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NCHRP 9-47

Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies

INTERIM REPORT

Prepared for
National Cooperative Highway Research Program (NCHRP)
Transportation Research Board
of
The National Academies

TRANSPORTATION RESEARCH BOARD
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October 2008

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Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies

CHAPTER 1 BACKGROUND

Research Problem Statement

Hot mix asphalt (HMA) is produced at temperatures between 138°C (280°F) and 160°C (320°F). These temperatures ensure that the aggregate is dry, the asphalt binder coats the aggregate, and the HMA mix has a suitable workability. HMA needs to be workable so it can be transferred into storage silos, transported, placed, and compacted. Even higher temperatures are used for HMA mixtures containing polymer-modified asphalt binders and crumb rubber asphalt binders.

Technology is now available to decrease HMA production temperature by 16°C (30°F) to over 56°C (100°F). These relatively new processes and products use various physicochemical means to reduce the shear resistance of the HMA at construction temperatures while reportedly maintaining or improving pavement performance.

While the current state of the practice for producing HMA has been shown to comply with existing environmental, health and safety standards, reducing HMA production and placement temperatures will provide several benefits, including reduced emissions, fumes, and odors, and a cooler work environment. An energy savings from lower production temperatures is evident with the use of warm mix asphalt (WMA) technology.

The quality of the HMA construction and performance may also be improved when production temperatures are lower. Workability improvements may result in higher in-place density. This decrease in in-place air voids decreases the permeability of the HMA and the long-term or in-service hardening of the asphalt binder as well as reducing water damage that can occur in the HMA.

Workability improvements also have the potential to extend the construction season and the time available for placement of the asphalt mixture during a given day. Due to enhanced workability of the HMA, it may be placed under cooler weather conditions.

A significant amount of asphalt binder aging occurs during the mixing and placing of HMA. Lower production temperatures for asphalt paving mixtures will decrease the aging of the asphalt binder during production. This decrease in aging can improve thermal and fatigue cracking resistance.

The use of WMA technology has some potential engineering challenges. Since the asphalt binders may not harden as much at the lower production temperatures, a softer binder will likely be in the HMA mixtures when the pavement is opened to traffic and the mixture may have a greater potential for rutting. In addition, traffic may not be allowed on the pavement at the conclusion of the compaction process until the mixture cools beyond what is normally

required for conventional HMA. Because binders may be softer and some WMA technologies use water as a workability aid, WMA may be more susceptible to moisture damage. The relationship among engineering properties of such mixes and field performance needs to be investigated to facilitate the implementation of this technology.

Project Objectives

The objectives of the NCHRP 9-47 project are to:

- § establish relationships among engineering properties of WMA binders and mixes and the field performance of pavements constructed with WMA technologies;
- § determine relative measures of performance between WMA and conventional HMA pavements;
- § compare production and laydown practices and costs between WMA and HMA pavements; and
- § provide relative emissions measurement of WMA technologies as compared to conventional HMA technologies.

Through effective planning and execution, the research project is intended to provide:

- 1) recommended modifications to the preliminary WMA mix design and analysis procedure being developed in NCHRP Project 9-43;
- 2) a protocol for laboratory evaluation of WMA performance;
- 3) guidelines for WMA production and construction; and
- 4) an updated emissions measurement protocol.

To achieve these objectives, the research will include both laboratory and field experiments evaluating different WMA technologies within four general categories:

- § Organic Additives (including waxes) – products such as Sasobit and Asphaltan B;
- § Water-bearing Zeolites – products such as Aspha-Min and Advera WMA;
- § Water-based Foaming Processes – products such as WAM Foam; and
- § Emulsion-based Processes – products such as Evotherm.

Although there will be lab experiments conducted to address specific questions regarding testing of WMA, most of the NCHRP 9-47 research effort will be focused on full-scale field experiments for the various categories of WMA technologies. By conducting duplicate trials within each classification of WMA technology, the research team will be able to properly compare HMA and WMA construction, emissions, and performance for the various technologies available. The research team will strive to select, where possible, different regions of the United States for test projects.

CHAPTER 2 WARM-MIX ASPHALT: STATE-OF-THE-KNOWLEDGE

The “state-of-the-knowledge” on WMA, as with any relatively new technology, is rapidly changing. Although this report provides the current knowledge on WMA, an excellent source of general knowledge is the publication Warm-Mix Asphalt: Best Practices published by the National Asphalt Pavement Association in 2007 as Quality Improvement Series 125 (available at www.hotmix.org). This document does a thorough job of describing the technologies, benefits, and best practices for the production of WMA. It includes some of the same information as is in the FHWA’s document Warm-Mix Asphalt: European Practice.

A general outline of this Chapter is shown below.

1. Introduction
 - 1.1. Description of warm-mix asphalt (WMA)
 - 1.2. Differences between WMA, HMA, Half-Warm Mix Asphalt, and Cold Mix Asphalt
2. WMA Technologies
 - 2.1. Organic additives
 - 2.2. Chemical additives
 - 2.3. Water-bearing additives
 - 2.4. Water-based processes
3. Why WMA?
 - 3.1. Reduced Fuel and Energy Use
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 - 6.3.2. Field
 - 6.4. Summary
- 7. Implementation
 - 7.1. Implementation Activities
 - 7.2. Challenges to Implementation

Introduction

“Hot-mix asphalt (HMA) consists of a combination of aggregates uniformly mixed and coated with asphalt cement. To dry the aggregates and obtain sufficient fluidity of asphalt cement for proper mixing and workability, both the aggregate and asphalt must be heated before mixing – hence the term hot-mix.”

Asphalt Institute, MS-4, *The Asphalt Handbook* [1]

In the preceding, warm-mix asphalt (WMA) could simply replace HMA in the definition and not alter the meaning. WMA is fundamentally no different than HMA – it still consists of aggregates and asphalt binder that are heated to obtain proper mixing and workability – but the difference lies specifically in the temperature used to obtain proper mixing and workability. Typically HMA is produced at 120-163°C (250-325°F) depending on a number of factors, but particularly the grade of the asphalt binder. WMA is produced at temperatures that are 20-30°C (35-55°F) lower than comparable HMA production, but still above the boiling point of water - 100°C (212°F) [2]. Mixtures produced at temperatures below the boiling point of water, but which are still heated, are termed “half-warm” mixtures. Mixtures produced near ambient temperatures are termed cold mix. This is illustrated graphically in Figure 1 below.

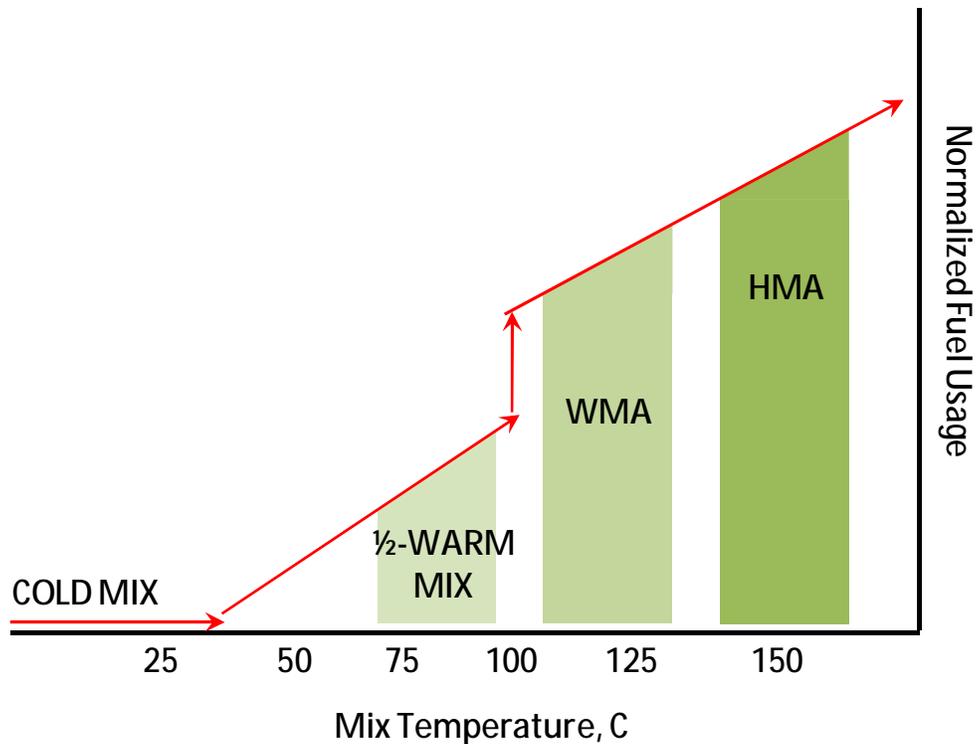


FIGURE 1 Asphalt Mixture Classification by Temperature

Warm-mix asphalt (WMA) has been described as representing “...a group of technologies which allow a reduction in the temperatures at which asphalt mixtures are produced and placed.” [3] There are many different processes, and products, that can be used to achieve this reduction in temperature, but generally WMA technologies can be separated into four categories:

- Organic additives – generally wax additives such as Fischer-Tropsch or Montan waxes;
- Chemical additives – surfactants or other chemical additives;
- Water-bearing additives – synthetic zeolites; and
- Water-based processes – non-additive processes based on foaming

Emulsion-based processes, such as the first generation of Evotherm, are also available, but have been replaced by the use of chemical additives to accomplish the same goals of temperature reduction.

Warm-Mix Asphalt (WMA) Technologies

Organic Additives [2]

In Europe, organic additives that have been used to produce WMA include: Sasobit (Fischer-Tropsch wax); Asphaltan-B (Montan wax); and Licomont BS-100. The experience in the United States has mainly been with Sasobit.

Sasobit is a Fischer-Tropsch wax manufactured by Sasol Wax that has a melting point of approximately 100°C and is completely soluble in asphalt at temperatures greater than 140°C. Fischer-Tropsch waxes have a different crystalline structure and longer carbon chain lengths than the naturally-occurring paraffin waxes that are found in asphalt binders. These longer chain lengths result in a higher melting point for the Fischer-Tropsch wax compared to the paraffin waxes. The finer crystalline structure of Fischer-Tropsch waxes are believed to also reduce brittleness at lower temperatures as compared to paraffin waxes.

Asphaltan-B is a Montan wax blended with a fatty acid amide. Montan waxes are also known as lignite or OP waxes and have a melting point of approximately 82-95°C.

Licomont BS-100 is a fatty acid amide that has a typical melting point of 141-146°C. Similar products have been used as viscosity modifiers in asphalt.

The behavior of an asphalt binder modified with an organic additive is shown conceptually in Figure 2.

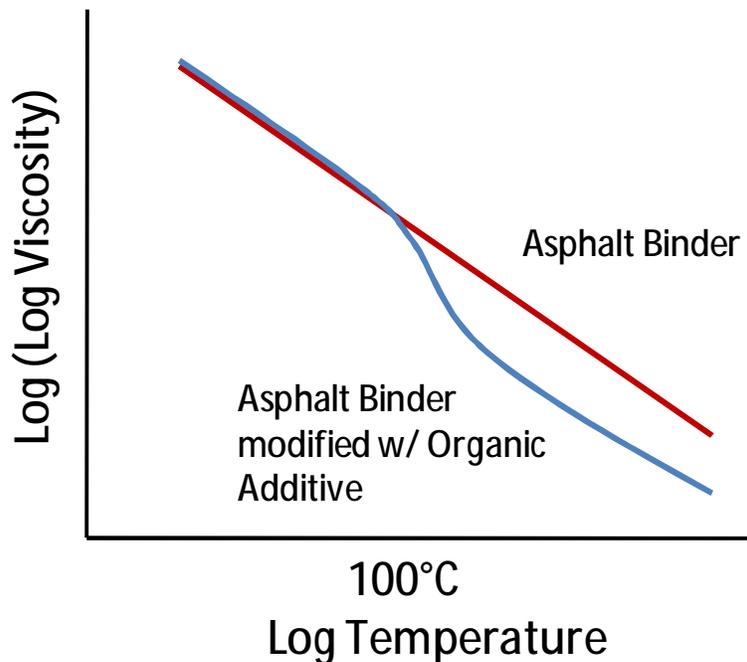


FIGURE 2 Temperature-Viscosity Behavior of Asphalt Binder Modified with Organic Additive [4]

Chemical Additives

Chemical additives, such as surfactants, are a relatively new, emerging group of additives for warm-mix asphalt. These surfactants help the asphalt binder coat the aggregate at lower temperatures. The Evotherm Dispersed Asphalt Technology (DAT) is produced by MeadWestvaco Asphalt Innovations.

REVIX was jointly developed by Mathy Technology and Engineering Services and Paragon Technical Services. It is an approach for producing reduced-temperature paving mixtures using additives that reduce the internal friction between binder and aggregate and between coated aggregate particles during mixing and compaction but does not rely on the principles of foaming or viscosity reduction. In addition to being marketed as REVIX, it is being marketed by MeadWestvaco as Evotherm 3G.

Rediset WMX is produced by Akzo Nobel and is a combination of organic additives and surfactants.

Water-Bearing Additives

Water-bearing additives include synthetic zeolites, which are composed of aluminosilicates and alkalimetals. These synthetic zeolites contain crystalline water which is released as the temperature is increased above 100°C. The water then creates a foaming effect that increases the volume of the asphalt binder and decreases the viscosity. The slow release of water from zeolite provides for an extended period of workability. [2]

In Europe, the most commonly-used synthetic zeolite has been Aspha-min, manufactured by Eurovia. It has been marketed in the United States by the Hubbard Group.

In the United States, Advera WMA has been produced by PQ Corporation.

Water-Based Processes [3]

Unlike the previous three categories – organic additives, water-bearing, additives, and chemical additives – this category only uses process to achieve WMA, not additives. Although several processes exist in Europe, the most common have been WAM Foam, which is a two stage-process where soft asphalt binder first coats the aggregates and is followed by a hard asphalt binder that is foamed, and LEA (low energy asphalt), which uses heated coarse aggregate blended with asphalt binder and wet fine aggregate to complete foaming.

In the United States, the prevalent processes have been the Double Barrel Green technology (produced by Astec) and the LEA process marketed by McConaughay Technologies.

The Double Barrel Green process uses a mixing chamber where water is injected through nozzles and the asphalt binder is foamed. Unlike the WAM-Foam process, it is a single-stage foaming of all of the asphalt binder.

The LEA process uses a small amount of coating and adhesion additive that is incorporated into the asphalt binder before mixing. Coarse aggregate is heated to normal production temperatures and mixed with asphalt binder at the appropriate temperature for the binder grade. Wet fine aggregate, containing 3-4% moisture is then mixed with the coated coarse aggregate. The moisture in the fine aggregate causes the asphalt binder to foam and allows for thorough mixing of the coarse and fine aggregate.

Why WMA?

There are a number of potential benefits generally associated with WMA that can be separated into three general categories: economic, operational, and environmental. Table 1 classifies some of the potential benefits by category.

TABLE 1 Potential Benefits of WMA

Potential Benefit	Economic	Operational	Environmental
Reduced fuel use	X		X
Late season (cool weather) paving		X	
Better workability and compaction	X	X	
Reduced plant emissions of greenhouse gases			X
Increased usage of RAP	X		
Improved working conditions for plant and paving crew			X

Reduced Fuel Use

Fuel usage is related to the mixing temperature of the mixture at the asphalt mixing facility. For HMA, higher temperatures are needed to both dry and heat the aggregates and to increase the asphalt binder viscosity so that proper mixing can be achieved. For WMA, the reduced need to completely dry the aggregates – particularly for processes and additives that depend on foaming of the asphalt binder for coating – and better coating at lower temperatures means that the mixing temperature doesn't need to be as high. Thus, the burner is used less, resulting in a reduction in fuel usage. Fuel savings have been reported in the range of 10-35%, but are highly dependent on a number of factors including temperature and moisture content. [3]

Effect of Plant Operating Temperature on Fuel Consumption

The impact of the lower plant operating temperatures of Warm Mix Asphalt (WMA) is affected by many factors. In broad terms, it has been reported that there is a decrease in fuel consumption of 2 to 3 percent for every drop of 10°F in the exit temperature of the mixture [5]. However, this decrease is affected by the following factors as well:

- Percent Moisture to be Evaporated from the Aggregate
- Dryer Exhaust Temperature
- Entrance Temperature of the Aggregate
- Type of Fuel Used
- Stoichiometric Volume of Air Ratio Used in Plant Operation
- Plant Elevation

It is fairly obvious that more aggregate moisture, to be driven off to achieve less than 0.5 percent by weight of mixture, and colder temperatures of the entering aggregate will increase the amount of fuel consumed. The dryer exhaust temperature is important because a higher exit temperature means less efficiency in aggregate drying. This exit temperature is often directly related to the amount of wear on the flights within the dryer [5]. The flights lift the aggregate and drop the aggregate through the hot gas stream, which impacts the “veiling efficiency”, the spread of the aggregate as it falls across the drum to be dried. If the heat is not absorbed by the aggregate, the exhaust from the plant will be at a higher temperature and more fuel will be consumed.

Each type of fuel used for the burner has a level of efficiency and a specific BTU conversion; usually this impact is also taken into account with the relative price of the fuel. The Stoichiometric volume of air is the exact volume of air necessary to provide just enough oxygen to burn the fuel (ratio = 1). However, dryers require more air than the stoichiometric volume to assure complete combustion of the fuel [6]. A ratio of 2 is fairly typical for dryers that are working properly and that have fairly good seals. Lower ratios imply very good plant efficiency and a very good dispersion of fuel, while higher ratios imply that an excessive amount of air is being used and is undesirable.

Finally, a plant operating at higher elevations may require more fuel if the same plant is moved without making changes in the flights to keep the exhaust temperature down. Because gas expands at higher elevations, it results in a higher rate of flow through the dryer, which makes it more difficult to maintain a lower dryer exhaust temperature. It should also be noted that the rate of production does not affect fuel consumption or exhaust volume. [6]

To evaluate some of these various impacts, tables were created for estimating the positive economic benefit of lowering the plant operation temperature with WMA, based on the National Asphalt Pavement Association procedure [6], assuming various conditions. For these calculations, the plant elevation was assumed to be a constant 636 feet above sea level, which is the average elevation of plants serving heavily built-up areas of the U.S [6]. A Stoichiometric volume of air ratio of 2.0 was also assumed.

In the tables, the dryer exhaust temperature was varied between 275°F (less efficient) and 225°F (more efficient). Fuel consumption and the required days of plant mixing operation were determined for an 80,000-ton project with a 10-hour working day duration. These determinations were made for mixture exit temperatures of 325, 300, 275, 250, and 225°F. Three types of fuel were evaluated: No.2 diesel fuel oil, propane, and natural gas. The most recent market fuel prices (June 2008) were obtained from the Energy Information Administration Petroleum Marketing Monthly on the internet and are summarized in the Appendix. For these calculations, the cost of No.2 fuel oil was assumed to be \$4.05 per gallon, for propane \$2.36 per gallon was assumed, and for natural gas, \$12.07 per 100 cubic feet was assumed.

Two material entrance temperatures (ambient) were selected, 70°F and 40°F, and two different required moisture evaporation percentages were selected, 6 and 3 percent. Six percent moisture evaporation equates to lowering the moisture content of the aggregate from 6.5 to 0.5 percent.

As an example, for a plant using No.2 fuel oil with a dryer exhaust temperature of 275°F, an ambient temperature of 70°F, and requiring 6 percent moisture evaporation, if the mixing temperature of WMA was 225°F, compared to Hot-Mix Asphalt (HMA) at 300°F, the savings in fuel cost would be $\$648,000 - \$563,760 = \$84,240$, or 13 percent. In addition, the required amount of days of mixing operation at peak dryer capacity would be reduced from 29.1 (274.9 tons/hour) to 26.3 (303.8 tons/hour) (or 2.8 days) to produce the same 80,000 tons.

If the ambient temperature was only 40°F, the savings in fuel cost would be $\$704,376 - \$612,807 = \$91,569$, or the same 13 percent. In addition, the required amount of days of mixing operation would be reduced from 31.6 to 28.6 to produce the same 80,000 tons. The margin is not affected by the ambient temperature, but the difference in plant production duration increased to a full 3 day savings.

If the same plant at 70°F, were operating more efficiently, with a dryer exhaust temperature of 225°F, the savings in fuel cost would be $\$628,560 - \$544,320 = \$84,240$, or 13.4 percent. In addition, the required amount of days of mixing operation would be reduced from 26.5 to 24.3 (2.2 days) to produce the same 80,000 tons.

If the original plant were using aggregate that was less moist (3 percent evaporation needed), the savings in fuel cost would be $\$453,600 - \$369,360 = \$84,240$, or 18.6 percent. In addition, the required amount of days of mixing operation would be reduced from 18.6 to 15.8 (2.8 days) to produce the same 80,000 tons.

Finally, if the original plant was burning natural gas instead of No. 2 fuel oil, the savings in fuel cost would be $\$281,048 - \$244,511 = \$36,537$, or the same 13 percent. In addition, the required amount of days of mixing operation would be reduced from 30.1 to 27.2 (2.9 days) to produce the same 80,000 tons, nearly the same difference. If the original plant was burning propane instead of No. 2 fuel oil, the savings in fuel cost would be $\$593,965 - \$516,749 = \$77,216$, or the same 13 percent. In addition, the required amount of days of mixing operation would be reduced from 29.2 to 26.4 (2.8 days) to produce the same 80,000 tons, the same difference.

The savings in fuel consumption of WMA over HMA can be significant. Beyond that, there can also be some significant savings in days of plant operation and paving if the peak production rate in tons per hour can be achieved.

Late-Season (Cool Weather) Paving

Case studies in Europe indicate that WMA has been produced, placed and properly compacted at ambient temperatures as low as -3°C [2]. Actual WMA production temperatures will vary depending on a number of factors including haul distance and ambient temperature, but are expected to be lower than HMA production temperatures exposed to the same conditions. What this means is that since WMA is compactable at lower temperatures than HMA, the mix can be produced at lower temperature and will remain compactable for a longer period of time than HMA. This allows paving contractors in most of the United States the opportunity to continue paving projects later into the year.

Better Workability and Compaction

Maintaining workability at lower temperatures enables the paving contractor the opportunity to achieve better compaction using WMA than HMA. Although “better” compaction is listed as a potential benefit of WMA compared to HMA, what is likely meant is “more consistent” compaction. The target density is specified by the user so that the pavement has adequate strength and permeability; it should have little to do with the means of achieving that density. WMA users have reported densities comparable to HMA densities.

Some WMA users have reported that the roller train is often tighter together (breakdown, intermediate, and finish rollers within reasonably close proximity of each other) than with HMA. Target densities may be achieved quicker, with fewer roller passes for WMA than HMA. The rationale for “more consistent” densities is that the roller train – by being closer together – is less likely to leave gaps in mat coverage. Thus the density could be expected to be more uniform across the mat.

Reduced Plant Emissions of Greenhouse Gases

In asphalt plants, the burning of fossil fuels generates heat needed to dry and heat aggregates so that they can be mixed and properly coated with asphalt binder. The asphalt mix is then stored at an elevated temperature to facilitate construction operations. The burning of fossil fuels also leads to the production of several combustion by-products including sulfur dioxide (SO_2), nitrogen oxide (NO_x), and carbon dioxide (CO_2).

Some of these by-products of fossil fuel combustion – specifically SO_2 and NO_x – lead to the production of ground-level ozone (O_3) and particulate matter air pollution. According to the American Lung Association (www.lungusa.org):

“Ozone (O₃) is an extremely reactive gas molecule composed of three oxygen atoms. It is the result of emissions of volatile organic compounds, including hydrocarbons, reacting with nitrogen oxides released in fuel combustion, in the presence of sunlight. Ozone is very harmful to breathe and attacks lung tissue by chemically reacting with it.”

The Environmental Protection Agency of the United States (www.epa.gov) defines particulate matter as “...a mixture of solid particles and liquid droplets found in the air. PM_{2.5} refers to particulate matter that is 2.5 micrometers or smaller in size.” It is these fine particles that are a concern for human health. As noted by the EPA:

“Particles this small easily penetrate the alveoli, the very smallest air sacs in the lung. Because this region of the lung is slow to clear itself of foreign substances, these small PM deposits can continue to cause damage for long periods of time.”

Fine particulates also contribute to air pollution in the form of haze and can travel great distances from their source. According to the EPA, “It is believed that one-third of the haze seen over the Grand Canyon comes from Southern California” as a result, in part, from fine particulate matter.

Finally, the EPA indicates that fine particulate matter contributes to the formation of acid rain. The following map from the United States Geological Survey (www.usgs.gov) shows the distribution of pH in rain in 1992. Not surprisingly, the lowest pH (highest acidity) appears in areas of non-attainment for air quality ozone and PM_{2.5} as shown in the next figure from the EPA.

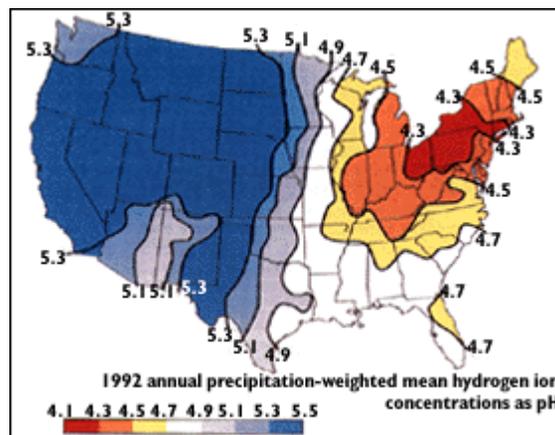


FIGURE 3 1992 pH Distribution in Rain (Source: www.usgs.gov)

Counties Designated Nonattainment for PM-2.5 and/or 8-hour Ozone Standard

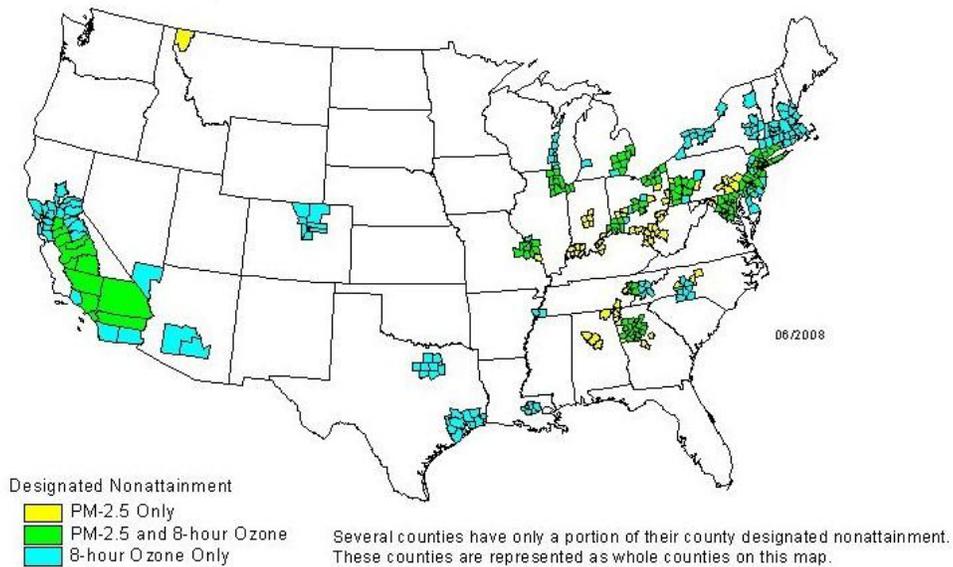


FIGURE 4 2008 Non-Attainment Areas for PM_{2.5} and/or 8-Hour Ozone Standard
(Source: www.epa.gov)

In addition to SO₂ and NO_x, the Kyoto Protocol, ratified in 1997 and implemented in 2005, sets binding targets for 37 industrialized countries and the European community for reducing greenhouse gas emissions by an average of 5% from 1990 levels between 2008 and 2012. The European Union pledged a 15% reduction, with Germany pledging a 25% reduction. The United States signed the Kyoto Protocol, but has not ratified it at this time.

Greenhouse gases, including CO₂, absorb infrared radiation and trap heat in the atmosphere. According to the Energy Information Administration of the U.S. Department of Energy (www.eia.doe.gov):

“Levels of several important greenhouse gases have increased by about 25 percent since large-scale industrialization began around 150 years ago. During the past 20 years, about three-quarters of human-made carbon dioxide emissions were from burning fossil fuels.”

The following figure demonstrates the growth of CO₂ in the atmosphere (left axis) over time correlated with anthropogenic (human-related) emissions shown on the right axis.

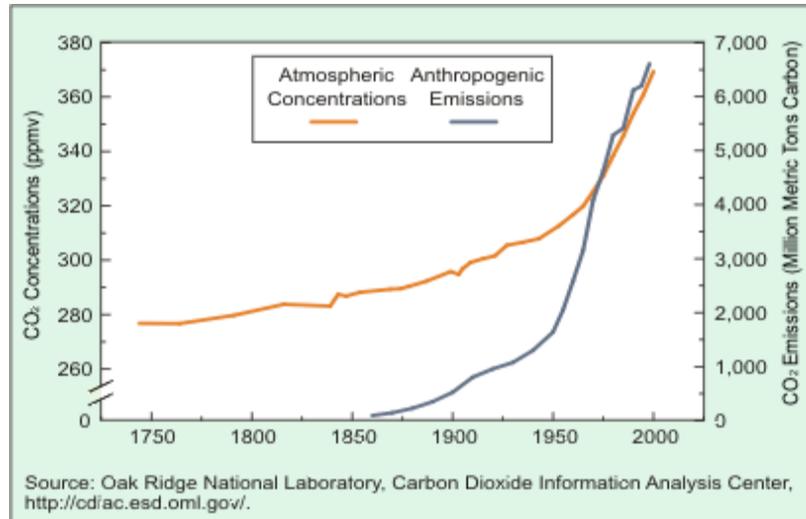


FIGURE 5 Atmospheric CO₂ Concentration Correlated with CO₂ Emissions over Time

It is important to note that the production of SO₂, CO₂, and NO_x resulting from asphalt plant operations is not a major contributor to the environmental effects discussed above [7]. However, the operation of asphalt plants in nonattainment areas – areas not meeting the national air quality standards established in 1997 – could be, and have been, restricted during daylight hours in times of the year when ozone production is a problem. This means limited (or nighttime) operations during the summer in many of our nation’s large urban areas. Reducing emissions at the asphalt plant could then lead to more operational flexibility.

In Europe, WMA production has resulted in observed reductions of 15-40% for CO₂, 18-35% for SO₂, and 18-70% for NO_x compared to HMA production. [2]

Increased Usage of RAP

Increased use of RAP has a potential economic benefit for the user and producer. The amount of RAP has been limited in HMA by many highway agencies because of concerns that at higher amounts of RAP the asphalt mixture would be too “aged” after production leading to a potential for early cracking. In WMA, the lower mixing temperatures means that the virgin asphalt binder would not be as aged as in an HMA, and therefore an increase in RAP could be possible before the resulting mix would be too stiff – leading to the potential of early cracking.

In Europe, WMA has been successfully produced with RAP at up to 50%. In the United States, there has been some WMA produced with 50% RAP, but, to date, most of the WMA projects containing RAP have used 20% or less.

Improved Working Conditions

Data in Europe has shown that worker exposure to asphalt fumes is lower with WMA as compared to HMA. Although sampling and analytical protocols are different for different countries, test data presented by the German Bitumen Forum indicated a 30-50% reduction in asphalt aerosols/fumes and polycyclic aromatic hydrocarbons (PAHs) [2]. Limited test data has been analyzed in the United States. However, in most cases, personal sampling devices indicated readings for benzene soluble matter (BSM) and total particulate matter (TPM) below detectable levels for both WMA and HMA. The lower mix temperature and reduction of visible smoke and odor – or perception thereof – for WMA may contribute to improved working conditions for the paving crew.

Laboratory Mix Design Procedures [8]

WMA mix design is the subject of the NCHRP 9-43 project, “Mix Design Practices for Warm Mix Asphalt” being conducted for the NCHRP by the research team led by Dr. Ramon Bonaquist, Advanced Asphalt Technologies. The research is currently in progress and nearing the completion of Phase I. The objective of the research is to develop a mixture design and analysis procedure for the wide range of WMA additives and processes that are currently in use or which may become used in the future. A summary of the proposed standard practice for WMA mix design and analysis is shown below:

WMA MIX DESIGN and ANALYSIS

1. Materials Selection
 - a. WMA Process Selection
 - b. Binder grade selection
 - c. Aggregate selection
 - d. RAP selection
 - e. Additive selection (WMA, adhesion, moisture susceptibility)
2. Design Aggregate Structure
3. Design Asphalt Binder Content
4. Evaluate Moisture Susceptibility
5. Evaluate Rutting Resistance
6. Evaluate Mix Performance (Discretionary)
 - a. Dynamic modulus
 - b. Fatigue cracking
 - c. Thermal cracking

Materials Selection

The selection of the WMA process and the associated temperature for production impacts both the binder grade selection and the allowable RAP content.

In binder grade selection, the research recognized that the aging that would occur during plant production is strongly affected by temperature. The research team then designed an RTFO aging experiment that examined the change in high temperature PG grade as a function of the temperature at which the RTFO test was conducted. A relationship was developed between the binder aging index and the rate of change of the RTFOT high temperature grade. The binder aging index is simply the ratio of the $G^*/\sin \delta$ value after RTFO aging to the ratio of the $G^*/\sin \delta$ value on the original, unaged asphalt binder at the high temperature performance grade temperature. Using this relationship with other assumptions (i.e., temperatures of standard HMA production, maximum allowable grade loss of 3°C) resulted in a table of minimum mix production temperatures required to avoid having to increase the high temperature grade. This table, shown below, is influenced by both the aging index of the asphalt binder and the binder grade. Generally speaking, the higher the aging index and the higher the PG grade, the greater the WMA production temperature would have to be to avoid increasing the binder grade by one high temperature grade.

