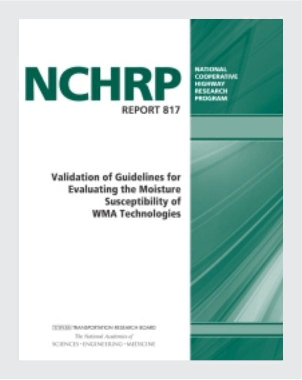

Validation of Guidelines for Evaluating the Moisture Susceptibility of WMA Technologies

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP REPORT 817

Validation of Guidelines for Evaluating the Moisture Susceptibility of WMA Technologies

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research is the most effective way to solve many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments and by committees of AASHTO. Topics of the highest merit are selected by the AASHTO Standing Committee on Research (SCOR), and each year SCOR's recommendations are proposed to the AASHTO Board of Directors and the Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

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FOREWORD

By Edward T. Harrigan
Staff Officer
Transportation Research Board

This report presents validated guidelines proposed for identifying potential moisture susceptibility in warm mix asphalt (WMA) during mix design. Thus, the report will be of immediate interest to materials engineers in state highway agencies and the asphalt pavement construction industry.

Over the past decade, the use of WMA for asphalt pavement construction has dramatically increased in the United States. WMA is seen as an alternative to hot mix asphalt (HMA), which offers the potential to lower energy demand during production and construction, reduce emissions at the plant and the paver, and increase allowable haul distances. However, questions remain about the long-term performance and durability of WMA pavements. One key issue is the moisture susceptibility of WMA pavements. Concerns about WMA moisture susceptibility include the possibility that aggregates will be inadequately dried at lower production temperatures and the fact that several WMA technologies introduce additional moisture in the production process.

NCHRP Project 9-49, which was completed in 2013, developed guidelines for WMA mix design and quality control to identify and minimize any possibility of moisture susceptibility. The guidelines were presented in *NCHRP Report 763* in the form of a flowchart of conditioning protocols and a choice of different standard test methods and corresponding thresholds that first assess the potential moisture susceptibility of a WMA mix design or field mixture and then recommend remedies to minimize such susceptibility. Specific test thresholds in the guidelines were based on the results of testing of WMA from field projects in Iowa, Montana, New Mexico, and Texas.

The objective of NCHRP Project 9-49B was to validate and revise, if necessary, the thresholds in the guidelines developed in NCHRP Project 9-49. The research was performed by the Texas A&M Transportation Institute, College Station, Texas.

The research was based on a survey of the state DOTs and paving contractors to identify WMA mixtures with available field performance, mix design, and quality assurance data, including wet indirect tensile (IDT) strengths and tensile strength ratios, wet resilient moduli and ratios, and Hamburg wheel tracking parameters. The survey identified 89 field projects with either IDT or Hamburg wheel tracking results. These results were analyzed to validate the thresholds established for the tests in NCHRP Project 9-49. The key practical outcome of the research is a flowchart (Figure 19 in the report) for conditioning and testing WMA laboratory specimens in the mix design process that incorporates the validated thresholds.

This report fully documents the research and includes two appendixes.

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

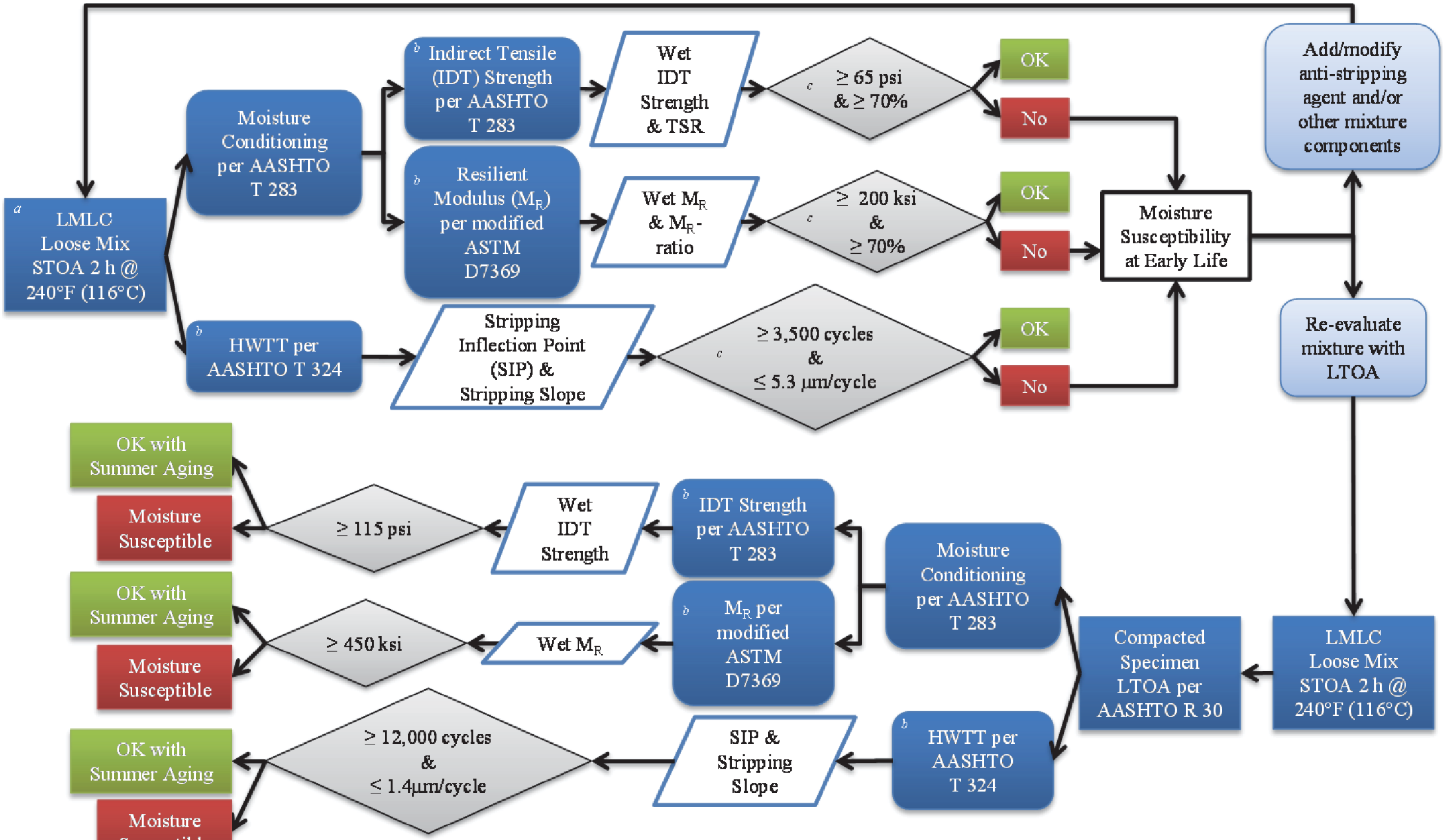
CHAPTER 1

Background

Economic, environmental, and engineering benefits motivate the reduction of production and placement temperatures for asphalt mixtures. The latest technology that has been rapidly adopted for this purpose is warm mix asphalt (WMA), which is traditionally defined as an asphalt concrete paving material produced and placed at temperatures approximately 50°F (28°C) cooler than those used for hot mix asphalt (HMA). However, in the context of this project, WMA is defined as an asphalt mixture produced with warm mix additives (i.e., surfactant, wax, etc.) or mechanical foaming processes regardless of the production temperature. WMA technologies offer many benefits such as improved workability and compactability, reduced aging, and better resistance to cracking and raveling. However, there has always been a concern regarding the early life performance of WMA mixtures, especially with respect to the potentially higher susceptibility to rutting and moisture damage due to the incomplete drying of the aggregates, reduced binder absorption by the aggregates at lower production temperatures, or the incorporation of additional moisture in the foaming process.

NCHRP Project 9-49 "Performance of WMA Technologies: Stage I–Moisture Susceptibility" focused on the evaluation of moisture susceptibility of WMA mixtures. Laboratory-mixed laboratory-compacted (LMLC) specimens, plant-mixed laboratory-compacted (PMLC) specimens, and field cores obtained from four field projects were evaluated to develop guidelines for identifying and limiting moisture susceptibility in WMA mixtures. The main product from NCHRP Project 9-49 is summarized in Figure 1, which details the proposed laboratory short-term oven aging protocols on asphalt loose mix and long-term oven aging protocols on compacted asphalt mixtures and thresholds for three different standard laboratory tests used to assess moisture susceptibility of WMA mixtures (Epps Martin et al., 2014). These thresholds were established by discriminating nine WMA mixtures from four field projects with good and poor field performance in terms of moisture susceptibility (i.e., raveling). The flow chart presented in Figure 1 was produced as a set of guidelines for mix design and quality assurance (QA) of WMA mixtures. Since the aging protocols and moisture susceptibility thresholds were developed based on a limited number of field projects, further validation of the flow chart or use on a trial basis was recommended prior to adoption.

The continuation work from NCHRP Project 9-49B "Performance of WMA Technologies: Stage I–Moisture Susceptibility Validation" described in this report focused on further corroboration of the moisture susceptibility thresholds included in the flow chart. A follow-up web-survey of state DOTs and contractors to the one conducted in NCHRP Project 9-49 was performed to identify WMA mixtures with available field performance plus mix design and/or QA data including wet indirect tensile (IDT) strength and tensile strength ratio (TSR) by AASHTO T 283, wet resilient modulus (M_R) and M_R ratio by modified ASTM D 7369, and Hamburg wheel tracking test (HWTT) per AASHTO T 324. Reports from related NCHRP Projects 9-47A "Properties and Performance of WMA Technologies" and 9-49A "Performance of WMA Technologies: Stage II–Long-Term Field Performance" were reviewed to identify additional WMA mixtures having this same type of information. In addition, recent relevant literature on field performance of WMA mixtures, laboratory moisture susceptibility tests, and moisture conditioning procedures were reviewed. Finally, a laboratory experiment was performed to assess additional moisture conditioning protocols as alternatives to the modified Lottman protocol per AASHTO T 283, and to explore various specimen-drying methods and their effects on the recommended moisture susceptibility parameters.



Note [a]: if WMA LMLC is not available, use trial batch prior to production for verification: on-site PMLC or off-site PMLC with minimal reheating

Note [b]: select a single test method and use it throughout the mix design verification

Note [c]: If trial batch off-site PMLC specimens are used, employ the following thresholds (TSR and M_R-ratio remain unchanged):
Wet IDT ≥ 100 psi, Wet M_R ≥ 300 ksi, SIP ≥ 6,000 cycles, stripping slope ≤ 2.0 µm/cycle

Figure 1. NCHRP Project 9-49 Proposed WMA moisture susceptibility evaluation for mix design and QA (Epps Martin et al., 2014).

CHAPTER 2

Recent Relevant Literature

This section provides a review of recent literature on field performance of WMA pavements, laboratory moisture susceptibility tests, and moisture conditioning procedures. The information gathered was considered when designing the laboratory experiment for evaluating additional moisture conditioning protocols and specimen-drying methods (Chapter 5).

A study by Azari and Mohseni (2013) evaluated a new practice for determining resistance of asphalt mixtures to moisture damage. A number of shortcomings for the AASHTO T 283 test were identified including long testing time, high sample-to-sample variability, inappropriate moisture conditioning components (i.e., vacuum saturation and freeze-thaw cycle), and non-uniform moisture conditioning due to specimen shape and size. To overcome these shortcomings, an experiment was performed to investigate sample shape and size for improved moisture accessibility, evaluate conditioning methods to improve effectiveness and reduce conditioning time, and explore the use of a different mechanical test to remove sample-to-sample variability. The incremental repeated load permanent deformation (iRLPD) test was proposed to evaluate moisture susceptibility of asphalt mixtures by comparing the permanent deformation before and after moisture conditioning. The iRLPD test is damaged-based, and thus, the level and duration of the load applied during the test is selected to avoid failure. This allows running the test on the same sample before and after moisture conditioning, significantly reducing sample-to-sample variability. The Minimum Strain Rate (MSR), which is the parameter obtained from the iRLPD test, shows high sensitivity to moisture induced damage. Laboratory test results indicated that smaller specimens (i.e., 100-mm IDT and 150-mm semi-circular bend [SCB]) were preferable over the 150-mm IDT specimens for the following reasons: a better distinction between moisture-susceptible and moisture-resistant mixtures, a lower load level required for achieving damage, and a greater number of specimens obtained from a single gyratory compacted specimen. In addition, the following two proposed moisture conditioning protocols showed effectiveness in causing moisture damage: (1) 30-minute vacuum suction at 15 mmHg followed by a 300-cycle increment of repeated load and (2) 3,500-cycle Moisture Induced Stress Tester (MIST) at 104°F (40°C) and 40 psi. Finally, complete drying of the moisture conditioned specimens before the mechanical test was recommended to reflect the true weakening of mixtures due to moisture conditioning, as water present in the pores of the mixture with incomplete drying artificially increased the specimen resistance to applied load.

Schram and Williams (2012) also indicated that agencies specifying the IDT strength test per AASHTO T 283 for field acceptance had logistical and practical challenges, including unavailability of a compression machine, tedious conditioning processing, and poor correlations with field pavement performance. Therefore, an alternative moisture susceptibility test was needed that had good repeatability and allowed for prompt reporting of results. In their study, laboratory tests including dynamic modulus (E*), flow number (FN), IDT strength, HWTT, and MIST were performed on PMLC specimens collected from 13 WMA pavements. The moisture susceptibility parameters obtained from the laboratory tests for all mixtures were ranked and compared against the ranking based on the field pavement performance. The difference in ranks for laboratory test parameters and field pavement performance was used to quantify the effectiveness of each moisture susceptibility parameter. Test results indicated that the percent swell after MIST and the submerged FN were the most effective moisture susceptibility parameters, followed by HWTT parameters including ratio of stripping slope over creep slope, stripping inflection point, stripping slope, and creep slope, and TSR after MIST. Considering the turnaround time and simplicity, the MIST and HWTT tests were recommended for further evaluation as alternatives to the IDT strength test per AASHTO T 283.

