A Proposed Technology Evaluation Program for Warm-Mix Asphalt

DETAILS

26 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-25833-3 | DOI 10.17226/22730

AUTHORS

McCarthy, Leslie

July 2012

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Responsible Program Officer: Edward T. Harrigan

Research Results Digest 374

A PROPOSED TECHNOLOGY EVALUATION PROGRAM FOR WARM MIX ASPHALT

This digest summarizes key findings from the project final report for NCHRP Project 20-07, Task 311, "Development of a Warm Mix Asphalt Technology Evaluation Program," conducted by Villanova University, Villanova, Pennsylvania, under the direction of the principal investigator, Dr. Leslie McCarthy. The project final report was prepared by Dr. McCarthy, Dr. Seri Park, and Mr. David Mensching.

CONTENTS

INTRODUCTION

Warm mix asphalt (WMA) has been gaining acceptance across the United States and Canada in recent years. A large number of state departments of transportation (DOTs) have hosted WMA demonstrations to determine if WMA should be allowed for state-funded paving projects. These demonstrations have shown that WMA is constructible and can reduce fuel usage and emissions associated with hot mix asphalt (HMA) production. However, many of these demonstrations were conducted with only one or two WMA technologies. Now there are over 25 commercially available WMA technologies in the United States. Most states do not approve a WMA technology for use on state-maintained roads without a well-documented demonstration project. The WMA technology suppliers that were not part of these early demonstration projects often are required to organize a demonstration on their own to gain approval for state paving projects.

A standard evaluation program for construction of WMA demonstration projects, including a process for laboratory evaluation of WMA mixtures, can encourage collection of reliable data sufficient for state agencies to approve a WMA technology. The American Association of State Highway and Transportation Officials (AASHTO) National Transportation Product Evaluation Program (NTPEP) successfully conducts over $1M in engineering materials evaluation testing per year. NTPEP represents a centralized system of testing, evaluation, and data reporting of engineering materials for the state DOTs. A prospective NTPEP process for evaluation of WMA technologies might consist of a combination of laboratory, plant, and field testing. NTPEP "one-time approval" of a product is indicative of its complying with key performance properties; however, each transportation agency could still follow its own process for accepting a NTPEP-compliant WMA technology.

RESEARCH OBJECTIVE

The primary objective of NCHRP Project 20-07, Task 311, was to define a WMA technology evaluation program that would be compatible with a centralized system of testing, evaluation, and data reporting of engineering materials for the state DOTs, such as the AASHTO NTPEP.

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

STUDY APPROACH

The objective of NCHRP Project 20-07, Task 311, was accomplished in four tasks:

1. Evaluate current state of practice in WMA,
2. Survey state DOTs on WMA use,
3. Prepare framework for WMA evaluation, and
4. Submit final report.

In Task 1, current practices reported in the literature by state DOTs, Federal Highway Administration (FHWA), academia, and industry for evaluating WMA technologies were reviewed. The review included (1) relevant results from NCHRP Projects 9-43, 9-47, and 9-47A; (2) the test frameworks and guidelines available from the WMA Technical Working Group at http://www.warmmixasphalt.com/Default.aspx; (3) National Asphalt Paving Association (NAPA) Publication QIP-125, "Warm-Mix Asphalt: Best Practices"; and (4) comparable AASHTO practices such as (a) R 15, Asphalt Additives and Modifiers, (b) R 26, Certifying Suppliers of Performance-Graded Asphalt Binders, (c) R 34, Evaluating Deicing Chemicals, and (d) R 31, Evaluation of Protective Coating Systems for Structural Steel.

In Task 2 the state DOTs, industry, and local agencies were surveyed to determine the types of information these stakeholders would require to make an informed decision about using a new WMA technology. A response rate of 94% was achieved for the DOT survey. The survey was submitted through the AASHTO Subcommittee on Materials/NTPEP Committee with an NCHRP transmittal letter. The survey was distributed via the online software, SurveyMonkey®. In order to encourage a more comprehensive stakeholder dataset, the asphalt industry in each of the states (i.e., state Asphalt Pavement Association) was also invited to participate in the survey in an effort to collect supplemental information and possibly capture a view of the use of WMA at the private industry level. Since there are a number of local agencies in the United States who have aggressively pursued implementation of WMA, feedback from at least five of these local agencies was solicited. Follow-up interviews were conducted via phone or email to gather more detailed information from agencies that have been using more advanced techniques for evaluating WMA technologies in their state. This task ultimately included additional surveys of both WMA manufacturers and accelerated pavement test facilities to further help shape the product in Task 3.

Based on the results of Tasks 1 and 2, a proposed work plan to evaluate WMA technologies by sponsoring organizations such as AASHTO NTPEP was prepared in Task 3. The work plan was focused on evaluating WMA technologies through both laboratory testing and field demonstration sections. The program was developed to be compatible with, and suitable for adoption by, NTPEP. A project final report summarizing the results, findings, and conclusions of Tasks 1 through 3 was prepared in Task 4.

LITERATURE SUMMARY

The numerous research reports, technical articles, presentations, and WMA manufacturer communications reviewed consistently cited measurement of WMA's resistance to rutting and moisture susceptibility as a critical element. Numerous research projects in the United States and abroad stressed the importance of conducting laboratory tests that would define a WMA mixture's propensity to rut, crack, or strip in the presence of water. Other important properties cited were mixture stiffness, workability, and compactability. Many of the research projects followed the evaluation of potential impacts to WMA performance in a manner similar to those defined in NCHRP Projects 9-47 and 9-47A (Anderson et al. 2008; Kvasnak et al. 2009):

- Rutting: reduced aging of the binder could increase rutting potential;
- Fatigue life: reduced aging of the binder may increase mixture fatigue capacity;
- Mixture stiffness: reduced aging of the binder may reduce the mixture stiffness;
- Moisture susceptibility: incomplete drying of the aggregate could increase moisture sensitivity of the mixture; and
- Low-temperature cracking: certain WMA additives may increase the potential for low-temperature damage, based on the results of binder tests. At the same time, the reduced aging of the binder could reduce the potential for low-temperature cracking.

The fact that WMA has been reported as having lower stiffness than traditional HMA provides the potential to incorporate more recycled asphalt pavement (RAP) in WMA. Laboratory tests showed that WMA appears to be more susceptible to stripping and coating issues; however, such moisture damage has not been evident in the field (Epps Martin et al. 2011).

Fuel savings was also reported as a by-product of using WMA in lieu of traditionally produced HMA. However, it should be noted that fuel savings can be offset by the cost of the WMA additives, estimated at $2 to $4 per ton of WMA produced (Anderson et al. 2008). It should also be noted that since 2008, fuel costs have risen significantly, enhancing the cost benefit of WMA use.

In April 2011, Northeast Asphalt User-Producer Group (NEAUPG) established a definition for WMA and criteria for qualification of WMA technologies. The definition adopted by NEAUPG was originally established by the New York State DOT as the following:

Warm Mix Asphalt (WMA) technologies generally allow a reduction in the temperature at which asphalt mixes are produced and placed, thus helping the environment and worker health and safety. WMA technologies can also be used as a compaction aid extending the paving season in colder climates when produced at normal temperatures at which the hot mix asphalt mixes are produced.

The issue of writing a specification for WMA alone was raised, and NEAUPG members agreed that writing such a specification would not be efficient. Rather, it was agreed that a process like that of AASHTO NTPEP or New York State DOT (NYSDOT) should be adopted by NEAUPG. NYSDOT has a qualification process to vet various WMA technologies and contractors. Once a technology is approved by NYSDOT, it is added to an approved products list. A contractor can then elect to use that approved technology in a paving project. The WMA qualification process may include laboratory testing of materials with the Hamburg rutting test (AASHTO T 324), APA rutting test (AASHTO T 340), and the dynamic modulus test (AASHTO T 342, AASHTO TP 79). As a result of the April 2011 meeting, the northeastern state DOTs plan to adopt NYSDOT's qualification process until AASHTO provides an NTPEP evaluation program for WMA.

SURVEY RESULTS

The results of the following three surveys were analyzed as part of this research project: a questionnaire for WMA producers; a questionnaire for state departments of transportation and local transportation agencies; and scoping interviews of Accelerated Pavement Test (APT) facilities. These results were used to define the WMA technology evaluation program presented in the following section.

Questionnaire for WMA Producers

The questionnaire for WMA producers solicited feedback from the WMA industry on what aspects should be addressed in the future potential development of a WMA technology evaluation program. The questionnaire was distributed to the 22 technology contacts listed in the *Warm-Mix Asphalt: Best Practices 2*nd Edition (Prowell et al. 2011) and a response rate of approximately 50% was obtained from these WMA producers, manufacturers, and contractors who construct with WMA.

Approximately 70 percent of manufacturers responded they were familiar with the AASHTO NTPEP process. Many respondents did not provide feedback regarding what aspects of an AASHTO NTPEP evaluation program they would recommend. However, the respondents who did provide feedback suggested the comparison of performance between HMA and WMA, moisture susceptibility tests, and rutting potential tests as being key elements. All manufacturers agreed they would be willing to participate in a compliance testing and evaluation process such as NTPEP. Many manufacturers are already working in several states and they see this potential evaluation process as a clear advantage. Seventy percent of the manufacturers indicated a willingness to spend $10,000 to participate in a program such as NTPEP compliant, while 30 percent would be willing to spend $25,000.

Energy and Emissions

A few questions were aimed at providing information as to the methods for emissions reductions and energy savings. Manufacturers were asked if they used a quantifiable method for measuring emissions. Sixty percent of manufacturers measure emissions at the plant and 10 percent also measure emissions during construction. Forty percent answered they do not have a quantifiable measure for emissions.

Manufacturers were also asked if they had a quantifiable method to measure the amount of energy expended to produce and construct their product. Figure 1 illustrates the responses to this question. Since

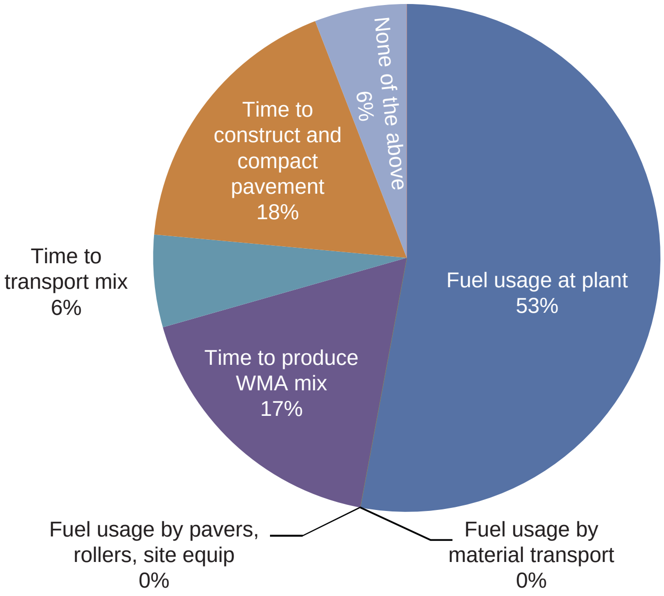


Figure 1. Methods used by WMA manufacturers for measuring energy savings.

a large portion of the fuel consumed at an asphalt plant is used in heating the binder, aggregate, and mix during mix production, 53% of the manufacturers were able to quantifiably measure their energy usage. Eighty percent of respondents reported having compared the energy used for HMA to the energy used for WMA. Some manufacturers calculated energy usage by analyzing the time it took to produce the WMA mix. There are circumstances in which asphalt mix may also require on-site reheating during construction. As a result, approximately 18% of manufacturer respondents indicated that they also measured fuel usage factors during construction. Only 6% reported measuring energy usage in terms of the time it took to transport the mix.