TABLE 2 Minimum WMA Production Temperature (°F) Without Increasing High Temperature Grade

PG	Aging Index											
	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6
52	<215	<215	<215	<215	<215	<215	220	220	225	225	230	230
58	<215	<215	<215	220	225	230	235	235	240	240	245	245
64	<215	<215	220	230	235	235	240	245	245	250	250	250
67	<215	220	230	235	240	245	250	255	255	255	260	260
70	<215	220	230	240	245	245	250	255	255	260	260	260
76	<215	225	235	245	250	255	260	260	265	265	265	270
82	<215	235	245	250	255	260	265	265	270	270	275	275

As an example, consider a project in Kentucky using a PG 64-22 asphalt binder with an Aging Index of 2.2. If a WMA process was selected that resulted in a mix production temperature of 235°F (113°C) or higher, then no grade change would be needed. However, if a WMA process was selected that resulted in a mix production temperature less than 235°F (113°C) or higher, then the asphalt binder grade would be increased to a PG 70-22.

This approach will need to be validated by the NCHRP 9-43 research team to ensure that the “grade bumping” procedure doesn’t result in the unintended use of a premium grade asphalt binder in a mixture that wouldn’t otherwise require one. The procedure also needs to be evaluated with the new high temperature specification parameter, J_{nr} , currently under ballot as Table 3 of AASHTO M320.

The rationale behind the suggestion that the allowable RAP content might need to be different for WMA compared to HMA lies with the blending between virgin and RAP binders. If substantial mixing does not occur between the virgin and RAP binders at WMA process temperatures, then the researchers have suggested that the RAP content of WMA would need to be limited. Testing to date using atomic force microscopy have: (1) confirmed the use of blending charts in AASHTO M323 for high levels of RAP; and (2) confirmed that virgin and RAP binders do in fact blend at 130°C. Based on these results, the research team suggests that HMA specifications apply to WMA for allowable RAP content at production temperatures at or above 130°C (265°F).

Except as noted above, all other materials selection follows the guidelines in AASHTO M323 for HMA mixtures. Selection of WMA additives will depend on the WMA process chosen for the project.

Design Aggregate Structure

Determination of the design aggregate structure for WMA follows the same procedures as in AASHTO M323 for HMA. As of this time, short-term oven aging for WMA remains as 2 hours at the compaction temperature. Limited research conducted by the NCHRP 9-43 team concluded that this time/temperature combination appeared to reasonably estimate the volumetric and mechanical properties of both WMA and HMA at the time of construction for the Colorado I-70 project. This recommendation will be further evaluated for validation.

Specimen preparation for SGC compaction and maximum theoretical specific gravity determination is specific to the WMA process selected. For the additives – organic, chemical, and water-bearing – the process is essentially the same as with HMA. The additive is weighed separately and added to the heated aggregate before blending with the asphalt binder. For the water-based processes, which depend upon foaming of the asphalt binder, it may be necessary to have special foaming equipment to mix the WMA. The exception to this is the LEA process which uses moisture in the fine aggregate to expand the volume of asphalt binder coating the coarse aggregates. [9]

For LEA, it is recommended that the heated aggregates are mixed in a mechanical mixer for 30 seconds before the wet fine aggregate (approximately 3-4% moisture is recommended) is added. The mixing then continues for another 60 seconds and the mix is checked to ensure that the temperature is at least 90°C.

In addition to the volumetric and densification properties, the draft WMA mix design procedure includes determination of workability and degree of coating. The research team is in the process of evaluating potential workability tests. Degree of coating is determined using an existing standard, AASHTO T195.

Design Asphalt Binder Content

Essentially the same process is used to determine the design asphalt binder content for WMA as HMA, with exceptions noted in the previous section.

Evaluate Moisture Susceptibility

The same process is used to evaluate WMA moisture susceptibility as is used with HMA. Specimen preparation for WMA is discussed the previous sections.

Evaluate Rutting Resistance

This step of the WMA mix design process is new relative to the current HMA mix design process. Specimens are prepared according to WMA process selected. After mixing, specimens are subjected to short-term oven aging of 2 hours at compaction temperature. Specimens, 150-mm diameter by 175-mm height, are compacted in the SGC to a target of $4.0 \pm 0.5\%$ air voids. Test specimens are then cored and sawed to dimensions of 100-mm diameter by 150-mm height from the SGC-compacted specimens.

Four test specimens are prepared to evaluate the WMA rutting resistance using the Flow Number Test using the SPT equipment. In the test, specimens are tested in an unconfined state using a repeated axial stress of 600 kPa. Tests are conducted at the design temperature at 50% reliability as determined using LTPPBind (v3.0). The depth at which the temperature is determined is either the top of the pavement layer (intermediate and base course mixtures) or 20 mm (surface course mixtures).

The Flow Number is determined for each specimen. The four test results are then averaged to produce a single test result that is compared to recommended criteria. Currently, the research team suggests the criteria shown in Table 3.

TABLE 3 Rutting Resistance Criteria

Design Traffic, x10⁶ ESAL	Flow Number¹
< 3	---
3 to <10	≥ 200
10 to <30	≥ 320
≥ 30	≥ 580

¹ Average of four specimens tested using the following conditions: 4.0% air voids; 600kPa repeated axial stress; unconfined; design temperature at 50% reliability and appropriate depth.

WMA Mix Analysis

The mix analysis section of the standard practice is an optional addition to the mix design procedure that will enable the user the opportunity to evaluate WMA performance using dynamic modulus, fatigue cracking, and thermal cracking. In all cases, specimens are prepared to a percentage of air voids that should be representative of the in-place air void content.

Dynamic modulus testing is conducted on two test specimens using the SPT equipment and recommended standard practice (temperature-frequency sweep). From the data, a master curve is generated and used to calculate dynamic modulus and phase angle at multiple combinations of temperature and frequency.

Fatigue testing is conducted on four test specimens using cyclic direct tension in the SPT equipment using a 2x2 combination of temperature (4 and 20°C) and strain (low and high). The analysis combines data from the four test specimens (modulus vs. cycles) and temperature shift factor data from the dynamic modulus testing to determine the continuum damage fatigue constant – which defines the rate of damage accumulation for the mixture at a reference temperature of 20°C. The continuum damage fatigue constant is used to calculate the inherent fatigue coefficient, which can be compared to recommended ratings to judge the fatigue resistance of the mixture.

Thermal cracking is conducted on three test specimens using the indirect tension test at low temperatures. Unlike the other performance tests, the indirect tension test specimens are 150-mm diameter by 50-mm height. Creep testing is conducted on each test specimen at 0, -10, and -20°C to determine creep compliance. Indirect tensile strength testing is conducted at -10°C. The data is used in thermal cracking analysis procedures such as LTSTRESS – which generates a critical cracking temperature – or the MEPDG – which generates a yearly prediction of thermal cracking in the pavement section. In either case, the results should be compared to some user-defined criteria to determine if the WMA has adequate low temperature cracking resistance.

Other WMA Mix Performance Tests

Although not included in the NCHRP 9-43 research procedure, many user agencies will likely add other performance test requirements to their WMA mixtures to coincide with requirements placed on HMA mixtures. An example would be loaded wheel tests, such as the APA or Hamburg, which are used by some agencies as proof tests to ensure adequate rutting resistance. WMA mix designers will need to be cognizant of these additional agency-specific tests and requirements.

Production and Construction

WMA may require changes in mix production compared to HMA. These changes could include modifications to the asphalt plant to incorporate the WMA technology, changes to burner operations, and stockpile moisture.

Plant Modifications

Some WMA technologies will require changes at the mixing plant, while others will not require any changes compared to conventional HMA. Table 4 briefly describes any plant modifications needed with selected WMA technologies.

TABLE 4 Plant Modifications Required for WMA Technologies

WMA Technology	Category	Plant Modifications
Sasobit	Additive: Organic	Direct blended into asphalt binder; added at RAP collar (drum); feeder – similar to fiber feeder – preferred (drum)
Evotherm DAT	Additive: Chemical	Added in-line (pump and metering system)
Rediset WMX	Additive: Organic-Chemical	Direct blended; dry addition (near binder line in drum)
REVIx	Additive: Chemical	Direct blended; added in-line (pump and metering system); dry addition
Aspha-min	Additive: Water-Bearing	Vane feeder to blow additive into binder stream (drum); can also use addition at RAP collar (drum) or in bulk in pugmill (batch)
Advera WMA	Additive: Water-Bearing	Modified fiber feeder preferred (drum)
Double Barrel Green	Process: Water-Based	Foaming manifold and feeder lines
LEA	Process: Water-Based	Added in-line (pump and metering system) for additive; additional cold feed bin for wet fine aggregate; moisture monitoring system
WAM Foam	Process: Water-Based	Depends on plant type, but at least requires a second asphalt binder line (for the hard asphalt binder) and water line

Stockpile Moisture

One of the concerns with WMA is that reduced production temperature may result in mixtures with a higher moisture content, thus leading to potential tenderness and stripping problems. The FHWA Scan Tour found that stockpile moisture likely wasn't an issue in European operations for a couple of reasons [2]:

- the aggregates used were generally less absorptive than the aggregates used in the United States; and

- In several instances it was observed that aggregate transfer belts and/or stockpiles were covered to keep help maintain control of aggregate moisture.

As a general rule of thumb, it takes 1.9 gallons of fuel per ton to dry and heat aggregates for HMA when the incoming aggregates have 5% moisture. Fuel consumption can be reduced by an estimate of 0.2 gallons per ton (or approximately 10%) for every 1% reduction in moisture content of the incoming aggregate. Thus, the combination of a reduction in moisture content in the incoming aggregates with the use of lower production temperatures in WMA should ensure that the WMA will not have an excessive moisture content and will maximize fuel savings.

Burner Adjustments

Before beginning production of WMA – whether for a small trial or a full-scale project – the plant operator should make sure that his burner has been properly adjusted to account for the reduction in operating temperature and to ensure complete fuel combustion. Proper burner operation will ensure maximum efficiency of fuel consumption regardless of the mixture that is being produced.

Incomplete fuel combustion is not often a problem at asphalt mixing plants – particularly if the burner has been maintained and adjusted to operate properly – but could more likely be a problem for WMA than HMA. Uncombusted fuel remaining in the mix after discharge will reduce mix stiffness and could increase the rutting and stripping potential of the mix. Carbon monoxide (CO) emissions should also increase in the stack. [3]

RAP in WMA

Most contractors are aware of the savings per ton of mix that can be realized by the addition of RAP. Traditionally, however, high RAP use has been limited in HMA because of the increased aggregate temperature needed to ensure that the RAP heats and blends within the mix and concerns that the use of a high percentage of previously-oxidized asphalt binder (in the RAP) to an asphalt mixture could result in premature cracking failures. For WMA, these concerns are alleviated. The higher aggregate temperature needed for RAP benefits WMA production in that it: (1) results in more complete removal of internal aggregate moisture; and (2) increases the temperature of the exhaust gas going into the baghouse (for operational efficiency). [3]

The addition of RAP in WMA may also help with the initial mix stiffness on the road. Since WMA does not age as simulated by the RTFO test (as shown by the NCHRP 9-43 work), the addition of a harder asphalt binder can help overcome any reduction in mixture stiffness due to a lack of aging.

Despite these advantages, of the projects listed in the Appendix as of this date, the vast majority (84%) used less than 25% RAP. With more understanding of the effects of RAP and WMA from this project as well as the NCHRP 9-43 and NCHRP 9-46 (*Improved Mix Design*,

Evaluation, and Materials Management Practices for Hot Mix Asphalt with High Reclaimed Asphalt Pavement Content) projects, these percentages should become more balanced, favoring the use of RAP in WMA. Table 5 provides a breakdown of the RAP usage in WMA projects shown in the Appendix.

TABLE 5 RAP Usage in WMA Projects (Appendix)

RAP Used	Number of Projects	Percentage
40% or more	7	5%
25-39%	16	11%
10-24%	37	26%
None	83	58%
	143	100%

Laydown and Compaction

Reports from contractors in Europe and the United States indicate that the laydown and compaction of WMA does not differ from the laydown and compaction of HMA, other than the temperature at which these operations occur. As noted earlier, some technologists believe that a more uniform compaction can be achieved with WMA because of its operating temperature, allowing the roller train to have better spacing and ensure proper mat coverage. Achieving minimum density does not seem to be an issue for WMA compared to HMA. No excess pickup on the roller drums has been noted when using WMA.

Comparison of WMA and HMA

WMA and HMA can, and have been, compared to evaluate similarities and differences in three main areas:

- Materials and production costs;
- Emissions; and
- Lab and field performance.

Materials and Production Costs

Assuming RAP use is the same in HMA and WMA – an assumption that may not be valid in the very near future for reasons described previously – then materials and production costs are affected by two main things: (1) fuel consumption and (2) cost of additives and/or plant modifications. Other, less quantifiable costs may also contribute to any differences between

WMA and HMA including electricity usage, elimination of compaction equipment (easier compaction = fewer rollers?), and changes in production rate.

As noted earlier, it has been reported that for every 10°F (6°C) reduction in temperature, fuel consumption is reduced by 2-3% [5]. Thus for a reduction of 50°F (28°C), which is fairly typical of WMA compared to HMA, fuel consumption should be reduced by 10-15%. Additionally, a reduction in the amount of moisture that is removed from the incoming aggregate also reduces fuel consumption. For every 1% reduction in moisture, fuel consumption is reduced by approximately 10%. In WMA production, these two effects often work together so that the total reduction in fuel consumption has been reported as 20-35%. [3]

Other than theoretical calculations, there are some reported comparisons in the literature. Davidson (McAsphalt Industries) reported only a slight reduction in fuel usage (approximately 5%) when comparing WMA (Evotherm Emulsion Technology) with conventional HMA. However, it was noted that the HMA was produced at a different plant, considered to be very efficient in its operations, than the WMA. Earlier small trial projects conducted by McAsphalt with WMA (Evotherm Emulsion Technology) indicated fuel savings of 23% and 55% [10].

Middleton (Lafarge Canada) reported a reduction in temperature of 41°C for WMA (Double Barrel Green) compared to HMA and a corresponding reduction in fuel consumption of 24%. With estimated natural gas prices in the region, Middleton calculated that the 24% reduction in fuel for WMA would result in a savings of \$0.76 per ton of mix produced [11].

Kristjánssdóttir provided detailed, theoretical cost calculations based on energy consumption and pricing for HMA [7]. An abbreviated form of the data from his calculations is shown in Table 6.

TABLE 6 Estimated Fuel Cost Comparison for WMA and HMA (after Kristjánssdóttir)

Location	Iceland	Hawaii	Illinois
Fuel	#2 Fuel Oil	Diesel	Natural Gas
Fuel Use per T on HMA	2-3 gal.	2-3 gal.	2.5-3.5 therms
Fuel Cost	\$2.50/gal.	\$2.20 - \$3.00/gal.	\$0.75/therm
Fuel Cost per ton HMA	\$5.00 - \$7.50	\$4.40 - \$9.00	\$1.88 - \$2.62
WMA Fuel Savings			
@20% reduction	\$1.00 - \$1.50	\$0.88 - \$1.80	\$0.38 - \$0.52
@35% reduction	\$1.75 - \$2.63	\$1.54 - \$3.15	\$0.66 - \$0.92
@50% reduction	\$2.50 - \$3.75	\$2.20 - \$4.50	\$0.94 - \$1.31

The fuel savings for WMA compared to HMA will depend largely on the temperature differential between the two mix types (i.e., how much cooler can the plant be operated for WMA) and the differential in moisture reduction in the aggregate. Depending on these factors, the contractor should expect to at least experience a fuel savings of \$0.38 per ton of WMA produced to a high end savings of \$4.50 per ton of WMA produced.

Middleton, in their literature, also provides a summary table of potential costs for various WMA technologies. This information is presented in Table 7.

TABLE 7 WMA Technology Costs (after Middleton)

Economic Component	WMA Technology					
	Evotherm®	Sasobit®	Aspha-min® (Zeolite), Advera (Zeolite)	Low Energy Asphalt (LEA)	WAM Foam®	Double Barrel® Green ¹
Equipment Modification or Installation Costs	\$1,000-\$5,000	\$5,000-\$40,000	\$5,000-\$40,000	\$75,000-\$100,000	\$60,000-\$85,000	\$100,000-\$120,000
Royalties	None	None	None	N/A	\$15,000 first yr / \$5,000 per plant / \$0.35 / t	None
Cost of Material	\$35-\$50 premium on Binder	\$1.75/kg	\$1.35/kg	None	\$75 premium on Soft Binder	None
Recommended Dosage Rate	30% Water / 70% AC	1.5-3% by weight of Binder	0.3% by weight of Mix	0.5% Coating additive weight of Binder	3% weight of Binder	2% Water to Binder
Approximate Increased Cost of Mix	\$3.50-\$4.00	\$2.00-\$3.00	\$3.60-\$4.00	\$0.50-\$1.00 (depending on use of coating additive)	\$0.27 + \$0.35 Royalty	None

The costs shown in Table 7 represent the approximate increase in mix cost for WMA technologies compared to conventional HMA. These costs generally seem to be in-line with the values reported from other sources. As with all products, we would expect the price to decrease as the volume increases.

From Tables 6 and 7, it is apparent that the estimated fuel savings is, at best, offset by the cost of the WMA additives at \$2-\$4 per ton. In the worst case, the WMA additives may result in an increase in mix price compared to conventional HMA.

The water-based process technologies – Double Barrel Green, LEA, and WAM-Foam – are more difficult to quantify. However, assuming just the initial investment as the cost and not the future value with interest rate, an investment of \$100,000 will require a production of approximately 55,000 to 265,000 tons of WMA to get fuel savings equivalent to the initial investment (assuming a 20% reduction in fuel consumption).

Emissions

The FHWA Report Warm-Mix Asphalt: European Practice [2] provides information from the Norwegian Public Roads Administration and LCPC (Laboratoire Central des Ponts et Chaussées) in France that reported reductions in plant emissions with WMA as follows:

TABLE 8 Comparison of WMA and HMA Stack Emissions

Emission	Reduction in Measured Emission – WMA (compared to HMA)
CO ₂	15-40%
SO ₂	18-35%
NO _x	18-70%
VOC	19-50%
CO	10-30%
Dust	25-55%

Data provided by Davidson from stack emissions testing indicates a decrease of approximately 20% for CO, CO₂, and NO_x and a slight increase in SO₂ for WMA (Evotherm Emulsion Technology) compared to conventional HMA. Stack emissions testing was conducted following the EPA protocols (see Appendix). Data is shown in Table 9. [10]

TABLE 9 Stack Emissions Data (after Davidson)

Emission Gas	Concentration		Change
	HMA	WMA (Evotherm ET)	
CO	41 ppm	33 ppm	-20%
CO ₂	2.19%	1.81%	-17%
NO _x	30 ppm	24 ppm	-20%
SO ₂	2.9 ppm	3.4 ppm	+17%

Davidson did note that the WMA data was generated after many process interruptions while the HMA data was from continuous monitoring.

Middleton also provided data in his paper on stack emissions, shown below in Table 10.

TABLE 10 Stack Emissions Data (after Middleton)

Emission Gas	Concentration		Change
	HMA	WMA (DB Green)	
CO	154 mg/m ³	138 mg/m ³	-10%
CO ₂	4.6%	4.1%	-11%
NO _x	24 mg/m ³	22 mg/m ³	-8%
SO ₂	2.1 mg/m ³	2.4 mg/m ³	+14%
Ave. Stack Temperature	109°C	92°C	-16%

As with the data provided by Davidson, there was a fairly consistent reduction in CO, CO₂, and NO_x for the WMA compared to the HMA and a slight increase in SO₂. The authors surmise in the literature that the slight increase in SO₂ may be within testing variability.

The FHWA Report Warm-Mix Asphalt: European Practice [2] also presents information indicating reduced worker exposure when placing WMA. The German Bitumen Forum in 2006 indicated that asphalt aerosols/fumes and polycyclic aromatic hydrocarbons (PAHs) were reduced 30-50% for WMA compared to HMA. Although direct comparisons are difficult because of the different sampling and testing protocols used in different countries, it is important to note that exposure data from corresponding HMA projects indicated values below the acceptable exposure limits.

This general observation is confirmed in several other sources, including a report from the Virginia Transportation Research Council in 2007 entitled Installation of Warm Mix Asphalt Projects in Virginia (Report No. FHWA/VTRC 07-R25) [12]. In this report, emissions from the laydown operations were measured for the HMA control and WMA test section (Evotherm ET). Data are shown below in Table 11.

TABLE 11 Comparison of Laydown Emissions (Virginia)

	Lab Results		ACGIH TLV ^a	NIOSH REL ^b
	HMA	WMA (Evotherm ET)		
Total Particulate Matter (TPM)	BDL ^c BDL	0.35 mg/m ³ BDL	n/a	5 mg/m ³
Benzene Soluble Matter (BSM)	BDL BDL	BDL BDL	0.5 mg/m ³	n/a

^a "ACGIH TLV" stands for American Conference of Government Industrial Hygienists Threshold Level Value

^b "NIOSH REL" stands for National Institute for Occupational Safety and Health Recommended Exposure Level

^c "BDL" indicates that the result is below detection level. For TPM the detection level is 0.28 mg/m³. For BSM the detection level is 0.0834 mg/m³.

San Antonio, Texas – August 2006

In August 2006, a WMA trial using Evotherm ET was placed in San Antonio, Texas. Details of the project, testing, and analysis can be found in the report by Button, et.al. A summary of the findings from lab testing of lab-molded samples and roadway cores is as follows [13]:

- Density of cores taken after 1 month of traffic showed no significant difference in density between the WMA and HMA sections. No further densification was apparent in the wheelpath of the WMA section (after 1 month).
- Evotherm ET WMA specimens were compacted at two different temperatures: 240°F and 300°F for laboratory testing in the Hamburg and overlay tester. Specimens compacted at 300°F performed better in the Hamburg than specimens compacted at 240°F. Almost all of the WMA specimens failed the TexasDOT Hamburg test requirements (≤ 12.5 mm rut depth at 20,000 passes). Almost all of the control HMA specimens passed the TexasDOT Hamburg test requirements.
- Although the test results indicate the potential for rutting or stripping in the WMA mix, these problems have not yet been evident in the field.
- Indirect tensile strength tests were performed during the mix design and on roadway cores for both WMA and HMA control mixes. The tensile strength of the HMA control mix was approximately 170 psi (both mix design and roadway cores). During the mix design process, the WMA mixture had a tensile strength of 60 psi. The tensile strength of the Evotherm ET roadway cores was much higher, 121-178 psi.
- Testing using the TTI Overlay Tester indicated poor performance for both the HMA control and WMA trial mixtures. There was no difference in the performance between the two mixtures.

NCAT Lab Studies

NCAT has done considerable work with laboratory testing of WMA technologies, including reports on Sasobit (NCAT Report 05-06), Aspha-Min (NCAT Report 05-04), and Evotherm ET (NCAT Report 06-02). Testing included resilient modulus, indirect tensile strength, APA rut testing, TSR, and Hamburg wheel tracking tests. In general the following table summarizes the lab performance of WMA compared to HMA.

TABLE 12 Comparison of WMA to HMA: Lab Performance (NCAT) [14]

WMA Technology	Resilient Modulus	Rutting	Indirect Tensile Strength
Sasobit	Same	Decreased ¹	Decreased
Aspha-Min	Same	Same ¹	n/a
Evotherm ET	Same	Decreased ¹	Decreased

¹ for all WMA technologies, the rutting increased compared to the HMA control when the mix temperature decreased (likely due to reduced binder aging)

NCAT Test Track

In November 2005, two WMA test sections using Evotherm ET were constructed at the NCAT Test Track. These test sections used a PG 67-22 asphalt binder, with and without the addition of 3% latex. The test sections were compared to an HMA control section using a PG 67-22 asphalt binder. After 500,000 ESALs, the reported rut depths for the Evotherm ET test sections were the same as for the HMA control section. It should be noted that the measured rut depths were practically non-existent – less than 1.5 millimeters (less than 1/16th of an inch) – for all sections.

Virginia – August 2006

In August-November 2006, three WMA test sections – two with Sasobit and one with Evotherm ET – were constructed along with control sections in Virginia. The Virginia Transportation Research Council (VTRC) reported on these projects in Report FHWA/VTRC 07-R25, Installation of Warm Mix Asphalt Projects in Virginia [12]. Field testing included density and permeability testing.

Results indicated that the use of the Sasobit additive did not cause substantial changes in volumetric properties. Measured in-place air voids and permeability were similar for the Sasobit and control HMA sections.

Laboratory rut testing was conducted on HMA controls, Sasobit, and Evotherm ET mixtures in Virginia in 2006. The APA rutting resistance of the Sasobit WMA mixtures and the HMA control mixtures was not statistically different. The APA rutting resistance of the Evotherm ET WMA mixture was higher than the corresponding HMA control mixture.

The VTRC also conducted moisture sensitivity (TSR) testing on plant-produced specimens of the HMA control mixtures and WMA trial mixtures.

Yellowstone National Park – August 2007

In August 2007, a trial project was constructed in Yellowstone National Park including an HMA control and two WMA technologies – Advera WMA and Sasobit. The average density of the HMA control was 92%. The average density for the two WMA mixtures was approximately 93.5%, without an increase in compactive effort (i.e., roller passes).

Hamburg wheel tracking tests were also conducted in cooperation with the Montana DOT. Hamburg test results indicated that the control HMA had the lowest average rut depth (5.5 mm after 20,000 passes). The Sasobit WMA had an average rut depth of 7.6 mm after 20,000 passes. The Advera WMA mixture had an average rut depth of 13.2 mm after 9,050 passes. [15]

Lufkin, TX – FM 324

A project in Lufkin, TX was constructed on FM 324 and consisted of 800 tons each of four different WMA technologies with an HMA control. The four WMA technologies used were Advera WMA, Sasobit, Rediset WMX, and Evotherm (unknown, presumed DAT). In-place densities were a little higher – approximately 0.5-1.5% – for the WMA mixtures than the HMA control.

Hamburg Wheel Tracking tests indicated that the control had the highest number of cycles to failure when using a two-hour cure (Figure 7).

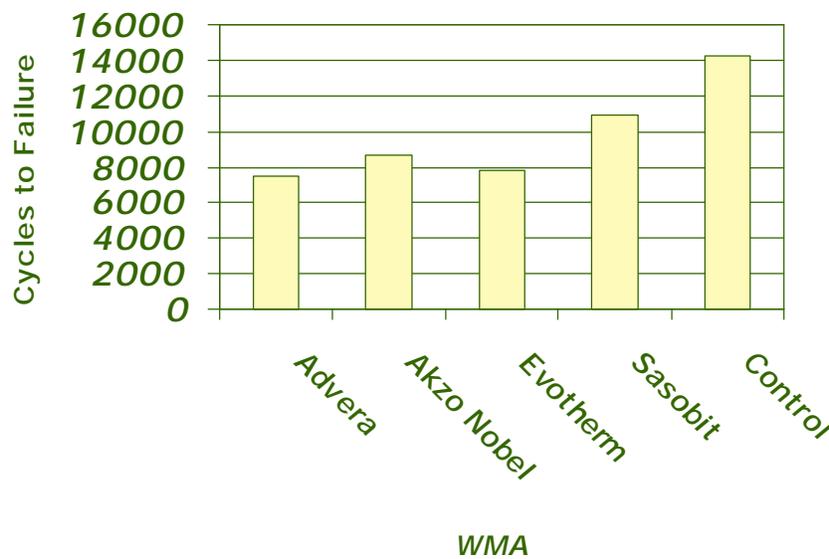


FIGURE 7 Hamburg Wheel Tracking Test Results – Lufkin, TX [16]

Lab Results – Texas Transportation Institute

Lab testing by the Texas Transportation Institute indicates that cure time, as expected, has a big influence on Hamburg wheel tracking test results (Figure 8).

Testing using the TTI Overlay Tester indicated a difference in cracking resistance for some of the WMA technologies compared to the control HMA (Figure 9).

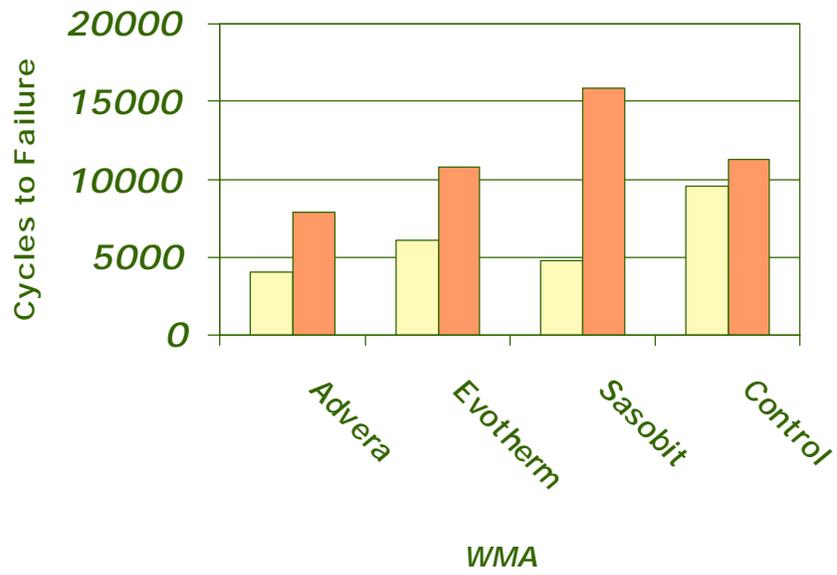


FIGURE 8 Influence of Cure Time on Hamburg Wheel Tracking Test Results [16]

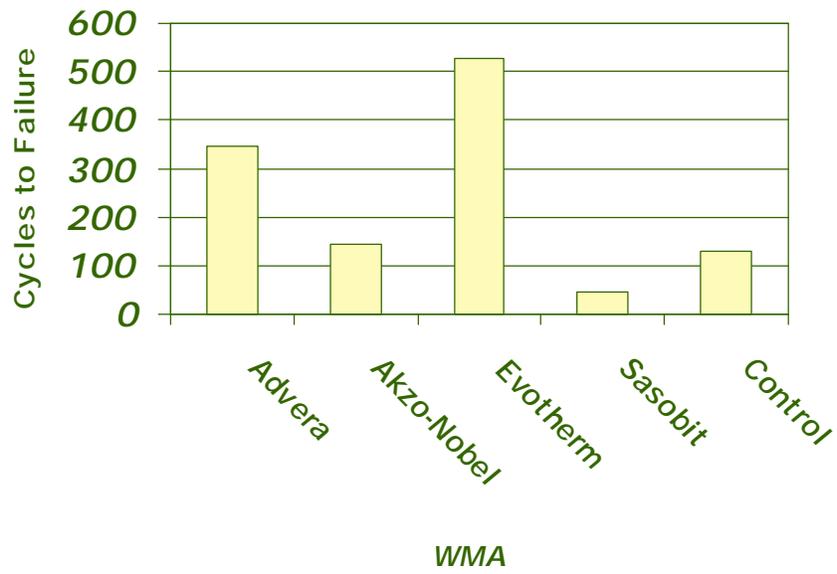


FIGURE 9 TTI Overlay Tester – Lab Study Results [16]

NCHRP 9-43 Performance Test Results

As part of the NCHRP 9-43 project, the research team sought to verify the performance test results of several field projects using dynamic modulus test data with the MEPDG to generate predicted rutting. Figures 10 and 11 illustrate the results of this testing and analysis.

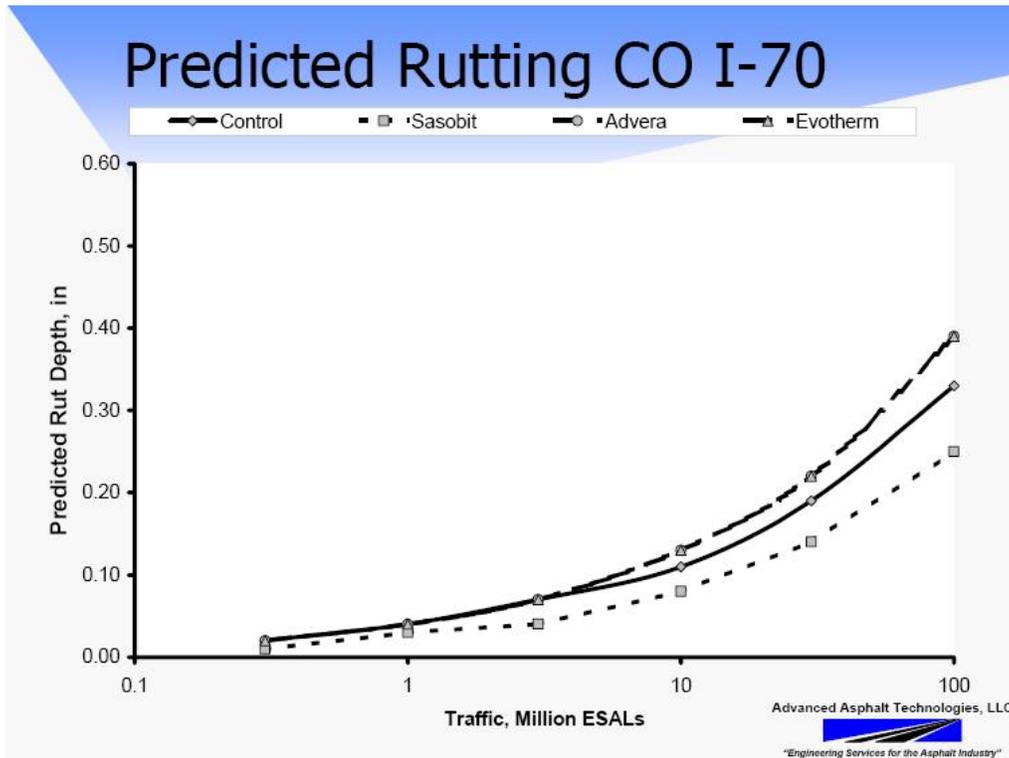


FIGURE 10 Colorado IH-70 Predicted Rutting (NCHRP 9-43) [17]

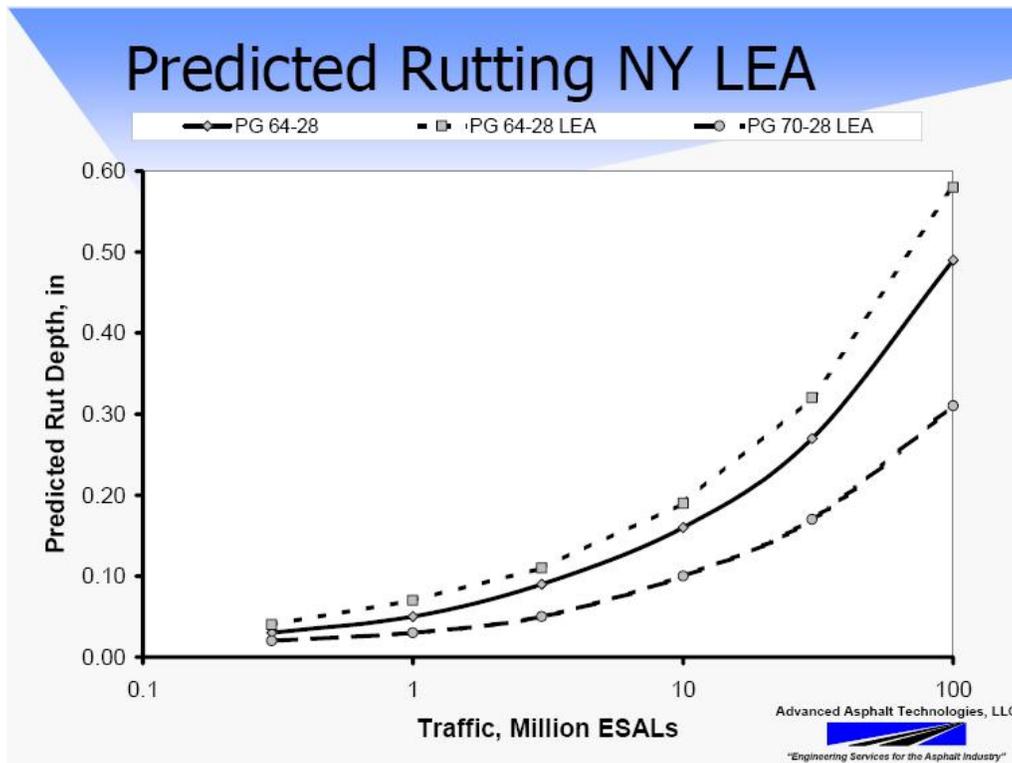


FIGURE 11 New York Predicted Rutting with LEA (NCHRP 9-43) [17]

In Figure 10, the predicted rutting is comparable for the WMA and HMA mixtures at 10 million ESALs. The Sasobit WMA mixture has slightly lower rutting than the control HMA mixture. The other two WMA technologies – Advera WMA and Evotherm ET – indicate slightly higher rutting than the HMA.

