EVALUATION OF LABORATORY CONDITIONING PROTOCOLS FOR WARM-MIX ASPHALT

A Thesis

by

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ABSTRACT

Warm-Mix Asphalt (WMA) refers to the asphalt concrete paving material produced and placed at temperatures approximately 50°F lower than those used for Hot-Mix Asphalt (HMA). Economic, environmental and engineering benefits have boosted the use of WMA technology across the world during the past decade. While WMA technology has been successfully utilized as a paving material, several specifications and mix design protocols remain under development. For example, currently, there is no consistent laboratory conditioning procedure for preparing WMA specimens for performance tests, despite being essential for mix performance.

Based on previous studies, several candidate conditioning protocols for WMA Laboratory Mixed Laboratory Compacted (LMLC) and off-site Plant Mixed Laboratory Compacted (PMLC) specimens were selected, and their effects on mixture properties were evaluated. Mixture stiffness evaluated in a dry condition using the Resilient Modulus (M_R) test (ASTM D-7369) was the main parameter used to select a conditioning protocol to simulate pavement stiffness in its early life. The number of Superpave Gyratory Compactor (SGC) gyrations to get 7±0.5% air voids (AV) was the alternative parameter. Extracted binder stiffness and aggregate orientation of field cores and on-site PMLC specimens were evaluated using the Dynamic Shear Rheometer (DSR) (AASHTO T315) and image analysis techniques, respectively. In addition, mixture stiffness in a wet condition was evaluated using the Hamburg Wheel-Track Test (HWTT) (AASHTO T324) stripping inflection point (SIP) and rutting depth at a certain number of passes.

Several conclusions are made based on test results. LMLC specimens conditioned for 2 hours at 240°F (116°C) for WMA and 275°F (135°C) for HMA had similar stiffnesses as cores collected during the early life of field pavements. For off-site PMLC specimens, different conditioning protocols are recommended to simulate stiffnesses of on-site PMLC specimens: reheat to 240°F (116°C) for WMA with

additives and reheat to 275°F (135°C) for HMA and foamed WMA. Additionally, binder stiffness, aggregate orientation, and overall AV had significant effects on mixture stiffness. Mixture stiffness results for PMFC cores and on-site PMLC specimens in a wet condition as indicated by HWTT agree with those in a dry condition in M_R testing.

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NOMENCLATURE

HMA	Hot-Mixed Asphalt
SMA	Stone-Matrix Asphalt
QC	Quality Control
QA	Quality Assurance
WMA	Warm-Mixed Asphalt
NCHRP	National Cooperative Highway Research Program
NAPA	National Asphalt Paving Association
DOT	Department of Transportation
PMLC	Plant Mixed Laboratory Compacted
M_R	Resilient Modulus
LMLC	Laboratory Mixed Laboratory Compacted
LEA	Low Emission/Energy Asphalt
STOA	Short-Term Oven Age
T_c	Compaction Temperature
IDT	Indirect Tensile Strength
APT	Accelerated Pavement Testing
HWTT	Hamburg Wheel-Track Testing
RAP	Reclaimed Asphalt Pavements
RAS	Recycled Asphalt Shingles
PMFC	Plant Mixed Field Compacted
PG	Performance-Graded

T_m	Mixing Temperature
TTI	Texas A&M Transportation Institute
SGC	Superpave Gyratory Compactor
AV	Air Voids
N	Number of SGC Gyration
SIP	Stripping Infection Point
DSR	Dynamic Shear Rheometer
G_{mm}	Rice Specific Gravity
P_{ba}	Percentage of Absorbed Binder
FT	Film Thickness
LVDT	Linear Variable Differential Transducers
ANOVA	Analysis of Variance
Tukey's HSD	Tukey-Kramer Honestly Significant Difference
G*	Complex Modulus

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1. INTRODUCTION

Hot-mix asphalt (HMA) is a well-established paving material with proven performance utilized on 94% of the more than 2.5 million miles (4.0 million km) of paved roads in the United States (FHWA, 2008; NAPA, 2010). HMA is produced by mixing asphalt binder and aggregate at an elevated temperature in either batch or drum mix plants and then placed by compacting the mixture at temperatures ranging from 275ºF (135ºC) to 325ºF (163ºC) (Kuennen, 2004; Newcomb, 2005a). These high production and placement temperatures are necessary to ensure complete drying of the aggregate and subsequent bonding with the binder, coating of the aggregate by the binder, and workability for adequate handling and compaction. All of these processes contribute substantially to good pavement performance in terms of durability and resistance to permanent deformation and cracking. Recent advances in asphalt technology, including polymer modified binders and stiff HMA mixtures with angular aggregate that improve resistance to permanent deformation [Stone Matrix Asphalt (SMA), for example] and an emphasis on compaction for Quality Control (QC)/Quality Assurance (QA) and subsequent good performance, resulted in further increases in HMA mixing and compaction temperatures up to a limit of 350ºF (177ºC) where polymer breakdown in the binder can occur. These high temperatures are linked to increased emissions and fumes from HMA plants (Stroup-Gardiner et al., 2005). In addition, the HMA production process consumes considerable energy in drying the aggregate and heating all materials prior to mixing and compacting.

