a major role in cost savings.

Table 1. State Agencies' Responses in Regards to WMA Cost Savings

State	(A)	(B)	(C)	(D)	(E)
AK	3	3	2	3	2
AZ	NA	NA	NA	NA	NA
CA	3	3	3	2	2
FL	2	2	2	3	3
GA	2	2	2	2	NA
IO	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA
KY	3	1	1	3	2
LA	2	2	2	2	2
MI	NA	NA	NA	NA	NA
MN	2	2	2	2	2
MO	3	3	3	3	1
NC	3	2	2	3	2
NY	Too many unknowns, variables, and interdependencies to fill in.				
OH	2	3	1	3	2
OR	2	2	2	2	2
PA	2	2	2.5	2.5	2
SD	NA	NA	NA	NA	NA
UT	2	2	2	2	2
VA	3	3	2	3	2
Ave.	2.43	2.29	2.04	2.54	2.00

A= Temperature, B= Haul Distance, C= Weather Conditions, D=Fuel Consumption, E=Environment
Ranking: 3 = Most Important, 2= Important, 1= Least Important

Table 2. State Agencies' Responses in Regards to WMA Cost Savings (Continued)

State	(F)	(G)	(H)	(I)	(J)	(K)
AK	2	2	2	1	2	3
AZ	NA	NA	NA	NA	NA	NA
CA	3	2	NA	NA	2	3
FL	3	2	3	1	2	2
GA	3	1	2	1	2	2
IO	NA	NA	NA	NA	NA	NA
NA	NA	NA	NA	NA	NA	NA
KY	2	3	NA	NA	NA	1
LA	2	1	3	2	3	3
MI	NA	NA	NA	NA	NA	NA
MN	2	2	2	2	3	3
MO	2	3	2	3	2	3
NC	2	3	3	2	2	3
NY	Too many unknowns, variables, and interdependencies to fill in.					
OH	2	3	1	3	1	2
OR	2	2	2	2	3	3
PA	2	2	2	2.5	2.5	3
SD	NA	NA	NA	NA	NA	NA
UT	2	2	2	2	2	2
VA	3	3	2	2	2	2
Ave.	2.29	2.21	2.17	1.96	2.19	2.5

F=Emissions, G=Additives, H=Viscosity, I=Thickness, J=Strength, K=Compaction
Ranking: 3 = Most Important, 2= Important, 1= Least Important

WMA uses technological advances that reduce the temperature needed to produce and compact asphalt for constructing highway pavements. This offers the reduction of construction costs by lowering the amount of energy used, improving efficiency, decreasing air emissions, and providing a healthier work environment. Tables 3-5 show the advantages and disadvantages from the survey that each State Agency experienced using WMA.

Some disadvantages that CalTrans found through the three years of working with WMA were the following:

- Warm mix stays tender longer
- The roller operators need some adjustment to the feel of the product
- HMA may rut slightly if traffic is opened too early
- Specifications allows traffic on the hot mat at a surface temperature of 160°F (71°C) but should actually wait for the surface temperature to fall to 140°F (60°C) instead.

New York State Department of Transportation (NYSDOT) has been using WMA for five years and has placed over 50,000 tons (45,359 metric tons) of WMA on projects. NYSDOT stated that that one might expect a price reduction in the future as the quantity of placing WMA will increase. The benefits were seen as the same from all other previous case studies stated on the environment and engineering aspects. However, the NYSDOT has not yet seen any disadvantages of using WMA. These are very similar findings that we saw throughout the questionnaire about the potential benefits and disadvantages of using WMA. The states that have not used WMA heavily or that are trying the technology but have not fully implemented it for widespread use, are prompting local asphalt mix producers to research the most cost-effective method of production and also to modify their plants.