In Figure 11, the LEA process is compared to the HMA control. At 10 million ESALs, the LEA mixture indicates slightly greater rutting, but probably not significantly so, as the HMA made with the same base asphalt binder. When the LEA is produced with a higher binder grade (PG 70-28 compared to PG 64-28), the predicted rutting is significantly improved over either the control HMA or the LEA with the PG 64-28 asphalt binder.

Summary of Comparison – WMA and HMA

As noted earlier, WMA and HMA mixtures have been compared to evaluate similarities and differences in three main areas:

- Materials and production costs;
- Emissions; and
- Lab and field performance.

A comparison of the materials and production costs indicates that while WMA mixtures offer savings from reduced fuel consumption, it may not be enough to immediately offset the cost of the initial investment (in the case of the water-based process technologies) or the additives (in the case of the remaining WMA additives). This is a somewhat tricky conclusion, however, as other benefits such as increased production or late-season paving may provide additional economic incentives for WMA mixtures.

A comparison of emissions indicates unequivocally that WMA mixtures will result in lower stack emissions. The magnitude of the reduction in CO, CO₂, SO₂, and NO_x is a function of the temperature used in the production of WMA, but should be expected to be at least 10% and perhaps much higher. Data from laydown emissions is very limited in the literature, but suggests that even HMA emissions at laydown are low, often below detection, and well-controlled.

A comparison of field and lab performance indicates that in many cases WMA should be comparable to HMA. Field densities appear to be similar, with slighter ease of compaction noted for WMA mixtures. Performance testing indicates that lack of plant aging may cause the WMA mixture to be initially more susceptible to rutting, but can be alleviated somewhat with proper asphalt binder grade selection (and use of RAP). The same lack of plant aging may allow WMA mixtures to have improved cracking resistance initially compared to HMA mixtures. Moisture susceptibility testing has been conducted with mixed results. The greatest concern is the effect of residual internal aggregate moisture in WMA mixtures on stripping resistance. No major concerns have been raised in regards to in-place performance of the road when using WMA mixtures.

Implementation

Implementation is proceeding rapidly within various states as user agencies and producers are working together to evaluate the WMA technology. The cost and availability of asphalt binder have led both parties to evaluate how best to use their resources. The double benefit of lower fuel consumption coupled with a higher use of RAP seems to favor the implementation of WMA at this time.

In addition to individual state trial projects, two national research efforts are underway in the NCHRP 9-43 (Mix Design Practices for Warm Mix Asphalt) and NCHRP 9-47 (Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies) projects. These projects are coordinated to address mix design, performance testing, production, construction, and field performance of WMA.

An FHWA Technical Working Group (TWG) on warm-mix asphalt is also very active, meeting several times each year and coordinating technical guidance such as the materials and emissions testing protocols to evaluate WMA compared to HMA. The TWG also has developed a draft specification that could be used by state agencies seeking to evaluate WMA.

The National Asphalt Pavement Association (NAPA) has also been a leader in promoting the implementation of WMA in the United States. Much information can be found on their website (www.hotmix.org) as well as www.warmmixasphalt.com.

Challenges to Implementation

The FHWA document, [Warm-Mix Asphalt: European Practice \[2\]](#), lists six challenges in the implementation of WMA in the United States as follows:

Challenge 1

Make sure that the overall performance of WMA is truly as good as HMA. On a life-cycle basis, if WMA does not perform as well, there will not be long-term environmental benefits or energy savings.

Challenge 2

Address initial product approval. How do we sort out good innovative products from poor products? Accepted performance tests are needed to separate the good from the bad. The traditional practice of products and technologies being approved on a state-by-state basis needs to be changed. Products and technologies should be approved on a national, or at least a regional, basis.

Challenge 3

Address issues with existing specifications that may prohibit the use of WMA. Examples include allowing blending of binders, minimum production and placement temperatures, and minimum ambient temperatures or cutoff dates.

Challenge 4

Adapt WMA products and technologies from low-production batch and drum plants used frequently in Europe to higher production plants used in the United States.

Challenge 5

Coarse aggregate must be dry. Aggregates with low water absorption, less than two percent, are used to produce both HMA and WMA in Europe. Aggregates with much higher water absorptions are used in parts of the United States. WMA processes must be adapted to produce dry aggregates in the mix. Best practices for drying and minimizing moisture in aggregates should be encouraged, including paving under stockpiles and, in certain conditions, covering stockpiles.

Challenge 6

Individual contractors need to determine what products and technologies will work over the widest range of applications. In the past, agencies have mandated changes. In Europe, contractors have staffs who routinely conduct research to develop new products and processes. In the United States, contractors generally do not have these resources available in their own organizations. Such resources in the United States are generally found in research institutions and consultancies.

Despite these challenges, the research team generally concurs with the conclusions of the FHWA WMA Scan Team that “there are no long-term barriers to the use of WMA in the United States”. User agencies need assurance that WMA pavements will perform as well as the HMA pavements they have been using traditionally. Contractors need the flexibility of choosing WMA as an alternative to HMA – whether for reasons of cost savings, improved workability/compactability, extended paving seasons, or lower emissions and better working conditions for their employees.

CHAPTER 3 PHASE II WORK PLAN

As this research project involves full scale field trials, many of the individual experiments will be established as fractional factorial experiments. Where possible, half-factorials will be used to allow complete isolation of main effects (assuming third order interactions – and higher order interactions – are negligible). If quarter-factorial experiments are conducted, the main effects are confounded with higher-order effects.

The research plan is divided into Field Experiments and Laboratory Experiments (including asphalt binder and mixture testing), with the Field Experiments requiring the majority of the effort.

FIELD EXPERIMENTS

As identified in the task objectives, the research team will seek to identify and conduct at least two field projects per technology, with an emphasis on different climatic regions and different traffic levels. For travel and coordination purposes, the team will endeavor to identify users and producers willing to evaluate multiple WMA technologies for a single project. This will help minimize travel costs, but likely wouldn't affect testing costs.

This portion of the research involves the following:

- Identifying projects where WMA trials can be conducted in connection with HMA controls;
- Conducting pre-construction mix design and performance testing in the laboratory on project materials;
- Coordinating with user agencies and contractors to ensure that research team members are available at the start of the project for sampling and testing;
- Conducting materials sampling of WMA and HMA mixtures to include compaction of specimens on-site and collection of samples (in 5-gallon buckets) to return for later reheating and testing;
- Monitoring compaction temperatures and procedures to evaluate differences between WMA and HMA mixtures;
- Monitoring fuel usage and production rates for the WMA trials and HMA controls;
- Conducting stack tests to monitor plant emissions;
- Evaluating field emissions using industrial hygiene protocols;
- Coordinating coring and/or trenching for determination of density and permeability after construction; and
- Establishing a post-construction pavement evaluation schedule to monitor performance of the WMA trial and HMA control sections.

In Phase 2, the research team will identify WMA field projects scheduled for construction in 2009 and 2010, and identify those that are suitable for emissions testing and that include HMA control sections. At this time the research team does not have any commitments by state DOTs to conduct full-scale field projects. However, the rapidly increasing interest in WMA nationwide makes it likely that full-scale field projects can be readily identified. The goal is to conduct duplicate trials within each classification of WMA technology in different regions of the United States – likely segregated by SHRP or LTPP environmental zones: Wet Freeze; Wet No-Freeze; Dry Freeze; and Dry No-Freeze. These environmental zones line up roughly with the boundaries of the User-Producer Groups. The planned matrix should conceptually appear similar to the following (with actual WMA Technologies and Climatic Zones being potentially different):

TABLE 13 Field Project Experimental Matrix

SHRP Climate		WMA Technology			
		Technology 1	Technology 2	Technology 3	Technology 4
Dry	Freeze				
	No-Freeze				
Wet	Freeze				
	No-Freeze				

In the preceding matrix, the technology classification is not identified since we do not currently know which technology (or technologies) a state DOT may have an interest in evaluating. For logistical purposes it would be best if more than one technology could be evaluated per project. In the matrix, this would mean that a single project in a Wet Freeze climate could be found that would evaluate both Technology 2 and 3. Figure 12 shows the LTPP Environmental Zones for the United States.

Of the four technology categories – Organic Additives, Chemical Additives, Water-Bearing Additives, and Water-Based Processes – in the opinion of the research team the following are most appropriate for this research:

- Organic Additives – Sasobit and Rediset WMX (included here because it is a mixture of organic and chemical additives)
- Chemical Additives – Evotherm DAT and REVIX
- Water-Bearing Additives – Advera WMA
- Water-Based Processes – Aztec Double Barrel Green and LEA

The least practical technology for the United States may be the water-bearing additives. With both the Aspha-min and Advera WMA additives, the mechanism for reducing mix temperature is the incorporation of fine-meshed zeolite into the drum or pugmill to release internal water. The water-based processes would seem to accomplish much the goal, but

without the addition of fine-meshed material. Nevertheless, the research team will attempt to identify a field project using the Advera WMA for testing.

Although a number of organic additives exist, the research team believes that Sasobit should be the primary additive selected since it is the most heavily used and a cheaper alternative to other organic additives. The Rediset WMX additive is similar to the Sasobit, but with the addition of a chemical adhesion promoter.

Chemical additives offer an attractive package to a contractor seeking to use WMA without significantly changing plant operations. Both Evotherm DAT and REVIX can be added by in-line blending. REVIX can also be directly blended with the asphalt binder.

Water-based processes also offer the ability to use WMA without the use of additives. The Aztec Double Barrel Green and Gencor Green Machine systems require plant modifications, but once modified do not require any other special processes or additives. The LEA process requires the use of in-line blending (for the adhesion additive), and possibly a moisture monitoring system and additional cold-feed bin.



FIGURE 12 United States Environmental Zones Classified by LTPP [18]

For each project, testing of WMA trial mixtures and HMA control mixtures will include the following:

- Pre-Construction Testing
- Construction Testing – Materials

- Construction Testing – Operations
- Construction Testing – Stack Emissions Sampling and Testing
- Construction Testing – Laydown Emissions Assessment
- Construction Testing – In-Situ Properties
- Post-Construction Testing

Pre-Construction Testing

For each field project, WMA trial and HMA control mixtures will be produced in the lab and tested using performance testing procedures. WMA mix designs will be conducted following procedures developed by the NCHRP 9-43 research. The research team will review the test methods and criteria developed in NCHRP 9-43 and other relevant NCHRP projects to assess the laboratory performance properties of WMA mix designs. A more detailed description of the tests is provided in the appendix.

At this time, the research team envisions conducting the tests shown in Table 14 for each WMA and HMA mixture to be evaluated in the lab. Note that tests that are part of the draft NCHRP 9-43 mix design and analysis procedure are shown in italics.

TABLE 14 WMA Mix Design Performance Testing

Test	Test Conditions	Reps	Specimen (mm)
Rutting Hamburg Wheel Tracking (Dry) <i>Repeated Load Axial (Flow Num.)</i>	T_{high}^1 <i>T_{high}^1; unconfined²</i>	2 4	SGC (150 Ø x 63 H) <i>SGC (100 Ø x 150 H)</i>
Fatigue Cracking Disk-shaped Compact Tension Flexural Beam Fatigue <i>Cyclic Direct Tension</i>	T_{int}^3 20°C; 600 ms <i>4 and 20°C; high and low strain</i>	3 3 4 ⁴	SGC (150 Ø x 50 H) Beam (50H x 63W x 380L) <i>SGC (100 Ø x 150 H)</i>
Thermal Cracking <i>Indirect Tensile Creep/Strength</i>	0, -10, -20°C	9 ⁵	<i>SGC (150 Ø x 50 H)</i>
Stiffness <i>Dynamic Modulus</i>	4, 21, 38°C; 0.1 to 10Hz; unconfined ²	2	<i>SGC (100 Ø x 150 H)</i>
Moisture Sensitivity <i>AASHTO T-283</i>	25°C; dry, wet subsets	6	<i>SGC (150 Ø x 95 H)</i>

¹ High temperature determined based on project conditions

² Unconfined testing to be conducted unless mix type (i.e., SMA) dictates otherwise

³ Intermediate temperature determined based on project conditions

⁴ One specimen per condition; 2x2 combination of temperature and strain

⁵ Three replicates per temperature yields a total of nine tests. Strength testing is only conducted at one temperature (i.e., -10°C), so only three test specimens are needed.

- Hamburg Wheel Tracking (Rutting) – conducted dry at appropriate high temperature for the project climate. Two (2) replicates. May also be conducted wet. Response variable is rut depth at a specified number of loading cycles (e.g., 20,000 cycles).
- Repeated Load Axial – Flow Number (Rutting) – conducted using Simple Performance Tester at appropriate high temperature. Four (4) replicates. Response variable is Flow Number.
- Disk-shaped Compact Tension (Fatigue Cracking) – conducted at intermediate test temperature on modified cylindrical specimens to generate information on fracture energy. Referred to as DC(T). Three (3) replicates. Response variable is fracture energy.
- Flexural Beam Fatigue (Fatigue Cracking) – conducted on prismatic specimens at 20°C at medium-high strain levels (400-800 microstrain) to achieve an estimate of the number of cycles to failure. Three (3) replicates. Response variable is N_f (cycles to failure).
- Cyclic Direct Tension (Fatigue Cracking) – conducted using Simple Performance Tester at two temperatures (4 and 20°C) and two strain levels (high and low). Total of four (4) specimens and tests. Response variable is the inherent fatigue coefficient, K_{fv} , calculated from test data.
- Indirect Tensile Creep/Strength (Low Temperature Cracking) – conducted on cylindrical specimens at three low temperatures (usually 0, -10, and -20°C) to generate information on a mixture critical cracking temperature. Three (3) replicates per temperature; nine (9) total tests. Response variable is thermal stress curve and estimated cracking temperature.
- Modified Lottman (Moisture Susceptibility) – conducted on cylindrical specimens to generate an estimate of moisture susceptibility. Remains the standard for moisture sensitivity evaluation. Response variable is Tensile Strength Ratio.
- Dynamic Modulus (Stiffness) – conducted on cylindrical specimens at a range of temperatures and loading frequencies. A dynamic modulus mastercurve will be generated from the test data and will be used to determine $|E^*|$, the response variable, at a range of frequencies and temperatures as provided within the MEPDG software.

As the testing listed above represents a very thorough evaluation of mix properties, it may be too extensive to conduct for every single project. It is expected that the first project and set of testing for each technology will be thorough, with subsequent trials having less complete testing. Duplicate sets of tests for a single distress – like conducting DC(T) and flexural beam fatigue tests – may be unnecessary. If so, the testing matrix will be greatly reduced.

Construction Testing – Materials

Research team members will be on site to sample and compact WMA and HMA specimens immediately. A minimum of two sampling times (tonnages) per day will be used for each mixture. The compacted specimens will then be tested, if possible, at the project site to

determine volumetric properties. Remaining compacted specimens will then be shipped back to the Asphalt Institute, MTE, and/or Paragon labs for performance-related testing.

Performance-related testing of field-produced mixture will principally be conducted for two purposes:

1. To compare the engineering properties of Field-Mixed Lab-Compacted (FMLC) specimens with Lab-Mixed Lab-Compacted (LMLC) specimens (from pre-construction testing); and
2. To compare FMLC specimens with Field-Mixed Field-Compacted (FMFC) specimens at the time of construction.

To accomplish the first goal, FMLC specimens will need to be tested using the same procedures that are used in the pre-construction testing. To accomplish the second goal, FMLC specimens will need to be tested using the same procedures that are used for cores taken from the pavement after construction. These tests may be different since pavement lift thickness will likely limit testing to procedures that can be conducted on specimens that are 50 mm thick.

To keep testing at a reasonable level, only one set of performance specimens will be compacted during production of each experimental mixture (WMA and HMA). At the discretion of the research team an additional set of performance specimens may be compacted and tested if the project is sufficiently large to justify additional testing.

Table 15 shows the anticipated performance testing to be conducted for each mixture on FMLC specimens.

TABLE 15 FMLC Performance Testing (per mixture)

Specimen (mm)	Air Voids	Number	Test	Test Conditions
SGC (150 Ø x 175 H)	4%	4	Repeated Load Axial (Flow Number)	T _{high} ; unconfined
SGC (150 Ø x 175 H)	7%	2	Dynamic Modulus	4, 21, 38°C; 0.1 to 10Hz; unconf.
SGC (150 Ø x 75 H)	7%	3	Disk-shaped Compact Tension, DC(T)	T _{int}
SGC (150 Ø x 50 H)	7%	6	AASHTO T-283	25°C; dry and wet subsets

In Table 15, dimensions are compacted specimen dimensions. For the Repeated Load Axial, Dynamic Modulus, and DC(T) tests, specimens will be cored (if needed) and cut to proper dimensions for the test. Note that the AASHTO T-283 test includes a dry subset that is tested using the Indirect Tensile Strength test at 25°C – which is the same test that will be conducted

on FMFC specimens (cores). The choice to use a specimen height of 50 mm for the T-283 test on FMLC specimens permits a direct comparison of tensile strength with the FMFC specimens, but may impact the resultant tensile strength ratio and not permit a direct comparison with T-283 results from pre-construction (mix design) testing of LMLC specimens.

The percentage of air voids for the specimens in Table 15 is a target value. The research team recognizes that actual values, and tolerances, may differ from the recommendation from the NCHRP 9-43 mix analysis procedure.

Finally, the number of specimens listed in Table 15 represents the number of test specimens needed for the corresponding test. Whenever possible, an additional specimen will be compacted for each test as a replacement (backup for specimens with significantly different air voids, damage, testing error, etc.).

Reheating of Field-Produced Samples

For HMA, many agencies collect samples at the plant or paving site and bring them back for quality assurance testing of volumetric properties. Since some WMA technologies obtain lower mixing and compaction temperatures through the release of water, how will these samples differ when returned to the quality assurance lab for reheating and compaction? To address this question, samples will be compacted at the project and compared with reheated samples.

Preliminary results from the NCHRP 9-43 research indicate that reheating WMA has a similar effect on mechanical properties as reheating HMA. According to the research, there is a stiffening of the middle portion of the dynamic modulus master curve which is most sensitive to changes in binder stiffness.

Reheating WMA and compacting at a central lab may not be an option for all WMA technologies. Two such technologies are the zeolite technology and Aztec's water injection technology. Once the water is gone all that is left is the original binder which presumably has to be heated to a hotter temperature than warm mix for compaction. Other technologies such as the organic additives (i.e., Sasobit) and other processes do lend themselves to being reheated at some reduced temperature (~ 230°F) and then compacted. However, not all technologies are similarly forgiving.

To evaluate if reheating is an option for WMA mixtures, additional mix will be sampled during construction and sealed in 5-gallon buckets for return to the lab. The mix will then be reheated and split to an appropriate sample size. Specimens will be compacted in the SGC to determine volumetric properties. Specimens will also be compacted for testing in the SPT using the same tests – dynamic modulus and repeated load axial tests – to evaluate if reheating and re-compacting of WMA specimens produces the same engineering properties as WMA specimens that were compacted immediately at the project site.

Residual Mixture Moisture

The research team opinion is that residual moisture in the mix is not the main issue often related with the moisture sensitivity of WMA, since all mixes acquire and/or retain moisture due to environmental factors. It is not the residual water that causes problems in WMA mixtures, but the possible reduction in bond strength due to the lower temperature in the as-produced mix. The research team members will check moisture at the time of laydown to confirm that the WMA and HMA mix is at or below 0.5% moisture.

Construction Testing – Operations

In addition to materials testing, the research team will collect information on the energy consumption of WMA trial mixtures and HMA control mixtures during plant production, laydown, and compaction. Material costs will also be collected so that the total production costs (materials and construction) can be calculated for the WMA trial mixtures and HMA control mixtures. The two documents produced by the WMA Technical Working Group – “Material Test Framework for Warm Mix Asphalt Trials” and “Documenting Emissions and Energy Reductions of WMA and Conventional HMA” – will be used as guidelines in evaluating operational differences between WMA and HMA. These documents are included in the Appendix.

To validate the concept that more consistent densities are achieved for WMA compared to HMA because of increased mat coverage, the research team has discussed the possibility of using rollers equipped with GPS to monitor compaction patterns. The research team will work with the contractors for the field projects to determine if this option is available. At the least, a measurement of density will be taken and compared after an equal number of passes to determine if higher density is achieved with the WMA for the same compactive effort.

Construction Testing – Stack Emissions Sampling and Testing

For emissions testing, the number of tests is defined in the TWG protocol described above. For stack testing, it is recommended that two or three 60-minute stack samples be conducted per mix.

Stack testing will follow the EPA-recommended test procedures historically used for HMA, including:

- Stack Gas Volumetric Flow Rate (USEPA Method 2);
- Stack Gas Temperature and Moisture Content (USEPA Method 4);
- NO_x Emissions (USEPA Method 7E);
- CO₂ Emissions (USEPA Method 3A); and
- VOC Emissions (USEPA Method 25A)

In addition, the research team believes that other emissions may need to be measured including carbon monoxide (CO) and formaldehyde. Levels would increase for both of these if incomplete fuel combustion occurs during plant operations – a problem that could arise from the lower operating temperatures used for WMA compared to HMA. This potential problem could also be simply a result of the burner not being properly tuned for its intended operation. The research team will discuss this possibility with the plant manager before WMA production begins to ensure that he/she understands the importance of having the burner properly tuned for production of WMA.

With both stack and paver testing, the total recommended test period is from 3-4 hours. In past WMA trials, MTE has conducted monitoring by producing one mix type (either WMA or HMA) in the morning and the other mix type in the afternoon. Although the testing time is tight, this process allows the research to minimize the number of other variables – such as weather effects – that could confound the test data.

Construction Testing – Laydown Emissions Assessment

In the initial work plan, the research team envisioned conducting worker exposure in addition to laydown emissions assessments. Laydown emissions are determined from monitoring in the area near the paving operations. To evaluate field emissions of warm mix asphalt compared to HMA, at least one, and preferably two, 3-4 hour sampling events are recommended for each mix.

As the standard, NIOSH Method 5042 will be used to measure total particulate matter (TPM) and benzene soluble matter (BSM) from emissions captured from the monitors. In addition, the Nitration Mutagenicity Assay will be used to supplement the NIOSH procedure. Since the Nitrated Mutagenicity Index is a relatively new procedure, the more common, standard mutagenicity index (MI) test will also be performed if enough sample can be collected.

In addition to area monitoring and testing by NIOSH 5042 to determine TPM and BSM, the research team will also utilize a portable gas chromatograph (GC) to collect relative emission data of total organics between HMA and various types of WMA mixtures. The portable GC has been used by MTE Services to evaluate and compare WMA and HMA projects constructed by Mathy Construction, most recently during September of 2007. The output data shown below illustrates relative amounts of total organics collected in the auger area of the paver and on the mat approximately 2 to 3 feet behind the paver. This figure was generated showing relative data for a project. “Total Counts per Second” reflects the total organics detected by the GC. It is easy to see from this plot the reduction in volatile organic compounds (VOCs) coming off the mix at its warmest temperature in the auger area of the paver, and then on the mat in very close proximity to the paver laydown.

The problem with area sampling is that there is no historical data indicating acceptable levels of TPM and BSM for an area; acceptable levels are based on personal exposure. The

best that this research can achieve from area samples is a relative indication of any reduction in TPM and BSM resulting from the use of WMA compared to HMA.

On the other hand, the problem with personal sampling is that the exposures that have been reported are so low as to be practically undetectable according to the test protocols. For HMA, personal exposure is generally considered to be low and well-controlled. Given that independent testing (not cited) has indicated that there is an approximate 60% reduction in total organic material for WMA compared to HMA, it is the opinion of the research team that individual worker sampling conducted during WMA production would generate results at or below detectable levels, rendering the sampling and testing ineffective.

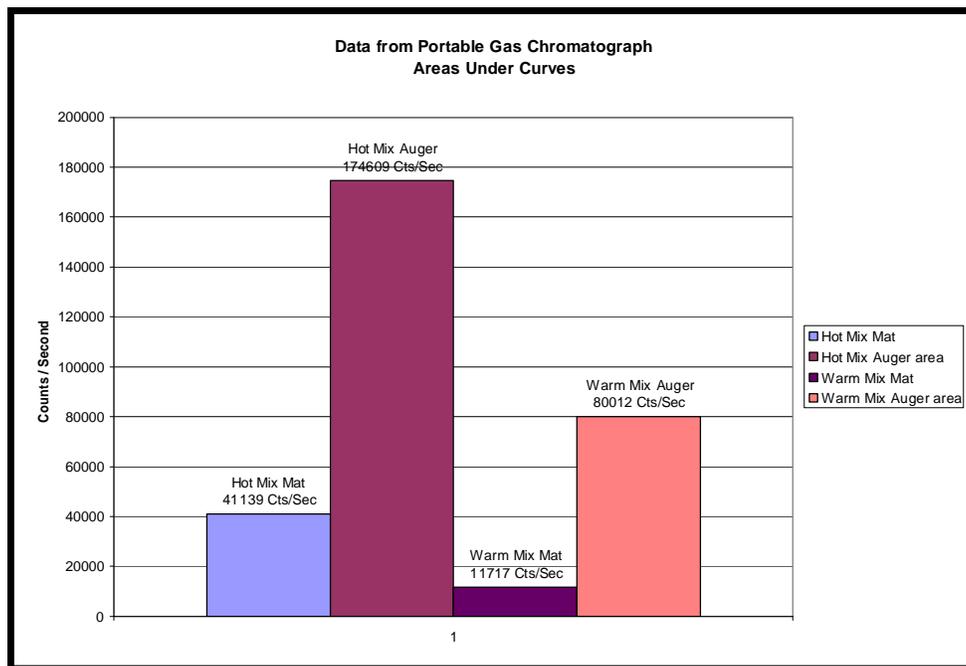


FIGURE 13 Use of Portable Gas Chromatograph (GC) Data to Quantify Total Organics

Construction Testing – In-Situ Properties

The research team will conduct the following in-situ pavement testing:

- Select five cross-sections of the pavement for each mix.
- Conduct testing at five locations across the mat as follows: one test across the construction joint and then 50 and 200 centimeters on either side of the joint.
- At each test location: (1) determine in-situ permeability using an air induced permeameter; (2) determine in-place density using the PQI gauge; and (3) obtain a 150 mm diameter core. This is illustrated in Figure 14.

- Conduct lab testing on the five cores at each cross-section to determine density and lab permeability. The bulk specific gravity of the cores will be determined using the CoreLok device and by conventional SSD testing. After lab permeability testing, two or more cores will be broken down and mixed to generate a sample for maximum theoretical specific gravity testing. This testing will enable a determination of the air voids in the cores.
- At one of the five cross-sections, take an additional twelve (12) cores as shown in Figure 15. These cores will be used for initial performance testing to provide a baseline for post-construction properties.
- Each of the twelve cores will be tested as follows (illustrated in Figure 16):
 - Between Wheel Path Cores (6) – three cores will be tested using the indirect tensile strength test at 25°C (50 mm/min.) and three cores will be tested to determine bond strength. The bond strength test to be used has yet to be determined. Research by NCAT in 2005 and the NCHRP 9-40 research, *Optimization of Tack Coat for HMA Placement*, will be considered before selecting a test procedure.
 - Wheel Path Cores (6) – as with the set of Between Wheel Path specimens, three cores will be tested using the indirect tensile strength test at 25°C (50 mm/min.). The remaining three cores will be tested using the disk-shaped compact tension test, DC(T), at intermediate temperature to evaluate fracture energy.

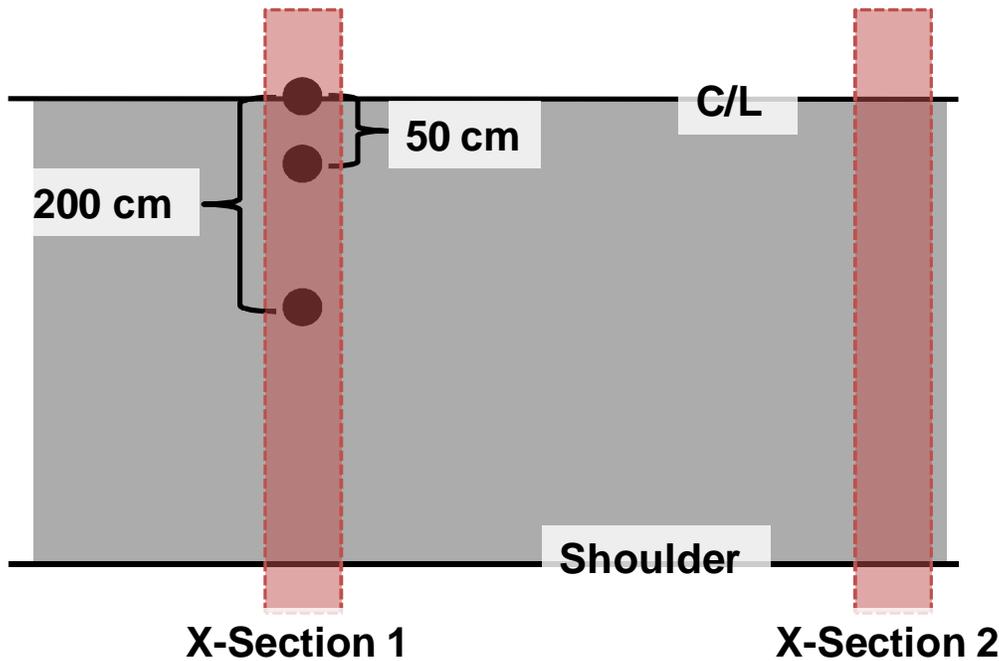


FIGURE 14 In-Situ Testing of WMA and HMA Sections

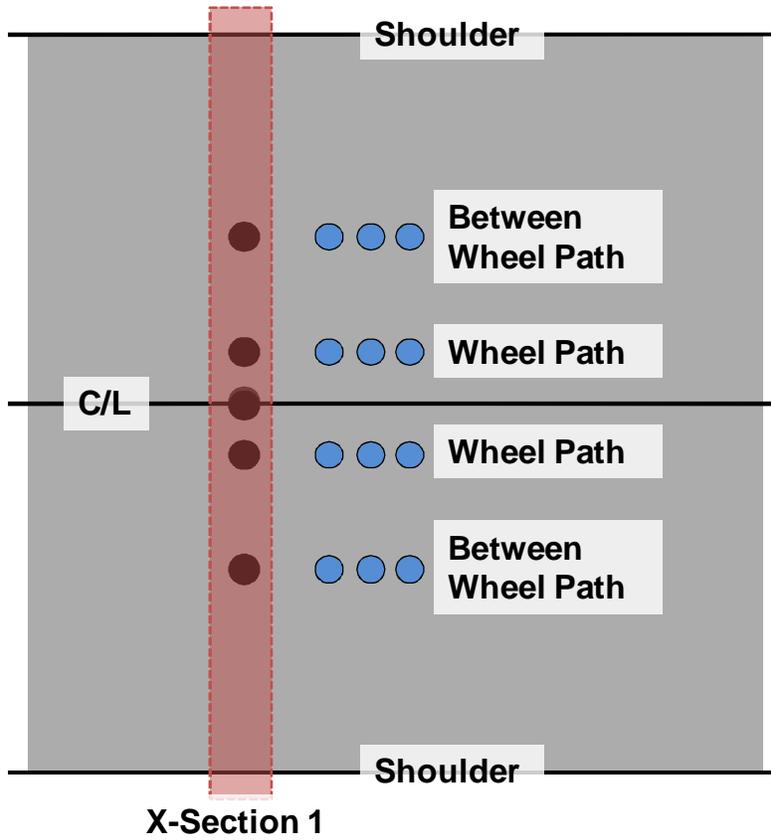


FIGURE 15 Field-Mixed Field-Compacted Cores for Performance-Related Testing

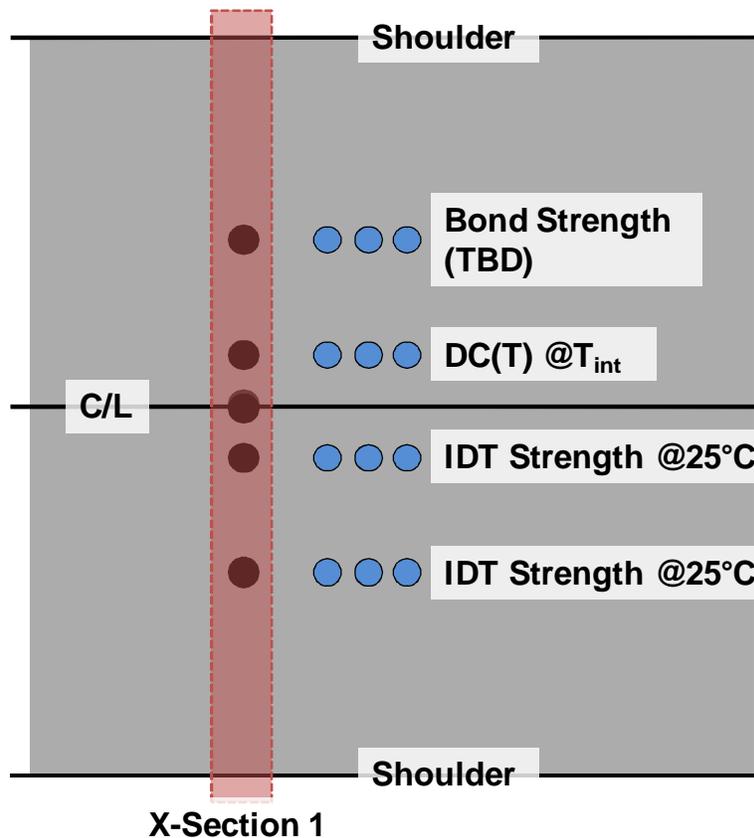


FIGURE 16 Performance-Related Testing of Field-Mixed Field-Compacted Cores

The purpose of the testing pattern is to compare both the overall compactability between the WMA and HMA sections along with the performance of the construction joint. The permeability testing will provide information relating to the potential susceptibility of each mix to moisture intrusion and damage. This plan for in-situ testing is the same as has been successfully used by the Kentucky Transportation Center on other field projects. Choosing five cross-sections ensures that the density and permeability of the mix can be evaluated longitudinally as well as laterally.