Another study by Bennert (2010) evaluated the moisture damage potential of WMA mixtures. Higher potential was identified in WMA as compared to HMA due to its method of production including inadequate drying at reduced production temperature and introduction of water in the foaming process. For the first WMA project implemented by New Jersey DOT, a TSR of 88% was obtained for Sasobit-modified WMA mix design specimens, while a significantly lower value of 56% was shown by the field cores obtained after construction. The difference in TSR values between laboratory specimens and field cores was attributed to differences in the moisture content of the aggregates. To address this issue, a modified laboratory mixing procedure was proposed to better simulate plant production that involved utilizing predetermined moisture content and drying aggregates with a propane "rosebud" torch. Additionally, various moisture conditioning and testing methods were investigated in the study for moisture damage evaluation. Laboratory test results indicated that the 4,000-cycle MIST at 104°F (40°C) and 40 psi produced equivalent moisture damage to the modified Lottman protocol per AASHTO T 283.

A more recent study by El-Hakim and Tighe (2014) evaluated the impact of freeze-thaw cycles on mechanical properties of asphalt mixtures. Four different asphalt mixtures were obtained from Highway 401 in southwestern Ontario, Canada, in the first year of service. E* testing was performed on those mixtures and corresponding E* master curves were constructed. Afterwards, the specimens were stored at the Center for Pavement and Transportation Technology test track and subjected to one complete winter of freeze-thaw cycles prior to retesting. Test results showed a significant reduction in E* values of all mixtures after one winter exposure in the Canadian climate, especially for E* values at 14°F (−10°C) and 39°F (4°C). Based on the results obtained, the authors recommended that the effect of freeze-thaw cycles on mixture property deterioration should be considered for developing perpetual pavements with adequate performance.

Kentucky Transportation Center surveyed 12 southeastern states regarding the use of WMA technologies and performance evaluation of WMA as compared to HMA in that region of the United States. According to the survey results (Graves, 2014), WMA technology had been used in all of the southeastern states and certain changes in standard specifications and special provisions were made to permit the use of WMA technologies. Laboratory experience with IDT strength test per AASHTO T 283 and HWTT per AASHTO T 324 indicated that WMA mixtures, in most cases, exhibited slightly higher moisture susceptibility than HMA mixtures; however, no moisture-related pavement distress had been observed to date on any of the WMA pavements placed in those states.

NCHRP Project 9-47A "Properties and Performance of WMA Technologies" evaluated the field performance of WMA technologies (West et al., 2014). Field cores after construction and plant loose mix were sampled from 6 existing and 8 new pavements. Each of the pavements included a HMA control section and at least one WMA section. For moisture susceptibility evaluation, the IDT strength test per AASHTO T 283 was performed on field cores and PMLC specimens. For most cases, the IDT strengths of WMA and HMA field cores obtained after construction were not significantly different, and remained statistically equivalent through the first 2 years of service. However, a different trend was observed for IDT strength results on PMLC specimens, where the IDT strengths were statistically lower for WMA as compared to HMA for more than half of the comparisons. For the TSR results, 27 out of 33 mixtures passed the standard minimum criteria of 80%, and only two mixtures would have failed a TSR limit of 75%. Since all pavements have performed well with no evidence of moisture damage observed to date, West et al., recommended that the TSR specification be reduced from 80% to 75%.

CHAPTER 3

Web-Survey Results

A follow-up web-survey of state DOTs and contractors to the one conducted in NCHRP Project 9-49 was performed in this project to identify WMA pavements with mix design and/or quality assurance (QA) data included in the flow chart for minimizing moisture susceptibility. The list of agency representatives and contact information was compiled from the information used in NCHRP Project 9-49 with updates from the current AASHTO Subcommittee on Materials roster and input from the NCHRP Panel.

The survey covered topics including: (1) availability of moisture susceptibility laboratory data (mix design and QA) for specific WMA pavements, (2) moisture susceptibility criteria in mix design and QA, (3) field performance for available WMA pavements, (4) WMA technology and materials (including any anti-stripping additives) used in available pavements, and (5) willingness to participate further in this project. The detailed survey questions are documented in Appendix A. The web-survey was launched in October 2014 with an invitation e-mail containing a brief description of the objectives of the project and the purpose of the survey. The invitation was sent to DOT representatives from 50 states. In total, 41 responses were received (i.e., an 82 percent response rate), and the results are summarized by question in Figures 2 through 9.

According to the survey results, WMA was used routinely in the majority of the states that provided a response (i.e., 88%), and the most common WMA technologies were Evotherm and foaming. With regard to the use of anti-stripping agents, 40% of the states that provided a response indicated that they did not require their use, while 60% indicated they did require the use of anti-stripping agents for various reasons such as aggregate type, on foamed mixtures, on all mixtures, or based on laboratory test results.

The majority of the DOTs (i.e., 90%) reported having a standard or specification including moisture susceptibility testing as part of the mix design and construction QA procedures, 12% indicated that the standard or specification was different for mix design and construction QA, and only 10% stated they did not have a standard or specification for moisture susceptibility testing. The predominant standard used for moisture susceptibility testing was AASHTO T 283 or a modified version of it with 50% of the respondents indicating these two choices; only 8% indicated the use of AASHTO T 324 HWTT as the standard or specification for moisture susceptibility. Accordingly, the moisture susceptibility test that was prescribed with more frequency was TSR with 58% of the responses. HWTT was the second most used with 21% of the responses, and the rest were other tests such as the immersion-compression test or the boil test.

With regard to WMA pavement performance, more than 90% of the states that provided a response indicated that no moisture-related distress had been observed to date on any of their WMA pavements with a range of pavement age from 3 to 8 years (5- and 6-year old pavements were predominant). Of the states that noted moisture susceptibility issues, the possible cause of failure (especially for early failures) was indicated to be the type of aggregate (i.e., gravel, sandstone, and granite), although the states clarified that these types of failures were not limited to WMA pavements but also occurred in HMA.

The majority of the survey respondents indicated having moisture susceptibility data available either from mix design, construction, or production data. A few offered technical reports and papers on trial/research WMA sections. In addition, about 55% of the states that provided a response indicated having upcoming projects and their willingness to share information about mix design, construction, materials and/or field performance monitoring.

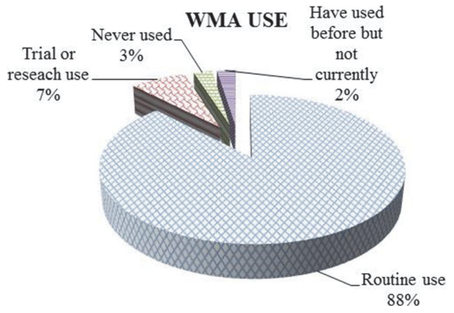


Figure 2. Question 2: To what extent does your organization utilize WMA?

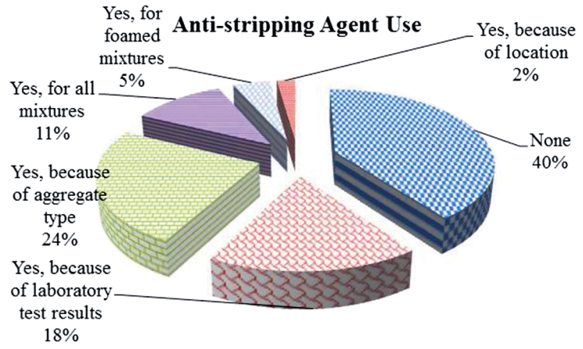


Figure 4. Question 4: Does your organization require the use of anti-stripping agents with WMA?

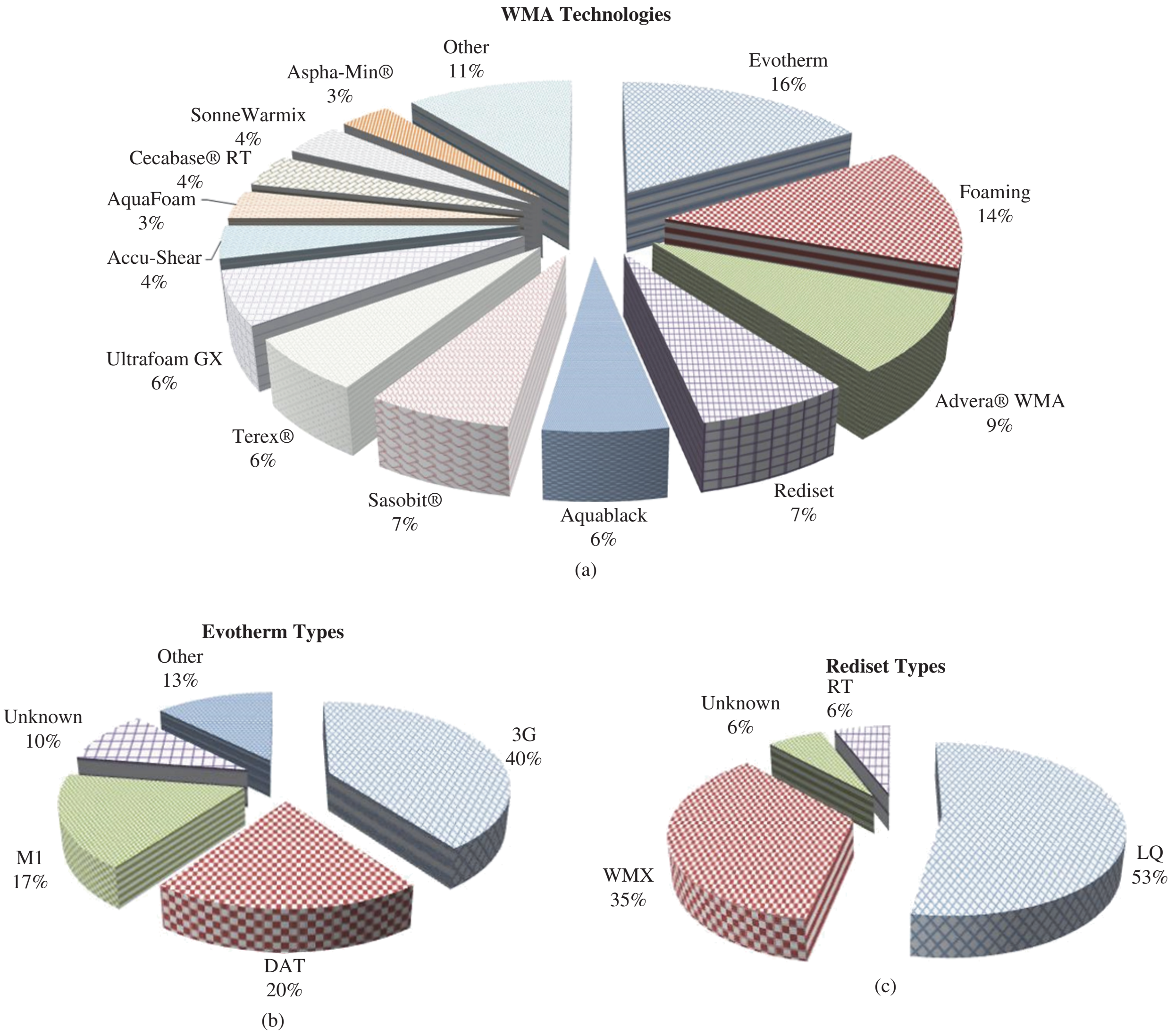
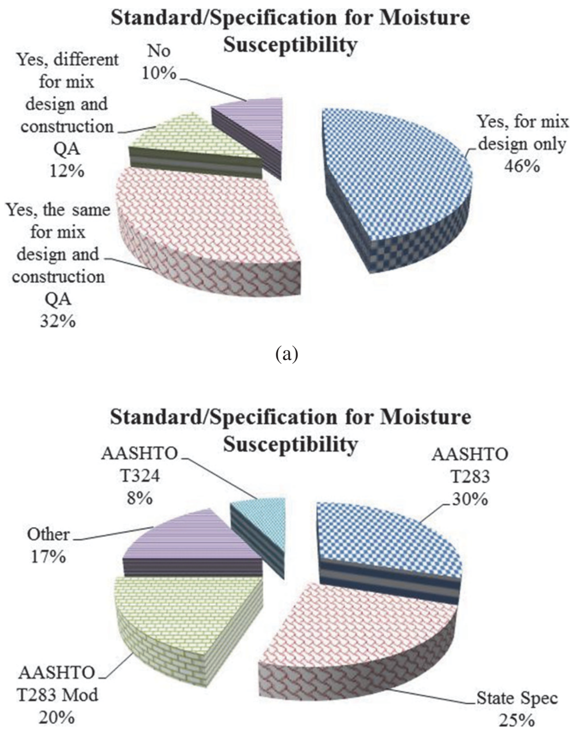


Figure 3. Question 3: What types of WMA technologies does your organization use?



(a)

(b)

Figure 5. Question 5: Does your organization have a standard or specification that includes moisture susceptibility laboratory testing as part of the mix design procedure or construction QA?

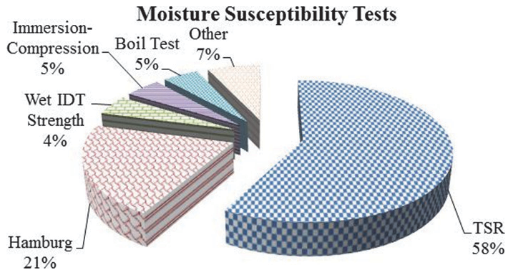


Figure 6. Question 6: What moisture susceptibility test(s) is (are) included in the standard/specification?

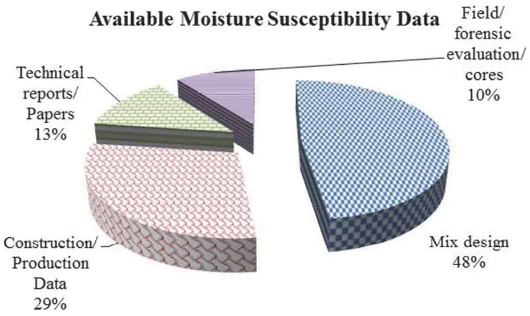


Figure 8. Question 8: Does your organization have laboratory test results (IDT, TSR, M_R, or HWTT) or other information relevant to the moisture susceptibility guidelines proposed in NCHRP Project 9-49 that can be made available to the researchers conducting this study?