WMA Advantages and Challenges

There are many advantages to using WMA compared to HMA or Cold Mix Asphalt (CMA). By lowering the viscosity of the asphalt binder at a given temperature, the WMA technology allows the mixing, transporting and laying down of asphalt mixtures at reduced temperatures ranging from 30ºF to 100ºF (16ºC to 56ºC) lower than the traditional methods, depending on the WMA process used. Along with lower mix temperatures, WMA offers several additional benefits. These benefits include: lowered emissions from the burning of fossil fuels, lower fumes and odor generation (both at the plant and the jobsite), reduction in emissions such as CO_2 and greenhouse gasses, allows longer hauling distances, use of RAP, easier lay down and compaction operations, and corresponding savings to dry and heat the aggregate. By reducing the difference between compaction temperature and ambient air temperature, this would also allow laying at lower ambient temperatures and extension of the laying season. In this case, WMA can take over HMA and CMA on the job site [9].

All asphalt plants must obtain an air permit from the Division of Air Quality in the U.S., which abides by state and federal air-quality regulations. Studies have shown that WMA fuel savings can range from 10 to 30% compared to the conventional HMA pavement. Its lower temperatures reduce plant emissions. Just by reducing the temperature in the asphalt plant, quality limits can also change. Today, the emissions include [9]:

- Limiting production rates
- Limiting hours of operation or decrease time
- Constructing taller emissions stacks
- Increasing the distance between facilities and property lines
- Using higher grades of fuel for asphalt heaters

The lower production temperatures provide numerous benefits such as [10], [11]:

- Reduced emissions: Data from European practices indicate that plant emissions are significantly reduced. Typical expected reductions are 30 to 40% for CO_2 and sulfur dioxide (SO_2), 50% for volatile organic compounds (VOC), 10 to 30% for carbon monoxide (CO), 60 to 70% for nitrous oxides (NO x), and 20 to 25% for dust.
- 55% documented energy savings during the production and application of WMA
- Reduced fuel usage: Burner fuel savings with WMA typically range from 11% to 35%. Fuel savings could be higher (possibly 50% of more) with processes such as low-energy asphalt concrete (LE AB) and low-energy asphalt (LE A) in which the aggregates (or a portion of the aggregates) are not heated above the boiling point of water.
- Paving benefits: Paving-related benefits discussed included the ability to pave in cooler temperatures and still obtain density, the ability to haul the mix longer distances and still have workability to place and compact, the ability to compact mixture with less effort, and the ability to incorporate higher percentages of reclaimed asphalt paving (RAP) at reduced temperatures.
- Reduced worker exposure: Tests for asphalt aerosols/fumes and polycyclic aromatic hydrocarbons (PAHs) indicated significant reductions compared to HMA, with results showing a 30-50% reduction.
- WMA technologies have been used with all types of asphalt mixtures, including dense-graded asphalt and stone-matrix asphalt (SMA).
- Porous asphalt. WMA has been used with polymer-modified binders and in mixes containing RAP.
- WMA has been placed on pavements with high truck traffic, up to 3,500 heavy vehicles per day, which over a 20-year design period would be expected to exceed 30 million, 18-kip-equivalent, single-axle loads.
- Improved worker safety due to the handling of cooler temperature materials.
- Streets and roadways are reopened quickly due to cooler final service temperatures after placement and compaction of the asphalt is complete.
- Performance and durability greater than or equal to traditional hot mix asphalt.

In addition, WMA has lower viscosity, which allows it to flow more easily, has a slower rate of cooling, the mix remains workable despite longer delays or cooler conditions, and trucks can haul WMA over longer distances. It also allows increased RAP to be substituted for virgin aggregate, which provides both financial and environmental benefits. The WMA's temperature also causes less aging of the asphalt binder, which can reduce cracking.