The additional twelve cores described in Figures 15 and 16 will provide initial performance-related data of the mix and provide a baseline for comparison with future testing.

Post-Construction Testing

Immediately after construction, the research team will extract, recover, and PG grade the binders including MSCR (multiple stress creep recovery) testing. FTIR testing will be conducted on the recovered binder to determine carbonyl and sulfoxides concentration. In addition to

FTIR, the T_g will be determined using modulated DSC (differential scanning calorimetry) to assess changes in low temperature properties.

The usefulness of GPC for characterizing wax additives is the subject of a study by the Asphalt Binder Expert Task Group. Research team members Gerry Reinke (MTE) and Gaylon Baumgardner (Paragon) are members of that study and will provide information on GPC use for evaluation of additives to the rest of the research team. As such, this research will not use GPC for tracking changes in WMA additives over time, with the exception of the organic additives.

Per the 2006 Draft Material Test Framework developed by the WMA Technical Working Group, additional coring will be planned for 3, 12, and 24 months. Coring will occur at the same location as the initial coring. Follow-up testing will mimic the testing done at initial construction. The testing schedule is shown in Table 16 with the numbers in the table corresponding to the number of cores tested at each post-construction time. This testing will allow a determination of the change in compaction from the initial construction and will provide an indication of the changes in performance-related properties as a function of time.

TABLE 16 Post-Construction Testing of WMA and HMA Sections

Test	Location ¹	Temperature	Post-Construction Time, mos.		
			3	12	24
Bond Strength	BWP	TBD	3	3	n/a
IDT Strength	BWP	25°C	3	3	3
	WP		3	3	3
DC(T)	WP	T_{int}	3	3	3
IDT Creep ² Strength	BWP	0, -10, -20°C -10°C	n/a	n/a	3 (9 tests) (3 tests)

1 Core location defined as Between Wheel Path (BWP) or in the Wheel Path (WP)

2 IDT Creep/Strength testing can be conducted on 3 cores by running creep tests first followed by strength tests

LABORATORY EXPERIMENTS

In addition to the field experiments, some lab experiments are also expected to address mix design and testing questions. Specifically, the following lab experiments are envisioned:

- Lab experimentation to recommend any necessary changes in extraction/recovery procedures of WMA mixtures;
- Lab experimentation to review the NCHRP 9-43 preliminary mix design method and recommend any changes; and
- Lab experimentation of aging protocols for WMA mixtures and binders (if in conflict with AASHTO M320).

The actual lab experiments conducted will depend on the findings of the NCHRP 9-43 research, which also has conducted a short-term aging experiment. Preliminary results from the Colorado I-70 field project – which used Advera WMA, Sasobit, and Evotherm (ET) technologies – indicates that two hours at compaction temperature appears to reasonably estimate the volumetric and mechanical properties of WMA and HMA at the time of construction. It should be noted that this is very preliminary data that will need to be further validated. The research team will work with the NCHRP 9-43 research team to ensure that the issue is properly addressed and that duplication of effort doesn't occur.

Extraction/Recovery Testing of WMA Mixtures

Simple lab experimentation is needed to ensure that WMA mixtures can be treated in the same manner as HMA mixtures using extraction and recovery procedures. This lab work will confirm that WMA binders can be successfully extracted and recovered without significantly affecting their rheological properties.

For the organic and chemical additives, a sample of the additive will be direct-blended with the asphalt binder. The blended asphalt binder will then be sampled for testing before blending with the aggregates. Once mixed, the WMA mixture sample will be split and: (1) allowed to cool to room temperature and (2) subjected to two hours of short-term oven aging at the compaction temperature before being allowed to cool to room temperature.

The blended asphalt binder will be tested in its original, unaged state and after short-term aging using the RTFO operating at the compaction temperature rather than 163°C. An experimental matrix is shown in Table 17 for the mixtures. Table 18 presents the experimental matrix for the asphalt binders. The nominal maximum aggregate size (NMAS) and asphalt binder content will be the same for all mixes.

In addition to the WMA portion of the experiment, the same procedures will be conducted for the base (unblended) asphalt binder and HMA mixture. This will provide a baseline on the understanding of the effects of extraction/recovery procedure on asphalt binder rheological properties.

TABLE 17 Extraction/Recovery Experiment for WMA Mixtures

		WMA				HMA	
		Sasobit		REVIX		NONE	
Agg Abs.	Aging	PG 58-28	PG 76-22	PG 58-28	PG 76-22	PG 58-28	PG 76-22
Low <1%	0	X	X	X	X	X	X
	2 hrs CT	X	X	X	X	X	X
High >2%	0	X	X	X	X	X	X
	2 hrs CT	X	X	X	X	X	X

TABLE 18 Extraction/Recovery Experiment for WMA Binders

Condition	Aging	WMA				HMA	
		Sasobit		REVIX		NONE	
		PG 58-28	PG 76-22	PG 58-28	PG 76-22	PG 58-28	PG 76-22
Original	None	X	X	X	X	X	X
	RTFO	X	X	X	X	X	X
After Rec.	None	X	X	X	X	X	X
	RTFO	X	X	X	X	X	X

In Table 17, aggregate absorption is defined as “Low” if the combined absorption is less than 1%. “High” absorption is defined as a combined water absorption greater than 2%.

If testing is conducted for all the cells in Table 17, then there will be a total of 24 extraction/recovery procedures conducted and samples that are subsequently tested. Since the WMA part of the experimental matrix is a 2⁴ factorial it is possible to design the experiment as a half-factorial and still isolate all main effects. This will change the total testing from 24 to 16 tests (assuming the HMA portion is maintained as a full 2³ factorial). A similar approach can be taken in Table 18.

The factorial can also be expanded if different additive levels are added. Sasobit has been typically used at a lower treatment level in the United States than in Europe.

The mix samples will then be extracted using AASHTO T 164 (Method A) and recovered using the AASHTO T319 procedure with a toluene/ethanol solvent. The extraction procedure in AASHTO T164 Method A is preferred over the AASHTO T319 extraction procedure because it is simpler and can, if needed, use a larger sample size to produce more recovered sample. The AASHTO T319 recovery procedure, however, is preferred over the ASTM D5404 recovery procedure (Rotavapor) since it uses a lower temperature (100°C compared to 140°C) and a higher vacuum during the recovery procedure. This could be very important for WMA.

In Table 18, RTFO aging will be conducted at the appropriate compaction temperature. For HMA this may be different than the standard procedure (163°C). The “Condition” variable refers to the state of the asphalt binder before beginning further aging or testing. In the “Original” condition, the asphalt binder is sampled and tested as is. For the “After Rec.” condition, the asphalt binder is subjected to the AASHTO T319 recovery procedure before further testing. In this case, the asphalt binder is blended with the appropriate amount of solvent (toluene/ethanol) that would normally be used in the extraction procedure. The resulting effluent will then be treated as if it had been produced during the extraction process.

Binder testing will consist of temperature/frequency sweep testing to generate a master curve. The main response variable will be G* at the binder grade temperature and AASHTO M320 specification frequency (10 rad/s).

Aging Protocols for WMA

The aging procedures for performance testing of HMA described in AASHTO R30 require that the loose mix is aged for four hours at 135°C (short-term aging). For long-term aging, the research recommends aging compacted specimens for 5 days at 85°C. The short-term aging procedure is intended to simulate the aging experienced by an HMA mixture as it goes through production and short-term aging in service. With significantly lower production temperatures, it appears likely that WMA mixtures should have a different aging procedure.

As noted earlier, the NCHRP 9-43 research is engaged in an experiment to evaluate short-term aging procedures for WMA. The research team will work with the NCHRP 9-43 research team to ensure that this issue is adequately addressed.

The long-term aging procedure may not need to be changed since it is intended to represent climatic aging irrespective of production temperatures and initial aging. To validate the long-term aging procedure, an additional experiment will be conducted similar to the Kemp experiment reported in 1981 (shown in Figure 17).

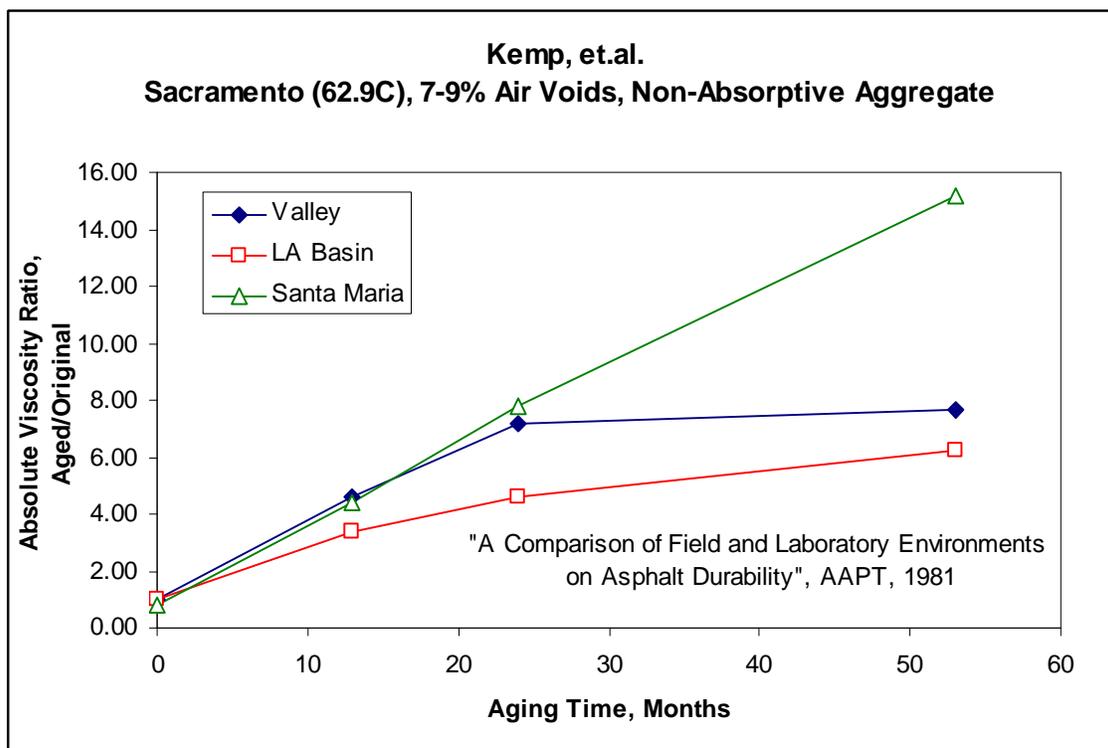


FIGURE 17 Change in Binder Viscosity as a Function of Aging [19]

In the experiment, lab-mixed, lab-compacted specimens will be prepared using two different WMA technologies. Before compaction, the WMA will be aged using the recommended short-term oven aging procedure – currently 2 hours at compaction temperature.

Twelve specimens (150-mm diameter) will then be compacted in the SGC to a height of approximately 170 mm. Six specimens will be stored in a frame and placed outside in an undisturbed area. Two of the remaining specimens will be cored and cut to test specimen dimensions of 100-mm diameter by 150-mm height and will have dynamic modulus testing conducted, as described in the pre-construction section. Two specimens will be subjected to long-term oven aging at 85°C for two days prior to specimen preparation and dynamic modulus testing. Two specimens will be subjected to long-term oven aging at 85°C for five days prior to specimen preparation and dynamic modulus testing.

The six specimens placed outside will stay undisturbed until they reach their testing age. Two specimens will be tested after 6 months; two specimens will be tested after 12 months; and the final two specimens will be tested after 24 months. Test results will be compared between the lab-simulated and environmental long-term aging specimens.

Based on testing conducted by MTE, recovery and testing of the binder after the specimens are aged shows that substantial mix stiffening occurred after 5 days of aging. Based on this work, a long-term aging procedure (compacted specimens) of 2 days at 85°C is recommended to simulate long-term aging in the field. This could be validated by conducting testing on materials from field projects.

Lab Compaction

As observed by the Asphalt Institute and other researchers, the laboratory compaction temperature generally has no significant effect on the volumetric properties of an HMA specimen compacted using the Superpave gyratory compactor [20]. Unlike Marshall compaction, which uses impact compaction and imparts a fixed amount of energy to the specimen during the compaction process, in the SGC the mix is forced to densify through a combination of vertical pressure, angle of gyration, and rotation. As a result, mix stiffness is irrelevant to the SGC in the compaction process (assuming that the frame compliance of the SGC is low). Research performed at the Asphalt Institute in 1995 (published in Transportation Research Record 1543) validates this lack of sensitivity to temperature. In the experiment a mix made with two different asphalt binder grades (PG 64-28 and PG 76-28) was compacted at a range of temperatures from 120°C to 180°C. With the exception of the PG 76-28 mixture compacted at 120°C, the percentage of air voids in both mixes, although different from each other, was not significantly affected by compaction temperature.

Since SGC compaction appears to be insensitive to temperature for HMA specimens, it stands to reason that the same could be true for WMA specimens, with the caveat that higher compaction temperatures for some WMA technologies would change the amount of water present during compaction. At this point a variable volume of water in the specimen would have the same effect as changing asphalt binder content (which does affect volumetric properties). The ease of compactability seen in the field could then potentially be identified by the level of initial compaction (N_{initial}). Compactability may also be aided by a higher volume of effective asphalt binder. At a lower compaction temperature, but with the same residual asphalt binder

stiffness, it is likely that a higher effective volume of asphalt binder will be available in the mixture – particularly for absorptive aggregates. This will result in the presence of more liquid in the mix specimen, thus making a higher G_{mb} and lower percentage of air voids. In this instance, applying HMA volumetric requirements and compactive effort equally to WMA may result in a lower design asphalt binder content.

Once again, the research team will coordinate any research on this issue with the NCHRP 9-43 research team. Currently, the NCHRP 9-43 research is considering the use of a compactability parameter in the WMA mix design procedure. In the draft mix design practice, the research team indicates that $N_{initial}$ may be used to ensure that the WMA mixture is sufficiently compactable.

PRODUCTS GENERATED FROM PHASE 2 RESEARCH ACTIVITIES

The field and lab experiments in Phase 2 are intended to provide information that can be used by the research team to complete the following implementation tasks (Table 19). These tasks, along with the results of the field and lab experiments, directly relate to the project objectives. The relationship between the Phase 2 research and the objectives is shown in Table 20.

TABLE 19 Implementation Tasks Resulting from Research

Task	Activity	Participating Team Members
7	Evaluate and Prepare Recommendations for Any Necessary Modifications to the Preliminary WMA Mix Design Procedure from NCHRP Project 9-43	Anderson, Reinke, Baumgardner, Blankenship, W. Jones, Dukatz, Scherocman
8	Prepare Draft AASHTO Practice on Lab Evaluation of WMA; Prepare Practical Guidelines to Address Differences Between WMA and HMA Production and Construction	Anderson, Reinke, Baumgardner, Blankenship, W. Jones, Dukatz, Scherocman, Graves, Fisher, Ashurst
9	Recommend Any Necessary Revisions to the Emissions Measurement Protocol	Anderson, Reinke, Baumgardner, Arp, Glidden, Blackburn

TABLE 20 Relationship Between Planned Field/Lab Experiments and Project Objectives

	Objective			
	Establish relationships among engineering properties of WMA binders and mixes and the field performance of pavements constructed with WMA technologies	Determine relative measures of performance between WMA and conventional HMA pavements	Compare production and laydown practices and costs between WMA and HMA pavements	Provide relative emissions measurement of WMA technologies as compared to conventional HMA technologies
Experiments/Testing				
<i>Field</i>				
Pre-Construction	X	X		
Construction – Materials	X	X		
Construction – Operations			X	
Construction – Stack Emissions				X
Construction – Laydown Emissions				X
Construction – In-Situ	X	X	X	
Post-Construction	X	X	X	
<i>Lab</i>				
Aging – STOA	X			
Aging – LTOA	X			
Extraction/Recovery	X			
Compactability	X			

Final Report

The final report will be generated from the findings of the research that:

1. Documents the lab experiments and significant findings regarding WMA testing and analysis.
2. Documents the results of emissions testing and analysis for field projects incorporating WMA technologies and compares the results to HMA controls.
3. Documents performance-related mix and binder properties determined on as-produced samples of various WMA technologies and compares results to the HMA controls.
4. Critically reviews material testing and emissions testing protocols for WMA technologies and provides recommended guidelines for field testing of WMA technologies.

5. Provides guidelines for conducting a laboratory evaluation of the performance of WMA, including recommended modifications to the preliminary WMA mix design procedure developed as part of the NCHRP 9-43 project.
6. Recommends any necessary changes to AASHTO tests, practices, and specification needed to make the standards applicable for WMA.
7. Provides guidelines for the production and construction of WMA for the various technologies studied.
8. Includes a CD-ROM containing a database of all experimental results.

CHAPTER 4 PROJECT ADMINISTRATION ACTIVITIES

Project Funding and Timeline

Project expenditures have been under expectations through this point in the research. To date, approximately \$31,000 has been spent. With the exception of one subcontractor, no research invoices have yet been. It is expected that total expenditures in Phase 1 will increase as these bills are submitted. Original projections indicated expenditures of \$94,700 in Tasks 1-5. A progress schedule is included in the appendix representing progress through September 30, 2008.

The project is slightly behind schedule as the research team anticipated completing the Interim Report by the end of September. The NCHRP panel meeting is tentatively scheduled for November 24, 2008. If the panel approves continuation of the research project, then Phase 2 of the research could begin in December 2008. With 33 months remaining at that time, the research team should still have ample time to complete the field and lab experiments described in Chapter 3.

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In addition to the References listed above, an excellent bibliography can be found in the National Asphalt Pavement Association's QIP 125, Warm-Mix Asphalt: Best Practices.

SELECTED WEBSITES

WMA Technologies

Advera WMA	www.pqccorp.com/Products/adverawma.asp
Aspha-min	www.aspha-min.de/en/index
Asphaltan-B	www.romonta.de/ie4/english/Romonta/i_start.htm
Double Barrel Green	www.astecinc.com/products/drying_mixing/db_mixers/default_green.htm
Evotherm	www.meadwestvaco.com/Products/MWV002106
Green Machine	http://gencorgreenmachine.com/index.html
LEA	www.mcconnaughay.com/lowemissionasphalt_intro.php
Rediset WMX	www.surfactants.akzonobel.com/asphalt/newwarmmixsystem.cfm
REVIK	n/a
Sasobit	www.sasolwax.com/Sasobit_Technology.html
WAM Foam	www.shell.com/home/content2/bitumen-en/about_shell_bitumen/sustainable_development_wamfoam_0112.html

Warm Mix Asphalt	www.warmmixasphalt.com
National Center for Asphalt Technology	www.eng.auburn.edu/center/ncat/
National Asphalt Pavement Association	www.hotmix.org
Federal Highway Administration	www.fhwa.dot.gov/pavement/asphalt/wma.cfm
Asphalt Institute	www.asphaltinstitute.org
US Environmental Protection Agency	www.epa.gov
US Geological Survey	www.usgs.gov
US Energy Information Administration	www.eia.doe.gov
American Lung Association	www.lungusa.org

APPENDIX A

WMA Trial Projects (listed by State or Province)

NCHRP 9-47

Project Name	City	State	Date	Technology	Binder	NMAS	Aggregate	Compaction	Design	RAP	Tonnage
NCAT Test Track	Opelika	AL	2005-10	Evotherm ET	PG 76-22	12.5	Granite/Limestone	SGC	80	0	150
NCAT Test Track	Opelika	AL	2005-11	Evotherm ET	PG 67-22	9.5	Granite/Limestone	SGC	80	0	100
US 79	Birmingham	AL	2007-08	Evotherm DAT	PG 67-22	12.5	Limestone, Slag	SGC	60	15	2000
Grogers Group	Little Rock	AR	2008-06	Evotherm 3G	PG64-22		limestone			0	
Fisher	Phoenix	AZ	2007-03	Evotherm DAT	PG70-10		River Rock			0	
Private	Vancouver	BC	2007-10&11	Double Barrel Green	80-100 Pen	9.5	Gravel	Marshall	75	25	2235
Montague Expressway	San Jose	CA	2006-10	Sasobit	PG 64-16	19	Granite	Hveem		0	330
	Chico	CA	2007-11	Rediset WMX	PG 64-10						
I-70	Silverthorne	CO	2007-07&08	Evotherm ET	PG 58-28	9.5	Gravel	SGC	75	0	1000
I-70	Silverthorne	CO	2007-07&08	Sasobit	PG 58-28	9.5	Gravel	SGC	75	0	1000
I-70	Silverthorne	CO	2007-07&08	Zeolite (Advera WMA)	PG 58-28	9.5	Gravel	SGC	75	0	1000
Private	Orlando	FL	2004-02	Zeolite (Aspha-min)	PG 67-22	12.5	Granite	SGC	75	20	112
Private	Daytona Beach	FL	2007-10	Double Barrel Green	PG 64-22, RA800	9.5	Limestone, NatSand	SGC	75	40	600
US 92	Lakeland	FL	2007-10	Evotherm DAT	PG 76-22	12.5	Granite	SGC	100	15	2000
SR 11	Daytona Beach	FL	2007-12	Double Barrel Green	PG 64-22	12.5	Granite	SGC	75	40	1100
Reeves	Macon	GA	2008-04	Evotherm 3G	PG67-22		?			15	
Reeves	Macon, GA	GA	2008-08	Evotherm 3G	PG67-22		Granite ?			15	
SR 33	Lawrenceville	IL	2007-08	Evotherm DAT	PG 64-22	9.5	Limestone	SGC	75	0	2500
900E	Brownsburg	IN	2005-07	Evotherm ET	PG 64-22	12.5	Dolomite	SGC	100	15	660
Scotty's	Bowling Green	KY	2008-07	Evotherm 3G	PG76-22		limestone			0	
Scotty's	Bowling Green	KY	Sept / Oct	Evotherm 3G	pg76-22						
SR 28	Montgomery Co.	MD	2005-06	Sasobit	PG 64-22	19	Serpentenite/Dol.LS	SGC	100	45	700
I-95	Waldorf	MD	2005-08	Sasobit	PG 76-22	19	Serpentenite/Dol.LS	SGC	100	0	800
SR 925	Charles Co.	MD	2005-12	Sasobit	PG 64-22	9.5	Serpentenite/Dol.LS	SGC	100	35	1000
M-95	Iron Mtn.	MI	2006-09	Sasobit	PG 58-34	9.5	Basalt	SGC	86	0	1000
CTR 11	Goodhue City	MN	2007-09	REVIX	PG 58-28	12.5	Limestone	SGC	60	20	710
Hall St.	St. Louis	MO	2006-05	Evotherm ET	PG 70-22	12.5	Porphyry, Limestone	SGC	100	10	3000
Hall St.	St. Louis	MO	2006-05	Sasobit	PG 70-22	12.5	Porphyry, Limestone	SGC	100	10	2400
Hall St.	St. Louis	MO	2006-05	Zeolite (Aspha-min)	PG 70-22	12.5	Porphyry, Limestone	SGC	100	10	1200
Route 291	Kansas City	MO	2007-10	Evotherm DAT	PG 64-22	12.5	Limestone	SGC	75	0	12000
Route CC	St. Louis	MO	2007-10&11	Evotherm DAT	PG 70-22	12.5	Limestone	SGC	100	15	12000
APAC	Columbia	MS	2007-11	Evotherm 3G	PG67-22		gravel			0	
Bonds	Tupelo	MS	2007-11	Evotherm 3G	PG67-22		limestone			15	
Private	Hattiesburg	MS	2007-11	REVIX	PG 67-22	12.5	Gravel/Limestone	Marshall	75	0	250
Highway 25	Smithville	MS	2007-11	REVIX	PG 67-22	12.5	Limestone/Gravel	SGC	65	15	1500
?	MS Gulf Coast	MS	Proposed		?						
Hwy 115	Charlotte	NC	2004-09	Zeolite (Aspha-min)	PG 70-22	9.5	Granite/Slag	SGC	100	10	220
	Sims	NC	2007-09	Double Barrel Green	PG 64-22					40	2500
Private	Hooksett	NH	2005-11	Zeolite (Aspha-min)	PG 64-28	12.5	Granite	SGC	75	0	340
Private	Hooksett	NH	2005-11	Zeolite (Aspha-min)	PG 64-28	12.5	Granite	SGC	75	0	100
Bardon	Las Vegas	NV	2008-01	Evotherm 3G	PG76-22NV		?			0	
Private	Cortland	NY	2006-07	LEA	PG 64-22	9.5	Gravel	SGC	65	0	300

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Project Name	City	State	Date	Technology	Binder	NMAS	Aggregate	Compaction	Design	RAP	Tonnage
Route 13	Cortland	NY	2006-09	LEA	PG 64-22	9.5	Gravel	SGC	65	0	1000
Route 11	Homer	NY	2007-07	LEA	PG 64-28	9.5	Gravel	SGC	65	0	1182
Bomax Rd.	Lansing	NY	2007-07	LEA	PG 64-28	9.5	Gravel	SGC	65	0	417
Route 96b	Ithaca	NY	2007-07&08	LEA	PG 64-28	9.5	Gravel	SGC	65	0	17253
Route 96b	Ithaca	NY	2007-07&08	LEA	PG 64-28	9.5	Gravel	SGC	65	0	365
Route 38	Groton	NY	2007-08	LEA	PG 64-28	9.5	Gravel	SGC	65	0	348
Route 38	Groton	NY	2007-08	LEA	PG 64-28	9.5	Gravel	SGC	65	0	701
Route 13	Cortland	NY	2007-08&09	LEA	PG 70-22	9.5	Gravel	SGC	75	0	2961
Route 13	Cortland	NY	2007-08&09	LEA	PG 64-22	9.5	Gravel	SGC	75	10	1349
Route 13	Cortland	NY	2007-08&09	LEA	PG 64-22	9.5	Gravel	SGC	75	0	7229
Route 79	Ithaca	NY	2007-09	LEA	PG 64-22	9.5	Gravel	SGC	65	0	2405
Private	Cortland	NY	2008-05	LEA	PG 64-22	37.5				25	614
Private	Cortland	NY	2008-05	LEA	PG 64-22	19				25	236
Cold Brook Rd	Cortland Co.	NY	2008-05	LEA	PG 64-22	25				0	2803
E. Homer-Baltimore Rd	Cortland Co.	NY	2008-05	LEA	PG 64-22	25				0	4768
Stager Rd	Cortland Co.	NY	2008-05	LEA	PG 64-22	25				0	3888
Stager Rd	Cortland Co.	NY	2008-05	LEA	PG 64-22	9.5				0	159
Level Green Rd	Caroline	NY	2008-06	LEA	PG 64-22	12.5				15	1178
Broadway	Cortland	NY	2008-06	LEA	PG 64-22	9.5				0	300
Elm St.	Cortland	NY	2008-06	LEA	PG 64-22	9.5				0	255
Groten Ave.	Cortland	NY	2008-06	LEA	PG 64-22	9.5				0	200
West Main St	Cortland	NY	2008-06	LEA	PG 64-22	9.5				0	350
Woodchuck Hill Rd	Dewitt	NY	2008-06	LEA	PG 64-22	9.5				0	1270
Briarwood Rd	Homer	NY	2008-06	LEA	PG 64-22	12.5				10	1093
Brown Hill Rd.	Scott	NY	2008-06	LEA	PG 64-22	9.5				0	532
Cold Brook Rd	Cortland Co.	NY	2008-07	LEA	PG 64-22	25				0	1850
Private	Cortlandville	NY	2008-07	LEA	PG 64-22	25				0	296
North Fulton St.	Homer	NY	2008-07	LEA	PG 64-22	9.5				0	495
Warren Rd.	Lansing	NY	2008-07	LEA	PG 64-22	12.5				0	470
Broad Rd	Onondaga	NY	2008-07	LEA	PG 64-22	9.5				0	1470
Ontario St	Syracuse	NY	2008-07	LEA	PG 64-22	25				0	143
Ontario St	Syracuse	NY	2008-07	LEA	PG 64-22	9.5				0	182
Cayuta Rd	Tompkins Co.	NY	2008-07	LEA	PG 64-22	25				0	1293
Stevens Rd	Tompkins Co.	NY	2008-07	LEA	PG 64-22	25				0	1925
Warren Rd.	Tompkins Co.	NY	2008-07	LEA	PG 64-22	12.5				0	870
Route 13		NY	2008-07	LEA	PG 64-22	9.5				0	9035
Pleasant Grove Rd	Cayuga Heights	NY	2008-08	LEA	PG 64-22	25				10	1860
Pleasant Grove Rd	Cayuga Heights	NY	2008-08	LEA	PG 64-22	9.5				10	600
South Ave	Cortland	NY	2008-08	LEA	PG 64-22	9.5				10	450
Grant St	Cortland Co.	NY	2008-08	LEA	PG 64-22	12.5				10	500
Otisco Valley Rd	Onondaga Co.	NY	2008-08	LEA	PG 64-22	12.5				0	930
Route 38		NY	2008-08	LEA	PG 64-22	9.5				0	6152

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Project Name	City	State	Date	Technology	Binder	NMAS	Aggregate	Compaction	Design	RAP	Tonnage
Allen Rd	Erie Co.	NY	2008-09	LEA	PG 64-22	25				0	4741
Allen Rd	Erie Co.	NY	2008-09	LEA	PG 64-22	25				13	3419
Allen Rd	Erie Co.	NY	2008-09	LEA	PG 64-22	9.5				13	2857
OH 541	Kimbolton	OH	2006-09	Evotherm ET	PG 70-22	9.5	Limestone, NatSand	Marshall	50	15	2300
OH 541	Kimbolton	OH	2006-09	Sasobit	PG 70-22	9.5	Limestone, NatSand	Marshall	50	15	2800
OH 541	Kimbolton	OH	2006-09	Zeolite (Aspha-min)	PG 70-22	9.5	Limestone, NatSand	Marshall	50	15	2500
Private	Columbus	OH	2007-10&11	Double Barrel Green	PG 64-22	19	Limestone	Marshall	50	25	14000
SR 4045	Buffalo	PA	2008-07	Evotherm	PG 58-28	9.5	Limestone, Gravel	SGC	75	15	4249
SR 2007	Deodate	PA	2008-07	Evotherm	PG 64-22	9.5	Dolomite/Limestone	SGC	75	0	3199
SR 0044	Turbotville	PA	2008-08	Evotherm	PG 64-22	9.5	Siltstone/Sandstone	SGC	75	10	1162
SR 0144	Centre Hall-Coburn	PA	2009 Spring	Evotherm	PG 64-22	9.5		SGC	75		
SR 0144	Centre Hall-Coburn	PA	2009 Spring	Green Machine	PG 64-22	9.5		SGC	75		
SR 0144	Centre Hall-Coburn	PA	2009 Spring	TBD	PG 64-22	9.5		SGC	75		
SR 0144	Centre Hall-Coburn	PA	2009 Spring	TBD	PG 64-22	9.5		SGC	75		
Laurel Ridge Rd.	Summerville	SC	2006-11	Evotherm ET	PG 67-22	9.5	Granite	Marshall	50	0	300
Maple St.	Summerville	SC	2007-04	Evotherm DAT	PG 67-22	19	Granite	SGC	75	30	2000
County	York	SC	2007-10	Double Barrel Green	PG 64-22	9.5	Granite	SGC	50	50	12000
Private	Chattanooga	TN	2007-04	Double Barrel Green	PG 64-22	19	Limestone	Marshall	50	30	250
Private	Chattanooga	TN	2007-04	Double Barrel Green	PG 64-22	9.5	Limestone	Marshall	50	30	250
Private	Chattanooga	TN	2007-04	Double Barrel Green	PG 64-22	9.5	Limestone	Marshall	50	0	250
Rogers Group	Nashville	TN	2007-05	Evotherm ET	PG67-22		Limestone			0	
North Terrace Rd.	Chattanooga	TN	2007-06	Double Barrel Green	PG 64-22	12.5	Limestone	Marshall	50	50	3400
SR 46	Nashville	TN	2007-10	Double Barrel Green	PG 70-22	12.5	Limestone, NatSand	Marshall	75	0	800
Lojac	Nashville	TN	2007-10	Evotherm DAT	PG70-22		limestone			0	
SR 46	Nashville	TN	2007-10	Evotherm DAT	PG 70-22	12.5	Limestone, NatSand	Marshall	75	0	800
SR 46	Nashville	TN	2007-10	Sasobit	PG 70-22	12.5	Limestone, NatSand	Marshall	75	0	800
SR 46	Nashville	TN	2007-10	Zeolite (Advera WMA)	PG 70-22	12.5	Limestone, NatSand	Marshall	75	0	1100
Highways	Algood	TN	2007-11	Evotherm 3G	PG64-22		?			0	
SR 53	Gainesboro	TN	2007-11	REVIX	PG 70-22	12.5	Limestone	Marshall	75	15	1500
Lojac	Rutherford Cty	TN	Oct	Evotherm 3G						0.5	
Lojac	Rutherford Cty	TN	Oct	Evotherm 3G						0.3	
Eskimo St.	San Antonio	TX	2005-10	Evotherm ET	PG 64-22	9.5	Limestone	Texas Gytratory		0	336
Eskimo St.	San Antonio	TX	2005-11	Evotherm ET	PG 82-22	9.5	Limestone	Texas Gytratory		0	340
Austin Hwy.	San Antonio	TX	2006-08	Evotherm ET	PG 76-22	12.5	Limestone, NatSand	Texas Gytratory		0	2400
Young	Bryant	TX	2007-04	Evotherm ET	PG76-22		Limestone			0	
Knife River	Waco	TX	2007-07	Evotherm DAT	PG76-22		Limestone			0	
Knife River	Waco	TX	2007-09	Evotherm DAT	PG64-22		Limestone			30	
Knife River	Waco	TX	2007-09	Evotherm DAT	PG64-22		Limestone			30	
City	San Antonio	TX	2007-09&10	Evotherm DAT	PG 64-22	12.5	Limestone	SGC	100	30	3000
Amarillo Roads	Amarillo	TX	2007-10	Evotherm DAT	PG70-28		?			0	
Gilven Terrill	Amarillo	TX	2007-10	Evotherm DAT	PG76-28		?			0	
Gilven Terrill	Amarillo	TX	2007-10	Evotherm DAT	PG64-22		?			30	