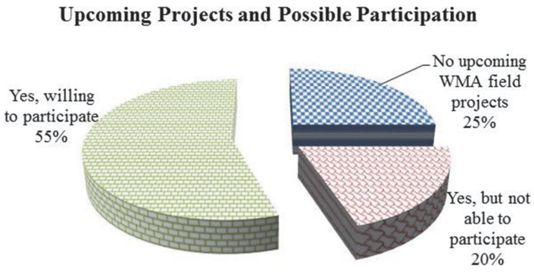
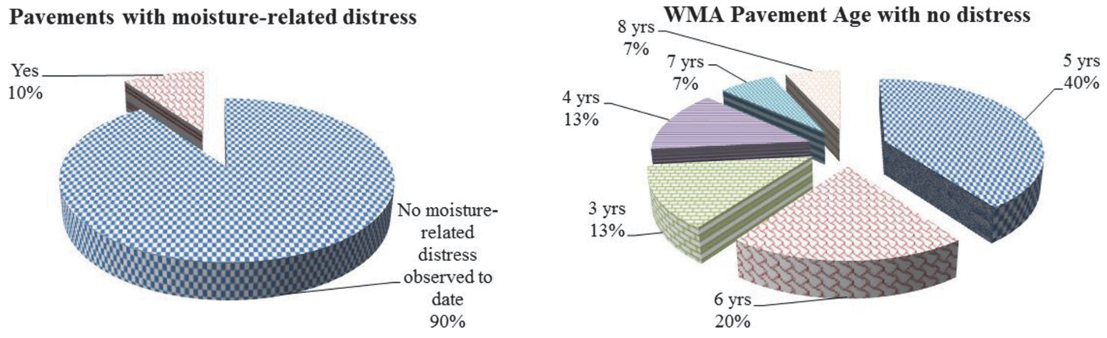


Figure 9. Question 9: Does your organization have upcoming WMA projects and is willing to participate in NCHRP Project 9-49B by sharing information about mix design, construction, materials, and/or field performance monitoring?



(a) (b)

Figure 7. Question 7: Have any the WMA pavements in your state experienced premature or extensive moisture-related distress?

CHAPTER 4

Guideline Threshold Validation

As summarized in Table 1, 64 WMA mixtures from 44 field projects with moisture susceptibility data available from mix design, construction, production, and field/forensic evaluation as well as technical reports and papers were identified from 11 web-survey respondents in addition to NCHRP Projects 9-47A and 9-49A.

Figure 10 and Figure 11 present the validation of moisture susceptibility thresholds for HWTT SIP and IDT strength test parameters, respectively. The validation for HWTT stripping slope and M_R test parameters (i.e., M_R ratio and wet M_R stiffness) was not performed since no WMA mixtures had those test results available. In Figure 10 and Figure 11, green markers indicate good field pavement performance, and red markers indicate poor field pavement performance with moisture-related distresses (i.e., raveling, stripping, etc.) observed. Based on the comparisons of moisture susceptibility parameters against the corresponding flow chart thresholds for these laboratory tests in Figure 1, the WMA mixtures that fall in the green shaded zone are expected to have good performance, while those that fall in the red shaded zone are potentially susceptible to moisture damage.

Figure 10 presents the HWTT SIP results of 20 out of 36 WMA mixtures identified from one state DOT and NCHRP Project 9-47A. No stripping in the HWTT test was observed for the other 16 mixtures, and thus, they are not included in Figure 10. As illustrated, only 4 WMA mixtures fell in the light gray zone, indicating SIP values lower than the minimum threshold of 3,500 load cycles. The two WMA mixtures with extremely low SIP values corresponded to a field project in Michigan, which used a soft PG 52-34 virgin binder. According to the web-survey responses, no moisture-related distress was observed on the WMA mixtures with HWTT SIP results available. Therefore, an approximately 89% (i.e., 32 out of 36) performance correlation was achieved for 36 WMA mixtures when comparing their HWTT SIP results against the proposed threshold.

Figure 11 presents the TSR and wet IDT strength results of 53 WMA mixtures identified from four state DOTs, one contractor, and NCHRP Projects 9-47A and 9-49A. Two different thresholds of 65 psi and 100 psi for the wet IDT strength were proposed for on-site and off-site PMLC specimens, respectively, to account for the stiffening effect of the reheating process (Epps Martin et al., 2014). As illustrated in Figure 11 (a) for on-site PMLC specimens, only 5 WMA mixtures fell in the light gray zone, indicating wet IDT strength values lower than 65 psi or TSR values lower than 70%. Two out of those five mixtures corresponded to the field project in Michigan that employed a PG 52-34 virgin binder mentioned previously. According to the field evaluation results, no moisture-related distress has been observed to date on any of the WMA mixtures with TSR and wet IDT strength results available. Therefore, 25 out of 30 (or approximately 83%) WMA mixtures showed adequate correlation between laboratory test results for on-site PMLC specimens and field pavement performance.

The TSR and wet IDT strength results for off-site PMLC specimens represented in Figure 11 (b) show that only 5 WMA mixtures had wet IDT strength values lower than 100 psi, and therefore fell in the light gray zone. Among those five mixtures, two exhibited raveling in the wheel paths, which corresponded with the proposed thresholds for the IDT strength test parameters. In addition, all of the WMA mixtures that fell in the dark gray zone had good field pavement performance. In general, 20 out of 23 (or approximately 87%) WMA mixtures showed good correlation with respect to the proposed thresholds of 70% TSR and 100 psi wet IDT strength for the off-site PMLC specimens.

To further validate the proposed thresholds for IDT strength test parameters, various TSR and wet IDT strength values were evaluated using the receiver operating characteristic (ROC) analysis by comparing against the moisture susceptibility data from 64 WMA mixtures. The ROC analysis was performed in accordance with the following rules and the TSR and wet IDT strength results were summarized in Table 2 and Table 3, respectively.

Table 1. Data collected to verify guideline thresholds.

Survey Respondents	Number of WMA Mixtures	Moisture Susceptibility Parameters
National Center for Asphalt Technology (NCHRP 9-47A) (West et al., 2014)	22 (on-site PMLC)	HWTT stripping inflection point (SIP)
	19 (on-site PMLC)	TSR & Wet IDT Strength
	1 (off-site PMLC)	TSR & Wet IDT Strength
Washington State University (NCHRP 9-49A) (Wen et al., 2013)	5 (on-site PMLC)	HWTT SIP
	4 (on-site PMLC)	TSR & Wet IDT Strength
COLAS Solutions™	2 (on-site PMLC)	HWTT SIP
	2 (on-site PMLC)	TSR & Wet IDT Strength
Alaska Department of Transportation (Saboundjian et al., 2011)	1 (off-site PMLC)	TSR & Wet IDT Strength
Colorado Department of Transportation	2 (on-site PMLC)	TSR & Wet IDT Strength
Georgia Department of Transportation	3 (on-site PMLC)	TSR & Wet IDT Strength
	2 (off-site PMLC)	TSR & Wet IDT Strength
Iowa Department of Transportation	2 (off-site PMLC)	TSR & Wet IDT Strength
Missouri Department of Transportation	17 (off-site PMLC)	TSR & Wet IDT Strength
Washington Department of Transportation	7 (off-site PMLC)	HWTT SIP

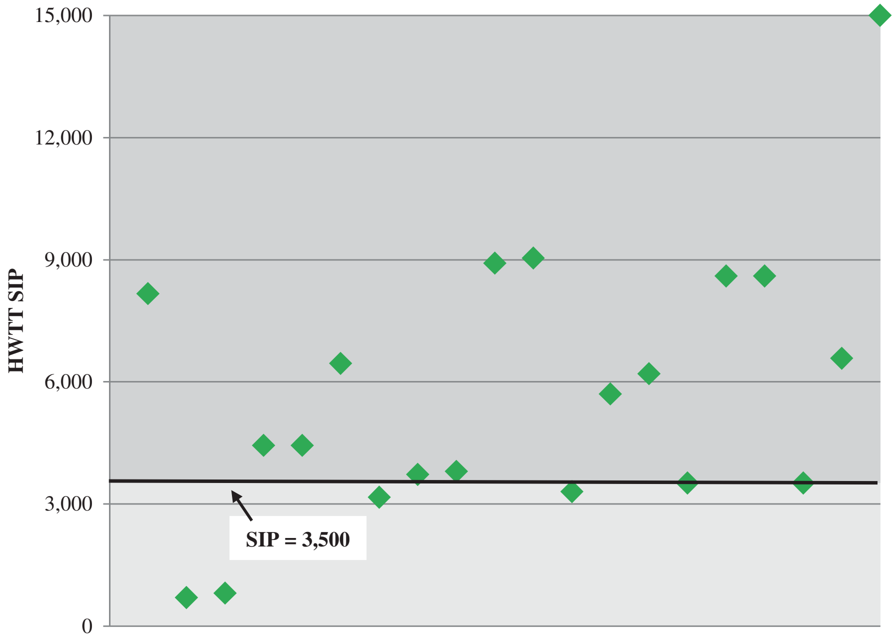
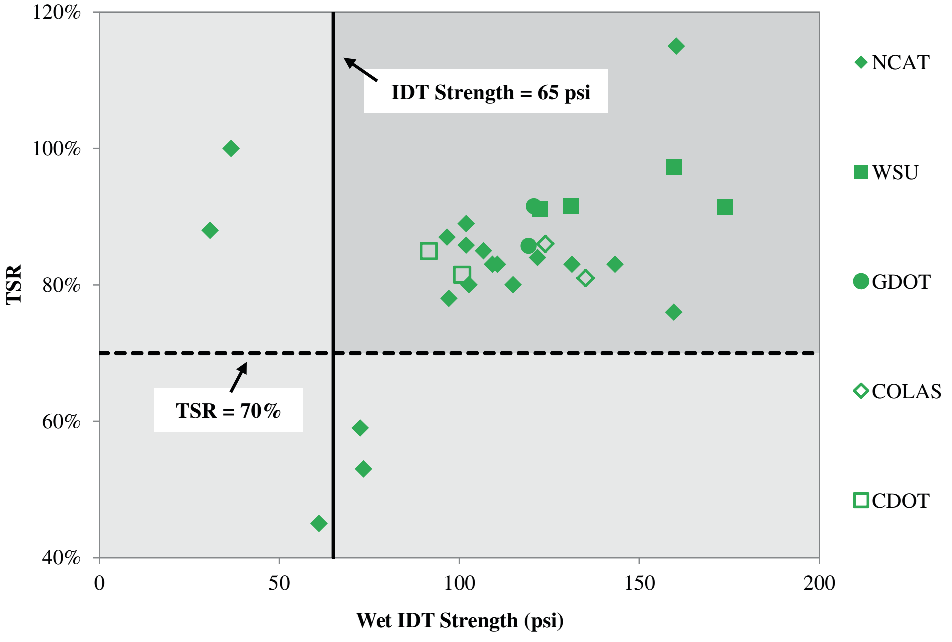
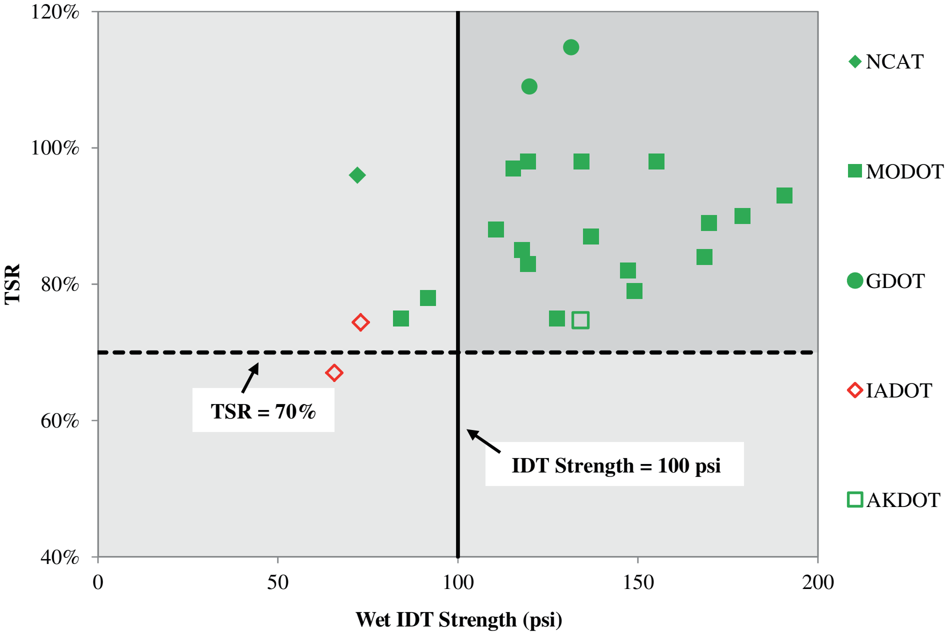


Figure 10. HWTT SIP threshold validation.



(a)



(b)

Figure 11. TSR and wet IDT strength thresholds validation; (a) on-site PMLC specimens, (b) off-site PMLC specimens.

Table 2. ROC analysis results for TSR thresholds.

TSR Threshold	65%	70%	75%	80%
True Positive	2	2	2	2
False Negative	0	0	0	0
False Positive	8	8	10	15
True Negative	43	43	41	36
TPR	1.00	1.00	1.00	1.00
FPR	0.16	0.16	0.20	0.29
Accuracy	0.85	0.85	0.81	0.72

Table 3. ROC analysis results for wet IDT strength thresholds.

Wet IDT Strength Threshold	70 psi	80 psi	90 psi	100 psi
True Positive	1	2	2	2
False Negative	1	0	0	0
False Positive	0	1	2	3
True Negative	21	20	19	18
TPR	0.50	1.00	1.00	1.00
FPR	0.00	0.05	0.10	0.14
Accuracy	0.96	0.96	0.91	0.87

True Positive: lab results < thresholds & moisture damage identified in the field;

False Negative: lab results > thresholds & moisture damage identified in the field;

False Positive: lab results < thresholds & no moisture damage identified in the field;

True Negative: lab results > thresholds & no moisture damage identified in the field;

True Positive Rate (TPR) = True Positive / (True Positive + False Negative);

False Positive Rate (FPR) = False Positive / (False Positive + True Negative); and

Accuracy = (True Positive + True Negative) / Total Population.