WMA does have a lot of benefits; however, it does have a few drawbacks as well. WMA has been used and tested for a little less than 10 years now. Its performance has been tested in the short term and has proven to work as well as HMA pavement. Simulations of 10 to 12 years of traffic damage over a two-year period have also been performed to project future performance of WMA and have been reported as good performance with low rutting [12]. Since it is fairly new, its performance is still being evaluated. Some disadvantages or risks that were found from the questionnaire (Tables 3-5) and from literature research are as follows:

- Difficulty in adjusting burners in the plant
- Asphalt that does not flow readily as HMA
- Pavement deformation
- Cracking at low temperatures
- A learning curve
- Traffic release on WMA pavement (may rut slightly if traffic is opened too early)
- Potential effects on moisture sensitivity and resistance to moisture induced damage (stripping)
- Unknown long-term performance

However, the risks that are known can be dealt with by understating them on a long-term evaluation and through past research studies. The major drawback that was found from the survey results was on moisture damage in WMA. A laboratory investigation was conducted on moisture damage in WMA mixtures containing moist aggregates. Indirect tensile strength (ITS), tensile-strength ratio, deformation, and toughness tests were performed to determine the mixtures' moisture susceptibilities. The experimental design included two percentages of moisture content (0% and 0.5% by weight of the dry mass of the aggregate), two WMA additives (Asphamin and Sasobit), and three aggregate sources. In this study, 15 mix designs were performed, and 180 specimens were tested. Test results indicated that, as expected, dry ITS values were affected by aggregate moisture and hydrated lime contents, whereas a WMA additive did not significantly alter the dry ITS and toughness values. Statistical analysis showed no significant differences in the wet ITS values of the WMA mixture of three types of mixtures (control, Asphamin, and Sasobit) under identical conditions (same moisture and lime contents). Future research, conducted with more aggregate sources, might be helpful in developing more accurate equations [12].

Another way to reduce these risks is to:

- Have proper equipment maintenance
- Operate at normal production rates
- Add additives with the right material properties
- Increase temperatures slightly if needed

Depending on the type of WMA technologies used, foaming or additives, upfront costs may seem high compared to the conventional HMA. However, all the other benefits such as reducing fuel cost, cost of material, and savings from increased RAP use can outweigh the drawbacks and make it a less costly alternative.

Conclusions and Future Directions

Environmental awareness has been increasing rapidly in recent years and stricter emissions regulations have led to the development of several new processes to reduce the mixing and compaction temperatures of hot mix asphalt, without sacrificing the quality of the resulting pavement. Because of environmental awareness, the hot-mix asphalt industry is constantly exploring technological improvements that will enhance the material's performance, increase construction efficiency, conserve resources, and advance environmental stewardship. It is logical that one approach to achieving these goals would involve methods to reduce material production temperatures by implementing warm-mix asphalt instead of hot-mix asphalt in highway projects. This concept has been tested for almost 10 years in Europe and over the last couple of years in the United States as a means to these ends. Warm-mix asphalt is produced at temperatures between 30°F and 100°F (16ºC and 56ºC) lower than typical hot-mix asphalt.

Through case studies and a questionnaire that was sent out to State Highway Agencies in the United States, the environmental benefits and costs of using Warm Mix Asphalt are clearly evident. This has been seen not only in Europe and other countries but also in the United States as well. Drastic reductions in mixing and placing temperatures have the obvious benefits of cutting fuel consumption and decreasing the production of greenhouse gases. While there is a great deal of promise that comes along with lower temperatures, there are concerns also. As long as the potential risks are known, best practices such as proper equipment maintenance and operating at normal production rates can minimize the concerns of WMA. This paper presents an initial study on the use of WMA in the United States and in other countries. Future research on a complete study of all the State Highway Agencies experience with WMA and the types of equipment, additives, and techniques is needed.