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Project Name	City	State	Date	Technology	Binder	NMAS	Aggregate	Compaction	Design	RAP	Tonnage
Sun Mt	Ft Worth	TX	2008-01	Evotherm DAT	PG64-22		Limestone			20	
Sun Mt	Ft Worth	TX	2008-01	Evotherm DAT	PG76-22		Limestone			0	
E TX AC	Tyler	TX	2008-01	Evotherm DAT	PG64-22		limestone			0	
	Dallas	TX	2008-02	Rediset WMX	PG 76-22					15	
Industrial AC	Austin	TX	2008-03	Evotherm DAT	PG76-22		limestone			0	
Austin Bridge & Road	Ft Worth	TX	2008-06	Evotherm DAT	PG64-22		limestone			30 - Fractionated	
Austin Bridge & Road	Ft Worth	TX	2008-06	Evotherm DAT	PG76-22		limestone			0	
Williams	San Antonio	TX	2008-06	Evotherm DAT	PG76-22		limestone			0	
Ramming	Austin	TX	2008-07	Evotherm DAT	PG64-22		limestone			0	
Ramming	Austin	TX	2008-07	Evotherm DAT	PG64-22		limestone			0	
Hunter Ind	Austin / San Antoni	TX	2008-07	Evotherm DAT	PG76-22		limestone			0	
Advanced Paving	Amarillo	TX	2008-08	Evotherm DAT	PG64-22		?			?	
APAC	Dallas	TX	2008-08	Evotherm DAT	PG64-22		limestone			0.3	
APAC	Dallas	TX	2008-08	Evotherm DAT	PG76-22		limestone			0	
AL Helmcamp	Timpson	TX	2008-08	Evotherm DAT	PG70-22		limestone			0	
AL Helmcamp	Timpson	TX	2008-08	Evotherm DAT	PG70-22		limestone			0	
I-10 Feeder	Beaumont	TX	2008-09	Rediset WMX	PG 76-22						800
Vulcan	San Antonio	TX	planned		?					target = 50+	
Vulcan	San Antonio	TX	planned		?					target = 50+	
Big Creek	Waco	TX	proposed	Evotherm DAT	PG76-22 - Latex in DAT						800
FM 324	Lufkin	TX		Advera WMA							800
FM 324	Lufkin	TX		Evotherm							800
FM 324	Lufkin	TX		Rediset WMX							800
FM 324	Lufkin	TX		Sasobit							800
US 380	Wichits Falls	TX		Double Barrel Green							75000
Route 220	Highland Co.	VA	2006-08	Sasobit	PG 64-22	12.5	Gravel/Limestone	SGC	65	10	320
Route 211	Rappahannock	VA	2006-08	Sasobit	PG 64-22	9.5	Siltstone/Granite	SGC	65	20	775
Route 143	York County	VA	2006-10	Evotherm ET	PG 70-22	9.5	Granite	SGC	65	20	530
Ryan Rd.	Milwaukee	WI	2006-06	Evotherm ET	PG 64-28	12.5	Gravel	SGC	75	14	1270
Ryan Rd.	Milwaukee	WI	2006-06	Sasobit	PG 64-28	12.5	Gravel	SGC	75	14	1000
Private		WI	2007-08	REVIX	PG 58-28	12.5	Limestone	SGC	60	20	300
STH 33	LaCrosse County	WI	2007-09&10	REVIX	PG 58-28	12.5	Limestone	SGC	40	30	1150
STH 33	LaCrosse County	WI	2007-09&10	REVIX	PG 64-28	12.5	Limestone	SGC	40	30	250
Yellowstone NP			2007-08&09	Sasobit	PG 58-34	19	Gravel/Granite/Basalt	Hveem		0	8375
Yellowstone NP			2007-08&09	Zeolite (Advera WMA)	PG 58-34	19	Gravel/Granite/Basalt	Hveem		0	8700

APPENDIX B

WMA Technical Working Group Material Test Framework for Warm-Mix Asphalt Trials

WMA Technical Working Group Emissions Test Framework for Warm-Mix Asphalt Trials

Material Test Framework for Warm Mix Asphalt Trials

A number of new processes have been developed to allow asphalt mixtures to be mixed and compacted at lower temperatures. These processes tend to reduce the viscosity of the mixture at mixing and compaction temperatures. Collectively, these processes are referred to as warm mix asphalt (WMA). In an effort to evaluate WMA technologies, contractors and agencies have constructed or are planning to construct trial sections. When considering a WMA trial, a minimum desired test section would be 800-1000 tons of WMA. This will allow a plant run of approximately four hours at reasonable production rates. Further, it is desirable to have a hot mix control section to be produced using the same mix design (without the WMA additives).

In order to maximize the benefit from these trial sections, it is desirable to have a framework which provides for a minimum level of uniform data collection which can be shared with other contractors and agencies. Additional testing is described, which may enhance the knowledge learned from the trial sections. The following is a working document which will be periodically updated in order to improve the knowledge gained. The primary goals of the framework are as follows:

- Document the WMA project,
- Evaluate the effect on laboratory compaction and volumetric properties to develop information for future mix design and quality control procedure,
- Evaluate potential impact on performance in terms of:
 - Rutting – reduced aging of the binder could increase rutting potential,
 - Moisture susceptibility – incomplete drying of the aggregate could increase moisture susceptibility,
 - Low temperature cracking – certain WMA additives may increase the potential for low temperature cracking based on binder tests, conversely the reduced aging of the binder could reduce the potential for low temperature cracking,
 - Mixture stiffness – reduced aging of the binder may reduce the mixture stiffness
 - Fatigue life – reduced aging of the binder may increase the mixtures fatigue capacity.
- Production, construction and in-place compaction,
- Provide a limited quantity of materials for future research.

The following describes the desirable data to be collected as part of a WMA trial:

- 1) Project Summary
 - a) Project location
 - b) Agency (if applicable)
 - c) Contractor
 - d) Paving date(s)
 - e) Paving time(s), day, night, ect.

- f) Weather conditions – particularly ambient air and surface temperatures during laydown
 - g) WMA process(es) used
 - h) Tonnage produced
 - i) Digital photos or video of the project during construction (production and/or laydown of HMA, photos of key operations, photos after completion, etc.)
 - j) Any reports about the project produced by the agency, contractor or others
 - k) Traffic: AADT, percent trucks and ESAL factor or load spectra, number of lanes, and ecetera
- 2) Material Properties
- a) Aggregate properties
 - i) Aggregate type(s)
 - ii) Dry bulk specific gravity
 - iii) Water absorptions
 - iv) Stockpile moisture contents
 - v) Superpave consensus and source properties (generally should be part of mix design, including: coarse aggregate angularity (ASTM D5821), uncompacted voids in fine aggregate (AASHTO T304 Method A), flat and elongated particles (ASTM D4791), sand equivalent (AASHTO T176), LA Abrasion (AASHTO T96), and soundness (AASHTO T104).
 - b) Binder properties
 - i) Binder supplier
 - ii) Binder grade (attach copy of Manufacturer's certification)
 - iii) Base binder grade, if WMA used to modify binder, e.g. Sasobit
 - iv) Modifiers (if any)
 - c) Mix Design (attach copy of mix design volumetric properties)
 - i) Nominal maximum aggregate size
 - ii) Target gradation
 - iii) Optimum asphalt content
 - iv) Laboratory compaction effort
- 3) Production information
- a) Plant type
 - b) Plant model
 - c) Describe method of introducing WMA additive(s)
 - d) Production rate
 - e) Aggregate discharge temperature (if applicable)
 - f) Mix discharge temperatures (history during production)
 - g) Observations regarding motor amperages, particularly drag chain
 - h) Collect fuel consumption data for both the HMA and WMA¹
 - i) Observations regarding baghouse after WMA run (moisture problem?)
 - j) Use of silos and typical storage time.
- 4) Laydown information
- a) Temperature range of WMA at load out
 - b) Truck type (tandems, live bottom etc.)
 - c) Haul distance/Haul time
 - d) Release agent used (if any)

- e) Observations regarding dumping material/sticking in truck beds (if any)
 - f) Use of windrow or transfer vehicles
 - g) Paver type and model
 - i) Vibratory screed on?
 - ii) Screed heated?
 - h) Compacted thickness
 - i) Temperature immediately behind screed (history)
 - j) Roller Train
 - i) Type and model
 - ii) Weight
 - iii) Amplitude and frequency of vibratory rollers (if applicable)
 - iv) Tire pressure of pneumatic roller (if applicable)
 - k) Roller Pattern – a separate roller pattern should be performed for the WMA and control mixes
 - l) Time and mat temperature when opened to traffic
- 5) Testing
- a) Laboratory Mix Tests (Field Mixed/Laboratory Comacted) – to be performed on both the WMA and control sections.
 - i) Moisture content of mix at load out (sampled from truck) – AASHTO T329
 - ii) Gyratory compaction of six pills for each sample to specified Ndesign compaction effort without reheating mix other than to desired compaction temperature. Record time needed to reheat samples (if any). After the volumetric properties are measured, the samples will be tested in the Asphalt Pavement Analyzer² (APA) for rutting potential at the recommended climatic high temperature for the site.
 - iii) Maximum specific gravity
 - iv) Prepare 6-8 samples to 7 ± 0.5 percent air voids and a height of 95 mm for Tensile Strength Ratio Testing³ without reheating mix other than to desired compaction temperature. Record time needed to reheat samples (if any).

The following equation has been used to estimate TSR sample weight in order to obtain 7 percent voids:

$$M = (0.915)(Gmm)(\pi)(56.25)(9.5) = 1536.1(Gmm)$$

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

- v) Compact three samples in the gyratory compactor to a height of 170 mm at the anticipated in-place (field) density for simple performance testing (SPT)⁴. The following equation has been used to estimate the target sample weight for 150 mm diameter samples compacted to a height of 170 mm. The first factor, 0.895, is the anticipated in-place density (93 percent of Gmm) minus 4.5 percent. The adjustment to the anticipated in-place density is necessary to

correct for surface texture and the fact that the center of the sample is denser than the total samples (100 mm diameter samples, 150 mm tall, will be cored from the oversize SGC samples).

$$M = (0.895)(Gmm)(\pi)(56.25)(17.0) = 2688.7(Gmm)$$

- vi) Low Temperature Cracking – comparisons can be made between the low temperature cracking potential using the IDT test (AASHTO T322).
- b) Field Tests (Field Mixed/Field Compacted) – to be performed on both the WMA and control sections
 - i) Density Tests – in-place density should be determined based on cores. A minimum of nine cores should be taken from stratified random locations from each section. The cores should be sawed and measured for thickness. After density testing, the indirect tensile strength of three of the cores should be determined at 77 °F. Loading rate for the indirect tensile strength shall be 2 inches/minute (same rate as for TSR).
 - ii) The three remaining cores should be used to determine bond strength between layers⁵.
 - iii) Recoveries should be performed on the cores and the recovered binder graded to assess the reduced aging during construction. Extractions and recoveries should be performed according to AASHTO T319 or AASHTO T164 Method A with Rotovap recovery. The extraction solvent should be toluene and 95% ethanol mixed at a ration of 85:15. The 95% ethanol contains 5 percent water. A maximum Rotovap temperature of 140 °C should be used, lower if reduced pressures are utilized.
 - iv) An additional six cores should be taken, three in and three between the wheel paths at three months, one year and two years after construction. The cores should be tested for density and the indirect tensile strength determined at 77 °F. The additional coring with time is to serve two purposes: 1) WMA additives have indicated reduced asphalt contents during design, the cores will be used to assess the in-place densification under traffic. This data will be related back to the QC air voids; 2) indirect tensile strength will be used to assess binder aging.
 - v) Recoveries should be performed on the cores taken after construction, once indirect tensile strength has been determined, and the recovered binder graded to assess the aging as a function of time. Extractions and recoveries should be performed according to AASHTO T319 or AASHTO T164 Method A with Rotovap recovery. The extraction solvent should be toluene and 95% ethanol mixed at a ration of 85:15. The 95% ethanol contains 5 percent water. A maximum Rotovap temperature of 140 °C should be used, lower if reduced pressures are utilized.
- c) Sampling
 - i) Obtain at least one-gallon of the binder, preferably in 4 quart cans.
 - ii) Obtain approximately 30 lbs of each aggregate stockpile and RAP, if used.
 - iii) Obtain three five-gallon buckets (approximately 180 lbs) of mix.
 - iv) Obtain at least a one-gallon sample of any warm mix additive added directly at the plant (zeolite or Sasobit).

- d) Additional Performance Testing (Field Mixed/Lab Compacted) – The following tests should be considered desirable, but not mandatory. Since WMA reduces the aging of the binder, it should improve mixture performance in terms of certain durability parameters such as fatigue life and low temperature cracking.
 - i) Hamburg Tests for moisture susceptibility and rutting
 - ii) Fatigue Life
 - (1) Beam fatigue tests – samples for beam fatigue testing should be prepared, preferably with out reheating, to the anticipated in-place air void content. Improved densification tends to improve fatigue life. Therefore, every effort should be made to capture the effect of improved compaction obtained with WMA (AASHTO T321).
 - (2) Fracture energy – an alternative method of assessing resistance to cracking is fracture energy testing, performed on SGC samples, using the IDT.
 - (3) Other methods of assessing cracking potential may also be used, such as the TTI overlay tester.
 - iii) TSRST Low Temperature testing
 - iv) Smoothness testing, prior to opening to traffic
 - v) Rut depth profiles, prior to opening to traffic (mark set locations for future testing)

- 6) Materials Testing Contacts:
 - a) Warm Mix Asphalt Technical Working Group (WMA TWG)
 - i) Dave Newcomb – National Asphalt Pavement Association – (888) 468-6499
DNewcomb@hotmix.org
 - ii) Matthew Corrigan – Federal Highway Administration – (202) 366-1549
Matthew.Corrigan@FHWA.DOT.gov

Testing Notes

¹Fuel consumption can be difficult to measure. Natural gas usage is the easiest to quantify. Tank dips can be inaccurate, particularly if recycled oil is used as fuel or another fuel which may not be completely atomized.

²APA testing to be conducted climatic PG high temperature, e.g. 64 °C, with a hose pressure of 100 psi and a vertical load of 100 lbs.

³The testing conducted by NCAT to date has been completed according to ASTM D4867. For laboratory prepared mixes, the 72-96 hour counter curing period of the compacted sample, specified in AASHTO T283, has been eliminated. Practically speaking, this curing period has been included in the field testing due to the shipping time required to get the samples back to the laboratory. One freeze-thaw cycle was applied to the conditioned samples. Freeze-thaw cycles simulate the pore pressure which develops in the mix under traffic and are valid even in areas where freezing temperatures are not likely to occur.

⁴Dynamic modulus and repeated load permanent deformation should be conducted according to the test procedures described in NCHRP Report 513. More up-to-date test procedures are available from the NCHRP 9-29 contractor. Repeated load creep testing to be performed at the base climatic PG binder grade -6°C, e.g. IF a PG 64-XX meets the climatic requirements, conduct the repeated load permanent deformation test at 58 °C. A vertical load of 600 kPa (87 psi) is generally believed to simulate mixed traffic expected on most sites. Confinement pressure is important for certain mix types such as OGFC and SMA. A confinement pressure of 20 psi is recommended. Repeated load creep testing may be conducted following dynamic modulus testing, assuming the maximum permanent strain criterion for dynamic modulus testing is not exceeded.

⁵There is some concern that the reduced mixture temperatures for WMA may fail to adequately bond to the underlying layer, particularly when PG binders are used as tack coat. A number of tests have been used to assess bond strength. Florida DOT and NCAT have both used guillotine type devices to measure bond strength. Some of NCAT's work is described in NCAT Report No. 05-08, which is available at www.NCAT.us

DOCUMENTING EMISSIONS AND ENERGY REDUCTIONS of WMA AND CONVENTIONAL HMA

PLANT AND PAVING OPERATIONS

Plant Emissions Stack Testing and Energy Requirements

Introduction:

Stack testing should include mass emissions rate measurement of NO_x, CO₂, and VOC to compare stack emissions from WMA technologies and conventional HMA. It is suggested that stack emissions reporting be standardized as lbs per hour (of mix produced) and include a recording and reporting of average production rate in tons HMA or WMA produced per hour, during each test period. Testing should be performed by a certified tester and should include either two (2) or three (3) 60-minute stack sampling runs per technology, if possible. Note: the number of runs may have to be adjusted to the available run time using WMA technology. Production rates should be recorded every 15 minutes during each test run and used to determine average production rate in tons mix produced per hour for each run. The data from all individual test runs during a test period (conventional HMA or WMA) should be averaged to determine the overall results for each technology. Stack gas volumetric flow rates, moisture content, and a variety of other parameters should also be determined for each run, in accordance with U.S. EPA stack testing methodology. In order to assess fossil fuel and energy use reductions, it is suggested that beginning and end fuel usage data be recorded for each test run. This may be accomplished with direct fuel usage meter readout, where available, or by tank gauging as appropriate.

Stack Emissions Testing and Analytical Methods:

Suggested test methods are in accordance with U.S. EPA protocol used historically in the HMA Industry and are as follows:

- Sampling point locations per USEPA Method 1, if ports have not been established during previous stack testing. If ports have been previously established, the test firm may wish to confirm that their location is consistent with that specified by USEPA Method 1. Access platforms and an appropriate power source must also be available during testing.
- Stack Gas Volumetric Flow Rate per USEPA Method 2
- Stack Gas Temperature and Moisture content per USEPA Method 4
- NO_x Emissions per USEPA Method 7E
- CO₂ Emissions per USEPA Method 3A (continuous method preferred over method 3 Orsat)

- VOC Emissions per USEPA Method 25A (reported as Molecular Weight of Propane)

Energy Requirements and Operational Data:

Attached is an Operational Data Entry sheet for use in identifying WMA technologies and binder characteristics, and for calculating the amount of energy required to produce the mix. As indicated on the Operational Data Entry sheet, recorded information will include:

- WMA technology and Binder characteristics
- RAP usage/rate (if applicable)
- Change in Drag Slat amperage for each technology
- Average Production Rate
- Unit fuel consumed per tons of mix processed

Suggested Reporting Of Stack Emissions and Energy Results:

- Average mix production rate in tons/hour
 - o Conventional Mix Test Period
 - o WMA Test Period
- lbs CO₂/hour; lbs NO_x/hours; lbs VOC/hour reported as MW of propane
 - o Conventional Test Period (average all runs)
 - o WMA Test Period (average all runs)
 - o percent Reduction
- Fossil Fuel Usage - Gallons or Cubic Feet Gas/Ton mix
 - o Type of Fuel Used i.e., #2 oil, Natural Gas, other
 - o Conventional Test Period (average all runs)
 - o WMA Test Period (average all runs)
 - o percent Reduction
- Include appendix for field test data and calculations summary

Approximate Costs Associated with Stack Emissions Testing:

- Any travel costs, outside locality, are not included.
- Complex reporting of results will incur extra charges; this is not anticipated.
- Costs for developing Test Plans are not included; however, Test Plans are not anticipated to be needed.
- There are minimal differences in costs (+/- \$300) associated with conducting either two or three stack tests.
- Baseline costs are anticipated to be approximately \$3,000 - \$5,000
 - o Per Technology (comparison with conventional HMA is an additional technology - i.e., a complete round of testing would be needed).

- o Includes three stack tests
- o Includes simple reporting of results
- o Costs are for a local company to conduct the emissions testing -- travel costs would be incurred for non-local companies.

Emissions Surrounding Laydown Operations

Introduction:

Ideally, placement of each mix, conventional and WMA, would use the same paving equipment; material placed one day apart, approximately during the same time-frame. To minimize variability, it is also recommended that the paving machines utilized are equipped with properly functioning engineering controls. The recommended test period, for field emissions, is between 3 and 4 hours; more detail follows.

Placement of Monitors

During the placement of each technology, conventional HMA and WMA, the paver hopper, screed, and paver operator areas and, if appropriate, paving crew member(s), will be monitored for asphalt fume emissions. The purpose of this testing is to document, with some statistical power, the reduction in field application emissions using WMA as compared with using conventional HMA. A certified industrial hygienist ("CIH") should be employed to oversee and/or conduct the exposure sampling; one or two assistants for the CIH may also be used to conduct field work. Stationary monitors will be placed on the paving machine to simulate worst case emissions potential and to document emissions reductions. This will assist in statistically validating changes in emissions due to mix technologies and temperature of application. Due to differences in paving machine configurations, six (6) location-specific stationary monitors (and up to 2 background monitors, if necessary) will be placed, as consistently as possible, with the criteria below. Placement of these monitors should be conducted with close cooperation between the industrial hygienist and the paving crew or the crew's machine shop as some of the sampler locations may need to be slightly fabricated with brackets or braces.

Monitoring cartridges should be placed as follows:

- > (1) Hanging off the back inside wall of the hopper, centrally located approximately 6 - 12 inches below the top of the hopper.
- > (1) Hanging in front of an Operator Panel, as central as possible on machine (ensure clearance of 6 inches from panel box); e.g., if there are two operator seats/panels, hang monitor on the front of one of them (preferably the one not being used)

as close to the central portion of the paving machine as possible.

- (1) Attached to the highest point of one side of the central step railing (document height off ground)
- (2) Each one hanging above each side of the screed/auger discharge area end box (typically located near guide bars or control box); ensure clearance of approx 6 inches from sides of paver and 4 feet above pavement mat (this may require field fabricating a mounting bracket). Note the length of screed extension as compared with placement of the monitor.
- (1) Extending off the central rear portion of screed walkway, 5 feet above pavement mat (this will require field fabricating a mounting bracket, tripod, or other apparatus or obtaining a pre-fabricated apparatus (with mounting bracket) from NCAT. This ensures consistent location placement (see diagram below). Please contact Brian Prowell at NCAT.

Note that typical paving equipment and the paving application process should be considered as a harsh environment for IH sampling equipment. It is recommended that each pump is enclosed in sturdy zip-loc type bags and secured to appropriate paving apparatus using duct-tape, fabricated brackets, and/or bungee cords. Because of the number of monitoring devices proposed, and the unusual work environment, it is recommended that either one highly experienced field hygienist is used for field monitoring, or two less-experienced field hygienists are utilized.



Sampling and Analytical Method

Traditional gravimetric procedures will be used to quantify asphalt fume emissions. NIOSH Method 5042 is to be used to measure asphalt fume emissions, as both Total Particulate Matter (TPM) and Benzene Soluble Matter (BSM). Stationary (and personal) sampling pumps (capable of 1 to 4 liters/minute) should be connected to a pre-weighed 2.0-micron PTFE membrane filter (SKC Cat. No. 225-17-07 or equivalent) with a cellulose support pad in a 37-mm cassette filter holder. Flow calibration will be performed pre- and post-sampling. Calibrate pumps for approximately 2 to 3 liters per minute. The goal is to collect a large enough sample to increase analytical sensitivity without overloading the sampling media. Keep completed samples cold by placing them in a cooler with ice packs and protect them from light by wrapping them with foil. This allows further chemical-specific analysis if warranted. Minimum field sampling collection times should be between 3 and 4 hours; two such sampling events are ideal, and 6 hours would be the maximum recommended sampling time using one single media cartridge. Based upon one full day of paving, at the speed of approximately 200 tons mix/hour with a 2"-3" lift, paving time would be approximately 6 and 8 hours, including an allowance for down time and other work-related stoppages / activities. If it is anticipated that the paving machine will not operate for a period longer than 30 minutes, the sampling pumps should be shut off. A concurrent log of work stoppages longer than 15 minutes should be documented and should be factored into the final 8 hour time-weighted average fume emissions reporting.

If there is availability of pumps, one or two background samples could be taken and positioned upwind of the paving operation; descriptive data should be collected on potential confounders from the site, e.g., construction dust and any other background interferences. The background samples are only needed if there is potential for confounding; the CIH should review specific circumstances. Depending on the proximity of the paver's diesel exhaust stack to the sampling locations, the CIH may need to obtain an additional sample to minimize the impact of diesel exhaust on asphalt fume measurements.

Three blank samples should be taken to the job site; the caps for the cassettes are removed and immediately replaced at the job site with no air being drawn through them. Both background and blank samples should be extracted and analyzed following the same testing and analytical protocol as the samples taken from around the paver.

While sampling in the field, mix temperatures (both in the hopper and on the mat as it exits the screed strike area) should be monitored and recorded every 30 minutes, during the test period, with an infrared thermometer gun.

It is essential that weather-related information be collected and documented at least four times during the sampling period. Information would include, at minimum: wind speed and direction, air temperature, humidity, and other weather related comments.

For any personal sampling, names of all workers will be recorded along with observations during sampling including smoking habits. Workers must be asked not to smoke, or if they must, pumps must be turned off while smoking. During any personal sampling, attempt to restrict job rotations, if possible, in order to provide a valid exposure evaluation of the position. Document pertinent information regarding work positions and activities.

Photographs, illustrating field application of these technologies, will be taken throughout the sampling event. Diagrams noting the area sample locations and locations of workers are also helpful. Noting the direction of the paving application is important, especially in relation to wind direction.

Suggested Reporting Of Results:

- Anomalies in sampling and results
- Visual observations of emissions
 - Conventional Test Period
 - WMA Test Period
- Mix temperature (hopper and mat)
 - Conventional Test Period
 - WMA Test Period
 - Percent reduction
- Weather data including ambient temperature and humidity
- Worker activities
- Diagrams and/or photographs documenting activities and sampling locations.
- Notation whether paver is equipped with functioning engineering (emission reduction) controls.
- Background-corrected asphalt fume emissions (TPM and BSM) reported in mg/m³
 - Conventional Test Period (average all runs)
 - WMA Test Period (average all runs)
 - percent Reduction

Approximate Costs Associated with Industrial Hygiene Field Emissions Testing:

- Any travel costs, outside locality, are not included.
- Analytical costs are approximately \$100 per sample (11 samples per 3 - 4 hour event) x 2 events per day
- Labor at approximately \$110 per hour (10 hours) x 2 people
- Report writing and miscellaneous at approximately \$600
- Baseline costs are anticipated to be approximately \$5,000 - \$6,000
 - o Per Technology (comparison with conventional HMA is an additional technology - i.e., a complete round of testing would be needed).
 - o Costs are for local hygienists to conduct the field monitoring -- travel costs would be incurred for non-local hygienists.
 - o Monitoring equipment (pumps) may or may not be included in the labor rates, but should not substantially affect the estimated baseline costs.

Facility Operational Data Needs and Energy Usage

3 Pages to be filled out during each Production run for each WMA technology and corresponding HMA control run:

Mix / Fuel Information

TRIAL DATE: _____

TYPE of MIX: HMA or Warm Mix Asphalt: _____

Asphalt Binder type/specification/PG-grade: _____

Polymer type or tradename (if known, e.g., SBR, SBS,) _____

Average RAP usage/rate (if applicable): _____

FUEL TYPE: _____

Production Data

Initial FUEL LEVEL (with units) @ **Beginning** of Run: _____

START TIME of Production Run: _____

Drag Slat AMPERAGE (typical)
(avoid recording during transitions): _____

RECORD Mix Production Rate approximately every 15 minutes

Time: _____ Rate Mix Processed (tons/hour): _____

RECORD Production Rate approximately every 15 minutes (continued)

Time: _____ Rate Mix Processed (tons/hour): _____

DOWN TIME: note any periods of down time

Start Time: _____ End Time: _____

Start Time: _____ End Time: _____

Start Time: _____ End Time: _____

RECORD Production Rate approximately every 15 minutes (continued)

Time: _____ Rate Mix Processed (tons/hour): _____

DOWN TIME: note any additional periods of down time

Start Time: _____ End Time: _____

Start Time: _____ End Time: _____

AVERAGE Hourly Production Rate (tons/hour) (from above): _____

END TIME of Production Run: _____

Ending FUEL LEVEL (with units) @ **End** of Run: _____

TOTAL RUN TIME (hours): _____

Total Amount of Mix Processed (tons): _____

Total Amount Fuel used (with units): _____

CALCULATED Hourly Production Rate (tons/hour)
(from fuel usage and amount processed): _____

CALCULATED Total Fuel Usage Rate
(units of fuel type) per ton Total Mix Processed: _____

ENVIRONMENTAL TESTING CONTACTS:

National Asphalt Pavement Association ~ 888-468-6499

Gary Fore ~ gfore@hotmix.org

Howard Marks ~ hmarks@hotmix.org

APPENDIX C

NCHRP 9-43 Draft Standard Practice for Design of Warm Mix Asphalt (WMA)

Proposed Standard Practice for

Design of Warm Mix Asphalt (WMA)

AASHTO Designation: PP XX-XX

1. SCOPE

- 1.1. This standard presents procedures for design and analysis of warm mix asphalt (WMA). WMA mixture design is based on the binder properties, aggregate properties, volumetric properties, and resistance to moisture damage contained in AASHTO M323 for hot-mix asphalt. Aggregate coating, workability, and compactability are also evaluated during mixture design. The Flow Number test is included in the mixture design procedure to ensure adequate resistance to permanent deformation. WMA mixture analysis consists of a series of optional performance tests and criteria to assess (1) modulus for structural design, (2) fatigue cracking, and (3) thermal cracking.
 - 1.2. An important part of the WMA design procedure is specimen fabrication procedures that replicate the WMA process. This standard includes specimen fabrication procedures that have been verified with plant produced mixtures for the following additives/processes: (1) foamed asphalt, (2) Evotherm DAT, (3) Low Energy Asphalt, (4) Sasobit, (5) WAM Foam, and (6) zeolites. For other additives/processes, the user should consult the manufacturer for detailed specimen fabrication procedures.
 - 1.3. *This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all of the safety problems associated with its use. It is the responsibility of the user of this procedure to establish appropriate safety and health practices and to determine the applicability of regulatory limitations prior to its use.*
-

2. REFERENCED DOCUMENTS

- 2.1. *AASHTO Standards:*
 - M 320, Performance-Graded Asphalt Binder
 - M 323, Superpave Volumetric Mix Design
 - R 30, Mixture Conditioning of Hot-Mix Asphalt (HMA)
 - T 2, Sampling of Aggregates
 - T 11, Materials Finer Than 75 μm (No. 200) Sieve in Mineral Aggregate by Washing
 - T 27, Sieve Analysis of Fine and Course Aggregate
 - T 59, Testing Emulsified Asphalt

- T 84, Specific Gravity and Absorption of Fine Aggregate
- T 85, Specific Gravity and Absorption of Course
- T 100, Specific Gravity of Soils
- T 166, Bulk Specific Gravity of Compacted Asphalt Mixtures using Saturated Surface-Dry Specimens
- T 195, Determining Degree of Particle Coating of Bituminous-Aggregate Mixtures
- T 209, Theoretical Maximum Specific Gravity and Density of Bituminous Paving Mixtures
- T 228, Specific Gravity of Semi-Solid Bituminous Materials
- T 248, Reducing Samples of Aggregate to Testing Size
- T 269, Percent Air Voids in Compacted Dense and Open Asphalt Mixtures
- T 275, Bulk Specific Gravity of Compacted Bituminous Mixtures Using Paraffin-Coated Specimens
- T 283, Resistance of Compacted Asphalt Mixture to Moisture-Induced Damage
- T 312, Preparing and Determining the Density of Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor
- T 322, Determining the Creep Compliance and strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Test Device

2.2. *Other Documents:*

- ASTM D 3549, Thickness of Height of Compacted Bituminous Paving Mixture Specimens
- SP-2, Superpave Mix Design
- MS-2, Mix Design Methods for Asphalt Concrete and Other Hot-Mix Types
- NCHRP 9-29 RT 01-07, Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Simple Performance Test System
- NCHRP 9-29 RP 01-07, Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Concrete Using the Simple Performance Test System
- NCHRP 9-29 RP 02-07, Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor
- User Manual for the M-E Pavement Design Guide, March, 2007

3. TERMINOLOGY

- 3.1. *WMA* – Warm Mix Asphalt. Warm mix asphalt refers to asphalt concrete mixtures that are produced at temperatures approximately 50 °F (28 °C) or more cooler than typically used in the production of hot mix asphalt. The goal with warm mix asphalt is to produce mixtures with similar strength, durability, and performance characteristics as hot mix asphalt using substantially reduced production temperatures.
- 3.2. *Design ESALs* – Design equivalent (80kN) single-axle loads (Note 1).