Economic, environmental, and engineering benefits motivate the reduction of production and placement temperatures for asphalt concrete paving materials. This section provides a short history of efforts to reduce these temperatures, a definition of the latest technology termed warm-mix asphalt (WMA), benefits and issues associated with WMA, problem statements, and research objectives.

1.1 History

Past efforts to reduce placement and production temperatures that date back to the late 1950s include binder foaming processes (using either steam or water), asphalt emulsification, and incomplete aggregate drying (Kristjansdottir, 2006; Zettler, 2006).

The latest technology adopted to reduce placement and production temperatures of asphalt concrete paving materials is WMA. This technology was first introduced in Europe in the mid-1990s as a measure to reduce greenhouse gas emissions, and the technology was transferred to the United States in the early 2000s largely through the efforts of the National Asphalt Paving Association (NAPA).

1.2 Definition

WMA is defined as an asphalt concrete paving material that is produced and placed at temperatures approximately 50°F (28°C) cooler than those used for HMA. As discussed subsequently, there are a number of technologies that satisfy this definition through different mechanisms and provide economic, environmental, and engineering benefits in terms of reduced viscosity of the binder and/or mixture to allow for complete coating of the aggregate by the binder, sufficient adhesion between the aggregate and binder, and mixture compactability at lower temperatures. Widespread use of this technology and realization of its benefits requires production of WMA with similar performance and durability as HMA at substantially reduced production and placement temperatures (Button et al., 2007; Jones, 2004; Prowell et al. 2011).

1.3 Benefits and Issues

WMA offers the following benefits (Button et al. 2007; Jones, 2004; Koenders et al., 2002; McKenzie, 2006; NCAT, 2005; Newcomb, 2005b; Newcomb, 2011):

<u>Short-Term Benefits</u>

- decreased energy consumption of 30 to 40% (Jenkins et al., 2002; Kuennen, 2004).

- reduced emissions and odors at the plant (30% reduction in CO_2) (Kuennen, 2004).
- reduced fumes and improved working conditions at the construction site (fumes below detection limits and significant dust reduction) (Newcomb, 2005a).
- decreased plant wear and costs.
- extended haul distances, a longer pavement construction season, and a longer construction day if produced at typical HMA temperatures (NCAT, 2005; Kristjansdottir, 2006).
- reduced construction time for pavements with multiple lifts (Kuennen, 2004).
- improved workability and compactability.
- reduced initial costs (in some cases).

Long-Term Benefits

- reduced aging and subsequent susceptibility to cracking and raveling.
- decreased life cycle costs (in some cases).

While WMA technology is successfully utilized in other countries, where the environmental benefits and high energy costs motivate implementation, many questions remain as it is adopted in the United States, where in addition to the reduced emissions and lower energy demand benefits, reduced plant wear and associated costs, extended haul distances, and a longer pavement construction season and construction day provide additional driving forces (Barthel et al., 2004; Cervarich, 2003; Kuennen, 2004; McKenzie, 2006). Some technologies result in an increase in initial costs ($3 to $4 per ton premium). However, these costs have decreased (to $0 to $3 per ton premium) as demand has increased and additional equipment required for some WMA technologies has become readily available. Other barriers to implementation include the following specific performance and mix design issues that need to be addressed (Kuennen, 2004; NCAT, 2005; Newcomb, 2011; Rand, 2008):

Short-Term Issues

- compaction in the laboratory (including mixing and compaction temperatures) and field.
- coating of aggregates with binder (some WMA technologies).
- conditioning/curing (to eliminate water) in the laboratory and field.
- mix design (including selection of binder grade and optimum binder content with or without additives).
- possible increased susceptibility to permanent deformation due to reduced aging.

Long-Term Issues

- possible increased moisture susceptibility due to incomplete drying of aggregate and differences in aggregate absorption of binder.

In summary, there has been a surge in WMA research and implementation in the United States; however, the impact of WMA technologies on mixture performance is still being evaluated.