As illustrated in Table 2, TSR thresholds of 65%, 70%, and 75% showed higher accuracy values than that of 80%. Referring to the ROC space shown in Figure 12(a), the TSR thresholds of 80%, 70%, and 75% were closer to the "perfect classification" corner than that of 65%, indicating a better predictive power. Therefore, 70% was one of the most effective TRB thresholds in discriminating moisture-resistant versus moisture-susceptible WMA mixtures. The ROC analysis results shown in Table 3 indicate that desirable accuracy values (approximately 0.9) were achieved by all four wet IDT strength thresholds. Referring to the ROC space shown in Figure 12(b), the thresholds of 80, 90, and 100 psi were closer to the "perfect classification" corner than that of 70 psi, indicating a better predictive power. Though slight improvement could be obtained by reducing the wet IDT strength threshold from 100 psi to 80 psi, the previously proposed threshold for wet IDT strength of 100 psi for off-site PMLC specimens was adequate in delineating moisture-susceptible versus moisture-resistant WMA mixtures.

Based on the results presented in Figures 10 through 12, the correlations between the proposed moisture susceptibility thresholds in the flow chart and field pavement performance are promising (i.e., 89% for HWTT SIP, and 83% and 87% for TSR and wet IDT strength for on-site and off-site PMLC specimens, respectively). Therefore, the proposed flow chart shown in Figure 1 could be considered for implementation by state DOTs and contractors in order to identify and minimize moisture susceptibility in WMA mixtures.

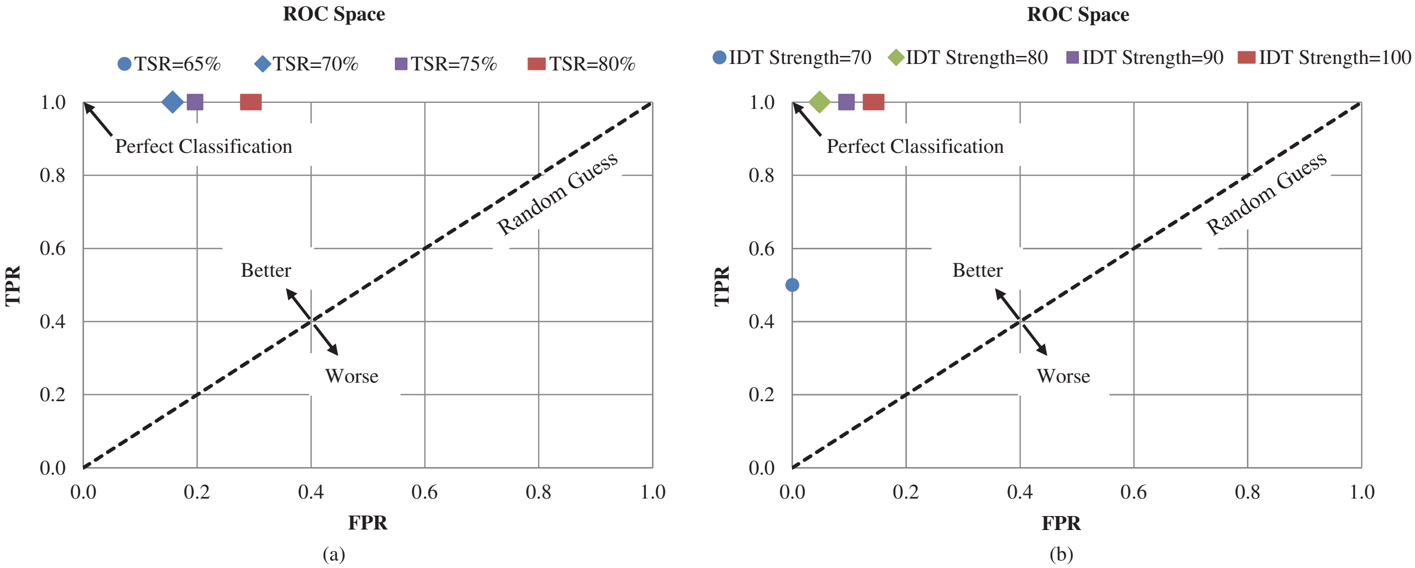


Figure 12. ROC space; (a) TSR thresholds, (b) Wet IDT strength thresholds.

CHAPTER 5

Laboratory Experiment and Results

The modified Lottman protocol per AASHTO T 283 was used in NCHRP Project 9-49 to evaluate moisture susceptibility of WMA. In order to assess alternative moisture conditioning protocols and to investigate various specimen-drying methods prior to laboratory testing, the laboratory experiment presented in Figure 13 was completed.

The selected mixture corresponded to a field project on State Route 196 in Wyoming. Four fractions of limestone aggregates and river sand were used to prepare the mixture. The inclusion of one percent lime as an anti-stripping agent was specified by the mix design, but it was not included in the laboratory experiment in order to promote moisture damage in the laboratory tests. The mix was coarse graded with a 12.5 mm nominal maximum aggregate size. A PG 64-22 binder was used in the mixture with an optimum binder content per mix design of 5.0 percent by weight of the mixture.

Additional moisture conditioning protocols evaluated in the experiment included MIST and hot water bath (HWB). Detailed moisture conditioning parameters for each protocol are summarized in Table 4; 1,000 and 2,000 MIST cycles at the equipment manufacturer's default settings (i.e., 140°F [60°C] and 40 psi) were selected based on previous experience and relevant literature, and they resulted in less time-consuming protocols than the modified Lottman protocol (half a day versus three days). The HWB at 140°F (60°C) was included as a simplified modified Lottman protocol without vacuum saturation and freezing, but it required the same time span of three days.

A set of laboratory fabricated specimens were subjected to the various moisture conditioning protocols prior to being characterized in the M_R, IDT strength, and Asphalt Pavement Analyzer (APA) tests. The APA test was selected in the experiment over the HWTT test due to the fact that HWTT specimens are tested in a wet condition (i.e., under water) and thus, no moisture conditioning is needed prior to testing. Test parameters including M_R stiffness, IDT strength, and APA rutting resistance parameter (RRP) were determined after each moisture conditioning protocol, and the corresponding ratios (M_R ratio, TSR, and APA RRP ratio) were used to quantify the reduction in mixture stiffness, strength, and rutting resistance after moisture damage, respectively. In addition, four different specimen-drying methods for moisture conditioned specimens were evaluated in the M_R and IDT strength tests after the modified Lottman protocol, including saturated-surface dry (SSD) per AASHTO T 166, 48-hour air dry at 77°F (25°C), CoreDry per AASHTO PP 75, and 24-hour oven dry at 104°F (40°C). Test results obtained in the experiment were used to determine if an equivalent level of moisture damage to the modified Lottman protocol was achieved by the MIST or HWB protocols, and to evaluate the effects of various specimen-drying methods on moisture susceptibility parameters.

Moisture Conditioning Protocols

Figures 14 through 16 present the M_R, IDT strength, and APA results for mixtures after various moisture conditioning protocols, including the modified Lottman protocol per AASHTO T 283 consisting of vacuum saturation plus one freeze-thaw cycle, 1,000- and 2,000-cycle MIST at 140°F (60°C) and 40 psi, and three-day HWB at 140°F (60°C). All moisture conditioned specimens were tested at SSD conditions. In each figure, the bars represent the average value of M_R stiffness at 77°F (25°C), wet IDT strength at 77°F (25°C), and APA RRP at 122°F (50°C); and the error bars represent one standard deviation from the average value of three replicates in the case of the M_R and IDT strength tests or two replicates in the case of the APA test. In addition, the mixture property ratios (M_R ratio, TSR, and APA RRP ratio) are shown in the text boxes above the bars.

As illustrated in Figure 14, the dry control specimens had significantly higher M_R stiffness than all the moisture conditioned specimens, indicating a significant reduction in mixture stiffness after moisture conditioning. In addition, equivalent mixture stiffness was achieved by the moisture conditioned specimens

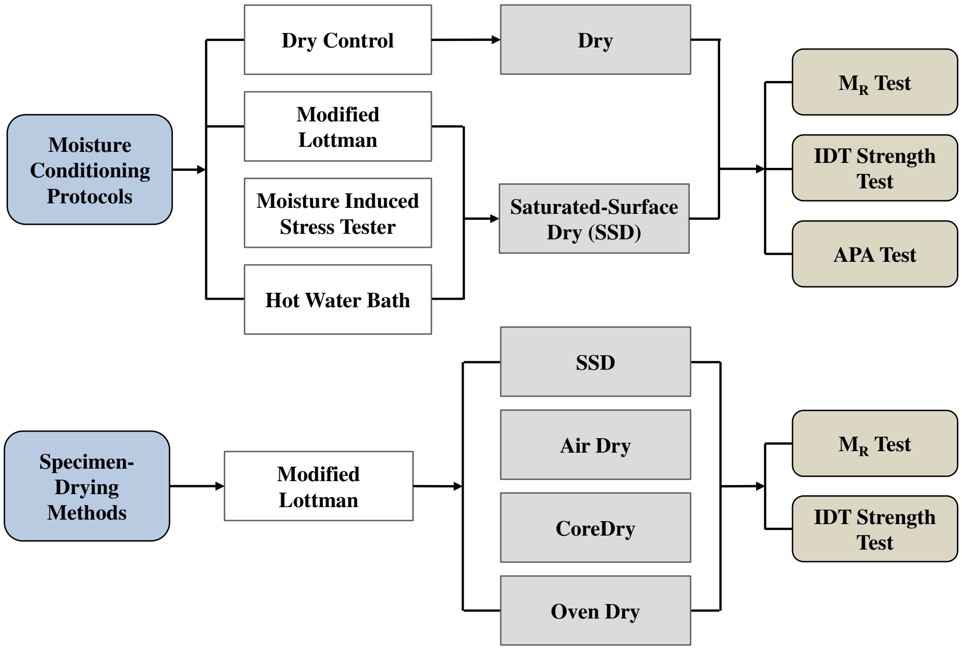


Figure 13. Laboratory experiment.

Table 4. Moisture conditioning protocols and parameters.

Moisture Conditioning Protocols	Parameters	Total Testing Time
Modified Lottman	Vacuum Saturation (70 to 80% degree of saturation) + One Freeze (-18°C) / Thaw (60°C) Cycle	3 Days
Moisture Induced Stress Tester (MIST)	Temperature: 60°C Pressure: 40 psi Number of Cycles: 1,000 and 2,000	0.5 Day
Hot Water Bath (HWB)	Temperature: 60°C	3 Days

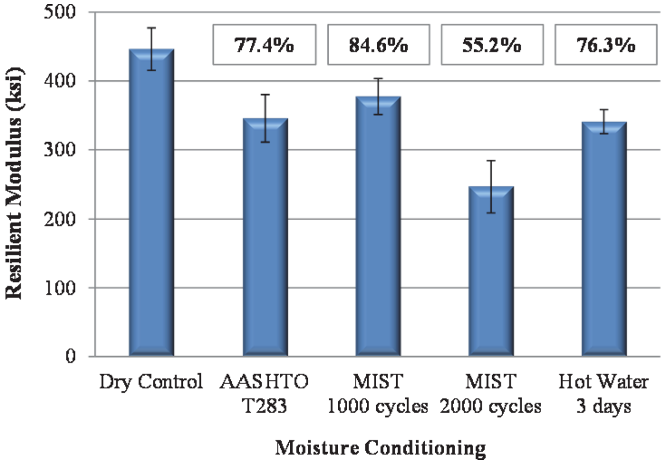


Figure 14. M_R stiffness results for various moisture conditioning protocols.

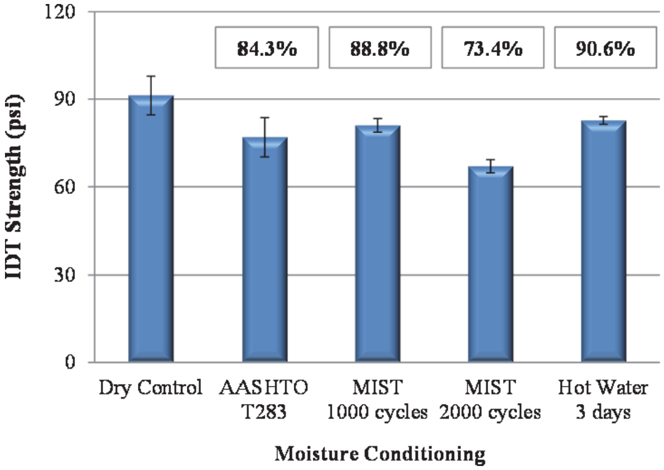


Figure 15. IDT strength results for various moisture conditioning protocols.

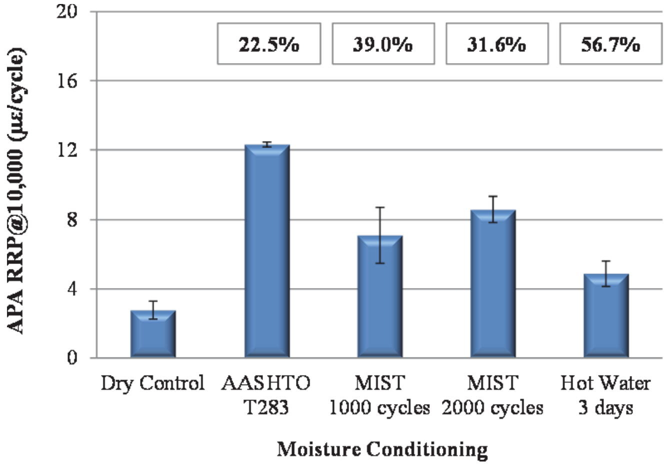


Figure 16. APA RRP results for various moisture conditioning protocols.

using the modified Lottman protocol, the 1,000-cycle MIST, and the three-day HWB, while a significantly lower mixture stiffness value was observed for the 2,000-cycle MIST. A statistical analysis including analysis of variance (ANOVA) and Student's *t*-test (for each pair) was performed with a 5% significant level (i.e., $\alpha = 0.05$) to further discriminate the M_R stiffness results considering their variability, and the detailed results are presented in Appendix B. The statistical analysis results in terms of connecting letters report shown in Table 5 further confirmed that the 2,000-cycle MIST had a significantly lower M_R stiffness, while no significant difference was shown for the other three moisture conditioning protocols. The same conclusion was also obtained by comparing the M_R ratio results for various moisture conditioning protocols versus the d2s acceptable range of 10.0% (Epps Martin et al., 2014).