NOTE 1 - Design ESALs are the anticipated project traffic level expected on the design lane over a 20-year period. For pavements designed for more or less than 20 years, determine the design ESALs for a 20 years when using this standard.

- 3.3. *Air voids (V_a)* – The total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture, expressed as a percent of the bulk volume of the compacted paving mixture (Note 2).

NOTE 2 – Term defined in Asphalt Institute Manual MS-2, Mix Design Methods for Asphalt Concrete and other Hot-Mix Types.

- 3.4. *Voids in the mineral aggregate (VMA)* – The volume of the intergranular void space between the aggregate particles of a compacted paving mixture that include the air voids and the effective binder content, expressed as a percent of the total volume of the specimen (Note 2).

- 3.5. *Absorbed binder volume (V_{ba})* – The volume of the binder absorbed into the aggregate (equal to the difference in aggregate volume when calculated with the bulk specific gravity and the effective specific gravity).

- 3.6. *Binder content (P_b)* – The percent by mass of binder in the total mixture including binder and aggregate.

- 3.7. *Effective binder volume (V_{be})* – The volume of binder which is not absorbed into the aggregate.

- 3.8. *Voids filled with asphalt (VFA)* – The percentage of the VMA filled with binder (the effective binder volume divided by the VMA).

- 3.9. *Dust-to-binder ratio ($P_{0.075}/P_{be}$)* – By mass, the ratio between the percent passing the 75 μ m (No. 200) sieve ($P_{0.075}$) and the effective binder content (P_{be}).

- 3.10. *Nominal maximum aggregate size* – One size larger than the first sieve that retains more than 10 percent aggregate (Note 3).

- 3.11. *Maximum aggregate size* – One size larger than the nominal aggregate size (Note 3).

NOTE 3 – The definitions given in 3.10 and 3.11 are the same as those used in AASHTO M323 and AASHTO R35, but may differ from the definitions published in other AASHTO standards.

- 3.12. *Reclaimed asphalt pavement (RAP)* – Removed and/or processed pavement materials containing asphalt binder and aggregate.

- 3.13. *Primary control sieve (PCS)* – The sieve defining the break point between the fine and coarse graded mixtures for each nominal maximum aggregate size.

- 3.14. *Fineness Modulus* – The sum of the percent passing the 0.075, 0.15, and 0.30 mm sieves
-

4. SUMMARY OF THE PRACTICE

4.1. Mixture Design

4.1.1. *WMA Process Selection*

- 4.1.1.1. **WMA Process.** Select the WMA process that will be used in consultation with the specifying agency and technical assistance personnel from the WMA suppliers.
- 4.1.1.2. **WMA Temperatures.** Determine the temperatures that will be used for mixture production and field compaction. Binder grade selection and allowable RAP content depend on the anticipated mixture production temperature.

4.1.2. *Materials Selection*

- 4.1.2.1. **Binder Grade.** Select the performance grade of the binder in accordance with Section 5 of AASHTO M323 considering the environment and traffic at the project site. Increase the high temperature performance grade based on the proposed production temperature.
- 4.1.2.2. **Aggregates.** Select aggregates in accordance with Section 6 of AASHTO M323 considering the traffic level and depth in the pavement structure.
- 4.1.2.3. **Recycled Asphalt Pavement.** The amount of RAP that can be used in WMA depends on the proposed production temperature. Select RAP materials in accordance with Section 6 of AASHTO M323.
- 4.1.2.4. **Additives.** Additives as required by the proposed WMA process or to obtain acceptable, coating, workability, compactability, and moisture susceptibility results.
- 4.1.3. *Design Aggregate Structure* – At least three trial aggregate blend gradations should be prepared using the selected new aggregate and RAP stockpiles (Note 4). For each trial gradation, an initial binder content is determined, and at least two specimens are compacted in accordance with AASHTO T 312. A design aggregate structure and an estimated design binder content are selected on the basis of satisfactory coating, satisfactory workability, satisfactory compactability, and conformance to the criteria in AASHTO M 323 for gradation, Va, VMA, VFA, and dust-to-binder ratio.

NOTE 4 – Previous mix design experience with proposed materials may eliminate the need for three trial blends.

- 4.1.4. *Design Binder Content Selection* – Replicate specimens are compacted in accordance with AASHTO T 312 at the estimated design binder content and at the estimated design binder content ± 0.5 percent and $+ 1.0$ percent. The design binder content is selected on the basis of satisfactory coating, satisfactory workability, satisfactory compactability, and conformance with the requirements of AASHTO M 323 for V_a , VMA, VFA, dust-to-binder ratio, and relative density at N_{max} .
- 4.1.5. *Evaluating Moisture Susceptibility* – The moisture susceptibility of the design aggregate structure is evaluated at the design binder content using AASHTO T 283. The conditioning procedure included in this Standard Practice shall be used in lieu of the conditioning procedure specified in AASHTO T 283. Specimens for moisture susceptibility testing shall be compacted in accordance with AASHTO T312 to an air void content of 7.0 ± 0.5 percent. The design shall meet the tensile strength ratio requirement of AASHTO M 323.
- 4.1.6. *Evaluating Rutting Resistance* – The rutting resistance of the design aggregate structure is evaluated at the design binder content using the Flow Number Test, NCHRP 9-29 RT 01-07. The Flow Number Test is conducted at the 50 percent reliability design temperature obtained from LTPPBind 3.0.

4.2. **Mixture Analysis**

- 4.2.1. Recommended tests and analysis procedures are described in this practice to evaluate other performance properties of WMA. Tests are provided to assess: (1) dynamic modulus, (2) fatigue cracking, and (3) thermal cracking.
- 4.2.2. The mixture analysis tests are performed at the discretion of the specifying agency. They may be performed on the design mixture at the design binder content to assess the overall performance, or they may be performed on variations of the mixture to assess the sensitivity of the mixture to variations during production.

5. **SIGNIFICANCE AND USE**

- 5.1. The mixture design procedure described in this practice is used to produce WMA which satisfies the mix design requirements for HMA contained in AASHTO M323 and provides adequate resistance against rutting and moisture damage for the design environment and traffic level.
 - 5.2. The mixture analysis procedures described in this practice can be used to evaluate the engineering characteristics of WMA, and to evaluate its expected performance for a specific project.
-

6. MIXTURE DESIGN PROCEDURE

6.1. WMA Process Selection

- 6.1.1. Select the WMA process that will be used in consultation with the specifying agency and technical assistance personnel from the WMA suppliers. Consideration should be given to a number of factors including: (1) available performance data, (2) the cost of the warm mix additives, (3) planned production and compaction temperatures, (4) planned production rates, (5) plant capabilities, and (6) modifications required to successfully use the WMA process with available field and laboratory equipment.
- 6.1.2. Determine the temperatures that will be used for plant mixing and field compaction. Binder grade selection and allowable RAP content depend on the production temperature. See Table 1 for production temperatures below which the high temperature grade of the binder should be increased one level. See Table 2 for limits on RAP content.

6.2. Material Selection

6.2.1. Binder

- 6.2.1.1. Select the performance grade of the binder in accordance with Section 5 of AASHTO M323 considering the environment and traffic at the project site. Increase the high temperature performance grade based on the proposed production temperature. Increase the high temperature performance grade by one grade when the plant discharge temperature is less than specified in Table 1.

Table 1 - Recommended Production Temperatures Below Which the High Temperature Grade Should be Increased One Grade.

PG High Temperature Grade	Aging Index (AI) ¹											
	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6
	Minimum WMA Mixing Temperature Not Requiring PG Grade Increase, °F											
52	<215	<215	<215	<215	<215	<215	220	220	225	225	230	230
58	<215	<215	<215	220	225	230	235	235	240	240	245	245
64	<215	<215	220	230	235	235	240	245	245	250	250	250
67	<215	220	230	235	240	245	250	255	255	255	260	260
70	<215	220	230	240	245	245	250	255	255	260	260	260
76	<215	225	235	245	250	255	260	260	265	265	265	270
82	<215	235	245	250	255	260	265	265	270	270	275	275

1. $AI = \frac{(G^* / \sin \delta)_{RTFOT}}{(G^* / \sin \delta)_{Tank}}$ at the high temperature performance grade temperature.

6.2.1.2. Determine the specific gravity of the binder in accordance with AASHTO T 288. For WMA processes using emulsions, the specific gravity should be determined on the residue obtained from AASHTO T 59.

6.2.2. New Aggregates

6.2.2.1. Select new aggregates in accordance with Section 6 of AASHTO M323 considering the traffic level and depth in the pavement structure.

6.2.2.2. Obtain samples of aggregate proposed to be used for the project from the aggregate stockpiles in accordance with AASHTO T 2.

Note 5 –Most projects employ three to five stockpiles to generate a combined gradation conforming to the job-mix formula and M 323.

6.2.2.3. Reduce the samples of each aggregate stockpile according to AASHTO T 248 to samples of the size specified in AASHTO T 27.

6.2.2.4. Wash and grade each aggregate stockpile according to AASHTO T 11 and AASHTO T 27.

6.2.2.5. Determine the bulk and apparent specific gravity for the coarse and fine fraction of each stockpile in accordance with AASHTO T 84 and AASHTO T 85, respectively.

6.2.2.6. Determine the specific gravity of the mineral filler in accordance with AASHTO T 100.

6.2.3. Recycled Asphalt Pavement

6.2.3.1. Select RAP to obtain RAP aggregate properties meeting the requirements of Section 6 of AASHTO M323 considering the traffic level and depth in the pavement structure. The sand equivalent requirement does not apply to the RAP aggregate. Appendix A presents a recommended procedure for sampling and testing RAP stockpiles.

6.2.3.2. Determine a representative binder content for the RAP in accordance with Appendix A.

6.2.3.3. Determine a representative gradation for the RAP aggregate in accordance with Appendix A.

6.2.3.4. Determine a representative specific gravity for the RAP aggregate in accordance with Appendix A.

6.2.3.5. Obtain a representative sample of the RAP aggregate for checking conformance of the trial blends with the requirements of Section 6 of AASHTO M323.

Note 6 –In most cases, the ignition oven, AASHTO T308, can be used to obtain the representative sample of RAP aggregate for consensus property testing.

6.2.3.6. The quantity of RAP that can be added to WMA depends on the anticipated production temperature. Table 2 presents recommended maximum RAP contents for various WMA production temperatures.

Table 2 - Recommended Maximum RAP Contents for WMA.

Anticipated Production Temperature °F	Maximum RAP Content, %
≤215	
240	
≥265	Per HMA Specifications

6.3. Design Aggregate Structure

6.3.1. Preparing Trial Blend Gradations

6.3.1.1. Prepare a minimum of three trial aggregate blend gradations; plot the gradation of each trial blend on a 0.45-power gradation analysis chart, and confirm that each blend meets the AASHTO M 323 gradation controls (see Table 3 of AASHTO M 323). Gradation control is based on four control sieve sizes: the sieve for the maximum aggregate size, the sieve for the nominal maximum aggregate size, the 2.36-mm or 1.18- mm sieve, and the 0.075-mm sieve. An example of the three acceptable trial blends in the form of a gradation plot is given in Figure 1.

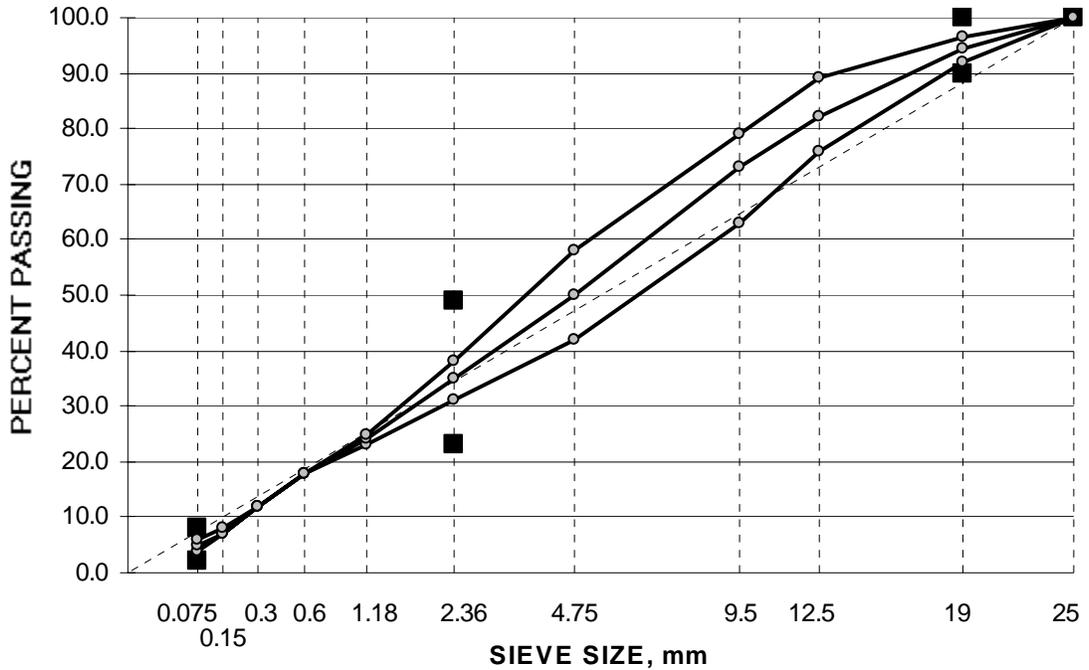


Figure 1 – Evaluation of the Gradations of Three Trial Blends (Example).

6.3.1.2. For mixtures with all new aggregate, the trial aggregate blend gradation is given by Equation 1:

$$P = A \times \left(\frac{a}{100} \right) + B \times \left(\frac{b}{100} \right) + C \times \left(\frac{c}{100} \right) + \dots \quad (1)$$

Where:

P = Percentage of material passing a given sieve for the trial aggregate blend.

A, B, C, \dots = Percentage of material passing a given sieve for stockpile A, B, C, etc.

a, b, c, \dots = Percentage of stockpile A, B, C, etc. used in the mixture where the total = 100.

6.3.1.3. When one or more RAP stockpile is used, a modified stockpile percentage is used in Equation 1 to account for the binder contained in the RAP stockpile (s).

$$\begin{aligned}
 a_m &= \left[\frac{a - \left(a \times \frac{Pb_a}{100} \right)}{100 - \left(a \times \frac{Pb_a}{100} + b \times \frac{Pb_b}{100} + c \times \frac{Pb_c}{100} + \dots \right)} \right] \times 100 \\
 b_m &= \left[\frac{b - \left(b \times \frac{Pb_b}{100} \right)}{100 - \left(a \times \frac{Pb_a}{100} + b \times \frac{Pb_b}{100} + c \times \frac{Pb_c}{100} + \dots \right)} \right] \times 100 \\
 c_m &= \left[\frac{c - \left(c \times \frac{Pb_c}{100} \right)}{100 - \left(a \times \frac{Pb_a}{100} + b \times \frac{Pb_b}{100} + c \times \frac{Pb_c}{100} + \dots \right)} \right] \times 100
 \end{aligned} \tag{2}$$

Where:

a_m, b_m, c_m, \dots = Percentage of aggregate from stockpile A, B, C, etc in the trial blend where the total = 100

a, b, c, \dots = Percentage of stockpile A, B, C, etc. used in the mixture where the total = 100.

$Pb_a, Pb_b, Pb_c \dots$ = RAP binder content for stockpile A, B, C, etc. For new aggregate stockpiles use 0.

6.3.1.4. Compute the bulk specific gravity of the aggregate blend using Equation 3.

$$G_{sb} = G_a \times \left(\frac{a}{100} \right) + G_b \times \left(\frac{b}{100} \right) + G_c \times \left(\frac{c}{100} \right) + \dots \tag{3}$$

Where:

G_{sb} = bulk specific gravity of the aggregate blend

G_a, G_b, G_c, etc = bulk specific gravity of the aggregate stockpile

a, b, c, etc = Percentage of aggregate from stockpile A, B, C, etc. used in the mixture where the total = 100. For mixtures with RAP, use the modified stockpile percentages from Equation 2.

6.3.1.5. Batch an aggregate sample for each of the trial blends to check the aggregate properties specified in Section 6 of AASHTO M323. For RAP mixtures use the RAP aggregate obtained in Section 6.2.3.5.

6.3.1.6. Conduct the aggregate quality tests specified in Section 6 of AASHTO M 323 to confirm that the aggregate in the trial blends meets the minimum quality requirements specified in AASHTO M 323.

Note 7 – At the discretion of the specifying agency, the designer may perform the quality tests on each stockpile instead of the trial aggregate blend. The test results from each stockpile can be used to estimate the results for various blends using Equation 3 and substituting the property of interest for the stockpile aggregate specific gravity. Care should be taken when using this approach with the fine aggregate angularity test, AASHTO T304, since aggregates from different sources may pack differently when combined.

6.3.2. Determining Initial Trial Binder Content

6.3.2.1. Designers can either use their experience with the material or the procedure given in Appendix B to determine an initial trial binder content for each trial aggregate blend gradation.

Note 8 – When using RAP, the initial trial asphalt content should be reduced by an amount equal to that provided by the RAP.

6.3.3. Compacting Specimens of Each Trial Aggregate Blend

6.3.3.1. From Table 3, determine the number of gyrations based on the design ESALs for the project. The $N_{initial}$ values given in Table 3 differ from those specified in AASHTO M323. $N_{initial}$ is used to assess the compactability of the mixture.

Table 3 – Gyrotory Compaction Effort

Design ESALs ^a (millions)	Compaction Parameters			Typical Roadway Application ^b
	N _{initial}	N _{design}	N _{max}	
< 0.3	10	50	75	Applications include roadways with very light traffic volumes such as local roads, country roads, and city streets where truck traffic is prohibited or at a very minimal level. Traffic on these roadways would be considered local in nature, not regional, intrastate, or interstate. Special purpose roadways serving recreational sites or areas may also be applicable to this level.
0.3 to < 3	10	75	115	Applications include many collector roads or access streets. Medium-trafficked city streets and the majority of country roadways may be applicable to this level.
3 to < 30	10	100	160	Applications include many two-lane, multilane, divided, and partially or completely controlled access roadways. Among these are medium to highly trafficked city streets, many state routes, U.S. highways, and some rural Interstates.
≥ 30	10	125	205	Applications include the vast majority of the U.S. Interstate System, both rural and urban in nature. Special applications such as truck-weighing stations or truck-climbing lanes on two-lane roadways may also be applicable to this level.
^a The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design the ESALs for 20 years.				
^b As defined by A Policy on Geometric Design of Highways and Stress, 1994, AASHTO.				

Note 9 – When specified by the Agency and the top of the design layer is ≥ 100 mm from the pavement surface and the estimated design traffic level is ≥ 0.3 million ESALs, decrease the estimated design traffic level by one, unless the mixture will be exposed to significant mainline construction traffic prior to being overlaid. If less than 25 percent of a construction lift is within 100 mm of the surface, the lift may be considered to be below 100 mm for the mixture design purposes.

Note 10 – When it is estimated that the design traffic level is between 3 and <10 million ESALs, the Agency may, at its discretion, specify $N_{initial}$ at 10, N_{design} at 75, and N_{max} at 115.

6.3.3.2. For each trial aggregate blend gradation, prepare separate mixture batches at the initial trial binder content for: (1) replicate gyrotory compacted samples, (2) replicate maximum specific gravity samples, and (3) one sample to evaluate workability and coating.

Note 11 – At least two replicate gyrotory specimens are required, but three or more may be prepared if desired. Generally, 4500 to 4700 g of aggregate is sufficient for each compacted specimen with a height of 110 to 120 mm for aggregates with combined bulk specific gravities of 2.55 to 2.70, respectively.

Note 12 – The maximum specific gravity for each trial mixture shall be the average of at least two tests.

- 6.3.3.3. Methods for specimen preparation are WMA process specific. Appendix C presents procedures for preparing specimens for (1) foamed asphalt, (2) Evotherm DAT, (3) Low Energy Asphalt, (4) Sasobit, (5) WAM Foam, and (6) zeolites. For other additives/processes, the user should consult the manufacturer for detailed specimen fabrication procedures.
- 6.3.3.4. Evaluate the workability of the mixture in accordance with the Appendix D of this standard.
- 6.3.3.5. Evaluate the degree of coating in accordance with AASHTO T195.
- 6.3.3.6. Condition the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³ in a forced draft oven at the proposed compaction temperature for 2 hours.
- 6.3.3.7. Compact gyratory specimens to N_{design} gyrations in accordance with AASHTO T 312. Record the specimen height to the nearest 0.1 mm after each revolution.
- 6.3.3.8. Determine the bulk specific gravity (G_{mb}) of each of the compacted specimens in accordance with AASHTO T 166 or AASHTO T 275 as appropriate.
- 6.3.3.9. Determine the theoretical maximum specific gravity (G_{mm}) according to AASHTO T 209 of the separate samples representing each of these combinations that have been mixed and conditioned to the same extent as the compacted specimens.

6.3.4. Evaluating Compacted Trial Mixtures

- 6.3.4.1. Calculate the V_a and VMA at N_{design} for each trial mixture using Equations 4 and 5:

$$V_a = 100 \times \left[1 - \left(\frac{G_{mb}}{G_{mm}} \right) \right] \quad (4)$$

$$VMA = 100 \times \left(1 - \frac{G_{mb} P_s}{G_{sb}} \right) \quad (5)$$

Where:

- G_{mb} = bulk specific gravity of the extruded specimen;
 G_{mm} = theoretical maximum specific gravity of the mixture;
 P_s = percent of aggregate in the mix, and
 G_{sb} = bulk specific gravity of the combined aggregate.

6.3.4.2. Estimate the volumetric properties at 4.0 percent air voids for each compacted specimen.

Note 13 – Although the initial trial binder content was estimated for a design air void content of 4.0 percent, the actual air void content of the compacted specimen is unlikely to be exactly 4.0 percent. Therefore, the change in the binder content needed to obtain a 4.0 percent air void content, and the change in the VMA caused by this change in the binder content, is estimated. These calculations permit the evaluation of VMA and VFA of each trial aggregate gradation at the same design air void content, 4.0 percent

6.3.4.2.1. Determine the difference in average air void content at N_{design} (ΔV_a) of each aggregate trial blend from the design level of 4.0 percent using Equation 6:

$$\Delta V_a = 4.0 - V_a \quad (6)$$

where:

V_a = air void content of the aggregate trial blend at N_{design} gyrations

6.3.4.2.2. Estimate the change in binder content (ΔP_b) needed to change the air void content to 4.0 percent using Equation 7:

$$\Delta P_b = -0.4 \times \Delta V_a \quad (7)$$

6.3.4.2.3. Estimate the change in VMA (ΔVMA) caused by the change in the air void content (ΔV_a) determined in section 6.3.4.4 for each trial aggregate blend gradation, using Equation 8 or 9.

$$\Delta VMA = 0.2 \times \Delta V_a \quad \text{if } V_a > 4.0 \quad (8)$$

$$\Delta VMA = -0.1 \times \Delta V_a \quad \text{if } V_a < 4.0 \quad (9)$$

Note 14 – A change in the binder content affects the VMA through a change in the bulk specific gravity of the compacted specimen (G_{mb}).

6.3.4.2.4. Calculate the VMA for each aggregate trial blend at N_{design} gyrations and 4.0 percent air voids using Equation 10:

$$VMA_{design} = VMA_{trial} + \Delta VMA \quad (10)$$

where:

VMA_{design} = VMA estimated at a design air void content of 4.0 percent; and

VMA_{trial} = VMA determined at the initial trial binder content.

- 6.3.4.2.5. Calculate the VFA for each aggregate trial blend at N_{design} gyrations and 4.0 percent air voids using Equation 11:

$$VFA_{design} = \frac{VMA_{design}}{(VMA_{design} - 4.0)} \quad (11)$$

- 6.3.4.2.6. Using the values of ΔV_a determined in Section 6.3.4.2.1 and Equation 12, estimate the relative density of each specimen at $N_{initial}$ when the design air void content is adjusted to 4.0 percent at N_{design} :

$$\%G_{mm_{initial}} = 100 \times \left(\frac{G_{mb} \times h_d}{G_{mm} \times h_i} \right) - \Delta V_a \quad (12)$$

where:

$\%G_{mm_{initial}}$ = relative density at $N_{initial}$ gyrations at the adjusted design binder content;

h_d = height of the specimen after N_{design} gyrations, from the Superpave gyratory compactor, mm; and

h_i = height of the specimen after $N_{initial}$ gyrations, from the Superpave gyratory compactor, mm

- 6.3.4.2.7. Compute the effective specific gravity of the aggregate using Equation 13.

$$G_{se} = \frac{(100 - P_b)}{\left(\frac{100}{G_{mm}} - \frac{P_b}{G_b} \right)} \quad (13)$$

where:

G_{se} = effective specific gravity of the aggregate

P_b = trial binder content

G_b = specific gravity of the binder

G_{mm} = maximum specific gravity of the trial mixture

- 6.3.4.2.8. Estimate the percent effective binder ($P_{be_{est}}$) and calculate the dust-to-binder ratio for each trial blend using Equations 14 and 15:

$$P_{be_{est}} = P_b + \Delta P_b - \left\{ (P_s \times G_b) \times \left[\frac{(G_{se} - G_{sb})}{(G_{se} \times G_{sb})} \right] \right\} \quad (14)$$

where:

$P_{be_{est}}$ = estimated effective binder content,

P_s = aggregate content,

G_b = specific gravity of the binder,
 G_{se} = effective specific gravity of the aggregate,
 G_{sb} = bulk specific gravity of the combined aggregate
 P_b = trial binder content
 ΔP_b = estimated change in binder content to reach 4.0 percent air voids content

$$\text{dust-to-binder ratio} = \frac{P_{0.075}}{P_{be_{est}}} \quad (15)$$

where:

$P_{0.075}$ = percent passing the 0.075-mm sieve.

$P_{be_{est}}$ = estimated effective binder content

6.3.4.3. Compare the properties of each trial blend to the criteria listed in Table 4. Select the trial aggregate blend that best satisfies the volumetric.

Table –4 Design Aggregate Structure Selection.

Property	Criteria
Gradation	Section 6 of AASHTO M323 for the traffic level and depth from the pavement surface
Aggregate Properties	Section 6 of AASHTO M323 for the traffic level and depth from the pavement surface
Coating	100 %
Workability	Satisfactory
Compactability	$N_{initial} \geq xx \%$
VMA	Section 7 of AASHTO M323 for the traffic level and nominal maximum aggregate size
VFA	Section 7 of AASHTO M323 for the traffic level and nominal maximum aggregate size
Dust-Binder-Ratio	Section 7 of AASHTO M323

Note 15 – Table 4 presents an example of the selection of a design aggregate structure from three trial blend gradations.

Note 16 – Many trial aggregate blend gradations will fail the VMA criterion. Section 12.1 gives a procedure for the adjustment of VMA.

Note 17 – If the trial aggregate gradations have been chosen to cover the entire range of the gradation controls, then the only remaining solution is to make adjustments to the aggregate production or to introduce aggregates from a new source. The aggregates that fail to meet the required criteria will not produce a quality mix and should not be used. One or more of the aggregate stockpiles should be replaced with another material which produces a stronger structure. For example, a quarry stone can replace crushed gravel, or crushed fines can replace natural fines.

Table 4 – Selection of a Design Aggregate Structure (Example)

Trial Mixture (19.0-mm Nominal Maximum Aggregate)				
20-Year Project Design ESALs = 5 million				
	1	2	3	
Property	At the Initial Trial Binder Content			Criteria
Coating	100	100	100	100 %
Workability	Good	Satisfactory	Good	Satisfactory
P_b (trial)	4.4	4.4	4.4	
% G_{mm} at $N_{initial}$ (trial)	88.3	88.0	yy	≥ xx %
% G_{mm} at N_{design} (trial)	95.6	94.9	94.5	
V_a at N_{design}	4.4	5.1	5.5	4.0
VMA (trial)	13.0	13.6	14.1	
<u>Adjustment to Reach Design Binder Content ($V_a = 4.0\%$ at N_{design})</u>				
ΔV_a	-0.4	-1.1	-1.5	
ΔP_b	0.2	0.4	0.6	
Δ VMA	-0.1	-0.2	-0.3	
<u>At the Estimated Design Binder Content ($V_a = 4.0\%$ at N_{design})</u>				
Estimated P_b (design)	4.6	4.8	5.0	
VMA (design)	12.9	13.4	13.8	≥ 13.0
VFA (design)	69.0	70.1	71.0	65 – 75
% G_{mm} at $N_{initial}$ (design)	88.7	89.1	yy	≥ xx %

Notes:

- The top of this table presents measured properties for specimens prepared for each aggregate trial blend at the initial trial binder content.
- None of the specimens had an air void content of exactly 4.0 percent. Therefore, the procedures described in Section 6.3.4 must be applied to: (1) estimate the design binder content at which $V_a = 4.0$ percent, and (2) obtain adjusted VMA and relative density values at this estimated binder content.
- The middle portion of this table presents the change in binder content (ΔP_b) and VMA (Δ VMA) that occurs when the air void content (V_a) is adjusted to 4.0 percent for each trial aggregate blend gradation.
- A comparison of the VMA and densities at the estimated design binder content to the criteria in the last column shows that trial aggregate blend gradation No. 1 does not have sufficient VMA (12.9 percent versus the requirement of ≥13.0 percent). Trial blend No. 3 does not meet the compactability criterion for relative density at $N_{initial}$ gyrations (yy versus a requirement of ≥ xx percent). Trial blend No.2 meets the requirement for relative density, VMA and VFA, and in this example, is selected as the design aggregate structure.

6.4. Selecting The Design Binder Content

6.4.1. Prepare separate mixture batches at four binder contents for: (1) replicate gyratory compacted samples, and (2) replicate maximum specific gravity samples. (See Notes 11 and 12) The binder contents are: (1) the estimated design binder content, P_b (design); (2) 0.5 percent below P_b (design); (3) 0.5 percent above P_b (design); and (4) 1.0 percent above P_b (design).

6.4.2. Methods for specimen preparation are WMA process specific. Appendix C presents procedures for preparing specimens for (1) foamed asphalt, (2) Evotherm DAT, (3) Low Energy Asphalt, (4) Sasobit, (5) WAM Foam, and (6) zeolites. For other

additives/processes, the user should consult the manufacturer for detailed specimen fabrication procedures.

- 6.4.3. Condition the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³ in a forced draft oven at the proposed compaction temperature for 2 hours. Stir the mixture once after the first hour.
- 6.4.4. Compact gyratory specimens to N_{design} gyrations from Table 2 in accordance with AASHTO T 312. Record the specimen height to the nearest 0.1 mm after each revolution.
- 6.4.5. Determine the bulk specific gravity (G_{mb}) of each of the compacted specimens in accordance with AASHTO T 166 or AASHTO T 275 as appropriate.
- 6.4.6. Determine the theoretical maximum specific gravity (G_{mm}) according to AASHTO T 209 of the separate samples representing each of these combinations that have been mixed and conditioned to the same extent as the compacted specimens.
- 6.4.7. Determine the design binder content which produces a target air void content (V_a) of 4.0 percent at N_{design} gyrations use the following steps:
- 6.4.7.1.1. Calculate V_a , VMA , VFA at N_{design} using Equations 4, 5, and 16:

$$VFA = \left(\frac{VMA - V_a}{VMA} \right) \times 100 \quad (16)$$

where:

VFA = voids filled with asphalt,
 V_a = air void content,
 VMA = voids in mineral aggregate

- 6.4.7.1.2. Calculate G_{se} , and the effective binder content P_{be} using Equations 13 and 17:

$$P_{be} = P_b - \left\{ (P_s \times G_b) \times \left[\frac{(G_{se} - G_{sb})}{(G_{se} \times G_{sb})} \right] \right\} \quad (17)$$

where:

P_{be} = effective binder content,
 P_s = aggregate content,
 G_b = specific gravity of the binder
 P_b = effective binder content,
 G_{se} = effective specific gravity of the aggregate,
 G_{sb} = bulk specific gravity of the combined aggregate, and

6.4.7.1.3. Calculate the dust-to-binder ratio using Equation 18.

$$\text{dust-to-binder ratio} = \frac{P_{0.075}}{P_{be}} \quad (18)$$

where:

$$P_{0.075} = \text{percent passing the 0.075-mm sieve.}$$

$$P_{be} = \text{effective binder content}$$

6.4.7.1.4. For each of the four mixtures, determine the average corrected specimen relative densities at $N_{initial}$ using Equation 19.

$$\%G_{mm_{initial}} = 100 \times \left(\frac{G_{mb} \times h_d}{G_{mm} \times h_i} \right) \quad (19)$$

where:

$$\%G_{mm_{initial}} = \text{relative density at } N_{initial} \text{ gyrations;}$$

h_d = height of the specimen after N_{design} gyrations, from the Superpave gyratory compactor, mm; and

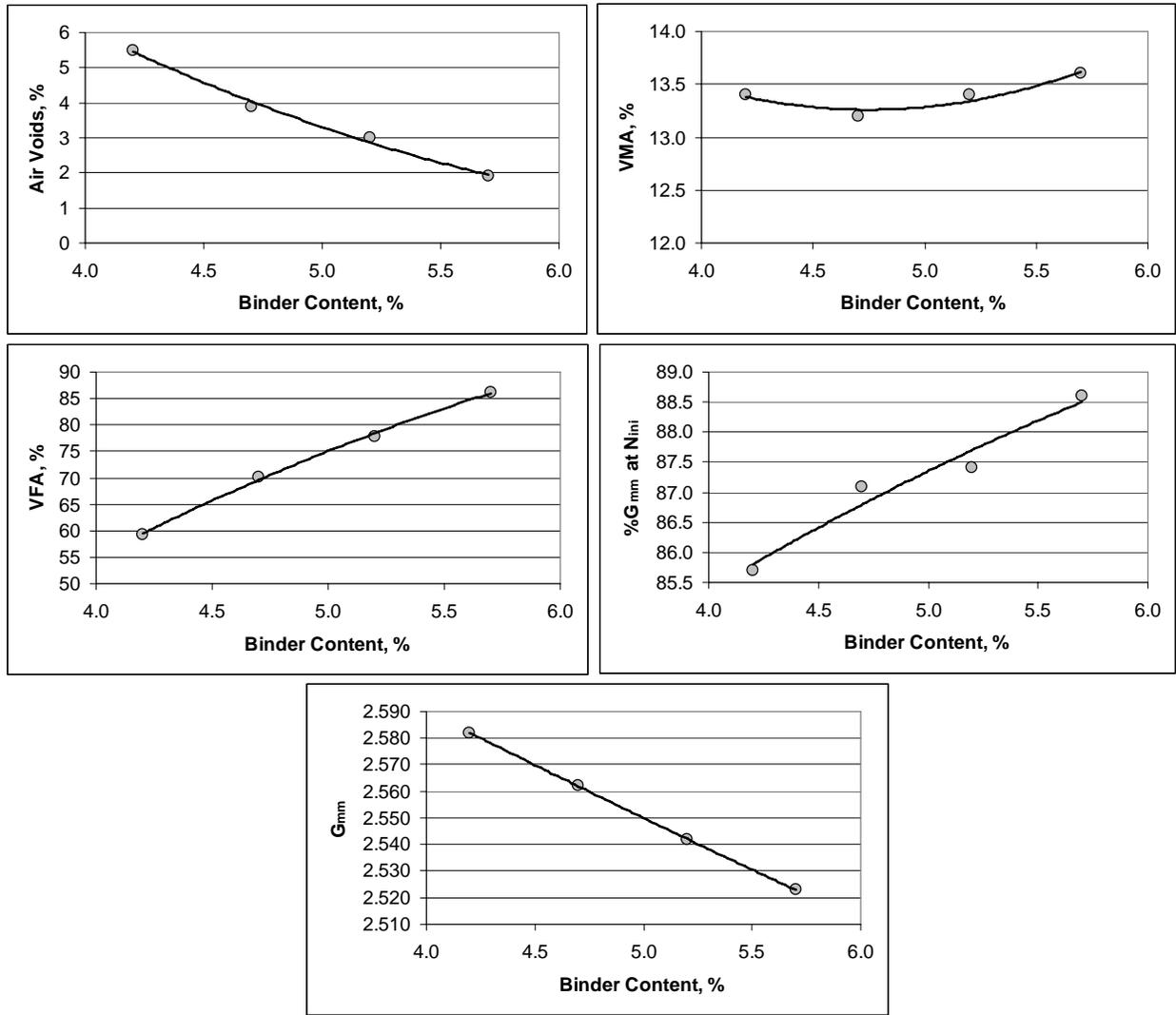
h_i = height of the specimen after $N_{initial}$ gyrations, from the Superpave gyratory compactor, mm

6.4.7.1.5. Plot the average V_a , VMA , VFA , relative density at $N_{initial}$ and G_{mm} for the replicate specimens versus binder content.