1.4 Problem Statement

In the United States, as of December 2011, 47 states Department of Transportation (DOT) and all Federal Lands offices had adopted specifications or contract language allowing HMA to be replaced with WMA on pavement projects. While WMA technology has been successfully utilized as a paving material, several specifications and mix design protocols remain under development. For example, currently, there is no consistent laboratory conditioning procedure for preparing WMA specimens for performance tests, despite being essential for accurate evaluation of mix performance.

1.5 Research Objectives

The goal of this study is to obtain a combination of conditioning temperature and time that produces WMA specimens calibrated to field cores or Plant Mixed Laboratory

Compacted (PMLC) specimens fabricated on-site based on a comparison of resilient modulus (M_R) between laboratory prepared specimens and their field counterparts. Based on previous studies, several candidate conditioning protocols for WMA Laboratory Mixed Laboratory Compacted (LMLC) and PMLC specimens will be selected to evaluate the effects on WMA performance. Consistent laboratory conditioning protocols for LMLC and PMLC specimens will be proposed as derived from test results, which may differ for each of the WMA technologies considered.

2. LITERATURE REVIEW

This chapter provides the results of literature review that included a review of written documentation on WMA technologies and previous research on laboratory conditioning protocols of WMA (Epps Martin et al., 2011).

2.1 WMA Technologies

WMA technologies allow for the production and placement of asphalt concrete paving materials at temperatures approximately 50°F (28°C) cooler than the temperatures typically used in the production of HMA. Table 2.1 shows a number of technologies that satisfy this definition through different mechanisms and provide economic, environmental, and engineering benefits in terms of reduced viscosity of the binder and/or mix to allow for complete coating of the aggregate by the binder, sufficient adhesion between the aggregate and binder, and mix compactability at lower temperatures. WMA technologies as described in this section can be classified by process type as those where water is introduced (foaming) or those where water is typically not utilized (additive). Reductions in viscosity at lower temperatures are realized with the foaming technologies through the expansion of water as it turns to steam. The additive technologies rely on surfactants, rheology modifiers, and/or other organic material or waxes alone or combined with each other. More detailed information on each of the WMA technologies, including necessary plant modifications and experience/usage in the United States can be found elsewhere (NAPA, 2008; Prowell et al., 2011). Of the WMA technologies listed in Table 2.1, the majority of large volume field sections in the United States utilize Double Barrel® Green, Evotherm®, Sasobit®, and Advera® WMA, since these were the first available WMA technologies (Prowell et at., 2011).

Table 2.1. WMA Technologies

Process	Category	Technology Brand	Brief Description	Recommended Quantity
Foaming	Hydrophilic Materials	Advera® WMA/ Aspha-min® (PQ Corporation)	Synthetic zeolite composed of both aluminosilicates and alkali metals with 20% water (mostly chemically combined)	0.25% by total weight of mix
	Wet Aggregate	Low Emission/Energy Asphalt (LEA) (McConnaughay Technologies)	Binder with additive coats coarse aggregate at high temperatures plus cold, wet fine aggregate (3-4% water)	0.5% by total weight of binder
	Free Water System	Double Barrel Green® (Astec Industries, Inc.)	Water microscopically added to binder using a multi-nozzle system	1 lb of water per ton of mix
		Terex® WMA System (Terex® Roadbuilding)	Expansion chamber provides binder/water mix at desired production rate	N/A
		Ultrafoam GX™ System (Gencor Industries, Inc.)	Water injected into binder using only energy of pump supplying binder and water	1.25~2.0% water by weight of total binder
		AquaBlack™ WMA System (Maxam Equipment Company, Inc.)	Foaming gun with nozzle designed to provide binder foaming	About 1/4 cup of water per ton of WMA
		Accu-Shear™ (StanSteel)	Shearing process to force binder and water to mix together to produce foam	N/A
		WAM Foam® (Shell Bitumen)	Soft binder coats aggregate with harder binder infused with a small quantity of cold water	Soft Binder: 20~30% Hard Binder: 2.0~5.0%
		Eco-Foam II (AESCO/MADSEN)	Shear zone turbulence to enhance mixing/foaming process	1.0~2.0% of the liquid asphalt flow rate
Additive		Evotherm™ (MeadWestvaco Asphalt Innovations)	Various forms including an emulsion (with water) plus a chemical package	Approximately 5% by weight of binder
		Rediset™ WMX (Akzo Nobel Surfactants)	Rheology modifiers and surfactants that may provide anti stripping effect	1.5~2.0% by total weight of binder
		Cecabase RT® (Arkema Group)	Surfactant package directly injected into binder	0.3~0.5% by total weight of binder
		QualiTherm/HyperTherm™ (Coco Asphalt Engineering)	Non-aqueous, fatty-acid based chemical additive	0.2~3.0% by weight of the total binder
		SonneWarmmix™/ ECOBIT™ (Sonneborn, Inc.)	High melt point, paraffinic hydrocarbon blend (wax)	0.5~1.5% by weight of the total binder weight