WMA Production and Quality Control Testing

The survey also asked how manufacturers of the various technologies ensure quality during production and construction of their products (Figures 2 and 3). All of the WMA manufacturers and contractors offer some type of training by their company to ensure successful production of their product; some also partner with NAPA or state APA activities related to WMA. Other efforts include overseeing plant modifications for use of their product, issuing a product specification, and developing a quality control (QC) plan for the plant. Only 8% of respondents mentioned sponsoring a control mix.

The majority of manufacturers (39%) ensure pavement contractors are capable or outfitted to construct WMA by offering contractor-specific training, as shown in Figure 3. In addition, 17% of respondents

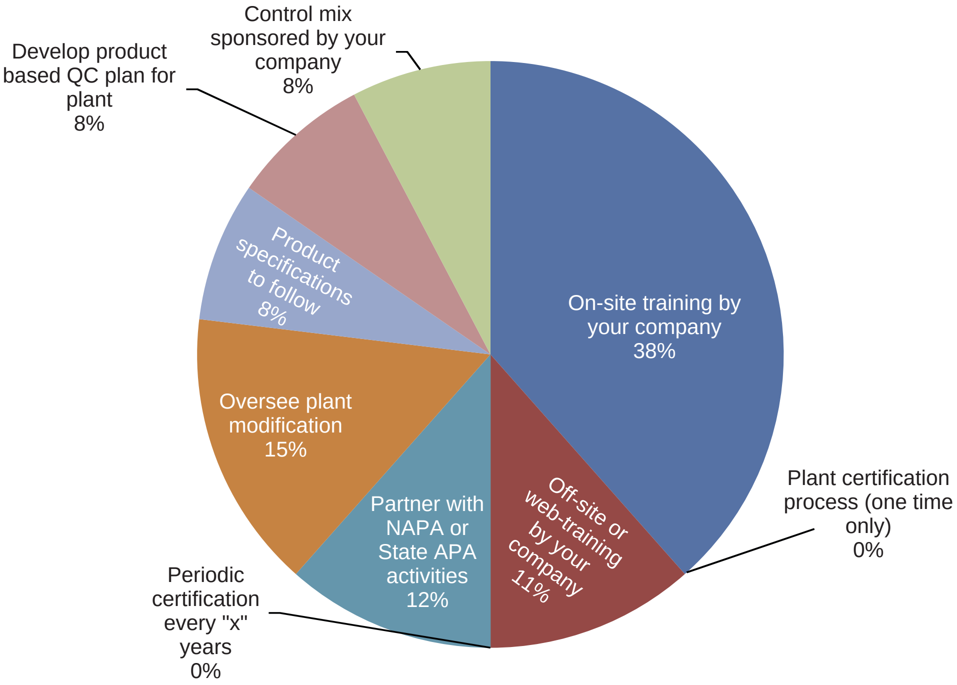


Figure 2. Methods used by WMA manufacturers for ensuring quality during production.

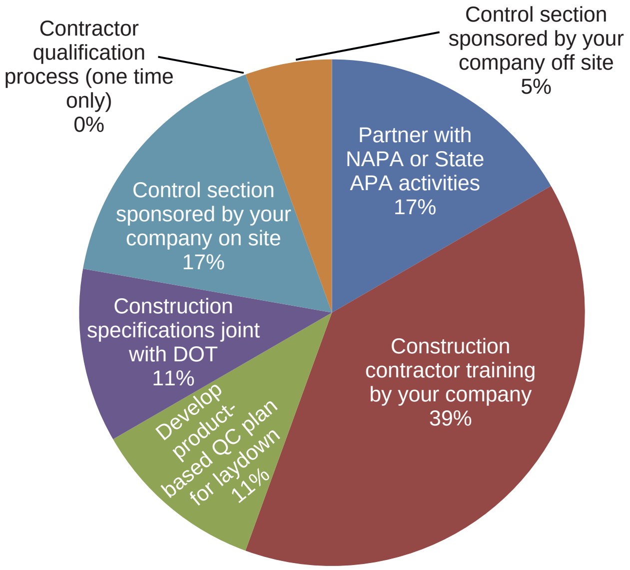


Figure 3. Methods used by WMA manufacturers for ensuring quality in construction.

also partner with NAPA or state APA activities. A few respondents actually develop a product-based QC plan (11%), sponsor an onsite (17%) or off-site control section (5%), or both. Two of the respondents developed a construction specification collaboratively with a transportation agency.

Seventy percent of manufacturers require or recommend running a full suite of commonly used laboratory tests to measure the physical properties of the WMA mix prior to construction. Manufacturers were asked to comment on what type of QC was important to successful implementation of their product. Some suggested that the same QC system currently in place for HMA be used. Other feedback cited proper installation and calibration of plant equipment was important as well as the use of best practices.

Factors Affecting WMA

The manufacturers were queried as to which types of field conditions may affect their products. Field conditions listed included the following: snow plows and studded tires; wet versus dry climate; freeze versus no-freeze climate; long haul distances; use of material transfer vehicle (MTV) versus no mix re-agitation; and heavy truck traffic (greater than 20% trucks). The results are shown in Figure 4.

When asked which mixture variations significantly alter the base condition performance of their products, half the respondents answered their product would not be affected. However, the factors that were mentioned as potentially requiring more attention included those shown in Figure 5.

Questionnaire for State Transportation Agencies and Local Public Agencies

The state DOT and local agency questionnaire gathered information on approaches used by agencies to make an informed decision about any new

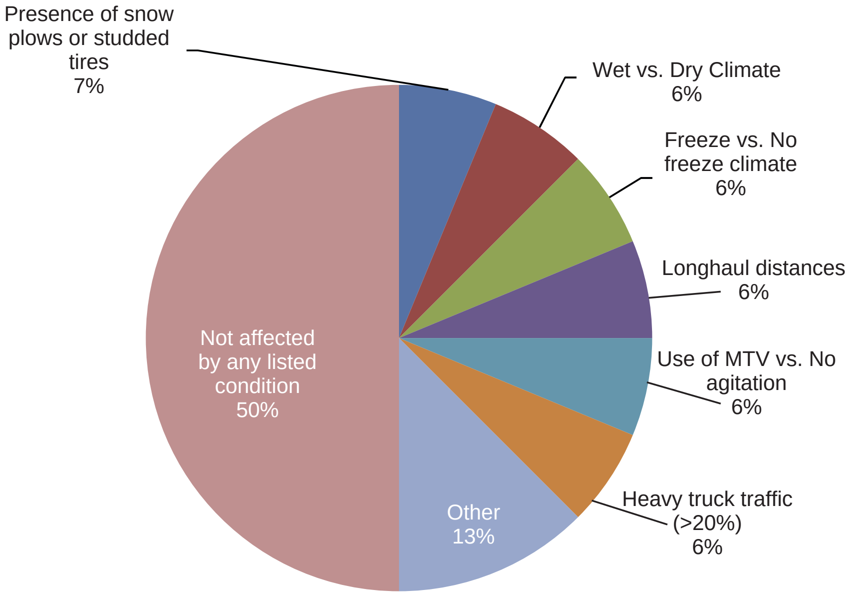


Figure 4. Field conditions assessed as potentially affecting WMA performance.

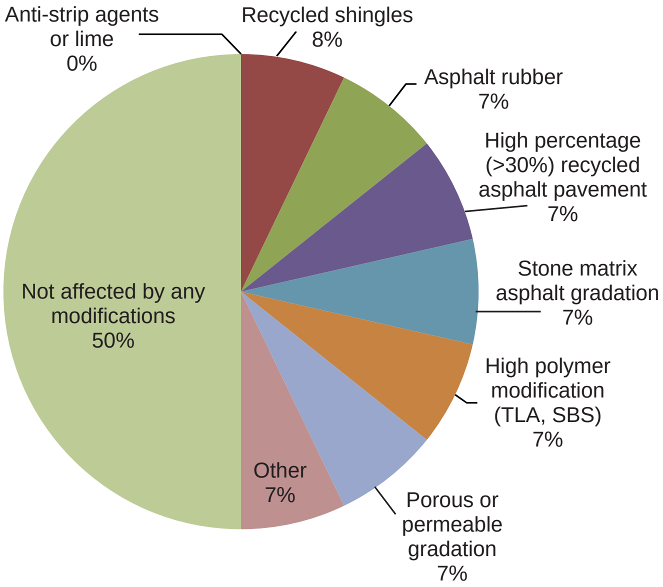


Figure 5. Mixture modifications ranked as potentially affecting WMA performance.

WMA technology. Numerous state DOTs hosted WMA demonstrations to determine whether WMA should be allowed for state-funded paving projects. Taken together, these demonstrations have established that WMA is constructible and can reduce fuel usage and emissions associated with hot mix asphalt (HMA) production. The majority of these demonstrations were conducted with one or two WMA technologies; a small number involved three.

A number of local public agencies have also used, or are imminently planning to use, WMA for paving projects in their jurisdictions. Data from the survey were analyzed to identify how agencies are handling the use of WMA and whether they are finding success in doing so.

The response rates for this survey were excellent, with 94% of state DOTs (including the District of Columbia, Puerto Rico, and FHWA Federal Lands); 130% of local public agencies (more replied than the number initially invited); and 16% of state asphalt pavement associations (APAs) providing input on what they see as items necessary to make informed decisions regarding implementation of WMA specifications. A total of 99 organizations responded to this questionnaire (53 DOT respondents, 6 state APAs, and 40 local agencies, including City of Oshawa in Canada). Figure 6 identifies the locations of the survey respondents.