Note 18 – Figure 2 presents a sample data set and associated plots.

6.4.7.1.6. By graphing or mathematical interpolation (Figure 2), determine the binder content to the nearest 0.1 percent at which the target V_a is equal to 4.0 percent. This is the design binder content (P_b) at N_{design} .

6.4.7.2. Compare the properties at the design binder content of each trial blend to the criteria listed in Table 5 to ensure the mixture complies with the volumetric design criteria.



Average V_a, VMA, VFA, G_{mm}, and Relative Density at N_{initial}

Pb (%)	V _a (%)	VMA (%)	VFA (%)	G _{mm}	%G _{mm} at N _{initial}
4.2	5.5	13.4	59.3	2.582	85.7
4.7	3.9	13.2	70.1	2.562	87.1
5.2	3.0	13.4	77.9	2.542	87.4
5.7	1.9	13.6	86.2	2.523	88.6

Notes:

1. In this example, the estimated design binder content is 4.7 percent, the minimum VMA requirement for the design aggregate structure (19.0-mm nominal maximum size) is 13.0 percent, and the VFA requirement is 65 to 75 percent.
2. Entering the plot of percent air voids versus percent binder content at 4.0 percent air voids, the design binder content is determined as 4.7 percent.
3. Entering the plots of percent VMA versus percent binder content and VFA versus percent binder content at 4.7 percent binder content, the mix meets the VMA and VFA requirements.

Figure 2 – Sample Volumetric Design Data

Table –5 Design Binder Content Selection.

Property	Criteria
Air Voids	4.0 %
Compactability	$N_{\text{initial}} \geq \text{xx} \%$
VMA	Section 7 of AASHTO M323 for the traffic level and nominal maximum aggregate size
VFA	Section 7 of AASHTO M323 for the traffic level and nominal maximum aggregate size
Dust-Binder-Ratio	Section 7 of AASHTO M323

- 6.4.8. Prepare separate mixture batches using the design aggregate structure at the design binder content for (1) replicate specimens to evaluate the relative density at N_{max} and (2) one sample to evaluate workability and coating (See Note 11).
- 6.4.9. Evaluate the workability of the mixture in accordance with the Appendix D of this standard. Workability must be rated as satisfactory or better.
- 6.4.10. Evaluate the degree of coating in accordance with AASHTO T195. Degree of coating must be 100%.
- 6.4.11. Condition the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³ in a forced draft oven at the proposed compaction temperature for 2 hours. Stir the mixture once after the first hour.
- 6.4.12. Compact gyratory specimens to N_{max} gyrations from Table 2 in accordance with AASHTO T 312.
- 6.4.13. Determine the bulk specific gravity (G_{mb}) of each of the compacted specimens in accordance with AASHTO T 166.
- 6.4.14. Determine the average specimen relative density at N_{max} , by using Equation 20, and confirm that the relative density at N_{max} satisfies the volumetric requirements in AASHTO M 323.

$$\%G_{mm_{max}} = \left(\frac{G_{mb}}{G_{mm}} \right) \times 100 \quad (20)$$

where:

$\%G_{mm_{max}}$ = relative density at N_{max} gyrations;

G_{mb} = average bulk specific gravity of specimens compacted to N_{max}

G_{mm} = maximum specific gravity at the design binder content

6.5. Evaluating Moisture Sensitivity

- 6.5.1. Prepare separate mixture batches of the design aggregate structure at the design binder content for six gyratory specimens.
- 6.5.2. Methods for specimen preparation are WMA process specific. Appendix C presents procedures for preparing specimens for (1) foamed asphalt, (2) Evotherm DAT, (3) Low Energy Asphalt, (4) Sasobit, (5) WAM Foam, and (6) zeolites. For other additives/processes, the user should consult the manufacturer for detailed specimen fabrication procedures.
- 6.5.3. Condition the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³ in a forced draft oven at the proposed compaction temperature for 2 hours. Stir the mixture once after the first hour..

Note 19 – Do not use the conditioning procedure in AASHTO T 283 or AASHTO R30 for WMA

- 6.5.4. Compact test specimens to 7.0 ± 0.5 percent air voids in accordance with AASHTO T 312.
- 6.5.5. Group, condition and test the specimens in accordance with AASHTO T 283.
- 6.5.6. If the tensile strength ratio is less than 0.80, as required in M 323, remedial action such as the use of anti-strip agents is required to improve the moisture susceptibility of the mix. When remedial agents are used to modify the binder, retest the mix to assure compliance with the 0.80 minimum requirements.

6.6. Evaluating Rutting Resistance

- 6.6.1. Rutting resistance is evaluated using the Flow Number Test. Details of the test procedure are given in NCHRP 9-29 RT 01-07, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Simple Performance Test System*.
- 6.6.2. The test is conducted on 100 mm diameter by 150 mm high specimens that are sawed and cored from larger 150 mm diameter by 175 mm high specimens. Refer to NCHRP 9-29 RP 02-07, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor*, for detailed procedures for test specimen fabrication.
- 6.6.3. The Flow Number Test is conducted at the design temperature at 50 % reliability as determined using LTPP Bind Version 3.0. The temperature is computed at 20 mm for surface courses, and the top of the pavement layer for intermediate and base courses.

- 6.6.4. The Flow Number Test is conducted unconfined using an axial stress level of 600 kPa.
- 6.6.5. Table 6 presents minimum Flow Numbers for as a function of traffic level for mixtures that meet the volumetric criteria in this standard.

Table 6 – Minimum Flow Number Requirements

Traffic Level, Million ESALs	Minimum Flow Number
<3	NA
3 to < 10	200
10 to < 30	320
≥ 30	580

- 6.6.6. Prepare four separate mixture batches of the design aggregate structure at the design binder content for four gyratory specimens that are 175 mm in height.

Note 20 – Refer to NCHRP 9-29 RP 02-07, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor*, for detailed procedures for test specimen fabrication.

- 6.6.7. Methods for specimen preparation are WMA process specific. Appendix C presents procedures for preparing specimens for (1) foamed asphalt, (2) Evotherm DAT, (3) Low Energy Asphalt, (4) Sasobit, (5) WAM Foam, and (6) zeolites. For other additives/processes, the user should consult the manufacturer for detailed specimen fabrication procedures.
- 6.6.8. Condition the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³ in a forced draft oven at the proposed compaction temperature for 2 hours. Stir the mixture once after the first hour.
- 6.6.9. Prepare the Flow Number Test specimens to 4.0 ± 0.5 percent air voids in accordance with AASHTO T 312 (See Note 20).
- 6.6.10. Perform the Flow Number Test at the design temperature at 50 % reliability as determined using LTPP Bind Version 3.0. Perform the tests unconfined with a repeated axial stress of 600 kPa.
- 6.6.11. Determine the Flow Number for each specimen, then average the results. Compare the average Flow Number with the criteria given in Table 5.

6.7. Adjusting The Mixture To Meet Specification Properties

- 6.7.1. *Adjusting VMA* – If a change in the mix design aggregate skeleton is required to meet the specified VMA, there are three likely options: (1) change the gradation (Note 21); (2) reduce the minus 0.075-mm fraction (Note 22); or (3) change the surface texture and/or shape of one or more of the aggregate fractions (Note 23).

Note 21 – Changing the gradation may not be an option if the trial aggregate blend gradation analysis includes the full spectrum of the gradation control area.

Note 22 – Reducing the percentage passing the 0.075-mm sieve of the mix will typically increase the VMA. If the percent passing the 0.075-mm sieve is already low, this is not a viable option.

Note 23 – This option will require further processing of existing material or a change in aggregate sources.

- 6.7.2. *Adjusting VFA* – The lower limit of the VFA range should always be met at 4.0 percent air voids if the VMA meets the requirements. If the upper limit of the VFA is exceeded, then the VMA is substantially above the minimum required. If so, redesign the mixture to reduce the VMA. Actions to consider for redesign include: (1) changing to a gradation that is closer to the maximum density line; (2) increasing the minus 0.075-mm fraction, if room is available within the specification control points; or (3) changing the surface texture and shape of the aggregate by incorporating material with better packing characteristics, e.g., less thin, elongated particles.
- 6.7.3. *Improving Coating*- Most WMA processes involve complex chemical reactions and/or thermodynamic processes. Consult the WMA additive supplier for methods to improve coating.
- 6.7.4. *Improving Workability*- Most WMA processes involve complex chemical reactions and/or thermodynamic processes. Consult the WMA additive supplier for methods to improve workability.
- 6.7.5. *Improving Compactability*- Most WMA processes involve complex chemical reactions and/or thermodynamic processes. Consult the WMA additive supplier for methods to improve compactability.
- 6.7.6. *Improving the Tensile Strength Ratio* – Some WMA processes include adhesion promoters to improve resistance to moisture damage. Consult the WMA additive supplier for methods to improve the tensile strength ratio.
- 6.7.7. *Improving Rutting Resistance*- The rutting resistance of WMA can be improved through changes in binder grade and volumetric properties. The following rules of thumb can be used to identify mixture adjustments to improve rutting resistance.

- Increasing the high temperature performance grade one grade level improves rutting resistance by a factor of 2.
- Increasing the fineness modulus (sum of the percent passing the .075, 0.150, and 0.300 mm sieves) by 50 improves rutting resistance by a factor of 2.
- Decreasing the design VMA by 1 % will improve rutting resistance by a factor of 1.2.
- Increasing N_{design} by one level will improve rutting resistance by factor of 1.2.

6.8. Reporting

- 6.8.1. The report shall include the identification of the project number, traffic level, and mix design number.
- 6.8.2. The report shall identify the proposed WMA process and the proposed temperatures for production, placement, and compaction.
- 6.8.3. The report shall provide a technical contact for responding to questions concerning the WMA process.
- 6.8.4. The report shall provide any process specific laboratory handling instructions.
- 6.8.5. The report shall include the following information on the materials used in the WMA:
 - 6.8.5.1. *Binder*- source, performance grade, and specific gravity.
 - 6.8.5.2. *New Aggregate Stockpiles* – source, mineralogy, gradation, bulk specific gravity, and quality characteristics.
 - 6.8.5.3. *RAP Stockpiles* – source, representative binder content, bulk specific gravity of the RAP aggregate, and quality characteristics for the RAP aggregate.
 - 6.8.5.4. *Additives* – type and amount.
- 6.8.6. The report shall include the following information on the design aggregate structure for the WMA:
 - 6.8.6.1. Stockpile Percentages and Design Blend Aggregate Gradation.
 - 6.8.6.2. Bulk Specific Gravity of the Design Blend.
 - 6.8.6.3. Quality Characteristics of the Design Blend Aggregate

6.8.7. The report shall include the following information on the properties of the WMA:

6.8.7.1. Design Compaction Level.

6.8.7.2. Tabulated data and plots for V_a , G_{mm} , VMA, VFA, % G_{mm} at N_{design} , and dust-binder ratio as a function of trial binder content.

6.8.7.3. Design Binder Content and coating, workability, V_a , G_{mm} , VMA, VFA, % G_{mm} at N_{design} , and dust-binder ratio at the design binder content.

6.8.7.4. Dry tensile strength and tensile strength ratio at the design binder content.

6.8.7.5. Flow Number at the design binder content.

7. MIXTURE ANALYSIS PROCEDURES

7.1. General

7.1.1. This section presents recommended test methods and analysis procedures for analyzing the expected performance of pavements incorporating WMA mixtures.

7.1.2. Tests are recommended for analysis of: (1) dynamic modulus, (2) fatigue cracking, and (3) thermal cracking.

7.1.3. Results from these tests can be use with the AASHTO MEPDG to analyze the performance of pavements incorporating WMA layers.

7.1.4. Mixture analysis is performed at the discretion of the specifying agency. The testing may be performed on the design mixture at the design binder content to assess the overall performance, or it may be performed on variations of the mixture to assess the sensitivity of the mixture to variations during production.

7.2. Dynamic Modulus

7.2.1. The dynamic modulus of WMA is needed to predict pavement performance using Level 1 inputs to the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) or to perform pavement structural design using other mechanistic-empirical pavement design methods. It is also needed for the fatigue analysis described in Section 7.3 below.

7.2.2. The recommended equipment for measuring the dynamic modulus of WMA is the Simple Performance Test System (SPT) using the standard test methods and practices developed for the SPT.

7.2.3. Specimen Preparation

- 7.2.3.1. Prepare two 100 mm diameter by 150 mm high test specimen.
- 7.2.3.2. Prepare test specimens in accordance with NCHRP 9-29 RP 02-07, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor*, except mixture preparation shall be as specified in Appendix C, and short-term oven aging shall be 2 hours at the proposed compaction temperature.
- 7.2.3.3. The target air void content for the dynamic modulus specimens should be representative of the in-place air void content required by the agency specifications.

7.2.4. Dynamic Modulus Testing

- 7.2.4.1. Test each dynamic modulus specimen at the temperatures and frequencies specified in NCHRP 9-29 RP 01-07, *Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Concrete Using the Simple Performance Test System*.
- 7.2.4.2. Conduct dynamic modulus tests in accordance with NCHRP 9-29 RT 01-07, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Simple Performance Test System*.

7.2.5. Data Analysis

- 7.2.5.1. Analyze the resulting data and prepare a dynamic modulus master curve in accordance with NCHRP 9-29 RP 01-07, *Developing Dynamic Modulus Master Curves for Hot-Mix Asphalt Concrete Using the Simple Performance Test System*.

Note 24 –A Microsoft Excel™ workbook “MASTERSOLVER2.1.xls” was developed in NCHRP Project 9-29 to perform this analysis.

- 7.2.5.2. From the fitted dynamic modulus master curve, compute the dynamic modulus at the following temperatures and frequencies for use in the MEPDG software. A total of 30 dynamic modulus values should be calculated.

Temperatures	Frequencies
-10, 4.4, 21.1, 37.8, and 54.4 °C (14, 40, 70, 100, 130, °C)	25, 10, 5, 1, 0.5, and 0.1 Hz

7.2.6. Report the following:

- 7.2.6.1. Mixture identification
- 7.2.6.2. Target air voids and the actual air voids for the specimens tested.

- 7.2.6.3. VMA and VFA of each specimen tested
- 7.2.6.4. Average VMA and VFA for the specimens tested
- 7.2.6.5. Measured dynamic modulus and phase angle data for each specimen at each temperature/frequency combination
- 7.2.6.6. Average measured dynamic modulus and phase angle at each temperature/frequency combination
- 7.2.6.7. Coefficient of variation of the measured dynamic modulus data at each temperature/frequency combination
- 7.2.6.8. Standard deviation of the measured phase angle data at each temperature/frequency combination.
- 7.2.6.9. Reference temperature
- 7.2.6.10. Parameters of the fitted master curve (Max , δ , β , γ , and ΔE_a)
- 7.2.6.11. Goodness of fit statistics for the fitted master curve (Se , Sy , Se/Sy , R^2)
- 7.2.6.12. Plot of the fitted dynamic modulus master curve as a function of reduced frequency showing average measured dynamic modulus data
- 7.2.6.13. Plot of shift factors as a function of temperature
- 7.2.6.14. Plot of average phase angle as a function of reduced frequency.
- 7.2.6.15. Tabulated temperature, frequency, and dynamic modulus for input into MEPDG.

7.3. Fatigue Testing and Analysis

- 7.3.1. The recommended method for analyzing the fatigue resistance of WMA uses cyclic direct tension fatigue testing and simplified continuum damage analysis.
- 7.3.2. This testing and analysis was designed to be compatible with the Simple Performance Test System (SPT), and to provide a complete characterization for the fatigue resistance of WMA using limited testing.
- 7.3.3. Determine the temperature shift factor from 4 °C to 20 °C for the mixture by conducting the dynamic modulus master curve testing described in Section 7.2.
- 7.3.4. Specimen Preparation

- 7.3.4.1. Prepare four 100 mm diameter by 150 mm high test specimen.
- 7.3.4.2. Prepare test specimens in accordance with NCHRP 9-29 RP 02-07, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor*, except mixture preparation shall be as specified in Appendix C, and short-term oven aging shall be 2 hours at the proposed compaction temperature.
- 7.3.4.3. To simulate long-term aging, condition the gyratory specimens and a companion loose mix sample in accordance with Section 9.3 of NCHRP 9-29 RP 02-07, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor*.
- 7.3.4.4. The target air void content for the fatigue test specimens should be representative of the in-place air void content required by the agency specifications.

7.3.5. Fatigue Testing

- 7.3.5.1. Perform cyclic direct tension fatigue tests in accordance with XXX for the following conditions:

Temperature, °C	Frequency, Hz	Strain Level	Maximum Cycles
20	10	Low	108,000
20	10	High	12,000
4	10	Low	108,000
4	10	High	12,000

$$Low\ Strain = 80 - \frac{|E^*|}{38,000} + 0.7 \times Gyration - 2.3 \times VTM$$

$$High\ Strain = 1.8 \times Low\ Strain$$

where:

Low Strain = low strain level, μ strain

High Strain = high strain level, μ strain

$|E^*|$ = dynamic modulus, psi

Gyrations = number of gyrations used to prepare the test specimen

VTM = air void content of the test specimen, %

- 7.3.5.2. Record the dynamic modulus of the specimen at the appropriate interval as required by XXX. The dynamic modulus will decrease as the test progresses. Stop the test when the maximum number of cycles listed in Section 7.3.5.1 is reached.

Note 25 – The Simple Performance Test System supplied by IPC Global, Ltd. has fixtures and software to perform the fatigue testing per XXX.

7.3.6. Analysis

7.3.6.1. The analysis combines the modulus versus loading cycles data from the four specimens tested in Section 7.3.5 to determine the continuum damage fatigue constant, C_2 , which defines the rate of damage accumulation for the mixture tested at a reference temperature of 20 °C.

7.3.6.1.1. For each load cycle that data has been collected, compute the damage ratio, $C(N)$:

$$C(N) = \frac{|E^*|_N}{|E^*|_{initial}} \quad (21)$$

where:

$C(N)$ = damage ratio for cycle N

$|E^*|_N$ = dynamic modulus measured for cycle N

$|E^*|_{initial}$ = average dynamic modulus measured over the first 10 cycles.

7.3.6.1.2. For each load cycle that data has been collected, compute the damage parameter, $S(N)$, for 10 values of the exponent α between 1.5 and 2.5.

$$S(N) = \left[\frac{\alpha N (-\ln C(N))^{1+\alpha} \varepsilon_0^{2\alpha} |E^*|_{initial}^{2\alpha}}{2^\alpha f_{20} (C(N)^{-\alpha} - 1)} \right]^{\frac{1}{1+\alpha}} \quad (22)$$

where:

$S(N)$ = damage parameter for cycle N

α = continuum damage exponent

$C(N)$ = damage ratio for cycle N

N = cycle number

ε_0 = strain amplitude

$|E^*|_{initial}$ = average dynamic modulus measured over the first 10 cycles.

f_{20} = reduced frequency at 20 °C = $10 \times a(T)$

$a(T)$ = temperature shift factor from the dynamic modulus master curve for a reference temperature of 20 °C

7.3.6.1.3. Plot $\ln[C(N)]$ versus $S(N)$ for each value of α . Select the value of α that best collapses the data from the four specimens onto a unique line.

7.3.6.1.4. Determine the continuum damage fatigue parameter, C_2 as the slope of the line of $\ln[C(N)]$ versus $S(N)$ for the value of α that best collapses the data from the four specimens onto a unique line.

Note 26 – A Microsoft Excel™ workbook to perform this analysis is available from IPC Global, Ltd.

7.3.6.2. Compute the inherent fatigue coefficient, K_{fv} , for the mixture.

$$K_{fv} = 650(-C_2)^{-2.74} |E^*|_{initial}^{-2.137} \quad (23)$$

C_2 = continuum damage parameter

$|E^*|_{initial}$ = average dynamic modulus measured over the first 10 cycles.

7.3.6.3. Determine the fatigue rating of the mixture from the table below:

K_{fv} Value	Fatigue Resistance
≥ 3.5	Excellent
≥ 1.5 to < 3.5	Good
≥ 0.7 to < 3.5	Average
≥ 0.3 to < 0.7	Poor

7.3.7. Report the following:

7.3.7.1. Mixture identification

7.3.7.2. Target air voids and the actual air voids for the specimens tested.

7.3.7.3. VMA and VFA of each specimen tested

7.3.7.4. Average VMA and VFA for the specimens tested

7.3.7.5. $|E^*|_{initial}$ for the specimens tested.

7.3.7.6. Temperature shift factor for 4 °C for a reference temperature of 20 °C from the dynamic modulus master curve. See Section 7.2.

7.3.7.7. Value of α that best collapses the data from the four specimens onto a unique $\ln[C(N)]$ versus $S(N)$ line.

- 7.3.7.8. Value of C_2 , the slope of the line of $\ln[C(N)]$ versus $S(N)$ for the value of α that best collapses the data from the four specimens onto a unique line.
- 7.3.7.9. The inherent fatigue coefficient, K_{fi} , and the fatigue rating for the mixture.
- 7.3.7.10. Tabulated values of cycle number (N), strain amplitude (ϵ_0), dynamic modulus ($/E^*$), damage ratio ($C(N)$), and damage parameter ($S(N)$) for the selected value of α .
- 7.3.7.11. A plot of $\ln[C(N)]$ versus $S(N)$ for the value of α that best collapses the data from the four specimens onto a unique line indicating the slope C_2

7.4. Thermal Cracking Analysis

- 7.4.1. The recommended method for analysis of thermal cracking in flexible pavements requires measurement of compliance and strength properties of the mixture at low temperatures. These properties are then used in a thermo-viscoelastic stress analysis to estimate the thermal stresses induced in the pavement during cooling cycles.
- 7.4.2. Mixture compliance and strength properties are obtained by testing specimens in the indirect tensile (IDT) mode in accordance with AASHTO T322.
- 7.4.3. Two software programs are available to perform the thermo-viscoelastic stress analysis:
 - 7.4.3.1. The AASHTO MEPDG includes a model to predict the extent of thermal cracking in a flexible pavement considering environmental conditions at the project site, and the thickness and properties of the asphalt concrete used in the pavement. This model has been calibrated using data from several in-service pavements.
 - 7.4.3.2. "LTSTRESS.xls" is a Microsoft Excel™ Workbook developed at the Northeast Center for Excellence in Pavement Technology to reduce data from AASHTO T322 and perform a simplified thermal cracking analysis. The output of this analysis is a critical cracking temperature, the temperature where the computed thermal stresses for a specified cooling rate exceed the tensile strength of the mixture. LTSTRESS has not been calibrated to observed cracking and should be used for comparative evaluation of mixtures.
- 7.4.4. Specimen Preparation
 - 7.4.4.1. Compact three 150 mm diameter by 115 mm high gyratory specimens in accordance with AASHTO T312 to an void content that is 1 percent higher than the target test specimen air void content. The target test specimen air void

content should be representative of the in-place air void content required by the agency specifications.

- 7.4.4.2. Prepare a companion sample of loose mix meeting the sample size requirements of AASHTO T 209.
 - 7.4.4.3. Mixture preparation shall be as specified in Appendix C, and short-term oven aging shall be 2 hours at the proposed compaction temperature.
 - 7.4.4.4. To simulate long-term aging, condition the gyratory specimens and the companion loose mix sample in accordance with Sections 7.3.4 through 7.3.6 of AASHTO R-30.
 - 7.4.4.5. Saw one 50 mm thick IDT specimen from the middle of each gyratory specimen.
 - 7.4.4.6. Determine the maximum specific gravity of the companion long-term oven aged loose mix sample in accordance with AASHTO T 209. Record the maximum specific gravity of the mixture.
 - 7.4.4.7. For dense- and gap-graded mixtures, determine the bulk specific gravity of the test specimen in accordance with AASHTO T 166. Record the bulk specific gravity of the test specimen.

Note 25 – When wet sawing methods are used, measure the immersed mass followed by the surface dry mass followed by the dry mass to minimize drying time and expedite the specimen fabrication process.
 - 7.4.4.8. For open-graded mixtures, determine the bulk specific gravity of the test specimen in accordance with Section 6.2 of AASHTO T 269. Record the bulk specific gravity of the test specimen.
 - 7.4.4.9. Compute the air void content of the test specimen in accordance with AASHTO T 269. Record the air void content of the test specimen.
 - 7.4.4.10. Using calipers, measure the diameter of each test specimen along axes that are 90 ° apart. Record the average diameter to the nearest 1 mm.
 - 7.4.4.11. Measure the height of each test specimen in accordance with Section 6.1.2 of ASTM D 3549. Record the average height to the nearest 1 mm.
- 7.4.5. Creep and Strength Testing
- 7.4.5.1. Instrument each test specimen and perform creep tests on each test specimen at temperatures of –20, -10, and 0 °C in accordance with AASHTO T322. A total of 9 creep tests will be performed.

- 7.4.5.2. Record the load, horizontal deformation on each face, and vertical deformation on each face at 0.1 sec intervals for the first 10 sec, then at 1 sec intervals from 10 to 100 sec.
- 7.4.5.3. Remove the specimen mounted instrumentation and perform a strength test at $-10\text{ }^{\circ}\text{C}$ in accordance with AASHTO T322. A total of 3 strength tests will be performed.
- 7.4.5.4. Determine the corrected tensile strength of each specimen using the following relationship:

$$S_{corrected} = 0.78 \times S_{uncorrected} + 38$$

where:

$S_{corrected}$ = corrected tensile strength for thermal cracking analysis, psi

$$S_{uncorrected} = \frac{2P_{max}}{\pi \times h \times d}$$

P_{max} = peak load during the strength test, lb

h = thickness of the test specimen, in

d = diameter of the test specimen, in

Note 26 – The corrected strength provides a good estimate of the AASHTO T322 first failure tensile strength of the specimen without the risk of damage to the specimen mounted instrumentation.

7.4.6. Thermal Cracking Analysis

7.4.6.1. Using LTSTRESS

- 7.4.6.1.1. Input the thickness and diameter of each specimen into the appropriate cells in the workbook.
- 7.4.6.1.2. Input the average VMA and VFA of the specimens tested into the appropriate cells in the workbook.
- 7.4.6.1.3. Input the maximum load for each specimen from the tensile strength test into the appropriate cells in the workbook.
- 7.4.6.1.4. Input the measured time history for the load and deformations for each specimen at each temperature into the appropriate cells in the workbook.
- 7.4.6.1.5. Input the desired pavement cooling rate into the appropriate cell in the workbook.
- 7.4.6.1.6. Perform thermal stress analysis and review summary report.

7.4.6.1.6.1. Standard error of fit for the master creep compliance curve should be less than 10 percent.

7.4.6.1.6.2. Record critical cracking temperature for the pavement.

7.4.6.2. Using the MEPDG

7.4.6.2.1. Reduce the creep test data for each temperature in accordance with Section 13 of AASHTO M322 and compute the average creep compliance as a function of loading time.

Note 27 – LTSRESS can be used to perform these computations.

7.4.6.2.2. Input General Information, Traffic, Climate, and Structure as required by the MEPDG software.

7.4.6.2.3. For Level 1 thermal cracking analysis, the following input data are required by the Structure input screens:

7.4.6.2.3.1. Average VFA for the test specimens and an estimate of the coefficient of thermal contraction for the aggregates used in the mixture.

7.4.6.2.3.2. Creep compliance versus time at 0, -10, and -20 °C and the corrected tensile strength at -10 °C.

Note 28 – Refer to the User Manual for the M-E Pavement Design Guide for detailed instructions for using the MEPDG software.

7.4.6.2.4. Run the MEPDG software and review thermal cracking results.

7.4.6.2.5. The MEPDG software provides a yearly prediction of the amount of thermal cracking in the pavement section in units of ft/500 ft of pavement.

7.4.7. Report the following:

7.4.7.1. Mixture identification

7.4.7.2. Target air voids and the actual air voids for the specimens tested.

7.4.7.3. VMA and VFA of each specimen tested

7.4.7.4. Average VMA and VFA for the specimens tested

7.4.7.5. Tabulated values of the average compliance versus time for -20, -10, and 0 °C.

7.4.7.6. Corrected tensile strength at $-10\text{ }^{\circ}\text{C}$

7.4.7.7. For analysis using LSTRESS

7.4.7.7.1. Reference temperature.

7.4.7.7.2. Master creep compliance curve parameters.

7.4.7.7.3. Standard error of fit for the master creep compliance curve.

7.4.7.7.4. Cooling rate.

7.4.7.7.5. Computed critical cracking temperature.

7.4.7.8. For analysis using MEDPG

7.4.7.8.1. MEDPG input data for General Information, Traffic, Climate, and Structure.

7.4.7.8.2. Tabulated yearly values of estimated thermal cracking.

8. KEYWORDS

8.1. Warm Mix Asphalt (WMA), WMA volumetric mixture design, WMA mixture analysis

Appendix A Recommended Procedure for Characterizing Reclaimed Asphalt Pavement Stockpiles

A1. Sampling

- A1.1. Obtain representative samples from 10 locations within the RAP stockpile in accordance with AASHTO T2.

Note A1 – The size of each sample should be large enough to determine the properties of the RAP stockpile as described in this Appendix and to have sufficient material for subsequent mixture design and analysis work. A 5 to 7 kg sample at each location is recommended for determining RAP stockpile properties. An additional 10 kg sample per mixture design is recommended at each location to provide sufficient RAP materials for mixture design and analysis.

- A1.2. From each sample location, split a 5 to 7 kg sample in accordance with AASHTO T248 for determining the properties of the RAP stockpile. Combine the remainder of the sample from each location for use in mixture design and analysis.

Note A2 – If AASHTO T308 will be used for determining asphalt content and a reasonable estimate of the correction factor for the aggregate is not known, split approximately 7 kg samples for 5 of the 10 samples to develop correction factors by determining asphalt contents using both AASHTO T164 and AASHTO T308.

- A1.3. From each 5 to 7 kg sample, split an appropriate size sample in accordance with AASHTO T 248 for determining asphalt content and gradation in accordance with AASHTO T308 or AASHTO T164. The sample size will depend on the nominal maximum aggregate size of the RAP.

Note A3 – If correction factors will be determined using AASHTO T164, split two samples (one for AASHTO T308 and one for AASHTO T164) from 5 of the 10 samples.

- A1.4. Combine the remainder of the stockpile property sample from each location. Then split the following representative samples in accordance with AASHTO T248:

Purpose	Approximate Size
RAP Binder Properties	2.5 kg
RAP Aggregate Properties	5.0 kg
RAP Aggregate Specific Gravity Using Effective Specific Gravity	0.5 to 4 kg depending on the maximum particle size

A2. Binder Content and Gradation

- A2.1. Determine the binder content of the RAP at each sampling location in accordance with AASHTO T308 or AASHTO T164.

Note A4 – If reasonable estimates of the ignition oven correct factor can be made use AASHTO T308. If the correction factors for local aggregate are highly variable use AASHTO T164 or determine correction factors by testing 5 of the 10 samples using both AASHTO T164 and AASHTO T308.

- A2.2. Determine the gradation of the RAP aggregate in accordance with AASHTO T 30.
- A2.3. Determine the average and standard deviation of the binder content and percent passing each sieve size.
- A2.4. Estimate the maximum RAP content that can be used based on variability from Table A1.