Table 3. Survey Responses from State Agencies' Experiences using WMA

State	Advantages	Disadvantages	Comments
AK	• Longer paving season and mix haul distances • Paving during low temperatures and wind conditions • Less restriction and enabling more production in non-attainment areas • Reduced fuel usage and emissions • Use of higher percentage of RAP	• Contractors dislike addition of extra equipment and devices to their equipment • Concerns that mix is softer initially and might be prone to permanent deformation and stripping in the future	• Do we add or increase the percentage of antistripping agent in the mix? • Where is the agent added for the foamed-asphalt process?
AZ	NA	NA	NA
CA	• Lower emissions • Lengthening life of asphalt binder due to decrease in oxidation exposure at lower temperature • Better compaction results on projects with long haul times (3 + hours) • Ambient temperatures (50°F plus falling) allows longer working time	• WMA more expensive than HMA • Stays tender longer • The roller operations need some adjustment to the feel of the product • May rut slightly if traffic is opened too early • Wait for surface temperatures to fall to 140°F (current specs allow traffic on hot material at surface temperatures of 160°F)	• Lower production temps at plant may require burner (aggregate heater) to be retuned to optimum performance at lower temperatures • Lower temps may have effect on bag
FL	• Reduced worker exposure to fumes and environmental • Reduce aging of binder • Reduce fuel consumption • More mix workability	• Concerns with using high RAP percentages with WMA • Concerns regarding moisture damage for the water injection WMA process • No way to perform mix design utilizing some WMA process	• Will the mix be hot enough o activate the binder on the RAP?
GA	• Extend paving season in some environmental locations or aid in compaction • Significant haul distance	NA	• Has not seen major benefits of WMA pavement
IO	NA	NA	NA
KS	NA	NA	NA

Table 4. Survey Responses from State Agencies' Experiences using WMA (Continued)

State	Advantages	Disadvantages	Comments
KY	• Less burner fuel consumption • Decreased emissions and odors • Lower mixing and compaction temperature	• Possibly moisture susceptibility • Mixture not blending well at lower temperatures • Experienced tender characteristics in WMA pavement produced from asphalt foaming that included difficulties in compacting mixture and pavement yielded poor density and smoothness (did not observe this with other water-injection asphalt foaming device)	• Considering the WMA produced to date using the water-injection/asphalt foaming process, we have not clearly identified any benefits from WMA (e.g., easier compaction, higher density, improved pavement durability).
LA	• Reduced aging • Reduced emissions • Easier compaction efforts	• Possibly moisture susceptibility • Mixture not blending well at lower temperatures	NA
MI	NA	NA	NA
MN	NA	NA	NA
MO	• Improved compaction • Reduce emissions • Extended construction season (due to improved compatibility) • Less disruption to traveling public	NA	NA
NC	NA	NA	• Fuel consumption is a benefit of WMA, however, most of the plant-foaming technologies require aggregate drying temperatures much higher than needed for conventional HMA. • Stack tests are very expensive for individual contractors and data remains limited. • What are we doing to our asphalt binders over the life of a pavement?

Table 5. Survey Responses from State Agencies' Experiences using WMA (Continued)

State	Advantages	Disadvantages	Comments
NY	• Less fuel usage • Less production of greenhouse gasses and emissions	None	NA
OH	• Worker exposure • EPA regulations • Fuel saving	• learning curve • Traffic release on WMA pavement	NA
OR	NA	• Concerned with not getting moisture out of aggregate on our projects which could lead to stripping	• Hope to see WMA work for longer hauls. The first trial we did with a long haul still arrived too cool to get good compaction.
PA	• Less aging of PG-binder through production plant, • Better mixture workability and compaction • Lower unit bid costs from production energy savings and potential less compactive effort required. • Lower unit bud costs due to less energy needed to produce WMA • Less emissions at plant and job site (heat and fumes) • Extended paving season	• Unknown long-term performance • Potential effects on moisture sensitivity and resistance to moisture induced damage (stripping)	• Better mixture workability and compaction especially if have long haul distance from production plant, high amount of hand work or intersection work, or colder temperatures which require increased compaction effort.
SD	NA	NA	NA
UT	NA	NA	NA
VA	• Extended paving season • Better in place density	• Moisture present in aggregate	NA

Acknowledgments

The authors are thankful to the International Journal of Engineering Technology for the support to develop this document.

References

[1] Newcomb, David (October 20, 2006). 'The Hot Mix Asphalt Industry: The Next Five Years.' North East Asphalt User/Producer Group. 2006 Conference presentations, Wilmingong-Chritina, DE. October 11-12, 2206. http://www.neaupg.uconn.edu/2006_presentations.html. Last accessed September 5, 2010.