Table 2.1 Continued

Process	Category	Technology Brand	Brief Description	Recommended Quantity
Additive		Revix™ (Mathy Technology and Engineering Services, Inc. & Paragon Technical Services)	Chemical package to reduce internal friction between binder and aggregate under high shear during production and placement	1.5~2.5% by weight of asphalt binder
		Sasobit® (Sasol Wax Americas, Inc.)	Synthetic long-chain paraffin wax reduces binder viscosity above wax melting point and solidifies at lower temperatures after placement	0.8~4% by total weight of binder
		TLA_{-X}™ Warm Mix (LakeAsphalt of Trinidad and Tobago)	Natural asphalt emulsion plus rheology modifying agents	N/A
		Shell Thiopave™ (Shell Sulphur Solutions)	Additive based on sulfur-extended asphalt technology plus compaction aid	2-2.5% by mass of the total mix

2.1.1 Foaming Processes

Foaming processes can be further categorized by how water is introduced, through hydrophilic materials, wet aggregates, or free water systems. All of these processes utilize water to create foam to reduce binder and/or mix viscosity and improve coating and compactability. When small amounts of water are added to heated asphalt binder, the water vaporizes and the vapor is encapsulated in the binder. This process causes a foaming in the binder, temporarily increasing its volume and lowering its viscosity, which improves coating and compactability.

Hydrophilic materials can be utilized as foaming admixes to introduce the small amount of water needed to produce the steam required to foam the asphalt binder and reduce its viscosity. These delivery systems release water gradually as steam at temperatures above 212°F (100°C). The most common hydrophilic material used as a foaming admix is Advera® WMA/ Aspha-min®, which is a synthetically manufactured zeolite that is approximately 20% water by mass. The water is released when pre-blended with heated binder just prior to mixing with aggregate at a high temperature of 250°F (121°C).

Wet aggregates can also be utilized to introduce water into WMA. Low Emission/Energy Asphalt (LEA) is an example of this type of WMA technology. Here, the mix viscosity is reduced by introducing cold, wet fine aggregates (3-4% moisture) to coarse aggregates that were coated with binder modified by a coating and adhesion additive at high temperatures just prior to mixing with the coarse aggregates. Again, the binder is foamed as the moisture from the fine aggregates turns to steam.

Free water systems use a foaming nozzle, a series of nozzles, or some other mechanical means of injecting the water required for foaming directly into the heated binder just prior to entering the mixing drum. Each system is designed to provide the appropriate water to binder ratio that governs the properties of the resulting foam. These systems rely on the fact that when water turns to steam at temperatures above 212°F (100°C), it expands and results in a reduction of viscosity of the binder. Many different

WMA technologies use the free water system (Table 2.1) including Double Barrel® Green, Terex® WMA System, Ultrafoam GX™ System, AquaBlack™, Accu-Shear™, and WAM Foam®. These various free water systems are a popular choice for WMA production due to relatively low cost as compared to other technologies.

2.1.2 Additives

WMA additives are chemical packages that are incorporated during mixing or added to the binder before mixing with aggregate. Detailed information concerning the exact mechanisms these additives use to produce WMA is not available due to proprietary limitations, but in general, surfactants and/or rheology modifiers and/or other organic material and waxes provide complete coating and improved adhesion and compactability.

Some chemical packages added to WMA include surfactants that work at the microscopic interface of the aggregates and the binder, and control and reduce the internal friction when the mix is subjected to high shear rates and high shear stresses during production and placement. These surfactants enhance the wetting action of the binder on the aggregate surface to facilitate complete coating and improved adhesion and compactability. Other chemical packages include waxes that reduce binder and mix viscosity when heated above the melting point of the wax, and solidify at temperatures below their melting point. Some additives such as Revix™ provide a reduction in internal friction for effective aggregate coating and compaction (Reinke et al., 2008). Other organic material such as natural occurring lake asphalt and sulfur are also included in some WMA additives.