Table A1- Maximum Standard Deviation for Various RAP Contents

Property	Percent RAP in Mixture				
	50	40	30	20	10
	Maximum Standard Deviation				
Coarse Aggregate Percent Passing (2.36 mm sieve and larger)	3.5	4.0	5.0	6.5	10
Fine Aggregate Percent Passing (0.15 mm to 1.18 mm sieves)	2.5	2.8	3.5	4.5	7.0
Percent Passing 0.075 mm sieve	1.0	1.2	1.5	2.2	4.0
Asphalt Content	0.35	0.40	0.50	0.70	1.15

A3. RAP Aggregate Properties

- A3.1. Remove the binder from the 5 kg combined sample of RAP in accordance with AASHTO T308 to obtain a sample of the RAP aggregate for testing.
- A3.2. Split the RAP aggregate sample on the 4.75 mm sieve.
- A3.3. Determine the bulk specific gravity of the coarse fraction of the RAP aggregate in accordance with AASHTO T85.
- A3.4. Determine the bulk specific gravity of the fine fraction of the RAP aggregate in accordance with AASHTO T84.

Note A5 – The bulk specific gravity of the RAP aggregate may be determined without removing the RAP binder if a reasonable estimate of the binder absorption is known. See Section A3.8 for details of this optional procedure.

- A3.5. Determine the angularity of the coarse fraction of the RAP aggregate in accordance with ASTM D5821.
- A3.6. Determine the amount of flat and elongated particles in the coarse fraction of the RAP aggregate in accordance with ASTM D4791.
- A3.7. Determine the angularity of the fine fraction of the RAP aggregate in accordance with AASHTO T304.
- A3.8. Alternative Method for Determining Bulk Specific Gravity of RAP Aggregate

Note A6 – A reasonable estimate of the binder absorption for the RAP aggregate must be known to apply this procedure. The accuracy of this approach depends on the accuracy of the estimated binder absorption.

- A3.8.1. Determine the maximum specific gravity of the RAP in accordance with AASHTO T209.
- A3.8.2. Compute the effective specific gravity of the RAP aggregate using Equation A1.

$$G_{se} = \frac{100 - P_b}{\frac{100}{G_{mm}} - \frac{P_b}{G_b}} \quad (A1)$$

where:

- G_{se} = effective specific gravity of the RAP aggregate
 P_b = binder content of the RAP (See Section A2)
 G_{mm} = maximum specific gravity of the RAP
 G_b = specific gravity of the RAP binder (assumed)

- A3.8.3. Compute the bulk specific gravity of the combined RAP aggregate using Equation A2.

$$G_{sb} = \frac{G_{se}}{\left[\left(\frac{P_{ba} G_{se}}{100 \times G_b} \right) + 1 \right]} \quad (A2)$$

where:

- G_{sb} = bulk specific gravity of the combined RAP aggregate
 G_{se} = effective specific gravity of the RAP aggregate (Equation A1)
 P_{ba} = percent absorbed binder (assumed)
 G_b = specific gravity of the RAP binder (assumed)

A4. RAP Binder Properties

- A4.1. Extract and recover approximately 100 g of RAP binder in accordance with AASHTO T164 and ASTM D5404.
- A4.2. Determine $G^*/\sin\delta$ for the recovered binder in accordance with AASHTO T315 at two temperatures; one resulting in $G^*/\sin\delta$ greater than 1.00 kPa, and one resulting in $G^*/\sin\delta$ less than 1.00 kPa.
- A4.3. Compute the As Recovered true high temperature grade to the nearest 0.1 degree using Equation A3.

$$T_{as\ recovered} = T_1 + \left[\frac{\log(G_1) \times (T_2 - T_1)}{\log(G_1) - \log(G_2)} \right] \quad (A3)$$

where:

$T_{as\ recovered}$ = temperature where $G^*/\sin\delta$ equals 1.00 kPa for the as recovered RAP binder

T_1 = test temperature where $G^*/\sin\delta$ is closest to but above 1.00 kPa

G_1 = $G^*/\sin\delta$ for temperature T_1 , kPa

T_2 = test temperature where $G^*/\sin\delta$ is closest to but below 1.00 kPa

G_2 = $G^*/\sin\delta$ for temperature T_2 , kPa

- A4.4. Condition the remaining binder in accordance with AASHTO T240.
- A4.5. Determine $G^*/\sin\delta$ for the RTFOT conditioned binder in accordance with AASHTO T315 at two temperatures; one resulting in $G^*/\sin\delta$ greater than 2.20 kPa, and one resulting in $G^*/\sin\delta$ less than 2.20 kPa.
- A4.6. Compute the RTFOT true high temperature grade to the nearest 0.1 degree using Equation A4.

$$T_{RTFOT} = T_1 + \left[\frac{(\log(G_1) - 0.3424) \times (T_2 - T_1)}{\log(G_1) - \log(G_2)} \right] \quad (A4)$$

where:

T_{RTFOT} = temperature where $G^*/\sin\delta$ equals 2.20 kPa for the RTFOT conditioned RAP binder

T_1 = test temperature where $G^*/\sin\delta$ is closest to but above 2.20 kPa

G_1 = $G^*/\sin\delta$ for temperature T_1 , kPa

T_2 = test temperature where $G^*/\sin\delta$ is closest to but below 2.20 kPa

G_2 = $G^*/\sin\delta$ for temperature T_2 , kPa

- A4.7. Condition the remaining binder in accordance with AASHTO R28.

A4.8. Determine $G^* \times \sin \delta$ for the PAV conditioned binder in accordance with AASHTO T315 at two temperatures; one resulting in $G^* \times \sin \delta$ greater than 5,000 kPa, and one resulting in $G^* \times \sin \delta$ less than 5,000 kPa.

A4.9. Compute the true intermediate temperature grade to the nearest 0.1 degree using Equation A5.

$$T_{intermediate} = T_1 + \left[\frac{(\log(G_1) - 3.6990) \times (T_2 - T_1)}{\log(G_1) - \log(G_2)} \right] \quad (A5)$$

where:

$T_{intermediate}$ = temperature where $G^* \times \sin \delta$ equals 5,000 kPa for the PAV conditioned RAP binder

T_1 = test temperature where $G^* \times \sin \delta$ is closest to but above 5,000 kPa

G_1 = $G^* \times \sin \delta$ for temperature T_1 , kPa

T_2 = test temperature where $G^* \times \sin \delta$ is closest to but below 5,000 kPa

G_2 = $G^* \times \sin \delta$ for temperature T_2 , kPa

A4.10. Determine the low temperature creep stiffness, S, and m-value for the PAV conditioned binder in accordance with AASHTO T313 at two temperatures; one resulting in S greater than 300 MPa, and one resulting in S less than 300 MPa.

A4.11. Compute the true low temperature grade for S to the nearest 0.1 degree using Equation A6.

$$T_S = T_1 + \left[\frac{(\log(S_1) - 2.4771) \times (T_2 - T_1)}{\log(S_1) - \log(S_2)} \right] \quad (A6)$$

where:

T_S = temperature where S equals 300 MPa for the PAV conditioned RAP binder

T_1 = test temperature where S is closest to but above 300 MPa

S_1 = S for temperature T_1 , MPa

T_2 = test temperature where S is closest to but below 300 kPa

S_2 = S for temperature T_2 , MPa

A4.12. Compute the true low temperature grade for the m-value to the nearest 0.1 degree using Equation A7.

$$T_m = T_1 + \left[\frac{(0.300 - m_1) \times (T_2 - T_1)}{(m_2 - m_1)} \right] \quad (A7)$$

where:

T_m = temperature where the m-value equals 0.300 kPa for the PAV conditioned RAP binder

T_1 = test temperature for the lower m-value.
 m_1 = m-value for temperature T_1
 T_2 = test temperature for the higher m-value.
 m_2 = m-value for temperature T_2

- A4.13. The critical high temperature grade for blending chart analyses is the lower of the two for the as recovered (Section A4.3) and the RTFOT condition (Section A4.6).
- A4.14. The critical low temperature grade for blending chart analyses is the higher of the two for the creep stiffness (Section A4.11) and the m-value (A4.12).
- A4.15. The critical intermediate grade for blending chart analyses is the true intermediate temperature grade determined in Section A4.9.

Appendix B. Procedure to Estimate an Initial Trial Binder Content

- B1. Calculate the bulk and apparent specific gravities of the combined aggregate in the trial blend using the specific gravity data for each fraction of each aggregate and Equations C1 and C2.

$$G_{sb} = \frac{P_1 + P_2 + P_3 + \dots P_n}{\frac{P_1}{G_{sb1}} + \frac{P_2}{G_{sb2}} + \dots \frac{P_n}{G_{sbn}}} \quad (C1)$$

where:

G_{sb} = bulk specific gravity for the combined aggregate

$P_1, P_2, \dots P_n$ = percentages by mass of aggregates 1, 2, ..., n in the blend

$G_{sb1}, G_{sb2}, \dots G_{sbn}$ = bulk specific gravity of aggregate 1, 2, ..., n in the blend

$$G_{sa} = \frac{P_1 + P_2 + P_3 + \dots P_n}{\frac{P_1}{G_{sa1}} + \frac{P_2}{G_{sa2}} + \dots \frac{P_n}{G_{san}}} \quad (C2)$$

where:

G_{sa} = apparent specific gravity for the combined aggregate

$P_1, P_2, \dots P_n$ = percentages by mass of aggregates 1, 2, ..., n in the blend

$G_{sa1}, G_{sa2}, \dots G_{san}$ = apparent specific gravity of aggregate 1, 2, ..., n in the blend

- B2. Estimate the effective gravity of the combined aggregate in the trial blend using Equation C3.

$$G_{se} = G_{sb} + 0.5(G_{sa} - G_{sb}) \quad (C3)$$

where:

G_{se} = effective specific gravity of the combined aggregate

G_{sb} = bulk specific gravity for the combined aggregate

G_{sa} = apparent specific gravity for the combined aggregate

Note B1 – The multiplier, 0.5, should be changed based on the expected asphalt absorption. Decrease the multiplier for low absorption. Increase the multiplier for greater absorption.

- B3. Estimate the mass of aggregate in 1cm³ of mix using Equation C4

$$W_s = \frac{\frac{0.96P_s}{100}}{\frac{100 - P_s}{G_b} + \frac{P_s}{G_{se}}} \quad (C4)$$

where:

W_s = mass of aggregate in 1 cm³

G_{se} = effective specific gravity of the combined aggregate

P_s = percent aggregate in the mixture (assume 95 as a first approximation)

B4. Estimate the volume of binder absorbed into the aggregate, V_{ba} , using Equations C5.

$$V_{ba} = W_s \left(\frac{1}{G_{sb}} - \frac{1}{G_{se}} \right) \quad (C5)$$

where:

V_{ba} = volume of absorbed binder

W_s = mass of aggregate in 1 cm³

G_{se} = effective specific gravity of the combined aggregate

G_{sb} = bulk specific gravity for the combined aggregate

B5. Estimate the effective volume of binder using Equation C6.

$$V_{be} = 0.176 - [0.0675 \log(S_n)] \quad (C6)$$

where:

V_{be} = effective volume of binder, cm³

S_n = nominal maximum size of the mixture

Note B2 – This regression equation is based on a design air void content of 4.0 percent and the relationship between minimum VMA and nominal maximum size contained in AASHTO M323.

B6. Estimate the trial binder content using Equation C7.

$$P_{bi} = 100 \times \left[\frac{G_b(V_{be} + V_{ba})}{G_b(V_{be} + V_{ba}) + W_s} \right] \quad (C7)$$

where:

P_{bi} = estimated trial binder content, percent by total weight of mix

V_{be} = effective volume of binder

V_{ba} = volume of absorbed binder

W_s = mass of aggregate in 1 cm³

Appendix C. Specimen Fabrication Methods for Selected Warm Mix Asphalt Processes

C1. Aggregate Processing

C1.1. New Aggregate Stockpiles

C1.1.1. Dry aggregate samples to constant weight at 105 to 110 °C.

C1.1.2. Separate aggregates by dry sieving into the following size fractions:

Passing	Retained
50 mm	37.5 mm
37.5 mm	25 mm
25 mm	19.0 mm
19.0 mm	12.5 mm
12.5 mm	9.5 mm
9.5 mm	4.75 mm
4.75 mm	2.36 mm
2.36 mm	

C1.1.3. Store the dried and sized aggregates in covered containers of appropriate size until needed.

C1.2. RAP Stockpiles

C1.2.1. Dry RAP stockpile samples to a constant weight at 60 °C. Depending on the moisture content, the drying time may take 24 to 48 hours.

C1.2.2. Store the dried RAP in covered containers of appropriate size until needed.

Note C1 – It is recommended that RAP stockpiles be added without further processing. When using RAP in this manner exercise care during batching to minimize the potential for segregation of the RAP.

C2. Batching

C2.1. Determine the number and size of specimens that are required. Table D1 summarizes approximate specimen sizes for various tests covered by this practice.

Note C2 – The mass of mixture required for the various specimens depends on the specific gravity of the aggregate and the air void content of the specimen. Trial specimens may be required to determine appropriate batch weights.

Table C1. Specimen Requirements.

Specimen Type	Gyratory Specimen Size	Approximate Specimen Mass	Number Required
Maximum Specific Gravity	NA	500 to 6,000 g depending on maximum aggregate size	2 per trial blend plus 8 to determine design binder content
Volumetric Design	150 mm diameter by 115 mm high	4,700 g	2 per trial blend plus 8 to determine design binder content
AASHTO T283	150 mm diameter by 95 mm high	3,800 g	6
Flow Number	150 mm diameter by 175 mm high	7,000 g	4
Dynamic Modulus	150 mm diameter by 175 mm high	7,000 g	2
Fatigue	150 mm diameter by 175 mm high	7,000 g	4
Thermal Cracking	150 mm diameter by 115 mm high	4,700 g	3

C2.2. Prepare a batch sheet showing the batch weight of each aggregate fraction, RAP, and the asphalt binder.

C2.3. Weigh into a pan the weight of each aggregate fraction.

Note C3 – For WMA processes that use wet aggregate, weigh the portion of the aggregate that will be heated into one pan and weigh the portion of the aggregate that will be wetted into a second pan.

C2.4. Weigh into a separate pan, the weight of RAP.

C3. Heating

C3.1. Place the aggregate in an oven set at approximately 15 °C higher than the mixing temperature.

Note C4 – The aggregate will require 2 to 4 hours to reach the temperature of the oven. Aggregates may be placed in the oven overnight.

C3.2. Heat the RAP in the oven with the aggregates, but limit the heating time for the RAP to 2 hours.

C3.3. Heat the binder to the mixing temperature.

- C3.4. Heat mixing bowls and other tools to the mixing temperature.
- C3.5. Preheat a forced draft oven and necessary pans to the proposed compaction temperature for use in short-term conditioning the mixture.

C4. Preparation of Mixtures Containing Zeolite Additive

- C4.1. Weigh the required amount of the zeolite additive into a small container.

Note C5 – The additive contains moisture and should be stored in accordance with the manufacturer’s instructions.

Note C6 – The zeolite additive is typically specified as a percent by weight of the WMA mixture.

- C4.2. If a liquid antistriper is required, weigh the required amount of the liquid antistriper into a small container and add it to the binder per the manufacturer’s instructions.
- C4.3. Heat the mixing tools, aggregate, RAP, and binder in accordance with Section C3.
- C4.4. Place the hot mixing bowl on a scale and zero the scale.
- C4.5. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.
- C4.6. Form a crater in the blended aggregate and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight.

Note C7 – If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of binder based on the oven dry weight of the aggregates and RAP as follows:

1. Record oven the dry weight of the aggregates and RAP, w_i
2. Determine the target total weight of the mixture

$$w_t = \frac{w_i}{\left(1 - \frac{P_{b_{new}}}{100}\right)}$$

where:

w_t = target total weight

w_i = oven dry weight from step 1

$P_{b_{new}}$ = percent by weight of total mix of new binder in the mixture

3. Add new binder to the bowl to reach w_t

- C4.7. Pour the zeolite additive into the pool of new asphalt binder.

Note C8 – Visible foaming will not occur when the zeolite is added to the asphalt binder.

C4.8. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.

C4.9. Place the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³ and place the pan in the forced draft oven at the compaction temperature for 2 hours. Stir the mixture once after the first hour.

C5. Preparation of Evotherm DAT Mixtures

C5.1. Weigh the required amount of the Evotherm DAT additive into a small container.

Note C9 – The Evotherm DAT additive is typically specified as a percent by weight of asphalt binder.

C5.2. Heat the mixing tools, aggregate, RAP and binder in accordance with Section C3.

C5.3. Place the hot mixing bowl on a scale and zero the scale.

C5.4. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.

C5.5. Form a crater in the blended aggregate and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight.

Note C10 – If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of binder based on the oven dry weight of the aggregates and RAP as follows:

1. Record oven the dry weight of the aggregates and RAP, w_i
2. Determine the target total weight of the mixture

$$w_t = \frac{w_i}{\left(1 - \frac{P_{b_{new}}}{100}\right)}$$

where:

w_t = target total weight

w_i = oven dry weight from step 1

$P_{b_{new}}$ = percent by weight of total mix of new binder in the mixture

3. Add new binder to the bowl to reach w_t

C5.6. Pour the Evotherm DAT additive into the pool of new asphalt binder.

C5.7. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.

- C5.8. Place the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³ and place the pan in the forced draft oven at the compaction temperature for 2 hours. Stir the mixture once after the first hour.

C6. Preparation of Low Energy Asphalt (LEA) Mixtures

- C6.1. Add the required moisture to the wet fraction of the aggregate, mix thoroughly, then cover and let stand for at least 2 hours before mixing with the heated fraction.
- C6.2. Weigh the required amount of the LEA additive into a small container.

Note C11 – The LEA additive is typically specified as a percent by weight of asphalt binder.

- C6.3. Add the LEA additive to the binder immediately before mixing with the heated fraction of the aggregate.
- C6.4. Heat the mixing tools, aggregate, and RAP in accordance with Section C3.
- C6.5. Place the hot mixing bowl on a scale and zero the scale.
- C6.6. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.
- C6.7. Form a crater in the blended aggregate and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight.

Note C12 – If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of binder based on the oven dry weight of the aggregates and RAP as follows:

1. Record oven the dry weight of the heated aggregates and RAP, w_i
2. Determine the target total weight of the mixture:

$$w_t = \frac{(w_i + w_{dwf})}{\left(1 - \frac{p_{b_{new}}}{100}\right)}$$

where:

w_t = target total weight

w_i = oven dry weight from step 1

w_{dwf} = oven dry weight of the wet fraction from the batch sheet

$p_{b_{new}}$ = percent by weight of total mix of new binder in the mixture

3. Determine the target weight of the heated mixture:

$$w_{thm} = w_t - w_{dwf}$$

where:

w_{thm} = target weight of the heated mixture

w_t = target total weight

w_{dwf} = oven dry weight of the wet fraction from the batch sheet

4. Add new binder to the bowl to reach w_{thm}

C6.8. Remove the mixing bowl from the scale and mix with a mechanical mixer for 30 sec.

C6.9. Stop the mixer and immediately add the wet fraction.

C6.10. Restart the mixer and continue to mix for 60 sec.

C6.11. Place the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³.

C6.12. Check the temperature of the mixture in the pan. It shall be no less than 90 °C.

C6.13. Place the pan in the forced draft oven at the compaction temperature for 2 hours. Stir the mixture once after the first hour.

C7. Preparation of Sasobit Mixtures

C7.1. Sasobit may be pre-mixed with the asphalt binder or added to the mixture.

C7.2. For premixing the Sasobit with the asphalt binder:

C7.2.1. Weigh the required amount of the Sasobit additive into a small container.

Note C13 – The Sasobit additive is typically specified as a percent by weight of binder. For mixtures containing RAP, determine the weight of Sasobit based on the total binder content of the mixture.

C7.2.2. Heat the asphalt binder in a covered container in an oven set at 135 °C until the binder is sufficiently fluid to pour. During heating occasionally stir the binder to ensure homogeneity.

C7.2.3. Add the required amount of Sasobit additive to the binder and stir until the additive is totally dispersed in the binder.

C7.2.4. Store the Sasobit modified binder at room temperature in a covered container until needed for use in the mixture design.

C7.2.5. Heat the Sasobit modified binder for mixture design as described in Section C3.

C7.3. For adding the Sasobit to the mixture:

C7.3.1. Weigh the required amount of the Sasobit additive into a small container.

Note C14 – The Sasobit additive is typically specified as a percent by weight of binder. For mixtures containing RAP, determine the weight of Sasobit based on the total binder content of the mixture.

C7.4. If a liquid antistrip is required, weigh the required amount of the liquid antistrip into a small container and add it to the binder per the manufacturer’s instructions.

C7.5. Place the hot mixing bowl on a scale and zero the scale.

C7.6. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.

C7.7. Form a crater in the blended aggregate and weigh the required amount of asphalt binder into the mixture to achieve the desired batch weight.

Note C15 – If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of binder based on the oven dry weight of the aggregates and RAP as follows:

1. Record oven the dry weight of the aggregates and RAP, w_i
2. Determine the target total weight of the mixture

$$w_t = \frac{w_i}{\left(1 - \frac{P_{b_{new}}}{100}\right)}$$

where:

w_t = target total weight

w_i = oven dry weight from step 1

$P_{b_{new}}$ = percent by weight of total mix of new binder in the mixture

3. Add new binder to the bowl to reach w_t

C7.8. If adding the Sasobit to the mixture, pour the Sasobit additive into the pool of new asphalt binder.

C7.9. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.

C7.10. Place the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³ and place the pan in the forced draft oven at the compaction temperature for 2 hours. Stir the mixture once after the first hour.

C8. Preparation of WAM Foam Mixtures

- C8.1. The preparation of WAM Foam mixtures includes a two step process (soft binder followed by hard foamed binder) and requires special asphalt binder foaming equipment to prepare the hard binder used in the second step.
- C8.2. Prepare the asphalt binder foaming equipment and load it with hard binder per the manufacturer's instructions.
- C8.3. Heat the mixing tools, aggregate, RAP, and soft binder in accordance with Section C3.
- C8.4. If a liquid antistriper is required, weigh the required amount of the liquid antistriper into a small container and add it to the soft binder per the manufacturer's instructions.
- C8.5. Place the hot mixing bowl on a scale and zero the scale.
- C8.6. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.
- C8.7. Form a crater in the blended aggregate and weigh the required amount of soft asphalt binder into the mixture to achieve the desired batch weight.

Note C10 – If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of soft and hard binder based on the oven dry weight of the aggregates and RAP as follows:

1. Record oven the dry weight of the aggregates and RAP, w_i
2. Determine the target total weight of the mixture

$$w_t = \frac{w_i}{\left(1 - \frac{p_{b_{new}}}{100}\right)}$$

where:

w_t = target total weight

w_i = oven dry weight from step 1

$p_{b_{new}}$ = percent by weight of total mix of new binder in the mixture

3. Determine the target total weight of the aggregate, RAP, and soft binder

$$w_1 = w_i + \frac{R_s}{100} \times \frac{p_{b_{new}}}{100} \times w_i$$

where:

w_1 = target total weight of aggregate, RAP, and soft binder

R_s = percent of the new binder that is soft binder

w_i = oven dry weight from step 1

$p_{b_{new}}$ = percent by weight of total mix of new binder in the mixture

4. Determine the weight of hard foamed binder to add

$$w_{fb} = \frac{R_{fb}}{100} \times \frac{P_{b_{new}}}{100} \times w_i$$

where:

w_{fb} = weight of foamed binder required

R_{fb} = percent of the new binder that is foamed binder

w_i = oven dry weight from step 1

$P_{b_{new}}$ = percent by weight of total mix of new binder in the mixture

5. Add soft binder to the bowl to reach w_I

C8.8. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.

C8.9. Return the mixing bowl to the oven.

C8.10. Prepare the foamed asphalt binder per the instructions for the foaming equipment. Foam the binder into a transfer container for adding it to the mixture.

C8.11. Tare the mixing bowl containing the mixture coated with the soft binder.

C8.12. Weigh the required amount of foamed asphalt binder into the mixture.

C8.13. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.

C8.14. Place the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³ and place the pan in the forced draft oven at the compaction temperature for 2 hours. Stir the mixture once after the first hour.

C9. Preparation of Foamed Asphalt Mixtures

C9.1. The preparation of foamed asphalt mixtures requires special asphalt binder foaming equipment that can produce foamed asphalt using the amount of moisture that will be used in field production.

Note C11 – Laboratory foaming equipment is available from Wirtgen America, Model WBL 10.

C9.2. Prepare the asphalt binder foaming equipment and load it with binder per the manufacturer's instructions.

C9.3. If a liquid antistriper is required, weigh the required amount of the liquid antistriper into a small container and add it to the binder in the foaming equipment per the manufacturer's instructions.

C9.4. Heat the mixing tools, aggregate, and RAP in accordance with Section C3.

- C9.5. Prepare the foamed asphalt binder per the instructions for the foaming equipment. Foam the binder into a transfer container for adding it to the mixture.
- C9.6. Place the hot mixing bowl on a scale and zero the scale.
- C9.7. Charge the mixing bowl with the heated aggregates and RAP and dry mix thoroughly.
- C9.8. Form a crater in the blended aggregate and weigh the required amount of foamed asphalt into the mixture to achieve the desired batch weight.

Note C12 – If the aggregates and RAP have been stored for an extended period of time in a humid environment, then it may be necessary to adjust the weight of soft and hard binder based on the oven dry weight of the aggregates and RAP as follows:

- 1. Record oven the dry weight of the aggregates and RAP, w_i
- 2. Determine the target total weight of the mixture

$$w_t = \frac{w_i}{\left(1 - \frac{p_{b_{new}}}{100}\right)}$$

where:

w_t = target total weight

w_i = oven dry weight from step 1

$p_{b_{new}}$ = percent by weight of total mix of new binder in the mixture

- 3. Add foamed binder to the bowl to reach w_t

- C9.9. Remove the mixing bowl from the scale and mix with a mechanical mixer for 90 sec.
- C9.10. Place the mixture in a flat shallow pan at an even thickness of 21-22 kg/m³ and place the pan in the forced draft oven at the compaction temperature for 2 hours. Stir the mixture once after the first hour.

Appendix D. Evaluating Workability of WMA

APPENDIX D

Description of Laboratory Performance Tests

Permanent Deformation – Rutting has typically been evaluated using loaded wheel tests such as the Asphalt Pavement Analyzer (APA), Hamburg Wheel Tracking (HWT), and repeated load tests. In the past, AI has used the repeated shear test at constant height (RSCH) developed during SHRP at the University of California at Berkeley. This test involves the application of repeated shear loading at high temperature (based on project conditions) to induce the development of permanent shear strain in a specimen. AI has used this test successfully to identify rutting susceptible mixes. Although the RSCH has been used in the past, the advent of the Simple Performance Test (SPT) equipment and procedures allows for a similar repeated load test to be performed axially. The repeated load axial, or Flow Number, test is used to induce the development of permanent axial strain in a specimen. The Flow Number is determined at the onset of tertiary flow in the mix specimen.

Recommended Rutting Tests: APA; HWT (dry); Repeated Load Axial (Flow Number)

Fatigue Cracking – Two types of load associated cracking are typically considered for fatigue cracking: classical bottom-up fatigue cracking and surface-initiated (top-down) cracking. For classical, bottom-up fatigue cracking, the most common approach remains the procedure developed during SHRP – the flexural beam fatigue test described in AASHTO T 321. In this test, prismatic beam specimens are prepared (by means of rolling wheel, kneading, or vibratory compaction) and tested in a beam fatigue fixture at a specified intermediate temperature (generally 20°C) using an applied strain level. Testing continues until micro-cracking occurs in the specimen. This point is defined in AASHTO T321 as the number of loading cycles where the stiffness decreases to 50% of the initial stiffness, although other analysis procedures suggest carrying the testing out to a much lower endpoint (such as 30% of the initial stiffness) to better capture the development of micro-cracking. This alternate procedure has been used by AI for evaluation of highly modified asphalt mixtures, and likely would be used for the initial evaluation of WMA.

To evaluate surface-initiated cracking, AI has recently been working with the Dissipated Creep Strain Energy (DCSE) approach advanced by Dr. Rey Roque and his colleagues at the University of Florida. In this approach, three indirect tensile tests are needed to determine the $DCSE_f$ (DCSE threshold for the mix) and the energy ratio (defined as the ratio of $DCSE_f$ to the minimum DCSE calculated from material properties and pavement structural conditions). Indirect tensile resilient modulus and indirect tensile strength tests are used to calculate $DCSE_f$. Indirect tensile creep (creep compliance) tests are used to calculate $DCSE_{min}$. The researchers have developed tentative criteria for $DCSE_f$ and Energy Ratio that has been correlated with surface-initiated cracking of in-service asphalt pavements in Florida. The use of cylindrical specimens produced using the SGC instead of beams is a big advantage to this approach for evaluating fatigue cracking.

Similar to the DCSE approach, AI has also explored the disk-shaped compact tension test, DC(T), for determining fracture energy of mixtures. This approach was developed by Dr. Bill Buttlar and his colleagues at the University of Illinois. Data from the testing and analysis has been presented at AAPT and is a published ASTM standard (D 7313-06).

Recommended Fatigue Tests: Flexural Beam Fatigue; DCSE (indirect tensile tests) or DC(T)

Thermal Cracking – Low temperature cracking will be evaluated using the approach developed during SHRP. Indirect tensile creep compliance tests at several low temperatures are used to develop a thermal stress curve. Indirect tensile strength tests are used to develop a tensile strength curve. Both tests are detailed in AASHTO T322. The intersection of the thermal stress and tensile strength curves is identified as the critical cracking temperature. This approach is essentially identical to the procedure used for evaluating the critical cracking temperature of asphalt binders using BBR and direct tension data.

Recommended Thermal Cracking Tests: Indirect Tensile Creep and Strength

Moisture Susceptibility – Although many agencies have questioned the value of the AASHTO T283 (modified Lottman) procedure for identifying moisture-susceptible mixtures, it remains the principal method for evaluating the moisture sensitivity of a mix. As such, the research team feels that it would be imprudent not to include the test procedure in the WMA evaluation.

The other proven approach for evaluating moisture susceptibility is the Hamburg Wheel Tracking test. Although many feel that the test is very harsh, it does provide an indication of stripping under dynamic loading.

Recommended Moisture Susceptibility Tests: HWT (wet); AASHTO T283

Stiffness – Dynamic Modulus testing will be conducted to evaluate the stiffness of the WMA at a range of temperatures and loading frequencies. This testing allows for generation of a master curve that can be used for pavement design. Specifically, AI has used a single loading frequency (usually 10 Hz) at a range of temperatures to determine when a minimum stiffness is achieved at high temperatures. Using this approach, asphalt mixtures can be assigned a “performance grade” much like asphalt binders. To evaluate the effects of aging, dynamic modulus testing is conducted on short-term aged and long-term aged mix specimens. Because aging is different for WMA, specimens will be evaluated after having been subjected to three levels of aging: none; short-term; and long-term.

Recommended Stiffness Tests: Dynamic Modulus (simple performance tester)

APPENDIX E

Project Schedule

**NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
PROGRESS SCHEDULE**

NCHRP Project No. 9-47 FY 2008 Month September
 Research Agency Asphalt Institute
 Principal Investigator R. Michael Anderson

PHASE I Research Task	2008												ESTIMATED % COMPLETION
	A	M	J	J	A	S	O	N	D				
1 Technical Literature Review - Engineering Properties and Performance	[Progress bar from 10 to 100]												100%
2 Technical Literature Review - Emissions and Environmental	[Progress bar from 10 to 100]												100%
3 State-of-the-Knowledge Report	[Progress bar from 30 to 100]												75%
4 Phase II Work Plan for Field and Lab Experiments	[Progress bar from 30 to 100]												75%
5 Interim Report	[Progress bar from 30 to 100]												60%

PHASE II Research Task	2008			2009												2010												2011					ESTIMATED % COMPLETION		
	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M		J	J
6 Conduct WMA Experiments - Materials, Construction, Emissions	[Progress bar from 4 to 11]			[Progress bar from 14 to 55]												[Progress bar from 58 to 100]																	0%		
7 Evaluate WMA Mix Design Procedure																[Progress bar from 8 to 100]																	0%		
8 Lab Evaluation of WMA and Guidelines for Production Differences																												[Progress bar from 25 to 100]					0%		
9 Revisions to Emissions Measurement Protocols																												[Progress bar from 25 to 100]					0%		
10 Final Report																												[Progress bar from 11 to 100]					0%		

FIG. A - OVERALL PROJECT SCHEDULE

FIG. B - CONTRACT FUNDS

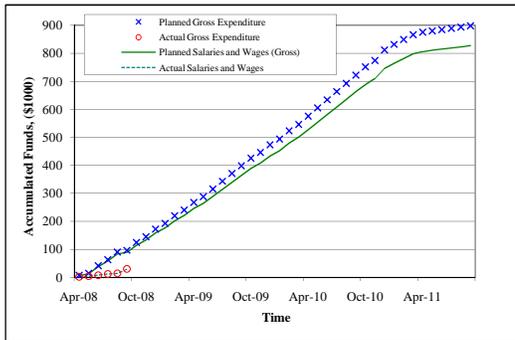
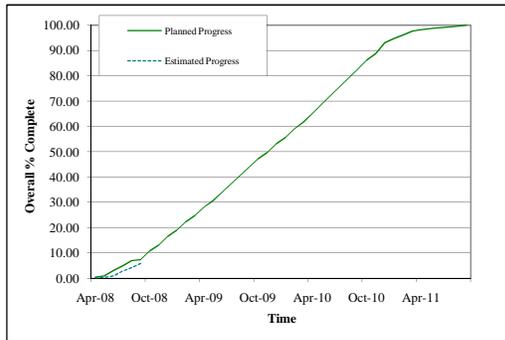


FIG. C - CONTRACT PERIOD



Funds Expended 3.4%
 Contract Amount \$897,837
 Expended This Month \$15,964
 Total Exp. To Date \$30,915
 Balance \$866,922

Time Expended ###
 Starting Date 31-Mar-08
 Completion Date 30-Sep-11

Salary and Wages Estimated This Month \$25,299
 Salary and Wages Spent This Month \$14,641
 Accumulated Salary and Wages to Date \$29,547