The survey first asked respondents about their WMA project experience to date. Approximately 65% (64 responses) have built WMA projects to date, 4% have designed but not yet built WMA projects, and 31% have not yet designed or built any WMA projects. When asked about their current specifications for constructing WMA pavements, the respondents' top two approaches were use of either a state agency WMA specification or a state agency HMA specification followed at lower temperatures. The use of as-is state agency HMA specifications

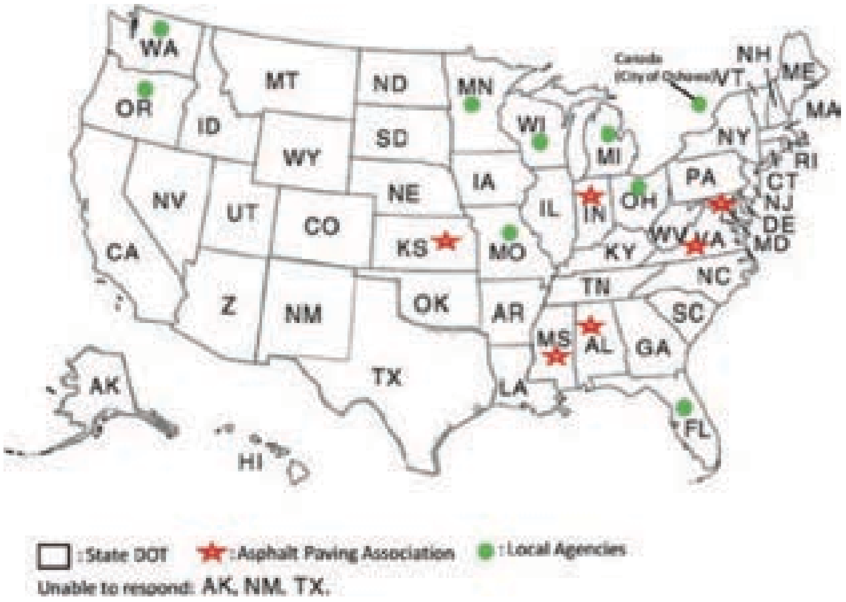


Figure 6. Distribution of NCHRP Project 20-07, Task 311, survey respondent locations.

was reported as the third most frequently used. These findings imply that most agencies, including local agencies, apply state-level specifications for WMA projects. When determining factors for mix design (e.g., mixing and compaction temperatures, mixture conditioning temperature, etc.), survey results showed that most agencies used the recommendations of the WMA manufacturer. Respondents were asked with which WMA technologies (chemically-processed, organic-additive, and foaming-processed/water-based) they have the most experience to date, in order to assess general application trends. Results showed that foaming-processed or water-based WMA technologies are the most frequently used by the majority of transportation agencies.

WMA Pavement Damage

Ninety-two (92%) percent of organizations reported having observed no damage since WMA pavements had been placed and exposed to traffic. However, since detailed information on the traffic exposure period was not captured, any firm conclusions regarding the WMA pavement performance would be premature. Two agencies observed moisture damage and three agencies observed reflective cracking damage in field WMA sections. Another phenomenon reported by one agency was a sheen observed on several projects after construction and construction-related raveling. Although the sample size was not significant enough to develop any further correlation between reported damage types and geographical location, it is interesting to note that all organizations who reported field damage are located in the Long-Term Pavement Performance (LTPP) freeze zone, which includes the United States north of about latitude 37° except for portions of California and the Pacific coasts of Washington and Oregon. The two organizations that reported evidence of moisture damage in WMA sections are located in LTPP Wet-Freeze zones (roughly the states in the Northeast, Middle Atlantic, and Midwest).

Subsequent phone interviews were conducted to obtain more detailed information on the observed field damage. All the interviewees indicated that the damage observed in their WMA pavement sections was comparable to that found in similar HMA sections or in the adjacent HMA control section. The main exception to this finding was with construction-related issues which the agencies could not conclusively attribute to the WMA additive or process as the primary cause of failure. In a few cases, agencies echoed concerns about the future of WMA in their respective regions due to the issues reported. However, a key finding of this survey is the lack of low-temperature cracking in the WMA sections and the impression that the damage in WMA sections is not reported as being more severe than that seen in HMA pavements when cracking does occurs.

Control Section and Post-Compaction Monitoring

The majority of agencies reported the use of HMA control sections; 4 organizations used a WMA control section; 17 did not use any control section. Methods used to test or document any noticeable differences between the control and WMA sections were also obtained. Most agencies performed volumetric testing and visual inspection. One agency paved a 3-mile stretch of two-lane rural highway with HMA and WMA side-by-side for testing and documentation. One organization stated that before a WMA technology could be approved, the contractor was asked to provide a WMA control section to demonstrate that the application can meet all construction specifications. For WMA post-compaction monitoring, the most widely used method involves taking pavement cores. The nuclear density gauge and visual distress survey were reported as the next most frequently followed methods. The Pavement Quality Indicator (PQI) non-nuclear gauge was also mentioned as being used by one organization.

WMA Mix Variation and Core Extraction

Recycled asphalt pavement (RAP) was the most commonly used WMA mix additive reported in the survey, with 83% of respondents using RAP. Polymer modifiers and anti-stripping agents were the next widely used, respectively. Only one organization used recycled ceramics or glass and Trinidad Lake asphalt (TLA) as mix design additives. Most of the organizations reported that they extract WMA cores at the time of construction and post-final compaction. It should also be noted that about 12% of respondents stated that they do not extract WMA cores. The number of cores collected ranged from 5 to 40, depending on the organization and project size.

Field Compaction Targets

Approximately 45% of organizations reported no difficulty with contractors reaching field compaction targets during completion of WMA projects.

Six organizations were unsure as to the exact cause of difficulty reaching compaction targets, while a few indicated it had been a function of mixture design and the plant mix produced. Some additional comments suggested that difficulty in reaching target density was due to a lack of experience or the learning curve associated with constructing a new technology.

Decision Making for Use of WMA

In order to capture the factors that would influence agencies when deciding when to use WMA, many questions associated with decision making were asked. Because there were a number of agencies who had not yet built WMA in their jurisdictions, responses in the following sections are split into two categories: (1) responses from organizations with WMA project experience, and (2) responses from organizations without WMA project experience. For both categories, agencies were asked which element they would monitor if there were no constraints on cost, staff resources, and time. It is interesting to note that regardless of whether the respondent has had actual WMA project implementation experience, most answers exhibited similar patterns. For example, the ability of the mix to resist rutting, followed by its ability to resist cracking and moisture damage, ranked as the most important elements to monitor for all respondents. This suggests that most agencies would like to generate a performance-related standard, such as through specifications, for actual production and construction of WMA. A few respondents alluded that there should be no requirement of additional testing for WMA as compared to HMA, with the exception of emissions testing.

The major factor that helped agencies decide whether to select WMA in lieu of HMA was reported to be the contractor's option or election to pave with WMA. This finding is aligned with the group of respondents who have already implemented WMA projects. Two main elements of the "other" category were budget and traffic conditions and respondents considered those main factors to guide their decision for selecting WMA. One DOT cited that haul distance was considered a major decision factor. No correlation was observed between an agency's geographical location and its decision to select WMA for paving sections.

The top two factors ranked as needing to be overcome for full-scale implementation of WMA were: (1) contractors' experience with WMA, and (2) lack of detailed WMA specifications. The two factors were observed to be related in that as an organization develops a standard set of specifications for WMA implementation, reliance on the contractors' experience may decrease. Therefore, the development of a standard process and specifications for WMA implementation were reported to be important. Other difficult factors to overcome were reported to be: cost of building WMA; lack of detailed information on various WMA technologies; lack of documented observations of long-term performance; and, especially, lack of education and training of employees involved with design and construction of WMA.

WMA performance was also evaluated by surveying the importance of different WMA material properties. The level of importance ranged from Very Important (value of 4) to Not Important (value of 1). Based on level of importance, in situ density and air void properties were reported to be the main factors in determining WMA performance. In addition, binder content, mixture tensile strength, and mixture compactability had average values higher than 3. Lesser values were assigned to moisture susceptibility, long-term raveling, and permanent deformation. One organization pointed out that the need for proper design, placement, compaction, and mix performance is common to WMA, HMA, or any other asphalt mix system.

When asked which pavement distress would be most critical in WMA pavements, the majority of respondents cited rutting or moisture damage. Long-term durability of a WMA technology as compared to an HMA technology, and the amount of moisture retained in the mix, were also reported as items which were important to monitoring pavement distresses.

WMA Paving Season and Interaction with WMA Producers and Contractors

As expected, summer was the predominant season in which WMA projects were constructed. Fall and spring were ranked as the next two seasons in which the majority of WMA projects had been paved. Forty-four (44) percent of respondents indicated that WMA did not enable them to pave outside their normal paving period, but 15% of organizations replied that they were able extend their paving season by using WMA instead of HMA.

The frequency with which respondents were approached by new WMA producers or contractors wanting to pave with a new WMA technology varied. Some respondents have never been approached, others were approached as often as monthly (11% of respondents); every 3 months (11% of respondents); or every 6 months (19% of respondents). One organization indicated that WMA producers often approach it to incorporate new WMA technologies but that contractors rarely request to use WMA. Another organization mentioned that it has been approached at the end of a normal paving season to switch from the specified HMA to a WMA application.

Certification Process

Among respondents currently implementing WMA projects, 21% have a WMA technology certification process or qualification program. Organizations that have some type of WMA certification process or qualification program were then asked about future implementation of WMA projects. Seventy-seven percent indicated that certification of WMA technologies in future projects would streamline project delivery.

Potential Use of AASHTO NTPEP as a WMA Technology Evaluation Program

About 40% of respondents were familiar with AASHTO NTPEP while 32% of respondents were not. The majority of respondents unfamiliar with NTPEP were local agencies. The majority of those familiar with AASHTO NTPEP were already participating in it.

Respondents were asked their level of willingness to use WMA technologies if NTPEP were to develop a WMA technology evaluation program. Ninety-two (92%) percent of organizations stated that they would be somewhat or very likely to use the results if NTPEP developed a WMA technology evaluation program. Some DOTs indicated they would require NTPEP evaluation and compliance, while others stated their usage of NTPEP would depend on how the WMA technology evaluation program is formulated. Of the 45 agencies who answered, 33% would require mandatory use of the NTPEP process, while 66% stated that NTPEP process would be optional.

When asked about issues related to the importance of a standard process on which to base WMA production decisions, the majority of respondents that it is very important and only 4% of respondents stated that a standard process would not be important at all. These results imply that a need exists for WMA production to be held to a standard process, accompanied by potential specification development.

WMA Material Sampling

Respondents were asked about the frequency with which they collect WMA materials, such as the binder from a supplier, sampling from aggregate and RAP stockpiles, loose bulk mixture, and the WMA additive. Agencies routinely collect samples of loose mix at the plant or at the paver (57% of respondents); binder at the supplier or plant (44% of respondents); aggregate stockpiles at the plant (38% of respondents); and RAP at the plant (31% of respondents). However, the WMA additive was rarely sampled at the plant, and 48% of respondents indicated that no WMA additive sampling is done. Sampling of RAP at the plant varied between “routinely collected” and “no sampling is done.” Interestingly, the results indicated that only a small percentage of organizations performed sampling on WMA demonstration projects.

Conditioning Methods for WMA Samples

When asked about the application of conditioning methods to WMA samples, 44% responding reported that no conditioning method was currently being used. Among those who did employ sample conditioning methods, the most frequently reported was 2 hours at the compaction temperature. The next most frequently used conditioning method was reheating to compaction temperature.