A similar trend is shown in Figure 15, where a higher IDT strength value was observed for the dry control specimen as compared to the moisture conditioned specimens. For the comparisons among various moisture conditioning protocols, the specimens conditioned using the 1,000-cycle MIST and three-day HWB protocols exhibited the highest IDT strength, followed by the modified Lottman protocol and then the 2,000-cycle MIST protocol. According to the statistical analysis results presented in Table 5, moisture conditioned specimens using the modified Lottman, 1,000-cycle MIST, and three-day HWB protocols had statistically equivalent wet IDT strength, which was higher than that of the specimens conditioned with the 2,000-cycle MIST protocol. The same conclusion was also obtained by comparing the TSR results for various moisture conditioning protocols versus the d2s acceptable range of 9.3% (Azari, 2010).

The effect on mixture rutting resistance in terms of APA RRP results from various moisture conditioning protocols is illustrated in Figure 16. The RRP value represents the visco-plastic strain increment of the mixture at a critical number of load cycles (i.e., 10,000); and therefore, mixtures with lower RRP values are expected to have better rutting resistance than those with higher RRP values (Yin et al., 2014). The dry control specimens had a lower RRP value as compared to the moisture conditioned specimens, indicating better rutting resistance in the APA test. Among the various moisture conditioning protocols, the modified Lottman protocol had the highest RRP value, followed by the 2,000-cycle and 1,000-cycle MIST protocols and then the three-day HWB protocol. To better discriminate various moisture conditioning protocols, the same statistical analysis introduced previously was performed to consider the variability of the APA RRP results. According to the statistical analysis results shown in Table 5, the effect of all moisture conditioning protocols on rutting resistance was significant and different from each other. The 2,000-cycle MIST protocol yielded the smallest difference as compared to the modified Lottman protocol, even though a statistically significant difference was observed.

Table 5 summarizes the statistical analysis results in terms of connecting letters report for various moisture conditioning protocols investigated in the study; the more detailed results are presented in Appendix B. According to the M_R stiffness and IDT strength results, the 2,000-cycle MIST protocol produced the most severe moisture damage, while no significant difference was shown for the other three protocols. However, a different trend was observed for the APA RRP results; the most severe moisture damage was created by the modified Lottman

Table 5. Statistical analysis results for various moisture conditioning protocols.

Moisture Conditioning Protocols	M_R Stiffness	IDT Strength	APA RRP
Dry Control	A	A	A
Modified Lottman	B	B	D
1,000-cycle MIST	B	B	B-C
2,000-cycle MIST	C	C	B
Three-day HWB	B	B	C-D

protocol, followed by the 2,000-cycle and 1,000-cycle MIST protocols, and then the three-day HWB protocol. Based on these results, the 1,000-cycle MIST protocol at 140°F (60°C) and 40 psi and three-day HWB protocol at 140°F (60°C) are proposed as two alternatives to the modified Lottman protocol per AASHTO T 283 that could be used as part of the moisture susceptibility guidelines in Figure 1.

Specimen-Drying Methods

Figures 17 and 18 present the M_R and IDT strength test results for moisture conditioned specimens with various specimen-drying methods, including SSD, 48-hour air dry at 77°F (25°C), CoreDry, and 24-hour oven dry at 104°F (40°C). In each figure, the bars represent the average value of M_R stiffness at 77°F (25°C) and wet IDT strength at 77°F (25°C) after the modified Lottman protocol per AASHTO T 283, and the error bars represent one standard deviation from the average value of three replicates in the case of the M_R and IDT strength tests or two replicates in the case of the APA test. In addition, the M_R ratio and TSR results for various specimen-drying methods are shown in the text boxes above the bars. The same statistical analysis introduced previously was performed for M_R stiffness and IDT strength results for various specimen-drying methods. Table 6 summarizes the analysis results in terms of connecting letter reports, and the more detailed results are presented in Appendix B.

As illustrated in Figure 17, an equivalent M_R stiffness value was observed for SSD specimens and CoreDry specimens, which was slightly higher than those of air dry specimens and 24-hour oven dry specimens. As previously mentioned, the testing of M_R specimens in the SSD condition could preclude an accurate measure of mixture property due to the fact that the water occupying the permeable pores of the specimens artificially increases mixture load-carrying capacity due to pore pressure and incompressibility of water (Azari and Mohseni, 2013; Laukkanen et al., 2012). This might be the primary reason for higher M_R stiffness values observed for SSD specimens versus the air dry and oven dry specimens shown in Figure 17. According to the statistical analysis results shown in Table 6, no significant difference was observed among the four different specimen-drying methods. However, a slightly different trend was obtained by comparing the M_R ratio results versus the d2s acceptable range of 10.0% (Epps Martin et al., 2014), where the air dry specimens had a slightly lower M_R stiffness than the SSD and CoreDry specimens (with a 11.4% difference in M_R ratio results).

The mixture strength results shown in Figure 18 illustrated that the SSD and air dry specimens had equivalent wet IDT

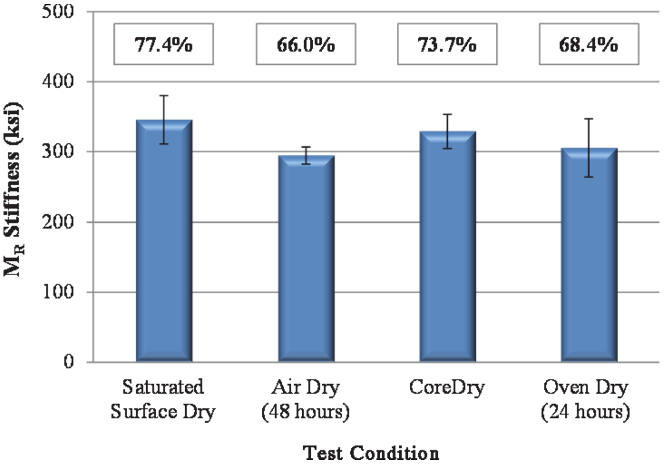


Figure 17. M_R stiffness results for various specimen-drying methods.

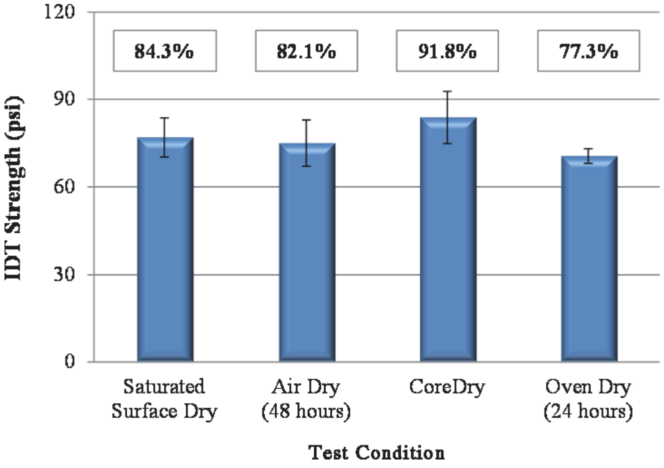


Figure 18. IDT strength results for various specimen-drying methods.

Table 6. Statistical analysis results for various specimen-drying methods.

Specimen-Drying Methods	M_R Stiffness	IDT Strength
SSD	A	A-B
Air Dry	A	A-B
CoreDry	A	A
Oven Dry	A	B

strength, while slightly higher and lower strength values were observed for the CoreDry and 24-hour oven dry specimens, respectively. The difference between the SSD and air dry specimens in wet IDT strength was significantly reduced as compared to the difference in M_R stiffness (Figure 17). This was possibly due to the fact that the IDT strength test is destructive and the specimens are loaded monotonically (instead of repeatedly), and thus, the water present in the specimens does not offer the load-carrying capacity benefit as it apparently did in the M_R test. According to the statistical analysis results shown in Table 6, no significant difference was observed for the four specimen-drying methods, with only one exception for CoreDry versus oven dry methods. A similar conclusion was obtained by comparing the TSR results versus the d2s acceptable range of 9.3% (Azari, 2010), where the CoreDry specimens had higher IDT strength than the air dry and oven dry specimens (with 9.7% and 14.5% differences in TSR results, respectively).

According to the results shown in Figures 17 and 18, the SSD and CoreDry specimens had higher M_R stiffness and IDT strength values than the air dry and oven dry specimens, although the difference was insignificant according to the statistical analysis results shown in Table 6. Considering that the water occupying the permeable pores of the specimens was likely to preclude an accurate measurement of M_R stiffness and IDT strength, the SSD method was excluded from use in the revised flow chart. Instead, the other three specimen-drying methods of CoreDry, 48-hour air dry at 77°F (25°C), and 24-hour oven dry at 140°F (60°C) were recommended, with the CoreDry method preferred due to the shorter time requirement.

CHAPTER 6

Conclusions and Recommendations

Economic, environmental, and engineering benefits motivate the reduction of production and placement temperatures for asphalt mixtures. The latest technology that has been rapidly adopted for this purpose is WMA. WMA technologies offer many benefits such as improved workability and compactability, reduced aging, and better resistance to cracking and raveling. However, barriers to the widespread implementation of WMA include the potentially increased moisture susceptibility and reduced rutting resistance due to the incomplete drying of the aggregates, reduced binder absorption by the aggregates at lower production temperatures, or the incorporation of additional moisture in the foaming process. NCHRP Project 9-49B "Performance of WMA Technologies: Stage I—Moisture Susceptibility Validation" focused on validating the thresholds in the flow chart for identifying and minimizing moisture susceptibility of WMA, which were initially proposed in NCHRP Project 9-49 "Performance of WMA Technologies: Stage I–Moisture Susceptibility" as a set of guidelines for mix design and QA of WMA mixtures.

A web-survey of state DOTs and contractors was performed to identify WMA mixtures with available field performance plus mix design and/or QA data including wet IDT strength and TSR by AASHTO T 283, wet resilient modulus (M_R) and M_R-ratio by modified ASTM D 7369, and HWTT per AASHTO T 324. Additionally, reports from related NCHRP Projects 9-47A "Properties and Performance of WMA Technologies" and 9-49A "Performance of WMA Technologies: Stage II–Long-Term Field Performance" were reviewed to identify additional WMA mixtures for which this same type of information was available. In total, 64 WMA mixtures from 44 field projects with moisture susceptibility data available from mix design, construction, production, and field/forensic evaluation as well as technical reports and papers were identified. The results were compiled and used to validate the proposed moisture susceptibility thresholds in the flow chart, which were initially developed using a limited number of mixtures.

Table 7 presents the correlations between WMA moisture susceptibility parameters and their corresponding field pavement performance. As illustrated, acceptable correlations of 89%, 83%, and 87% were achieved for HWTT stripping inflection point (SIP), and TSR and wet IDT strength for on-site and off-site PMLC specimens, respectively. Therefore, the proposed thresholds in the flow chart could be considered for implementation by state DOTs and contractors to identify and minimize moisture susceptibility in WMA mixtures.

A laboratory experiment was performed to assess additional moisture conditioning protocols as alternatives to the modified Lottman protocol per AASHTO T 283 included in the flow chart, and to explore various specimen-drying methods and their effects on moisture susceptibility parameters. The selected mixture corresponded to a field project on State Route 196 in Wyoming. Three moisture conditioning protocols were evaluated besides the modified Lottman protocol consisting of vacuum saturation (70 to 80% degree of saturation) plus one freeze-thaw cycle (16 hours at 0°F [–18°C] and 24 hours at 140°F [60°C]) per AASHTO T 283; these included 1,000-cycle and 2,000-cycle MIST protocols at 140°F (60°C) and 40 psi and three-day HWB at 140°F (60°C). A set of laboratory fabricated specimens were subjected to various moisture conditioning protocols prior to being tested for M_R stiffness, IDT strength, and APA RRP values. In addition, four different specimen-drying methods were evaluated in the M_R and IDT strength tests after the modified Lottman protocol, including SSD per AASHTO T 166, 48-hour air dry at 77°F (25°C), CoreDry per AASHTO PP 75, and 24-hour oven dry at 104°F (40°C). Test results obtained in the experiment were used to determine if an equivalent level of moisture damage to the modified Lottman protocol was achieved by the MIST or HWB protocols, and to evaluate the effects of various specimen-drying methods on moisture susceptibility parameters.

The laboratory test results obtained for various moisture conditioning protocols demonstrated a significant reduction

Table 7. Summary of guideline threshold validation.

Moisture Susceptibility Parameters	Minimum Thresholds	Number of WMA Pavements for Validation	Performance Correlation
HWTT SIP	3,500 (LMLC & on-site PMLC) 6,000 (off-site PMLC)	36	89%
TSR & Wet IDT Strength	70% & 65 psi (LMLC & on-site PMLC)	30	83%
	70% & 100 psi (off-site PMLC)	23	87%

in mixture properties for all moisture conditioned specimens as compared to the dry control specimens. According to the M_R stiffness and IDT strength results, the 2,000-cycle MIST protocol produced the most severe moisture damage, while no significant difference was observed for other protocols. However, the APA RRP results showed a distinct trend; the modified Lottman protocol produced the most severe moisture damage, followed by 2,000-cycle and 1,000-cycle MIST protocols, and then the three-day HWB protocol. Based on these results and the moisture susceptibility parameters included in the flow chart, the 1,000-cycle MIST protocol at 140°F (60°C) and 40 psi and three-day HWB protocol at 140°F (60°C) were recommended for use in the moisture susceptibility guidelines as alternatives to the modified Lottman protocol per AASHTO T 283 prior to M_R and IDT strength tests.