[2] Gambatese, J.A. and Rajendran, S. (2005). "Sustainable Roadway Construction: Energy Consumption and Material Waste Generation of Roadways." *Proceedings of the Construction Research Congress 2005*, San Diego, CA, April 5-7, 2005. Reston, VA: ASCE, 104-110.

[3] Kuennen, Tom (June 2004). 'Warm Mixes are a Hot Topic.' Road Science. *Better Roads Magazine*, Washington, D.C.

[4] Hurley, Graham C. (June 2005). 'Evaluation of Sasobit for use in Warm Mix Asphalt.' *National Center for Asphalt Technology Report* No. 05-06.

[5] MedWestvaco Corporation (2009). 'Evotherm: Asphalt Additives Pave a Better Way.' http://www.meadwestvaco.com/PackagingSolutions/Cas-eStudies/CaseStudiesGeneralContent/MWV008465. Last accessed on September 1, 2009.

[6] The German Bitumen Forum, Rühl, R., and Lindemeier, B., Ed., "Progress Report 2006, The German Bitumen Forum," (in English), Edition 2, Heinrich Lauck GmbH, Germany, 2006.

[7] Cervarich, Margaret Blain (2003). 'Cooling Down the Mix: Hot Mix Asphalt Technologies Developed in Europe.' *Hot Mix Asphalt Technology*. MARCH/APRIL 2003. http://www.warmmixasphalt.com. Last accessed September 1, 2010.

[8] Perkins, Steven W. (November 2009). "Synthesis of Warm Mix Asphalt Paving Strategies for use in Montana Highway Construction." FHWA/MT-09-009/8117-38, Washington, D.C.

[9] North Carolina Department of Environment and Natural Resources (NCDENR) (May 2009). 'Division of Air Quality: Asphalt Plant Brochure.' http://daq.state.nc.us. Last accessed on September 3, 2010.

[10] Angelo, John D., Eric Harm, John Bartoszek, Gaylon Baumgarder, Matthew Corrigan, Jack Covsert, Thomas Harman, Mostafa Jamshidid, Wayne Jones, Dave Newcomb, Brian Prowell, Ron Sines, and Bruce Yeaton (February 2008). 'Warm-Mix Asphalt: European Practice.' Federal Highway Association, FHWA-PL-08-007. Washington, D.C.

[11] Walker, Dwight, P.E. (June 24th, 2009). 'Emerging Warm Mix Asphalt Technologies.' http://www.asphaltmagazine.com. Last accessed on September 3, 2010.

[12] Xiao, Feipeng, Jayson Jordan, Serji N. Amirkhanian (2009). "Laboratory Investigation of Moisture Damage in Warm-Mix Asphalt Containing Moist Aggregate," Journal of Transportation Research Board, Volume 2126, Washington, D.C. pp 115-124.

Biographies

SOFIA M. VIDALIS received the B.S. degree in Civil Engineering in 1999, the M.S. degree in Civil Engineering in 2000, and the Ph.D. degree in Civil Engineering in 2005 from the University of Florida, Gainesville, Florida, respectively. Currently, she is an Assistant Professor of Civil Engineering at Pennsylvania State University-Harrisburg. Her teaching and research areas include construction management, quality control, and transportation. Dr. Vidalis may be reached at svidalis@psu.edu.

RAJARAJAN SUBRAMANIAN received the B.E. degree in Civil and Structural Engineering in 1982 and the M.E. in Structural Engineering in 1989 from Annamalai University, India. He has also received the M.S. degree in Civil Engineering in 1993 and the Ph.D. degree in Civil Engineering in 2006 from the University of Florida, Gainesville, Florida, respectively. Currently, he is a Transportation Engineer at Maryland State Highway Administration. His research areas include materials, transportation, and quality control. Dr. Subramanian may be reached at RSubramanian@sha.state.md.us.