As reheating of WMA specimens can have a critical effect on their measured performance, respondents were asked when they believe that the reheating of WMA specimens should be allowed. The majority reported that reheating of specimens is allowed for Independent Assurance and Acceptance. For dispute resolution testing and quality assurance, some agencies (greater than 20%) allowed reheating of WMA specimens, but 19% responded that they did not permit reheating of mix in any situation. Supplemental comments provided by respondents varied significantly regarding the topic of reheating WMA specimens. For example, one organization stated that it follows the same reheating process as done for HMA; whereas others reported that reheating is allowed only for research purposes, or for the correction of discrepancies related to end-of-load segregation issues, or for determining asphalt content.

Sixty-three percent of respondents do not follow any standard process for reheating WMA specimens. For those who do follow a standard reheating process, 62% consider the time and temperature of reheating as a necessary part of the evaluation procedure.

Scoping Interviews of Accelerated Pavement Test Facilities

Scoping interviews were conducted to solicit key information from staff of Accelerated Pavement Testing (APT) facilities since their use was considered to be a critical element of any WMA technology evaluation program measuring field performance. The interviews gathered general cost information on both full-scale field control test sections and APT control sections. Interviews were conducted with five APT facilities, one DOT, and one local agency.

The average cost of installing a typical test section in an APT facility was reported to be approximately $200,000. Additional in-house costs, such as personnel, indirect costs, and equipment monitoring, were not included in this estimate. The range of reported costs for an APT experiment and test section varied from $20,000 to $400,000. The length of test sections constructed was generally reported to be approximately 200 ft. However, one facility constructs 550-foot sections. All facilities constructed sections that were at least 50 ft beyond the intended monitoring length; i.e., for a 550-ft section, the monitored length was 500 ft, and for a 250-ft section, the monitored length was 200 ft. The number of lanes per APT facility varied from 2 to 12. One facility split up its lanes into 44-ft sections to enable more varied types of testing. Most of the facilities reported that duplicate sections are not routinely installed.

Fifty percent of respondents reported their facilities conducted test cycles in less than 1 year. The other 50% of respondents indicated an average cycle time of 3 to 5 years. One facility could control temperature from 10 to 70°C. Another facility reported it was capable of maintaining temperature at 50 to 52°C. The rest of the respondents used ambient temperature at their facilities. Reported load levels ranged from 10 to 20 kips. Half of the facilities reported that super-single loading is used, while the other facilities use dual and dual tandem loads. Most facilities employ a unidirectional load with wander and one facility incorporated a live traffic section of interstate highway.

When asked what aspects of a WMA technology evaluation program they consider important, most respondents cited monitoring of rutting, moisture damage, and fatigue cracking.

Agencies reported that it was difficult to estimate a cost for monitored, full-scale WMA field sections subjected to live traffic and typical construction conditions, since these were placed in conjunction with HMA projects. The respondents indicated that breaking out the actual cost for the HMA alone would have been difficult. However, one agency did provide a rough estimate of $150,000 for conducting the full-scale field evaluation.

One local public agency conducted a field evaluation of HMA and WMA by constructing WMA test sections adjacent to new HMA sections. Both pavement sections received virtually the same monitoring; i.e., ARAN, visual inspection, and PASER. Distresses monitored included smoothness, cracking, and rutting. Both sections were exposed to live traffic. There were no special warranty or acceptance criteria involved in either section.

WORK PLAN AND COMMENTARY FOR A PROPOSED WMA TECHNOLOGY EVALUATION PROGRAM

This section presents a proposed work plan for a WMA technology evaluation program, with associated commentary.

Definition of WMA

Based on the information gathered via the literature review, survey responses, and subsequent detailed interviews with manufacturers and state DOTs, the majority of the asphalt industry defines WMA as a material essentially having the same basic mixture volumetrics and performance properties as HMA. The major differences between HMA and WMA were reported to be how the mixture is produced and whether modification is accomplished through the use of additives or an alternate production process at the plant. This feedback from industry was key to establishing the proposed work plan for the WMA technology evaluation program described herein.

Cost Supportable by WMA Manufacturers

Based on the survey results, the main challenge to implementation of a WMA technology evaluation program would be the cost to complete APT for field performance. All of the WMA manufacturers who responded to the survey indicated that they would be willing to pay between $10,000 and $25,000 to have their product evaluated in a national program like AASHTO NTPEP. There were several reasons for this relatively low level of funding.

Many of the WMA manufacturers who have been active in the United States and Canada over the past 10 years have already sponsored a substantial number of demonstration pavement sections in multiple states or provinces. Because of this past investment, they are not willing to invest an additional significant amount for evaluation and certification. However, the manufacturers were interested in modestly investing to participate in a national program. In addition, they indicated that as new modifications or products are integrated into their systems, there are benefits to being evaluated through an ongoing third-party program (such as AASHTO NTPEP). A few manufacturers also indicated that such a program would be a major benefit to others who have not yet made significant investments toward sponsoring individual state DOT pavement sections.

Thus, the cost of intensive testing necessary for rigorously evaluating a potential WMA additive or process (in particular in the field with APT) is far greater than the amount that manufacturers indicated that they could support. These findings were instrumental in shaping the details of the proposed laboratory and field testing presented below.

Results of the survey of six APT facilities throughout the United States estimated that for an APT facility with multiple cells, based on an average cost of $200,000 and multiple small (e.g., 50 ft by 14 ft) test sections, a number of manufacturers' products could be installed and tested simultaneously during a 1-year evaluation cycle. In this case, it may be feasible that each WMA section could cost $5,000 to $10,000. However, each manufacturer would be asked to sponsor one WMA and one HMA control test section, resulting in an approximate cost of $10,000 to $20,000 per manufacturer for APT field testing in one location. The field test data would be captured and analyzed by a designated independent laboratory or test facility. The field testing cost might conceivably fit into the $10,000 to $25,000 range reported as reasonable by the WMA manufacturers; however, this amount excludes the cost of laboratory testing, installation, material transport, sampling equipment, etc. Moreover, if the testing were required to be done in two different climatic locations (wet-freeze and wet-no freeze), then the estimated costs would double, at a minimum.

Proposed Work Plan and Commentary

Summary

This work plan is furnished for the benefit of (1) manufacturers interested in participating in a WMA technology evaluation program and (2) state and local agencies that are interested in reviewing and utilizing the data generated through such a product evaluation. The testing format has been established to provide test results which can be used to assess the performance of material additives or processes for WMA applied to traditional hot mix asphalt production.

This work plan defines the evaluation procedures for material additives and processes for WMA that could potentially serve as a proposed standard testing protocol for a WMA technology evaluation program (such as through AASHTO NTPEP).

The testing facility may be any public or private laboratory appropriately equipped and capable of performing the required evaluations. Evaluation reports will provide performance data but will not indicate that the technology passed or failed specific criteria.

Terminology

COMMENTARY: Terms provided here are derived from those provided in AASHTO specifications and *NCHRP Report 691* (Bonaquist 2011).

Accelerated pavement testing (APT)—The controlled application of a prototype wheel loading, at or above the appropriate legal load limit to a prototype or actual, layered, structural pavement system to determine pavement response and performance under a controlled, accelerated accumulation of damage in a compressed time period.

Air voids (V_a)—The total volume of 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.

Chemically-processed warm mix asphalt—Asphalt mixing process which includes technologies that use a combination of emulsification agents, surfactants, polymers, and additives to improve coating, mixture workability, and compaction, as well as adhesion promoters. The chemical additive package is used either in the form of emulsion or added to bitumen in mix production process and then mixed with hot aggregate.

Creep—The time-dependent portion of strain that results from stress.

Creep compliance—The time-dependent strain divided by the applied stress.

Dynamic modulus—$|E^*|$—the absolute value of the complex modulus calculated by dividing the peak-to-peak stress by the peak-to-peak strain for a material subjected to a sinusoidal loading.

Dynamic modulus master curve—A composite curve constructed at a reference temperature by shifting dynamic modulus data from various temperatures along the log frequency axis.

Flow number—F_N, the number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated load test.

Foaming-processed warm mix asphalt—Asphalt mixing process which includes processes that introduce small amounts of water to hot asphalt, either via a foaming nozzle, damp aggregate, or a mineral additive such as zeolite.

Organic-additive warm mix asphalt—Asphalt mixing process which includes technologies that use organic or wax additives to achieve the temperature reduction by reducing viscosity of binder.

Tensile strength—The strength shown by a specimen subjected to tension.

Voids in the mineral aggregate (VMA)—The volume of the intergranular void space between the aggregate particles of a compacted paving mixture that includes air voids and the effective binder content, expressed as a percent of the total volume of the specimen.

Voids filled with asphalt (VFA)—The percentage of the VMA filled with binder (the effective binder volume divided by the VMA).

Warm mix asphalt (WMA)—Warm mix asphalt refers to asphalt concrete mixtures that are produced at temperatures approximately 28°C (50°F) 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 HMA using substantially reduced production temperatures.

Manufacturer Participation

COMMENTARY: One item addressed as part of the DOT, industry, and manufacturer surveys was the type of specimens (both conditioned and manufactured) to be used in the work plan. The majority of survey respondents indicated that they allow reheating of specimens but do not have a standard procedure for doing so.

The survey also queried agencies as to the importance of including various types of plant-produced specimens. The response was that plant-mixed laboratory-compacted (PMLC) and plant-mixed field-compacted (PMFC) specimens were ranked of almost equal importance for inclusion in a WMA technology evaluation program. For this reason, the mixture performance tests proposed are to be done on both bulk mixture plant samples and cores extracted from the in-place pavement mat, and do not include laboratory-mixed, laboratory-compacted (LMLC) specimens.

Manufacturers of material additives and processes for WMA who elect to participate in the program must submit a completed application form. For the purposes of this testing program, products intended for vertical or any non-highway applications **will not** be evaluated.

The manufacturer shall supply sufficient quantities of each product to perform the required testing. The testing facility determines what constitutes “sufficient quantities” for laboratory testing and installation. The manufacturer shall supply bulk mixture samples of WMA (commonly referred to as plant-mixed, laboratory-compacted [PMLC] specimens), preferably compacted immediately after sampling to eliminate the need for mixture reheating (commonly referred to as plant-mixed, quality control laboratory-compacted [PMQLC] specimens). The manufacturer shall also supply cores extracted from the testing facility test pavement (commonly referred to as plant-mixed, field-compacted [PMFC] specimens). The test materials shall be labeled with sample numbers traceable to the WMA produced.

COMMENTARY: In addition, a requirement for plant-mixed, quality control laboratory-compacted (PMQLC) specimens may cause challenges in that the majority of contractors do not have the capability of compacting tall gyratory specimens. Moreover, there has been significant evidence that reheating plant samples above the field compaction temperature can alter the true properties of an asphalt mixture.

For these reasons, the following two options regarding PMQLC specimens should be considered: (1) allow manufacturers to choose as part of their submittal whether they will allow reheating of their product and, therefore, place the responsibility of defining specimen type (PMLC versus PMQLC) on the manufacturers; or (2) establish a maximum reheating temperature as part of the laboratory testing framework regardless of whether specimens are manufactured as PMLC or PMQLC.