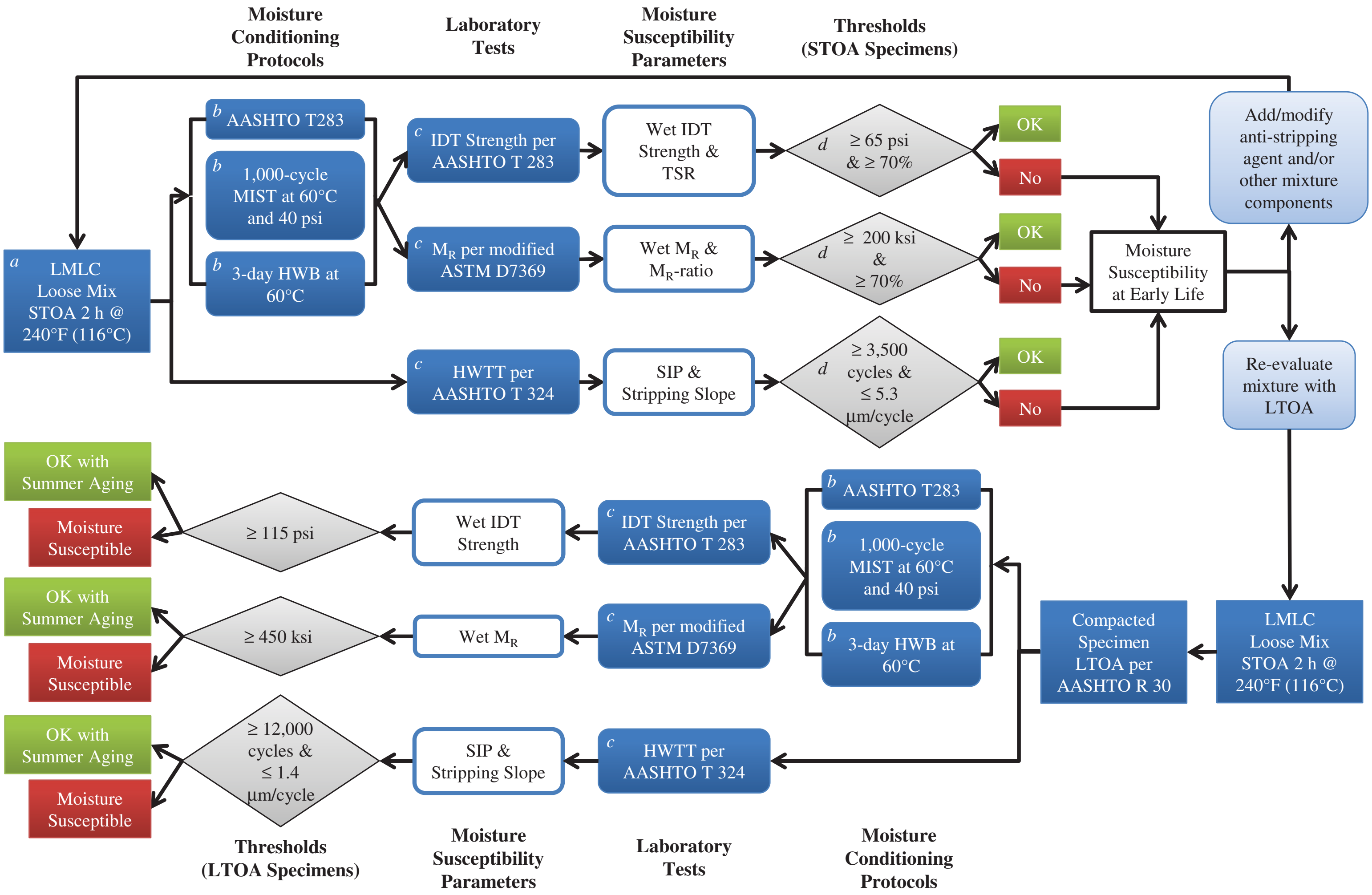
The laboratory test results obtained for various specimen-drying methods after the modified Lottman moisture conditioning indicated that SSD and CoreDry specimens had higher M_R stiffness and IDT strength values than air dry and oven dry specimens, although the difference was insignificant. The testing of SSD specimens in the M_R and IDT strength tests was problematic as the water occupying the permeable pores of the specimens could artificially increase mixture load-carrying capacity due to pore pressure and incompressibility of water. Therefore, the other three specimen-drying methods of CoreDry, 48-hour air dry at 77°F (25°C), and 24-hour oven dry at 140°F (60°C) were recommended to dry the moisture conditioned specimens prior to M_R and IDT strength measurements, with the CoreDry method being preferred due to its shorter time requirement.

Figure 19 presents the revised flow chart for evaluating moisture susceptibility of WMA during mix design or QA based on the results obtained in this project. If appropriate laboratory equipment is not available to fabricate LMLC specimens with the WMA technology, testing may be conducted on PMLC specimens fabricated on-site or off-site with minimal reheating from plant trial batch materials.

After mixing WMA LMLC specimens according to AASHTO R 35, loose mix is subject to short-term oven aging (STOA) for 2 hours at 240°F (116°C) prior to compaction. Next, a performance test to evaluate moisture susceptibility is selected based on available equipment, costs, and prior experience from the following three options: wet and dry IDT strengths at 77°F (25°C) and TSR per AASHTO T 283, wet and dry M_R stiffness at 77°F (25°C) per modified ASTM D7369, or HWTT SIP and stripping slope per AASHTO T 324 at 122°F (50°C). For the IDT strength and M_R tests, three moisture conditioning protocols including the modified Lottman per AASHTO T 283, 1,000-cycle MIST at 140°F (60°C) and 40 psi, or 3-day HWB at 140°F (60°C) are available. Depending on the available equipment, the moisture conditioned specimens should be dried using one of the following methods prior to wet M_R and IDT strength measurements: CoreDry, 48-hour air dry at 77°F (25°C), or 24-hour oven dry at 104°F (40°C).

Two criteria for each performance test for these STOA specimens are shown in Figure 19. These criteria were initially proposed in NCHRP Project 9-49 by discriminating between the results of WMA mixtures with good versus poor field and laboratory performance, and then verified by 64 additional WMA mixtures evaluated in this project. If the WMA passes both criteria for the selected test, the mixture is expected to have adequate performance in terms of moisture susceptibility. Otherwise, early life moisture susceptibility is probable. Mixture modifications in terms of (1) adding, modifying the dosage of, or changing anti-stripping agents; (2) changing other mixture components (i.e., binder grade or inclusion of recycled materials); or (3) any combination of these modifications is recommended prior to a second evaluation of the modified WMA with the same criteria.

If the modified WMA still fails at least one criterion for the selected test, another evaluation is proposed for LMLC specimens after both STOA and long-term oven aging (LTOA) of 5 days at 185°F (85°C) per AASHTO R 30 to evaluate if the WMA performance improves with aging. After long-term aging, the same selected laboratory test is used but with revised criteria that reflect the stiffening effects due to oxidative aging, as shown in Figure 19. If the LTOA WMA passes all criteria for the same



Note [a]: if WMA LMLC is not available, use trial batch prior to production for verification: on-site PMLC or off-site PMLC with minimal reheating
Note [b]: select a single moisture conditioning protocol and use it throughout the mix design verification
Note [c]: select a single test method and use it throughout the mix design verification
Note [d]: If trial batch off-site PMLC specimens are used, employ the following thresholds (TSR and M_R-ratio remain unchanged):
Wet IDT ≥ 100 psi, Wet $M_R \geq 300$ ksi, SIP ≥ 6,000 cycles, stripping slope ≤ 2.0 µm/cycle

Figure 19. Revised WMA moisture susceptibility evaluation for mix design or quality assurance.

selected test, moisture susceptibility in early life is probable and scheduling construction is recommended so that a summer of aging occurs prior to multiple freeze-thaw cycles or wet and cold days. Otherwise, the mixture is considered moisture susceptible. Finally, if the alternative off-site PMLC specimens are used to evaluate WMA moisture susceptibility, the thresholds are increased for wet IDT strength, wet M_R stiffness, SIP, and stripping slope as noted at the bottom of Figure 19.

Figure 19 was produced as a set of guidelines for identifying and minimizing moisture susceptibility of WMA. Before being considered for implementation, the guidelines should be used on a trial basis. This will provide additional data to further refine the proposed moisture susceptibility thresholds and laboratory aging and moisture conditioning protocols to particular needs and conditions of individual agencies. Data from additional WMA mixtures will provide increased confidence in the guidelines. In addition, continuous monitoring of the WMA mixtures used for proposing and validating moisture susceptibility thresholds in NCHRP Projects 9-49 and 9-49B is suggested.

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APPENDIX A

Web-Based Survey

E-mail Introduction

The Texas A&M Transportation Institute (TTI) is conducting National Cooperative Highway Research Program (NCHRP) Project 9-49B *Performance of WMA Technologies: Stage I–Moisture Susceptibility Validation* as follow-up work to completed NCHRP Project 9-49. This validation study includes a web-based survey (http://tti.tamu.edu/nchrp-9-49b-web-based-survey/) to identify WMA pavements with mix design and quality assurance (QA) data that include laboratory test results from any of the following methods included in the guidelines generated in completed NCHRP Project 9-49 (see figure below):

- *Dry and wet indirect tensile (IDT) strength and tensile strength ratio (TSR) per AASHTO T 283*
- *Dry and wet resilient modulus (M_R) per ASTM7369 with moisture conditioning per AASHTO T 283*
- *Hamburg Wheel Tracking Test (HWTT) per AASHTO T 324*

This survey is being sent to state departments of transportation and selected contractors. We estimate that the survey will take approximately 15–30 minutes to complete. We would appreciate your response by November 14, 2014. If you feel you are not the appropriate person to complete this survey, please send the alternate contact information to the Principal Investigator Amy Epps Martin (a-eppsmartin@tamu.edu). Any questions or comments about the survey can also be directed to her. For questions about your rights as a research participant, or if you have questions, complaints, or concerns about the research, you may contact the Texas A&M University Human Subjects Protection Program at 979.458.4067, toll-free at 1.855.795.8636, or email at irb@tamu.edu.

Your participation is entirely voluntary, and you will receive no direct benefit from completing the survey. Responses will be confidential, but results will only be released in aggregate form and possibly by organization/company without identification of specific individual respondents. Questions marked with an asterisk (*) are necessary to make your survey usable. Please use the survey link above to start the survey if you consent to participate in this study. If at any point you change your mind and decide not to participate, you can simply close the browser. Only complete responses will be recorded.

Thank you in advance for your participation. Your response will help provide guidance to pavement professionals and practitioners.

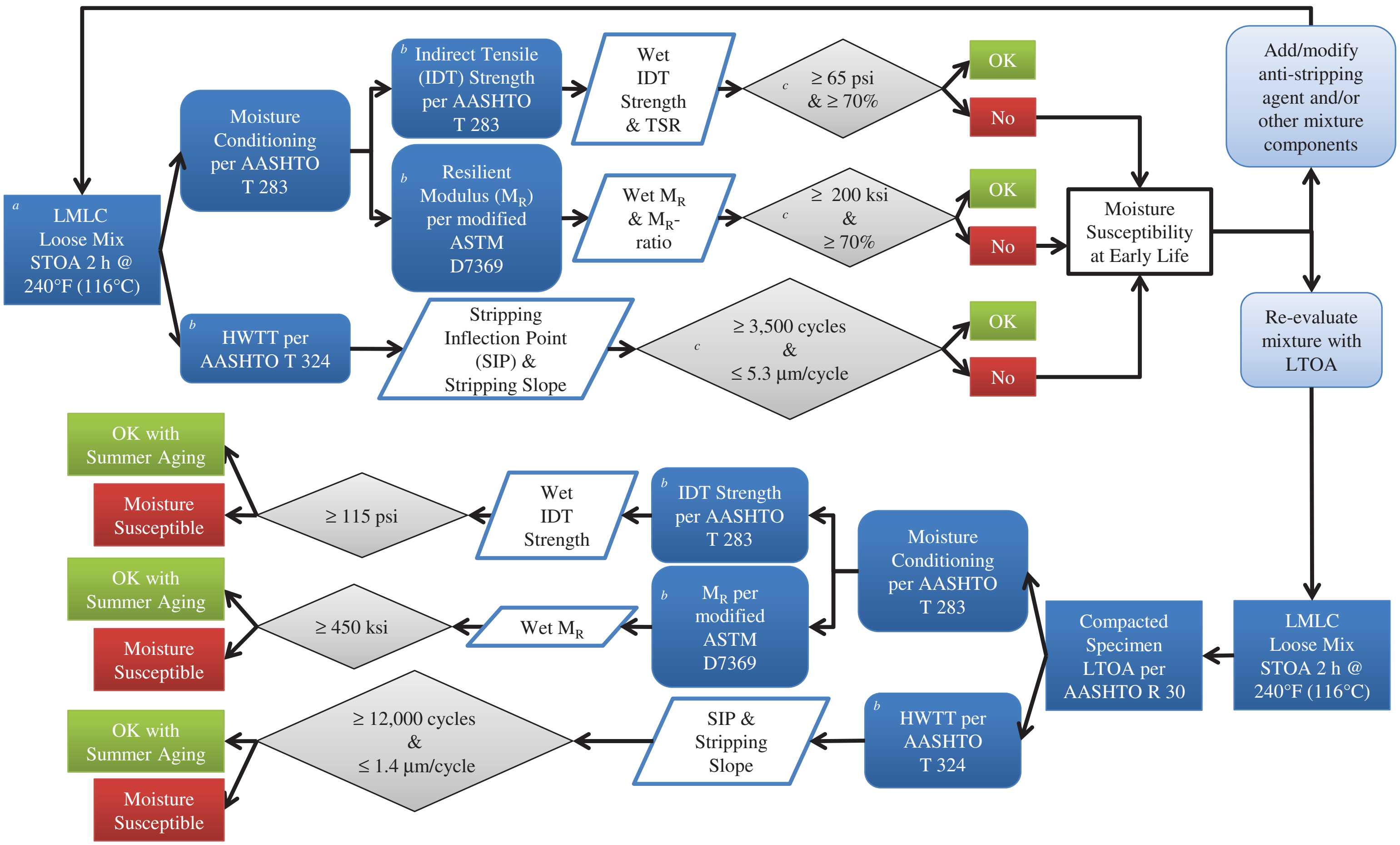
Web-Based Survey Introduction

You are invited to complete an online survey as part of National Cooperative Highway Research Program (NCHRP) Project 9-49B *Performance of WMA Technologies: Stage I–Moisture Susceptibility Validation*. The purpose of this web-based survey is to identify WMA pavements with mix design and QA data that include laboratory test results from any of the following methods:

- *Dry and wet indirect tensile (IDT) strength and tensile strength ratio (TSR) per AASHTO T 283*
- *Dry and wet resilient modulus (M_R) per ASTM7369 with moisture conditioning per AASHTO T 283*
- *Hamburg Wheel Tracking Test (HWTT) per AASHTO T 324*

Your response will be used to validate the thresholds proposed in the NCHRP Project 9-49 guidelines for identifying potential moisture susceptibility in WMA. A follow-up phone interview may be necessary to clarify some responses to the survey.