Testing Facility Criteria

Candidate facilities that wish to be designated as an authorized test facility shall meet the following Facilities requirements:

1. Provide documentation to demonstrate experience in performing testing of asphalt materials and mixtures.
2. Verify that the facility has the equipment, facilities, and capability to perform the required testing procedures contained in this work plan by providing a list of equipment that it uses for testing asphalt materials and mixtures.
3. State its policies regarding qualifications and training of its staff to ensure high quality performance. This shall include performance reviews of testing proficiency and Standard Operating Procedures for each testing procedure as detailed in the Quality Assurance portion of this document.
4. State the administrative procedures in place to ensure a high quality of comparative testing results.
5. Demonstrate the ability to complete all laboratory testing of the WMA materials within 3 months of the date that samples are received.
6. Verify that the facility is in conformance with applicable federal and state occupational safety and health regulations.
7. Verify that it performs all testing in conformance with the requirements of the specified individual test methods. Accreditation through the AASHTO Accreditation Program is the preferable verification. However, accreditation through other nationally recognized programs such as the National Voluntary Laboratory Accreditation Program or the International Organization for Standardization (ISO) Technical Committee 176 (TC 176, Quality Management and Quality Assurance) ISO 9000 and TC 261 (Additive Manufacturing) may be considered.

Candidate facilities that wish to be designated as an authorized test facility shall meet the following Personnel requirements:

1. Provide an organizational chart that identifies the names and positions of management personnel and each person that will be involved in or associated with testing and the review of test reports. A laboratory Quality Control Manager shall be designated for review of all Standard Operating Procedures and proficiency evaluations of technicians as described herein.
2. Provide resumes or credentials for all persons identified in the organizational chart. The responsible persons supervising the laboratory and the staff performing the testing shall have levels of formal education appropriate for their duties.

Quality Control. The laboratory shall identify procedures used to ensure that all testing is conducted at an acceptable quality level. The QC process shall be based upon statistically supported conclusions. The conclusions shall verify that the laboratory is capable of producing reproducible and repeatable test results. The preferred technique for comparative conclusions is to obtain results based on tests performed on identical samples by other laboratories that are statistically evaluated for their comparative similarity. The comparative testing must be performed using the testing procedures required by the WMA technology evaluation program.

Testing proficiencies of all technicians shall be evaluated and documented by the laboratory Quality

Control Manager. These evaluations shall be performed at 6-month intervals unless the technician does not routinely perform the test. In this case, proficiency of the technician shall be evaluated and documented prior to testing of products for this program.

Testing Capability. The testing facility shall be comprised of a single entity or a combination of no more than three entities.

When more than one facility is used, a single lead facility shall be responsible for the coordination and oversight of all testing and reporting and for the compilation of the final report. The lead facility is responsible for identifying the tests that will be subcontracted and for determining that each of the facilities is properly accredited and operates under a rigorous QC plan. Subcontracted facilities cannot be changed without the approval of the sponsoring organization(s).

The field testing shall be at an appropriate testing facility as designated by sponsoring organization(s).

Tests and Test Methods

The standard tests and methods are detailed later in this work plan.

Test Report

The primary testing facility is responsible for entering data generated in its facility into an online database (or other appropriate storage medium) and reviewing any data generated at subcontracted facilities that is entered in the database.

All information noted in the Test Report Section of this work plan shall be included in the test report.

Product Submission Guidelines

Once the manufacturer is notified that its WMA technology system has been accepted for evaluation, the test facility will request that the manufacturer submit clearly marked samples of the product.

Once the laboratory testing has been started or the field installation process is complete, no direct written or verbal correspondence between the manufacturer and the testing laboratory is permitted. Any implication of interference from the manufacturer during the testing will be cause for the evaluation to cease.

Testing Fees

Testing fees are assessed to cover all costs associated with laboratory testing, material installation, field evaluation, administrative costs, and report generation and distribution.

Laboratories will be reimbursed for testing performed if a system is withdrawn after testing has begun. If the manufacturer elects to withdraw initial samples after testing begins and resubmit products, the manufacturer will be charged additionally for all costs incurred by the laboratory during the initial testing.

Policy for Withdrawing Materials from the WMA Technology Evaluation Program

A written request to withdraw the material from the evaluation cycle must be received at least 5 business days before scheduled sampling is to occur. If sampling has occurred, a handling fee of 10 percent of the testing fee will be charged in addition to any laboratory test costs that may have been incurred for evaluation.

Testing and Reporting Requirements

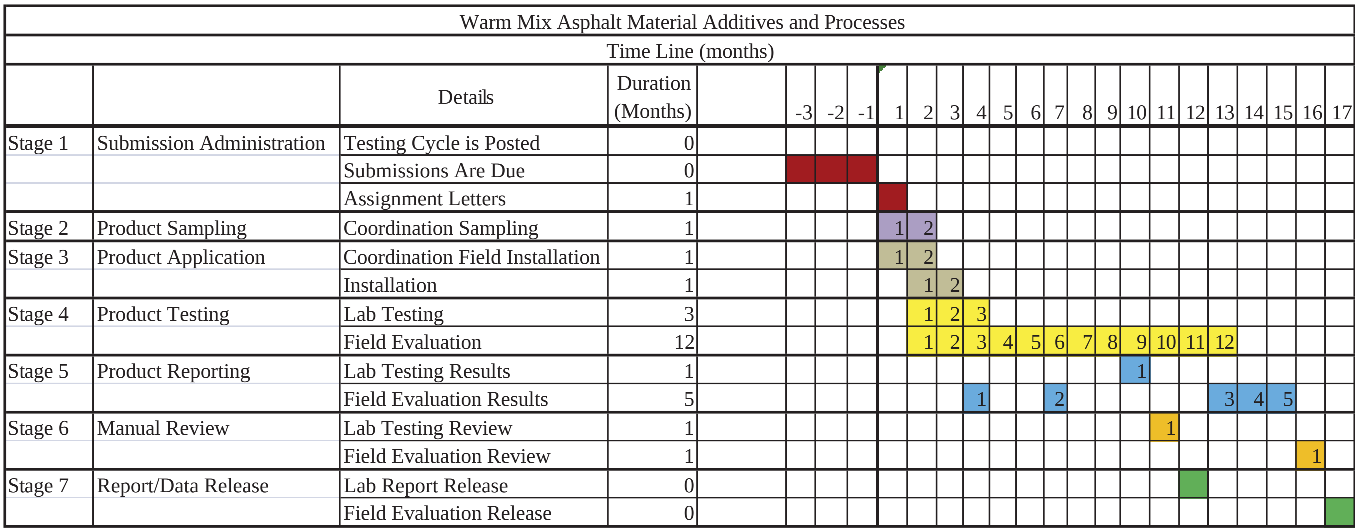
The laboratory and field evaluation procedures consist primarily of AASHTO and, if necessary because of the lack of a comparable AASHTO method, ASTM tests. It should be noted that this evaluation program is intended for structural asphalt mixtures; thus, bituminous seals, coatings, preservation, or other experimental materials are not included as part of this work plan.

Results of the laboratory and field evaluations will be entered directly into an online database or other appropriate storage medium. A timeline for product evaluations is shown in Figure 7.

Material Criteria

The program will accept three types of additive or process submittal:

1. Foaming-processed warm mix asphalt includes processes that introduce small amounts of water to hot asphalt binder, either via a foaming nozzle, damp aggregate, or through an additive such as zeolite.
2. Chemically-processed warm mix asphalt includes technologies that use a combination of emulsification agents, surfactants, polymers, and additives to improve coating, mixture workability, and compaction, as well as adhesion promoters. The chemical



Warm Mix Asphalt Material Additives and Processes

Time Line (months)

		Details	Duration (Months)		-3	-2	-1	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Stage 1	Submission Administration	Testing Cycle is Posted	0																					
		Submissions Are Due	0		🟥	🟥	🟥																	
		Assignment Letters	1					🟥																
Stage 2	Product Sampling	Coordination Sampling	1					1	2															
Stage 3	Product Application	Coordination Field Installation	1					1	2															
		Installation	1						1	2														
Stage 4	Product Testing	Lab Testing	3						1	2	3													
		Field Evaluation	12						1	2	3	4	5	6	7	8	9	10	11	12				
Stage 5	Product Reporting	Lab Testing Results	1														1							
		Field Evaluation Results	5								1			2						3	4	5		
Stage 6	Manual Review	Lab Testing Review	1															1						
		Field Evaluation Review	1																				1	
Stage 7	Report/Data Release	Lab Report Release	0																🟩					
		Field Evaluation Release	0																					🟩

COMMENTARY: It is proposed that all accelerated field testing of trial WMA sections be conducted within 12 months. This recommendation is based on the survey feedback from a number of APT facilities that indicated that a full-scale pavement experiment is typically completed within a 1-year timeframe. In the rows that compose Stage 5 Product Reporting, both laboratory and field testing is indicated at 3, 6, and 12 months (after installation) to address cores which are extracted commentary from the APT pavement lift and taken into the laboratory for testing.

Figure 7. Timeline for WMA technology evaluation program.

additive package is used either in the form of emulsion or added to asphalt binder in the mix production process and then mixed with hot aggregate.

3. Organic-Additive warm mix asphalt includes technologies that use organic or wax additives to achieve temperature reduction by reducing binder viscosity.
4. In order to be classified as WMA, the mixture must be produced at a plant temperature less than or equal to 132°C (270°F) which is approximately 28°C (50°F) lower than current HMA production temperatures.

Material submittals may be limited per manufacturer per year. A generic material composition description and Material Safety Data Sheet (MSDS) must accompany the submittal for classification and worker safety purposes.

WMA material additives and processes may be required to be resubmitted and tested (in the laboratory only) at a specified interval of time. A signed certification from the manufacturer will be required with the re-submittal stating that the formulation has not changed since the original submission.

Once a manufacturer has submitted a product and a sample ID has been assigned, the manufacturer and product name will remain unchanged throughout the reporting cycle.

Laboratory Tests

Laboratory Testing to Be Performed. Standard tests should be used to evaluate WMA material additives and processes. There are also provisional, non-standard AASHTO procedures which can assist in ensuring materials are tested to best evaluate their quality. Both bulk mixture sampled during production and cores extracted from pavement test sections will be evaluated in the laboratory. Any testing of bulk mixture sampled during production must be conducted after 5 days but before 30 days after specimen fabrication. An exception to the 30-day rule can be made only if specimens are vacuum-sealed and stored at constant temperature and humidity.

COMMENTARY: The recommendation for types of samples and the associated testing timeframe is based on the guidelines established in *NCHRP Research Results Digest 370* (Baker et al. 2012). Since the testing facilities may have up to 3 months to complete testing of the manufacturer's materials, adherence to the recommended time frame between fabrication and testing of the samples is encouraged.

Binder Testing. The continuous performance grade of original WMA binder and extracted WMA binder shall be determined to ascertain the impact of WMA additive or process on binder stiffness. A dynamic shear rheometer (DSR) suitable for testing stiff asphalt binders shall be used. Tests shall be run on original and extracted WMA binder both before and after aging in the pressure aged vessel (PAV). The same process shall then be completed on rolling thin-film oven (RTFO)-aged binder for short-term aging performance. Asphalt binder extraction shall be performed using AASHTO T 164 Method A or ASTM D5404. The use of trichloroethylene (TCE) solvent is not permitted for extraction.