Your participation is entirely voluntary, and you will receive no direct benefit from completing the survey. We would appreciate your response by November 14, 2014. Responses



Note [a]: if WMA LMLC is not available, use trial batch prior to production for verification: on-site PMLC or off-site PMLC with minimal reheating
Note [b]: select a single test method and use it throughout the mix design verification
Note [c]: If trial batch off-site PMLC specimens are used, employ the following thresholds (TSR and M_R-ratio remain unchanged):
Wet IDT ≥ 100 psi, Wet M_R ≥ 300 ksi, SIP ≥ 6,000 cycles, stripping slope ≤ 2.0 µm/cycle

NCHRP 9-49 Proposed WMA moisture susceptibility evaluation for mix design and QA.

will be confidential, but results will only be released in aggregate form and possibly by organization/company without identification of specific individual respondents. Questions marked with an asterisk (*) are necessary to make your survey usable. Please press NEXT SCREEN if you consent to participate in this study by completing the survey. If at any point you change your mind and decide not to participate, you can simply close the browser. Only complete responses will be recorded.

Contact Info

1. *Please provide your contact information*
   **Name:*
   **Company/Organization:*
   **Address:*
   **City:* **State:* **Zip:*
   **Phone Number:*
   **Email Address:*

WMA Use and Materials

2. *To what extent does your organization utilize warm mix asphalt (WMA)?*
   - ○ *Routine use*
   - ○ *Trial or research projects only*
   - ○ *Have never used WMA*
     - ○ *Have used WMA before but not currently – please provide reason for discontinuation of use*
   - ○ *I do not know*

3. *What types of WMA technologies does your organization use (please check all that apply)?*
   - ○ *Accu-Shear™*
   - ○ *Advera® WMA*
   - ○ *Aquablack™*
   - ○ *AquaFoam*
   - ○ *Aspha-Min®*
   - ○ *Cecabase® RT*
   - ○ *Double Barrel Green®*
   - ○ *ECOFOAM-II*
   - ○ *Evotherm™ – please specify type(s)*
   - ○ *LEADCAP*
   - ○ *Low Emission Asphalt (LEA)*
   - ○ *Meeker WMA*
   - ○ *Rediset™ – please specify type(s)*
   - ○ *REVIX™*
   - ○ *Sasobit®*
   - ○ *Shell Thiopave™*
   - ○ *SonneWarmix*
   - ○ *Terex®*
   - ○ *TLA-X Warm Mix*
   - ○ *Tri-Mix*
   - ○ *Ultrafoam GX™*
   - ○ *WAM Foam®*
   - ○ *Other – please list*

4. *Does your organization require the use of anti-stripping agents with WMA?*
   - ○ *Yes, because of aggregates with a history of moisture susceptibility problems*
   - ○ *Yes, because of laboratory test results indicating moisture susceptibility*
   - ○ *Yes, due to other reason – please specify*
   - ○ *No*

Moisture Susceptibility Tests and Criteria

5. **Does your organization have a standard or specification that includes moisture susceptibility laboratory testing as part of the mix design procedure or construction QA?*
   - ○ *Yes, for mix design only – please write the standard/specification*
   - ○ *Yes, for construction QA only – please write the standard/specification*
   - ○ *Yes, for both mix design and construction QA*
     - ○ *The same for mix design and construction QA – please write the standard/specification*
     - ○ *Different for mix design and construction QA – please write the standards/specifications*
   - ○ *No*
   - ○ *I do not know*

6. **[1] [2] [3] What moisture susceptibility test(s) is (are) included in the standard/specification? Check all that apply and provide for each one details about the specimen fabrication protocol (short-term oven aging – STOA – of the loose mix prior to compaction), moisture conditioning procedure (or water temperature for Hamburg), and pass/fail criteria for hot mix asphalt (HMA) and WMA if they are different.*
   - ○ *Wet Indirect Tensile (IDT) Strength*
     Specimen Fabrication Protocol
     - ○ *Same for HMA and WMA – please specify STOA time and temperature*
     - ○ *Different for HMA and WMA*
       - ○ *Protocol for HMA – please specify STOA time and temperature*

---

[1] This question will only appear when "Yes" is selected as answer for Question 5.

[2] The details under each option will only appear when selected.

[3] If the respondent selected "Different for mix design and construction QA" in Question 5, Question 6 needs to formulated as follows: 6a. "What moisture susceptibility test(s) is (are) included in your moisture susceptibility specification for mix design (you will provide details for the construction QA specification in the following question)?" and 6b. "What moisture susceptibility test(s) is (are) included in your moisture susceptibility specification for construction QA?" Both 6a and 6b will include all options listed under Question 6.

- ○ *Protocol for WMA – please specify STOA time and temperature*

Moisture Conditioning Procedure

- ○ *Per AASHTO T 283*
- ○ *Per modified AASHTO T 283 – please specify*
- ○ *Other–please specify*

Pass/Fail Criteria

- ○ *Same for HMA and WMA – please specify*
- ○ *Different for HMA and WMA*
  - ○ *Criteria for HMA – please specify*
  - ○ *Criteria for WMA – please specify*

- ○ *Tensile Strength Ratio (TSR)*
  - ***Specimen Fabrication Protocol***
  - ○ *Same for HMA and WMA – please specify STOA time and temperature*
  - ○ *Different for HMA and WMA*
    - ○ *Protocol for HMA – please specify STOA time and temperature*
    - ○ *Protocol for WMA – please specify STOA time and temperature*
  - ***Moisture Conditioning Procedure***
  - ○ *Per AASHTO T 283*
  - ○ *Per modified AASHTO T 283 – please specify*
  - ○ *Other – please specify*
  - ***Pass/Fail Criteria***
  - ○ *Same for HMA and WMA – please specify*
  - ○ *Different for HMA and WMA*
    - ○ *Criteria for HMA – please specify*
    - ○ *Criteria for WMA – please specify*
- ○ *Resilient Modulus* (M_R)
  - ***Specimen Fabrication Protocol***
  - ○ *Same for HMA and WMA – please specify STOA time and temperature*
  - ○ *Different for HMA and WMA*
    - ○ *Protocol for HMA – please specify STOA time and temperature*
    - ○ *Protocol for WMA – please specify STOA time and temperature*
  - ***Moisture Conditioning Procedure***
  - ○ *Per AASHTO T 283*
  - ○ *Per modified AASHTO T 283 – please specify*
  - ○ *Other – please specify*
  - ***Pass/Fail Criteria***
  - ○ *Same for HMA and WMA – please specify*
  - ○ *Different for HMA and WMA*
    - ○ *Criteria for HMA – please specify*
    - ○ *Criteria for WMA – please specify*
- ○ *Wet to Dry* M_R *Ratio*
  - ***Specimen Fabrication Protocol***
  - ○ *Same for HMA and WMA – please specify STOA time and temperature*
  - ○ *Different for HMA and WMA*
    - ○ *Protocol for HMA – please specify STOA time and temperature*
    - ○ *Protocol for WMA – please specify STOA time and temperature*
  - ***Moisture Conditioning Procedure***
  - ○ *Per AASHTO T 283*
  - ○ *Per modified AASHTO T 283 – please specify*
  - ○ *Other – please specify*
  - ***Pass/Fail Criteria***
  - ○ *Same for HMA and WMA – please specify*
  - ○ *Different for HMA and WMA*
    - ○ *Criteria for HMA – please specify*
    - ○ *Criteria for WMA – please specify*
- ○ *Hamburg Wheel Tracking Test*
  - ***Specimen Fabrication Protocol***
  - ○ *Same for HMA and WMA – please specify STOA time and temperature*
  - ○ *Different for HMA and WMA*
    - ○ *Protocol for HMA – please specify STOA time and temperature*
    - ○ *Protocol for WMA – please specify STOA time and temperature*
  - ***Water Temperature***
  - ○ *Single water temperature irrespective of the binder PG grade*
  - ○ *Different water temperature based on the binder PG grade – please specify*
  - ***Pass/Fail Criteria***
  - ○ *Same for HMA and WMA – please specify*
  - ○ *Different for HMA and WMA*
    - ○ *Criteria for HMA – please specify*
    - ○ *Criteria for WMA – please specify*
- ○ *Other – please specify*
  - ***Specimen Fabrication Protocol***
  - ○ *Same for HMA and WMA – please specify STOA time and temperature*
  - ○ *Different for HMA and WMA*
    - ○ *Protocol for HMA – please specify STOA time and temperature*
    - ○ *Protocol for WMA – please specify STOA time and temperature*
  - ***Moisture Conditioning Procedure***
  - ○ *Per AASHTO T 283*
  - ○ *Per modified AASHTO T 283 – please specify*
  - ○ *Other – please specify*
  - ***Pass/Fail Criteria***
  - ○ *Same for HMA and WMA – please specify*
  - ○ *Different for HMA and WMA*
    - ○ *Criteria for HMA – please specify*
    - ○ *Criteria for WMA – please specify*

Pavement Performance

7. **Have any of the WMA pavements in your state experienced premature or extensive moisture-related distress?*
    - ○ *No moisture-related distress observed to date – please indicate the range of age of the pavement(s) showing adequate moisture-related performance*
    - ○ *Yes – please indicate the type, extent, and severity of the failure, age of the pavement, and possible cause of failure (e.g., asphalt content, compaction level, aggregate type, etc.)*

8. **Does your organization have laboratory test results (IDT, TSR, M_R, or HWTT) or other information relevant to the moisture susceptibility guidelines proposed in NCHRP 9-49 that can be made available to the researchers conducting this study (please check all that apply)?*
    - ○ *Mix design*
        - ○ *Construction quality assurance*
    - ○ *Field/forensic evaluation*
    - ○ *Technical reports*
    - ○ *Field cores*
    - ○ *Other – please specify*

9. **Does your organization have upcoming WMA projects and is willing to participate in NCHRP Project 9-49B by sharing information about mix design, construction, materials, and/or field performance monitoring?*
    - ○ *Yes, willing to participate*
    - ○ *Yes, but not able to participate*
    - ○ *No upcoming WMA field projects*

Additional Comments

10. *Please provide any additional comments, experiences, or challenges you wish to share about moisture susceptibility of WMA pavements.*

APPENDIX B

Statistical Analysis Outputs

Moisture Conditioning Protocols

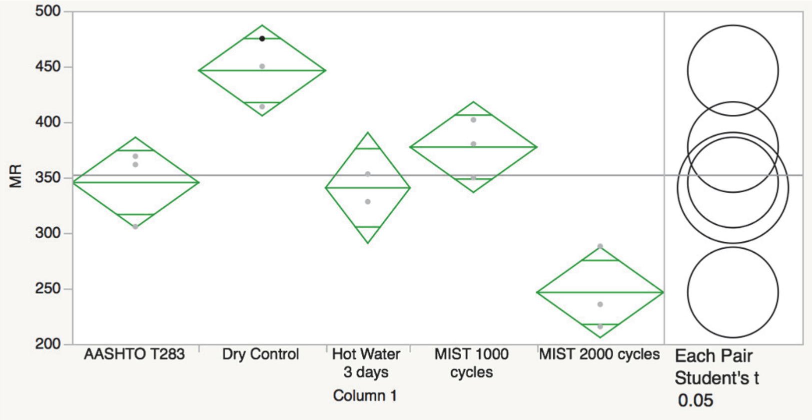


Figure 14. M_R stiffness results.

Missing Rows
1Excluded Rows
15
One-way Anova
Summary of Fit

Rsquare	0.87698
Adj Rsquare	0.822304
Root Mean Square Error	31.19243
Mean of Response	352.0143
Observations (or Sum Wgts)	14

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Column 1	4	62424.285	15606.1	16.0397	0.0004*
Error	9	8756.712	973.0		
C. Total	13	71180.997			

Means for One-way Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
AASHTO T283	3	345.467	18.009	304.73	386.21
Dry Control	3	446.333	18.009	405.59	487.07
Hot Water 3 days	2	340.650	22.056	290.75	390.55
MIST 1000 cycles	3	377.367	18.009	336.63	418.11
MIST 2000 cycles	3	246.467	18.009	205.73	287.21

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
2.26216	0.05

LSD Threshold Matrix
Abs(Dif)-LSD

	Dry Control	MIST 1000 cycles	AASHTO T283	Hot Water 3 days	MIST 2000 cycles
Dry Control	-57.61	11.35	43.25	41.27	142.25
MIST 1000 cycles	11.35	-57.61	-25.71	-27.70	73.29
AASHTO T283	43.25	-25.71	-57.61	-59.60	41.39
Hot Water 3 days	41.27	-27.70	-59.60	-70.56	29.77
MIST 2000 cycles	142.25	73.29	41.39	29.77	-57.61

Positive values show pairs of means that are significantly different.

Connecting Letters Report

Level							Mean
Dry Control	A						446.33333
MIST 1000 cycles		B					377.36667
AASHTO T283		B					345.46667
Hot Water 3 days		B					340.65000
MIST 2000 cycles			C				246.46667

Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Dry Control	MIST 2000 cycles	199.8667	25.46852	142.253	257.4805	<.0001*
MIST 1000 cycles	MIST 2000 cycles	130.9000	25.46852	73.286	188.5138	0.0006*
Dry Control	Hot Water 3 days	105.6833	28.47467	41.269	170.0975	0.0048*
Dry Control	AASHTO T283	100.8667	25.46852	43.253	158.4805	0.0033*
AASHTO T283	MIST 2000 cycles	99.0000	25.46852	41.386	156.6138	0.0037*
Hot Water 3 days	MIST 2000 cycles	94.1833	28.47467	29.769	158.5975	0.0091*
Dry Control	MIST 1000 cycles	68.9667	25.46852	11.353	126.5805	0.0241*
MIST 1000 cycles	Hot Water 3 days	36.7167	28.47467	-27.698	101.1308	0.2294
MIST 1000 cycles	AASHTO T283	31.9000	25.46852	-25.714	89.5138	0.2419
AASHTO T283	Hot Water 3 days	4.8167	28.47467	-59.598	69.2308	0.8694

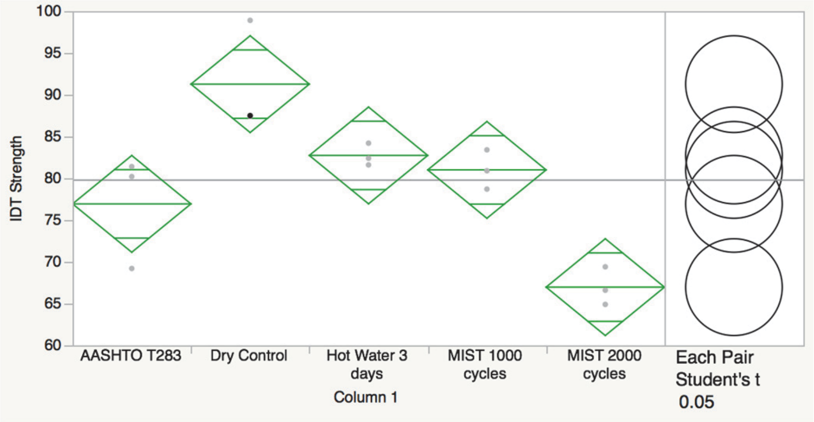


Figure 15. IDT strength results.

Excluded Rows
15
One-way Anova
Summary of Fit

Rsquare	0.823079
Adj Rsquare	0.75231
Root Mean Square Error	4.502962
Mean of Response	79.78
Observations (or Sum Wgts)	15

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Column 1	4	943.3173	235.829	11.6306	0.0009*
Error	10	202.7667	20.277		
C. Total	14	1146.0840			

Means for One-way Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
AASHTO T283	3	76.9333	2.5998	71.141	82.726
Dry Control	3	91.2667	2.5998	85.474	97.059
Hot Water 3 days	3	82.7333	2.5998	76.941	88.526
MIST 1000 cycles	3	81.0000	2.5998	75.207	86.793
MIST 2000 cycles	3	66.9667	2.5998	61.174	72.759

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
2.22814	0.05

LSD Threshold Matrix
Abs(Dif)-LSD

	Dry Control	Hot Water 3 days	MIST 1000 cycles	AASHTO T283	MIST 2000 cycles
Dry Control	-8.192	0.341	2.075	6.141	16.108
Hot Water 3 days	0.341	-8.192	-6.459	-2.392	7.575
MIST 1000 cycles	2.075	-6.459	-8.192	-4.125	5.841
AASHTO T283	6.141	-2.392	-4.125	-8.192	1.775
MIST 2000 cycles	16.108	7.575	5.841	1.775	-8.192

Positive values show pairs of means that are significantly different.

Connecting Letters Report

Level							Mean
Dry Control	A						91.266667
Hot Water 3 days		B					82.733333
MIST 1000 cycles		B					81.000000
AASHTO T283		B					76.933333
MIST 2000 cycles			C				66.966667

Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Dry Control	MIST 2000 cycles	24.30000	3.676653	16.1079	32.49209	<.0001*
Hot Water 3 days	MIST 2000 cycles	15.76667	3.676653	7.5746	23.95876	0.0016*

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Dry Control	AASHTO T283	14.33333	3.676653	6.1412	22.52543	0.0030*
MIST 1000 cycles	MIST 2000 cycles	14.03333	3.676653	5.8412	22.22543	0.0034*
Dry Control	MIST 1000 cycles	10.26667	3.676653	2.0746	18.45876	0.0190*
AASHTO T283	MIST 2000 cycles	9.96667	3.676653	1.7746	18.15876	0.0219*
Dry Control	Hot Water 3 days	8.53333	3.676653	0.3412	16.72543	0.0427*
Hot Water 3 days	AASHTO T283	5.80000	3.676653	-2.3921	13.99209	0.1458
MIST 1000 cycles	AASHTO T283	4.06667	3.676653	-4.1254	12.25876	0.2946
Hot Water 3 days	MIST 1000 cycles	1.73333	3.676653	-6.4588	9.92543	0.6474

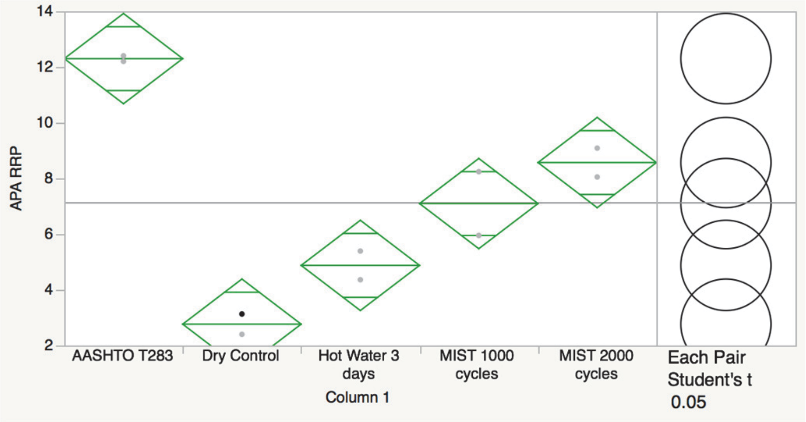


Figure 16. APA RRP results.

Missing Rows
5Excluded Rows
15
One-way Anova
Summary of Fit

Rsquare	0.963816
Adj Rsquare	0.934869
Root Mean Square Error	0.891579
Mean of Response	7.1205
Observations (or Sum Wgts)	10

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Column 1	4	105.86866	26.4672	33.2957	0.0008*
Error	5	3.97456	0.7949		
C. Total	9	109.84322			

Means for One-way Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
AASHTO T283	2	12.3000	0.63044	10.679	13.921
Dry Control	2	2.7650	0.63044	1.144	4.386
Hot Water 3 days	2	4.8750	0.63044	3.254	6.496
MIST 1000 cycles	2	7.0950	0.63044	5.474	8.716
MIST 2000 cycles	2	8.5675	0.63044	6.947	10.188

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
2.57058	0.05

LSD Threshold Matrix
Abs(Dif)-LSD

	AASHTO T283	MIST 2000 cycles	MIST 1000 cycles	Hot Water 3 days	Dry Control
AASHTO T283	-2.2919	1.4406	2.9131	5.1331	7.2431
MIST 2000 cycles	1.4406	-2.2919	-0.8194	1.4006	3.5106
MIST 1000 cycles	2.9131	-0.8194	-2.2919	-0.0719	2.0381
Hot Water 3 days	5.1331	1.4006	-0.0719	-2.2919	-0.1819
Dry Control	7.2431	3.5106	2.0381	-0.1819	-2.2919

Positive values show pairs of means that are significantly different.

Connecting Letters Report

Level							Mean
AASHTO T283	A						12.300000
MIST 2000 cycles		B					8.567500
MIST 1000 cycles		B	C				7.095000
Hot Water 3 days			C	D			4.875000
Dry Control				D			2.765000

Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
AASHTO T283	Dry Control	9.535000	0.8915787	7.24312	11.82688	0.0001*
AASHTO T283	Hot Water 3 days	7.425000	0.8915787	5.13312	9.71688	0.0004*
MIST 2000 cycles	Dry Control	5.802500	0.8915787	3.51062	8.09438	0.0013*
AASHTO T283	MIST 1000 cycles	5.205000	0.8915787	2.91312	7.49688	0.0021*
MIST 1000 cycles	Dry Control	4.330000	0.8915787	2.03812	6.62188	0.0046*
AASHTO T283	MIST 2000 cycles	3.732500	0.8915787	1.44062	6.02438	0.0086*
MIST 2000 cycles	Hot Water 3 days	3.692500	0.8915787	1.40062	5.98438	0.0090*
MIST 1000 cycles	Hot Water 3 days	2.220000	0.8915787	-0.07188	4.51188	0.0552
Hot Water 3 days	Dry Control	2.110000	0.8915787	-0.18188	4.40188	0.0642
MIST 2000 cycles	MIST 1000 cycles	1.472500	0.8915787	-0.81938	3.76438	0.1595

Specimen-Drying Methods

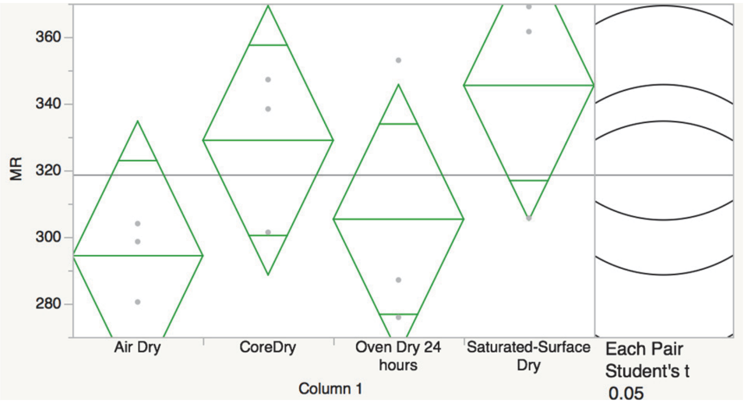


Figure 17. M_R stiffness results.

Excluded Rows
18
One-way Anova
Summary of Fit

Rsquare	0.39387
Adj Rsquare	0.166572
Root Mean Square Error	30.32215
Mean of Response	318.5417
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Column 1	3	4779.669	1593.22	1.7328	0.2374
Error	8	7355.460	919.43		
C. Total	11	12135.129			

Means for One-way Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Air Dry	3	294.367	17.506	254.00	334.74
CoreDry	3	329.000	17.506	288.63	369.37
Oven Dry 24 hours	3	305.333	17.506	264.96	345.70
Saturated-Surface Dry	3	345.467	17.506	305.10	385.84

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
2.30600	0.05

LSD Threshold Matrix
Abs(Dif)-LSD

	Saturated-Surface Dry	CoreDry	Oven Dry 24 hours	Air Dry
Saturated-Surface Dry	-57.092	-40.625	-16.959	-5.992
CoreDry	-40.625	-57.092	-33.425	-22.459
Oven Dry 24 hours	-16.959	-33.425	-57.092	-46.125
Air Dry	-5.992	-22.459	-46.125	-57.092

Positive values show pairs of means that are significantly different.

Connecting Letters Report

Level							Mean
Saturated-Surface Dry	A						345.46667
CoreDry	A						329.00000
Oven Dry 24 hours	A						305.33333
Air Dry	A						294.36667

Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
Saturated-Surface Dry	Air Dry	51.10000	24.75793	-5.9919	108.1919	0.0729
Saturated-Surface Dry	Oven Dry 24 hours	40.13333	24.75793	-16.9586	97.2252	0.1437
CoreDry	Air Dry	34.63333	24.75793	-22.4586	91.7252	0.1994
CoreDry	Oven Dry 24 hours	23.66667	24.75793	-33.4252	80.7586	0.3671
Saturated-Surface Dry	CoreDry	16.46667	24.75793	-40.6252	73.5586	0.5247
Oven Dry 24 hours	Air Dry	10.96667	24.75793	-46.1252	68.0586	0.6695

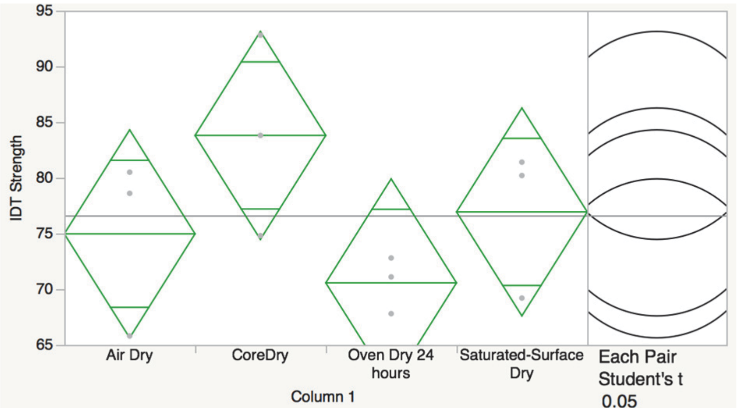


Figure 18. IDT strength results.

Excluded Rows
18
One-way Anova
Summary of Fit

Rsquare	0.409828
Adj Rsquare	0.188514
Root Mean Square Error	7.010706
Mean of Response	76.56667
Observations (or Sum Wgts)	12

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Column 1	3	273.04667	91.0156	1.8518	0.2161
Error	8	393.20000	49.1500		
C. Total	11	666.24667			

Means for One-way Anova

Level	Number	Mean	Std Error	Lower 95%	Upper 95%
Air Dry	3	74.9667	4.0476	65.633	84.301
CoreDry	3	83.8000	4.0476	74.466	93.134
Oven Dry 24 hours	3	70.5667	4.0476	61.233	79.901
Saturated-Surface Dry	3	76.9333	4.0476	67.599	86.267

Std Error uses a pooled estimate of error variance

Means Comparisons
Comparisons for each pair using Student's t
Confidence Quantile

t	Alpha
2.30600	0.05

LSD Threshold Matrix
Abs(Dif)-LSD

	CoreDry	Saturated-Surface Dry	Air Dry	Oven Dry 24 hours
CoreDry	-13.200	-6.333	-4.367	0.033
Saturated-Surface Dry	-6.333	-13.200	-11.233	-6.833
Air Dry	-4.367	-11.233	-13.200	-8.800
Oven Dry 24 hours	0.033	-6.833	-8.800	-13.200

Positive values show pairs of means that are significantly different.

Connecting Letters Report

Level							Mean
CoreDry	A						83.800000
Saturated-Surface Dry	A	B					76.933333
Air Dry	A	B					74.966667
Oven Dry 24 hours		B					70.566667

Levels not connected by same letter are significantly different.

Ordered Differences Report

Level	- Level	Difference	Std Err Dif	Lower CL	Upper CL	p-Value
CoreDry	Oven Dry 24 hours	13.23333	5.724218	0.0333	26.43340	0.0495*
CoreDry	Air Dry	8.83333	5.724218	-4.3667	22.03340	0.1614
CoreDry	Saturated-Surface Dry	6.86667	5.724218	-6.3334	20.06674	0.2646
Saturated-Surface Dry	Oven Dry 24 hours	6.36667	5.724218	-6.8334	19.56674	0.2983
Air Dry	Oven Dry 24 hours	4.40000	5.724218	-8.8001	17.60007	0.4642
Saturated-Surface Dry	Air Dry	1.96667	5.724218	-11.2334	15.16674	0.7400

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America’s Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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