COMMENTARY: The section on binder testing is based on findings by Bonaquist (2011). These are also in line with a portion of the binder testing required in *NCHRP Research Results Digest 370* (Baker et al. 2012). Additional testing information included herein is based on both user-producer group (NEAUPG) and DOT protocols for binder testing with and without WMA additives.

It should be noted that the full sweep of acceptance testing should be considered in cases where new additives (e.g., rubber, recycled shingles, anti-stripping agent, a new polymer modification, etc.) have been combined with a WMA technology. In addition, when processes are used that introduce foam into the binder as it enters the plant, sampling binder at the plant may be preferable. However, it may not be possible to safely sample foamed binder at the plant, depending on how the plant is configured.

The exclusion of TCE as an extraction solvent is founded on research presented by the Federal Highway Administration that showed TCE hardens the extracted binder. The use of 85/15 toluene/ethanol is recommended instead (Baker et al. 2012).

One 1-gallon sealed bucket of asphalt binder should be sampled from the plant.

COMMENTARY: The recommendation for one 1-gallon sealed bucket of binder comes from Minnesota DOT Report MN/RC 2007-43 (Marasteneau and Zofka 2007) that designates quantities required for state DOT field sampling sites.

COMMENTARY: The FHWA WMA Technical Working Group had considered the use of the multiple stress creep recovery (MSCR) test on asphalt binders to gauge their potential for fatigue and thermal cracking, following the approach presented by Wen et al. (2010). The work plan proposed herein does not include the MSCR test due to time and budget constraints, as well as questions about the test's precision and bias; however, it should be noted that this test may prove to be more accurate than the current AASHTO methods in gauging the potential for fatigue and thermal cracking.

Aggregate Testing. Contractor QC data shall be submitted from aggregate tests conducted prior to production of the test mixtures by the manufacturer. Data must be furnished for the following aggregate properties: gradation, bulk specific gravity, absorption, stockpile moisture content, coarse aggregate angularity, fine aggregate uncompacted voids, flat and elongated, and sand equivalent. For gradation properties, AASHTO T 27 will be employed, while bulk specific gravity and absorption will be obtained through AASHTO T 84 and T 85 procedures.

COMMENTARY: Laboratory-mixed laboratory-compacted (LMLC) specimens will not be tested. Therefore, the aggregates used in the manufacturer's mix design are not the focus of the evaluation, as long as highly absorptive aggregates or those with a history of stripping are not used. The provision of the aggregate property data (e.g., stockpile moisture content, coarse aggregate angularity, fine aggregate uncompacted voids, flat and elongated, and sand equivalent) is critical to tracking mixture performance. The proposed suite of tests to be conducted by the testing facilities does not include aggregate testing. State DOTs using the results of the evaluation should still rely on their own individual quality verification or quality acceptance procedures in practice.

The laboratory aggregate tests proposed herein are based on those listed by Baker et al. (2012). Only three of the tests shall be conducted by the testing facility (AASHTO T 27, T 84, and T 85), which can be compared to contractor QC laboratory data; all other test results shall be provided by contractor data.

Mixture Volumetric Testing. Reheat bulk mixture sampled during production from ambient temperature for 2.5 hours at the WMA compaction temperature. Conduct mix design verification with test data from specimens produced by contractor or state DOT laboratory and with 150-mm (6-inch) diameter and 115-mm (4.5-inch) high Superpave gyratory specimens at the design number of gyrations (N_{design}). Conduct in-place density and thickness tests on cores extracted from the WMA test section to compare with properties tested on bulk mixture samples.

COMMENTARY: The mixture volumetric testing required as part of the proposed work plan is limited since the main intent is not mix acceptance. Testing is limited to comparison of the bulk mixture properties with those of the extracted cores. For this reason, the primary tests proposed include G_{mm}, compaction to N_{design}, air voids, and G_{mb}. These tests agree with the suite of tests and specimen conditioning recommended by Baker et al. (2012).

Sealed metal buckets totaling 660 lb of loose asphalt mix should be sampled from multiple points in the truck bed at the production site or plant. One-hundred fifty (150)-mm (6-inch) outside diameter cores should be extracted to include all asphalt layers down to the interface with the aggregate base.

COMMENTARY: The recommendation for sealed metal buckets totaling to 660 lb of loose asphalt mixture to be sampled from multiple points in the truck bed at the plant comes from the sampling practice employed by the FHWA Mobile Asphalt Mixture Testing Laboratory.

The recommendation for 6-inch outside diameter cores, extracted to include all asphalt layers down to the interface with the aggregate base, was based on the Minnesota DOT field sampling program (Marasteneau and Zofka 2007), which designates quantities required for sampling state DOT field sites. The report lists minimum original material quantities based on different types of laboratory tests and sample geometry requirements.

Mixture Performance Testing. Standard laboratory tests shall be used to evaluate the performance of WMA. All laboratory test specimens shall be prepared from bulk mixture sampled during production of the test materials (PMLC) and cores extracted from the paved surface (PMFC). The manufacturer will have the option of providing PMLC or plant-mixed QC laboratory-compacted (PMQLC) material for mixture testing. Preferably, the contractor producing mix for the evaluation shall have a Superpave gyratory compactor equipped to compact tall specimens in its QC laboratory.

COMMENTARY: As stated previously, two options regarding PMQLC specimens may be considered: (1) allow the manufacturers to choose, as part of their submittal, whether they will allow reheating of their product and therefore, place the responsibility of defining specimen type (PMLC versus PMQLC) on the manufacturer;

or (2) establish a maximum reheating temperature as part of the laboratory testing framework regardless of whether specimens are manufactured as PMLC or PMQLC.

If the contractor participating with the manufacturer as part of the evaluation has the capability of compacting tall specimens, it is recommended that plant-mixed QC laboratory-compacted (PMQLC) samples be a suitable alternative to the PMLC specimens as long as no reheating (or reheating within specified limits) is applied to the mixture sampled. A major component of carrying out this step successfully is to ensure that the contractor selected to produce WMA for the evaluation has a Superpave gyratory compactor (SGC) equipped to compact tall samples.

Compactability. Determine the number of gyrations to 92 percent relative density in accordance with section 8.3 of the draft appendix to AASHTO R 35 (Bonaquist 2011) with the following modifications: maximum increase in gyrations of 25% at 30°C (54°F) below the planned field compaction temperature, and at the planned field compaction temperature.

COMMENTARY: Compactability was considered an element of interest as per the survey responses and the discussion presented in Section 8.3 of the draft appendix to AASHTO R35 (Bonaquist 2011). Although compactability testing is more akin to mixture design testing, its inclusion is recommended as it would provide a data point to fall back upon if premature field damage occurs during the subsequent field testing phase.

Dynamic Modulus. Bulk mixture test specimens shall be conditioned 2 hours at the WMA compaction temperature, followed by 16 hours at 60°C (140°F), and an additional 2 hours at the WMA compaction temperature. A target air void level of 7% ± 1% shall be used for compacting bulk mixture test specimens. AASHTO TP 79 and PP 61 shall be followed to determine the dynamic modulus of the mixture.

COMMENTARY: Conditioning of bulk mixture test specimens is in accordance with the procedure provided in Baker et al. (2012) and AASHTO T 312. The target air void level of 7% ± 1% for compacting bulk mixture test specimens is chosen to represent a typical air void content based on agency construction specifications and the average air void level after rolling. The dynamic modulus testing is conducted in accordance with AASHTO TP 79 and PP 61.

The dynamic modulus may be used as input to a structural design analysis program such as DARWin-ME to estimate pavement rutting and fatigue cracking levels over the expected service life. If DARWin-ME is not available for use, the spreadsheet program AMPT_QA_Program (Jeong 2010), which uses pre-solved solutions of the MEPDG to permit estimation of rutting and fatigue cracking, uses the dynamic modulus as input.

The survey responses did not indicate a strong concern with fatigue cracking and most respondents likened the fatigue performance of WMA to be similar to that of HMA. However, a few respondents did report having observed transverse reflective cracking in WMA field sections that were placed over jointed Portland cement concrete (JPCP) or over HMA pavement layers. In Minnesota, reflective cracking is being reported in WMA over JPCP and WMA over HMA sections. However, the cracking was not as severe as seen in similar HMA sections. In Cass County, MI, reflective cracking was noted on a WMA over HMA section. The county indicated that the transverse cracks observed in the WMA section were no more severe than those in the HMA control section. In Oregon, reflective cracking was observed in a section where a cement-treated base in poor condition was underlying the WMA. There were no cracking problems in similarly located HMA sections, but the substructure characteristics were different.

For the reasons discussed above, the stiffness properties of WMA would be of interest, albeit with measurements made with the Asphalt Mix Performance Tester (AMPT) at the reduced set of test conditions (temperature and frequency) called for in AASHTO TP 79 compared to the full set required by AASHTO T 342. Justification for the reduced set of test conditions was presented by Bonaquist and Christensen (2005), who found that the reduced data set produces comparable results at less than half the cost of necessary test equipment ($50,000 compared to $125,000) and could be performed in a single day, requiring only 13.5 hours to complete.

The testing conditions specified in AASHTO TP 79 include:

- Frequencies of 10, 1, 0.1, and 0.01 Hz
- Temperatures of 4°, 20°, and 35°, 40° or 45°C (determined by the asphalt binder performance grade)

COMMENTARY: Use of the Indirect Tension (IDT) Method to calculate the dynamic modulus of asphalt concrete from PMFC samples (Kim et al. 2004) was seriously considered. The practical benefit of extracting core samples (38 to 50 mm) from the field test section for the IDT test could be a more accurate measure of in situ dynamic modulus. The proposed work plan does not include this test due to limits on the time available to complete the laboratory testing and lack of IDT equipment at many laboratories.

Rutting. Specified tests shall be performed to evaluate the test mixture's propensity to rut. Testing shall be done on both loose bulk mixture from the plant and extracted cores from the test facility's field section. Air void tolerance for test specimens and specimen size shall be in accordance with AASHTO TP 79. Specimens shall be conditioned for 2 hours at the WMA compaction temperature, followed by 16 hours at 60°C (140°F), and an additional 2 hours at the WMA compaction temperature.

Repeated load (triaxial confined) testing shall be done on bulk mixture sampled during production in accordance with the procedure in AASHTO TP 79 for measuring flow number (F_N) with the Asphalt Mixture Performance Tester (AMPT). The repeated axial load applied shall be 483 kPa (70 psi); a confining pressure of 69 kPa (10 psi) shall be used.

COMMENTARY: In the near future, AASHTO may consider revising the Flow Number section of AASHTO TP 79 to include the latest developments in the evaluation of rutting presented in *NCHRP Report 719* (Von Quintus et al. 2012). Guidance presented in the report on preparing and testing the bulk mixture PMLC specimens (e.g., target air void level, number of specimens, load conditions, test procedure) to measure plastic deformation is followed in the Rutting section of this work plan. A method presented in the report for recovering cores from the in-place HMA mat is also proposed for use here as is the concept of using an equivalent test temperature option for testing bulk mixture sampled during production. The report suggests that the analysis use "one test temperature that is defined as the equivalent temperature that will result in the same level of rutting at the end of the design period with the rutting predicted using temperatures defined for that climate and structure."

COMMENTARY: In the case of the WMA technology evaluation program, the climate would be that of the location of the APT facility and the structure would be that built into the field section at the accelerated pavement testing facility. The procedure presented in Von Quintus et al. (2012) to determine equivalent test temperature offers two methods. The advantage of using this method to determine the flow number is the reduced number of specimens (down to three) required for testing and its applicability to plant produced specimens, both of which may result in time and cost savings.

AASHTO T 324 shall be conducted on bulk mixture laboratory-compacted samples and extracted core specimens at standard conditions and 50°C (122°F) under water. Top and bottom of cores shall be sawed in accordance with AASHTO PP 60, followed by measurement of bulk specific gravity (AASHTO T 166 or T 275) and calculation of air voids of each specimen (AASHTO T 269). For comparison, laboratory-compacted samples shall be compacted to a common air void content for verification purposes.

COMMENTARY: The proposed laboratory testing work plan includes Hamburg rut testing of both bulk plant mixture samples compacted in the lab (PMLC) and cores extracted from the pavement (PMFC).

AASHTO T 340 shall also be conducted on bulk mixture laboratory-compacted samples and extracted core conditions using the Asphalt Pavement Analyzer (APA) to evaluate rutting. Six (6) cylindrical specimens, 150-mm (6-inch) in diameter and 75 ± 2-mm (3.0 ± 0.1-inch) tall, are required to be tested at the high performance-grade temperature of the asphalt binder to evaluate rutting susceptibility of the mixture. Air voids shall be determined through the measurement of the bulk specific gravity (AASHTO T 166) after sawing. For test result verification purposes, laboratory-compacted specimens shall be compacted to a common air void content.

COMMENTARY: The proposed laboratory testing framework includes APA rut testing of both bulk plant mixture samples compacted in the lab (PMLC) and cores extracted from the pavement (PMFC). This recommendation is based on NJ DOT and NEAUPG WMA protocols; in addition, the APA is a commonly utilized procedure for rut testing reported among DOT survey respondents. The FHWA WMA Technical Working Group also recommends the use of the APA test for rutting resistance of PMLC WMA specimens.

Low-Temperature Cracking. Testing to determine the test mixture's propensity to low-temperature cracking is not included in the work plan for the WMA technology evaluation program.

COMMENTARY: Although a moderate number of DOT and industry survey respondents indicated that low-temperature (thermal) cracking would be a concern for WMA performance, none of the respondents reported having observed thermal cracking in WMA field sections. Interviews with responding agencies who reported observing transverse cracks in their WMA (and HMA control) sections traced the damage back to non-temperature related causes such as construction issues or reflective cracking propagating up from joints or cracks in the underlying layer.

Therefore, the WMA technology evaluation program does not include laboratory evaluation of low-temperature properties of WMA mixtures. This recommendation allows streamlining the laboratory testing portion of the program to include only low-temperature binder performance tests. The reasons for not requiring low-temperature mixture testing include: lack of low-temperature damage reported as observed in actual field WMA pavement sections; costs of conducting low-temperature mixture testing (considering amount of funds manufacturers willing to pay); and time required to conduct low-temperature mixture testing (12-month evaluation period proposed).

Durability. Bulk mixture test specimens shall be compacted to 150-mm (6-inch) diameter and 62-mm (2.5-inch) height for analysis with AASHTO T 283. The amount and type of anti-strip additive included in the test mixture shall be recorded and the proposed appendix to AASHTO R 35 (Bonaquist 2011) shall be followed for evaluation of moisture sensitivity using AASHTO T 283. Specimens shall be conditioned 16 hours at 60°C (140°F) followed by 2.5 hours at the compaction temperature. One freeze/thaw cycle shall be included in the test sequence. AASHTO T 283 and T 324 tests shall be run on both specimens prepared from bulk mixture sampled during production and those extracted from the pavement mat at the APT facility.

COMMENTARY: The majority of DOT and industry survey respondents cited concern with durability issues in WMA pavements. In particular, the survey indicated that respondents believed WMA might be more susceptible to moisture damage than traditionally produced HMA. However, the existence of moisture damage (stripping) in WMA field sections was only reported as having been observed by one agency (Taylor County, WI) to date.

The specimen conditioning and testing process for preparing moisture sensitivity test (AASHTO T 324 and T 283) samples is proposed to follow the consensus in *NCHRP Research Results Digest 370* (Baker et al. 2012).

COMMENTARY: Section 4.1.6 of *NCHRP Report 691* (Bonaquist 2011) described the issue of WMA processes that include anti-strip additives, and their resultant effect on tensile strength ratio in AASHTO T 283 test results. This information was the basis of the requirements in this proposed work plan for recording the amount and type of anti-strip additive included in the test mixture, and following the draft appendix to AASHTO R 35 for evaluation of moisture sensitivity using AASHTO T 283.

Summary of Laboratory Tests

Tables 1 through 4 provide a summary of the laboratory tests for binder, aggregates, mixture volumetrics, and mixture performance.

Products may be tested either as supplied (neat) or modified with a maximum amount of 15% recycled asphalt pavement (RAP) allowed according to the manufacturer's written instructions. However, the same mix design used in the field installation must be used in the laboratory testing.

COMMENTARY: The DOT and industry survey found that an overwhelming majority of respondents are adding RAP to their WMA mixes. For this reason, it is proposed that the WMA technology evaluation work plan allow candidate WMA material additives and processes to be tested as either part of a neat mixture or a mixture modified **with a maximum amount of 15%** RAP. The decision whether to include RAP in the laboratory and field tested mixtures should lie with the manufacturer.

Review of some other DOT-proposed WMA specifications included: (a) PR DOT allows 20% maximum RAP content; and (b) NJ DOT allows up to 35% maximum recycled products (RAP, recycled asphalt shingles, and crushed recycled container glass) for intermediate and base asphalt lifts. It should be noted that the NEAUPG WMA Qualification Process requires test results for WMA, and a corresponding HMA control mixture, designed without RAP.

Table 1 Summary of laboratory tests: binder.

Test	Specification
Performance grade of original binder	AASHTO R 28, R 29, and T 240
Performance grade of extracted binder	AASHTO R 26, R 28, R 29, and T 240 or AASHTO T 164 with Rotovap recovery
Performance grade of base binder	AASHTO R 28, R 29, and T 240

Table 2 Summary of laboratory tests: aggregates.

Test	Specification
Gradation	AASHTO T 27
Bulk specific gravity and absorption	AASHTO T 84 and T 85
Flat and elongated or AIMS method	ASTM D 4791 or use state or contractor data
Sand equivalent	AASHTO T 176 or use state or contractor data
Stockpile moisture content	AASHTO T 255 or use state or contractor data
Coarse aggregate angularity	AASHTO T 335 or use state or contractor data
Fine aggregate uncompacted voids	AASHTO T 304 or use state or contractor data
Geologic type	Use state or contractor data
Soundness	AASHTO T 104 or use state or contractor data
LA abrasion or Micro Deval test	AASHTO T 96 or T 327, or use state or contractor data

Table 3 Summary of laboratory tests: mixture volumetrics.

Test	Specification
Theoretical maximum specific gravity and density of HMA	AASHTO T 209
Preparing and determining density of HMA specimens by means of superpave gyratory compactor	AASHTO R35 and T 312
Practice for superpave volumetric design for HMA	AASHTO R35
Laboratory confirmation of extracted core density	AASHTO T 166 or T 275
Laboratory confirmation of extracted core thickness	ASTM D 3549

Table 4 Summary of laboratory tests: mixture performance.

Test	Specification
Mixture design verification with 150-mm diameter	AASHTO T 320
Rutting	AASHTO TP 79, T 324, and T 340
Dynamic modulus	AASHTO TP 79 and PP 61
Compactability	AASHTO R35 draft appendix section 8.3
Durability	AASHTO T 283 and T 324

Field Performance Tests

COMMENTARY: The pavement structure and supporting layer material properties of the test sections should be designed (to the greatest extent possible) to isolate the WMA lift and limit damage in the section to that occurring in the WMA surface layer.

COMMENTARY: Use of an APT facility in lieu of a field site serves the purpose of isolating the performance of an asphalt mixture processed with (1) a system to produce warm mix or (2) a warm mix additive, and allows the opportunity to observe whether failures are due to a deficiency of the WMA system itself. Isolating the asphalt layer's performance characteristics from those of the entire pavement system should be considered. A conventional pavement structure is proposed with 4 inches of asphalt mix, 8 inches stabilized granular base, and a subgrade prepared to optimum water content and maximum dry unit weight. This pavement configuration and conditions are suggested based on the findings in *NCHRP Report 719* (Von Quintus et al. 2012). Preparation of subgrade conditions may dictate the timing of construction at the APT facility.

Accelerated Pavement Testing. Two pavement locations will be selected at an APT facility. Sites should generally meet the following criteria:

- 102-mm (4-inch) WMA surface lift, excluding overlays or interlayers.

COMMENTARY: The recommendation for a 4-inch conventional surface lift is based on the discussion provided in *NCHRP Report 719* (Von Quintus et al. 2012) on site features and layer properties. The report notes that maximum rut depths were slightly greater for thin HMA layers than in thick (8 inches or thicker) lifts.

- Wet, no-freeze climate and wet, freeze climate.

COMMENTARY: The WMA technology evaluation program suggests field performance testing in both a freeze and no-freeze environment. However, requiring accelerated pavement testing to be done in both a no-freeze and freeze climate will substantially increase the total cost of the field evaluation (i.e., double the cost of APT testing by having two separate experiments in two different sites being conducted simultaneously). Ultimately, a decision on climate should be based on consideration of whether the plant process or binder grade has the greater effect on WMA performance.

- 205-mm (8-inch) stabilized granular aggregate base, suitable for rutting and fatigue cracking testing applications.

COMMENTARY: This requirement is based on review of the forensic investigations of field pavements described in Von Quintus et al. (2012), where it was found that asphalt treated base layers exhibited much greater rut depths than sections without asphalt stabilized base. Likewise, the report also documented high levels of rutting in untreated aggregate base lifts that were susceptible to moisture due to periods of heavy rainfall during construction.

A careful review of the type and amount of stabilization proposed for the base lift, dependent on the location and climate of the APT facility, is mandatory. A suitable granular base may be used to allow for rutting and fatigue cracking evaluation in the WMA lift without the risk of inducing reflective cracking (especially when using a cement treated base).

Three survey respondents (Cass County, Michigan; Oregon DOT; and Minnesota DOT) noted the presence of reflective cracking in WMA field observations. Therefore, the field sections should not be placed over badly cracked or badly jointed HMA, or jointed concrete pavement, in order to eliminate the presence of joints that cause reflective cracking.

- Subgrade conditioned to optimal water content and maximum dry unit weight.

COMMENTARY: This requirement is based on the discussion of calibration and validation for unbound layers discussed in *NCHRP Report 719* (Von Quintus et al. 2012). The report indicated that sections with highest measured rut depths were a result of subgrade soils with higher moisture contents and lower densities. Thus, the testing facility should prepare the subgrade soil to isolate the effects of rutting to the WMA lift only.

- Field test areas will be 200 feet long by 12 to 14 feet wide.

COMMENTARY: This recommendation is based on dimensions of test sections reported from the brief survey of APT facilities in the United States. The minimum test section length was consistently reported to be 200 feet. It is recommended that the manufacturer be allowed to stipulate the required test section length as part of its initial submittal. In addition, it is recommended that the manufacturer be required to produce, present, and place the WMA (and control HMA) mixtures in the selected test sections.

- Equivalent HMA control section adjacent to the WMA section. The HMA control pavement shall have the same dimensions, compaction target, aggregate source, mix design (excepting any elements of the WMA process or additives), structure, and number of traffic load applications.

COMMENTARY: The DOT and industry survey respondents overwhelmingly agreed that an HMA control section must be used as part of any WMA field testing framework. The HMA control section can provide direct comparison to isolate the effects of the material additive or process used to transform the same HMA material into WMA.

- Load level of 44 kN (10 kips) on a single axle.

COMMENTARY: This recommendation is consistent with the average load level reported in the survey of U.S. APT facilities.

- Testing conducted at ambient temperature of the APT facility locations.

COMMENTARY: This recommendation is based on the results of the APT survey which reported that the majority of accelerated pavement testing facilities conducts performance testing at the ambient temperature of their facilities.

Installation. The manufacturer will supply all labor and equipment to completely install the properly sampled and produced WMA mixture. The facility will provide site preparation and preparation of the subgrade and stabilized base layers. Paving of the WMA and HMA surfaces will be the manufacturer's responsibility. At the time of installation the manufacturer will provide written instructions to the paving contractor for the proper installation of the material.

COMMENTARY: The testing facility shall develop the supporting structure of the APT section including preparation of the base and subgrade layers.

Traffic control and installation scheduling will be arranged by the manufacturer, if deemed necessary by the nature of the APT facility. The manufacturer's representative will certify that the WMA mixture produced is constructed in accordance with the construction specifications identified for use and to the manufacturer's satisfaction. If the representative indicates that the installation using its product was unsatisfactory, notification to the testing facility must be made in writing, within 1 week of the installation. Upon notification, the manufacturer's installation may be dropped from further testing without a refund of fees. If no written notification is received within the first week, the installation will be accepted and included in the field testing.

COMMENTARY: It is recommended that the field evaluation be conducted only at APT facilities that do not include real-time traffic, unless the facility will receive sufficient loading to guarantee failure within the timeframe specified in the evaluation program. It is additionally recommended that the construction specifications of the state in which the testing facility resides be used during construction of the APT section.

If the manufacturer is absent during the scheduled construction, or fails to carry out its responsibilities during the scheduled production and paving of the WMA and HMA sections, all costs associated with labor, materials and equipment, preparation of the test site, and any potential repairs of the paving site will be charged to the manufacturer.

If an alternate date can be arranged it will be the manufacturer's responsibility to furnish traffic control (if necessary), prepare the pavement underlying layers, and provide for the construction and placement of both the HMA control section and the pavement section with WMA manufactured using its product or process.

Field Observations. Testing will commence upon completion of the installation and continue for 1 year. Field observations will be made during installation; at 3 months; 6 months (interim); and 12 months (final). Accelerated loading will be applied in equal frequencies and cycles to both the HMA and WMA test sections over a 12-month period.

COMMENTARY: Challenges to successful implementation of full-scale field-section testing are (1) the time required to observe the performance of actual field sections and (2) the cost of potential maintenance and protection of traffic. In order to completely characterize the performance of WMA produced with any particular process or additive, a field section would require monitoring for many years (e.g., upwards of 5 years) in order to capture distresses either visually or through the use of nondestructive testing (NDT). Manufacturers indicated in the survey that they would support reporting of key results within 2 years of application, but preferably sooner. Although indications of damage generation may be potentially captured sooner through the use of instrumented field sections (fitted with strain gauges, etc.), the instrumentation required would cost significantly more than what the manufacturers can support. Thus, the use of field sections to evaluate the WMA technologies does not appear feasible.

It is proposed that all accelerated field testing of trial WMA sections be conducted within 12 months. Another reason for this recommendation, in addition to those previously mentioned, stems from the APT survey in which fifty percent (50%) of respondents reported that their facilities typically conduct test cycles in less than 1 year.

Field performance test results shall be compiled into an electronic report by the testing facility.

COMMENTARY: The following field monitoring data types to be collected are based on information from field projects in various states and other related research projects. The field data types proposed for collection are based on those reported with the following qualities: most frequently used; lower in cost; and most widely available. In addition, the work plan may be amended to include field monitoring tools that will capture key elements of WMA such as amount of fuel savings and ease of compactability.

That report shall include, as a minimum, the following field performance monitoring data:

- Rut depth profile at construction using profilograph.
- ASTM E965 sand patch test for moisture susceptibility of the compacted mat.
- Visual distress survey using LTPP manual to capture percentages of fatigue cracking, low-temperature cracking, and other distress types.
- Ground penetrating radar (GPR) or seismic analysis surface wave (SASW) equipment at construction.
- Falling weight deflectometer (FWD) to predict cracking potential and in situ stiffness.
- Bond strength between layers by taking three (3) cores at construction (West et al. 2005).
- In-place thickness and density by extracting cores at the following frequencies: 9 at installation; 3 in the wheelpath at 3, 6, and 12 months; and 3 between the wheelpaths at 3, 6, and 12 months.
- Level of compactive effort during placement of test section.

COMMENTARY: Since some WMA additives have been promoted as reducing the level of compactive effort, the possibility of measuring that characteristic during construction of the field trial pavement sections should be considered. One potential tool for capturing this element is to use Intelligent Compaction to document the number of passes required to achieve the desired mat density.

During the field evaluation, if a product fails to the extent that it becomes a safety issue for the travelling public (if installed on an APT facility that includes real-time traffic), as determined by the testing facility, the manufacturer will be charged for the actual cost incurred by the DOT to repair the pavement section. This charge will include all labor, materials, maintenance, and protection of traffic (MPT) set-up and equipment costs.

COMMENTARY: This paragraph may be deleted if a decision is made to only use APT facilities that do not include real-time traffic.

REFERENCES

Anderson, R., G. Baumgardner, R. May, and G. Reinke. (2008). Unpublished Phase I Interim Report for NCHRP Project 9-47: Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies. Transportation Research Board, National Research Council, Washington, DC. Available on request to NCHRP.

Baker, T., M. Corrigan, J. Bukowski, J. Epps, D. Newcomb, and E. Harrigan. (2012). *NCHRP Research Results Digest 370: Guidelines for Project Selection and Materials Sampling, Conditioning, and Testing in WMA Research Projects*. Transportation Research Board, National Academies, Washington, DC.

Bonaquist, R. (2011). *NCHRP Report 691: Mix Design Practices for Warm Mix Asphalt*. Transportation Research Board, National Academies, Washington, DC.

Bonaquist R. and D. Christensen. (2005). *Practical Procedure for Developing Dynamic Modulus Master Curves for Pavement Structural Design*. Transportation Research Record 1929:208–217, National Academies, Washington, DC.

Epps Martin, A., E. Arambula, C. Estakhri, et al. (2011). Unpublished Phase I Interim Report for NCHRP Project 9-49: Performance of WMA Technologies: Stage I—Moisture Susceptibility. Transportation Research Board, National Academies, Washington, DC.

Jeong, M. (2010). Manual of Practice: HMA Quality Assurance Spreadsheet Program Using Measured Values of E* and D. Excerpt of Ph.D. Dissertation, Arizona State University, Tempe, AZ. Available at http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP09-22_AMPT_QA_SoftwareManualOfPractice.pdf. Accessed March 20, 2012.

Kim, Y.R., Y. Seo, et al. (2004). *Dynamic Modulus Testing of Asphalt Concrete in Indirect Tension Mode*. Transportation Research Record 1891: 163-173, National Academies, Washington, DC.

Kvasnak, A., B. Prowell, et al. (2009). Unpublished Phase I Interim Report NCHRP Project 9-47A: Engineering Properties, Emissions, and Field Performance of Warm Mix Asphalt Technologies. Volume 1: Literature Review. Transportation Research Board, National Academies, Washington, DC. Available on request to NCHRP.

Marasteneau, M., and A. Zofka. (2007). Report MN/RC 2007-43: Investigation of Low-Temperature Cracking in Asphalt Pavements—A Transportation Pooled Fund Study. Minnesota Department of Transportation, St. Paul, MN.

Prowell, B., G. Hurley, and B. Frank. 2011. NAPA QIP 125: Warm-Mix Asphalt: Best Practices: 2nd Edition. National Asphalt Pavement Association, Lanham, MD.

Von Quintus, H., J. Mallela, R. Bonaquist, C. Schwartz, and R. Carvalho. 2012. *NCHRP Report 719: Calibration of Rutting Models for Structural and Mix Design*. Transportation Research Board, National Academies, Washington, DC.

Wen, H., S., Shen, Z. Ma, J. Wang. (2010). Modeling the Effects of Temperature and Loading Rate on Fatigue Property of Asphalt Binder. *Journal of Testing and Evaluation* 38:6, 6 pp.

West, R.C., J. Zhang, and J. Moore. (2005). NCAT Report 05-08: Evaluation of Bond Strength Between Pavement Layers. National Center for Asphalt Technology, Auburn University, Auburn, AL.

Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

THE NATIONAL ACADEMIES™
Advisers to the Nation on Science, Engineering, and Medicine

The nation turns to the National Academies—National Academy of Sciences, National Academy of Engineering, Institute of Medicine, and National Research Council—for independent, objective advice on issues that affect people's lives worldwide.
www.national-academies.org

ISBN 978-0-309-25833-3
90000
9 780309 258333

Subscriber Category: Highways • Materials

These digests are issued in order to increase awareness of research results emanating from projects in the Cooperative Research Programs (CRP). Persons wanting to pursue the project subject matter in greater depth should contact the CRP Staff, Transportation Research Board of the National Academies, 500 Fifth Street, NW, Washington, DC 20001.

COPYRIGHT INFORMATION

Authors herein are responsible for the authenticity of their materials and for obtaining written permissions from publishers or persons who own the copyright to any previously published or copyrighted material used herein.

Cooperative Research Programs (CRP) grants permission to reproduce material in this publication for classroom and not-for-profit purposes. Permission is given with the understanding that none of the material will be used to imply TRB, AASHTO, FAA, FHWA, FMCSA, FTA, or Transit Development Corporation endorsement of a particular product, method, or practice. It is expected that those reproducing the material in this document for educational and not-for-profit uses will give appropriate acknowledgment of the source of any reprinted or reproduced material. For other uses of the material, request permission from CRP.

Copyright National Academy of Sciences. All rights reserved.