2.1.3 Possible Complications that Arise from Differences in the Production of WMA as Compared to that of HMA

There are several possible complications that arise from differences in the production of WMA as compared to the production of HMA. These possible complications include residual or added moisture and reduced binder absorption that may lead to reduced binder-aggregate bond strength. Aggregates used in WMA production may not dry completely due to lower production temperatures, and the free water foaming technologies introduce additional moisture. This additional or residual moisture may disrupt the binder-aggregate bond. In addition, reduced binder absorption by aggregates may occur at lower production temperatures. This lower binder absorption may also decrease the binder-aggregate bond strength. Therefore, these differences in the production process may have an adverse effect on the performance of WMA.

2.2 Previous Research on Laboratory Conditioning Protocols for WMA

To simulate the binder absorption and aging that occurs during construction, the standard practice for laboratory mix design of asphalt concrete paving materials is to Short Term Oven Aging (STOA) or condition the loose mix prior to compaction for a specified time at a specific temperature. For HMA, the recommended procedure when preparing samples for performance testing is 4 hours at 275°F (135°C); for mix design, when aggregate absorption is less than 4%, the conditioning time can be reduced to 2 hours (AASHTO R30). In the past few years, a number of studies were conducted to evaluate the effect of different conditioning protocols on WMA mixture properties. However, there is currently no standard specification for WMA.

As part of recently completed National Cooperative Highway Research Project (NCHRP) 9-43 (Bonaquist, 2011), the recommended conditioning protocol for WMA is 2 hours at the planned compaction temperature (Tc). This conditioning protocol was selected based on comparisons of maximum specific gravity (AASHTO T209) and indirect tensile strength (IDT) (AASHTO T283) of LMLC specimens with those from PMFC cores. The maximum specific gravity comparison showed that the maximum theoretical density of LMLC and PMFC cores specimens was the same, indicating the same binder absorption level. The difference in indirect tensile (IDT) strength between LMLC specimens and PMFC cores was not significant based on a paired t-test comparison with a 95% confidence interval. Therefore, short-term conditioning of 2 hours at Tc was recommended for use for volumetric design and performance testing. In addition, further research was recommended to develop a two-step WMA conditioning procedure for the evaluation of moisture susceptibility and rutting resistance using the performance criteria applied to HMA. The first step would be conditioning for 2 hours at Tc to simulate pavement construction and the second step an extended conditioning time at a representative high in-service temperature but no longer than 16 hours (Bonaquist, 2011).

A study conducted at the University of California Pavement Research Center utilized the conditioning protocol of 4 hours at Tc for preparing LMLC specimens as part of a comprehensive accelerated pavement testing (APT) program (Jones, 2011). Results showed no difference in rutting depth between WMA and control HMA after HWTT (AASHTO T324) and full-scale accelerated load tests (using the heavy vehicle simulator) with this conditioning protocol. However, WMA without conditioning prior to compaction was more susceptible to rutting. These results confirm that additional laboratory conditioning significantly increases the stiffness of WMA such that equivalent performance to HMA is eventually achieved.

A recent study by Estakhri et al. (2010) evaluated the effect of three conditioning protocols [2 hours at 220°F (104°C) and 250°F (121°C) for WMA and HMA, respectively; 2 hours at 275°F (135°C); and 4 hours at 275°F (135°C)] on HWTT results for WMA mixtures prepared with a common chemical package. In addition, WMA mixtures prepared with a different chemical package and with a wax additive were conditioned with two of these protocols [2 hours at 220°F (104°C) and 250°F (121°C) for WMA and HMA, respectively, and 4 hours at 275°F (135°C)]. The results for the common chemical package showed that the number of passes to a 0.5in (12.5mm) rut depth rose with increasing conditioning temperature and time, and that the mixture conditioned for 4 hours at 275°F (135°C) showed equivalent performance to the control HMA conditioned at 250°F (121°C). The HMA showed only a slight decrease in the number of passes to a 0.5in (12.5mm) rut depth when conditioned at 250°F (121°C) versus 275°F (135°C). However, the change for the WMA mixtures prepared with the three different technologies was significant for the two conditioning temperatures. The number of passes for all of the WMA mixtures was similar when conditioned at 220°F (104°C), and all three mixtures sustained much higher numbers of passes to a 0.5in (12.5mm) rut depth when conditioned at 275°F (135°C). Based on these observations, a recommendation to condition WMA for 4 hours at 275°F (135°C) was made.

A study at Illinois (Al-Qadi et al., 2010) focused on short term characterization and performance of WMA utilizing the following three different WMA technologies: Evotherm™, Sasobit, and foaming. Preliminary test results indicated that the effect of conditioning time on WMA performance varies with different WMA additives. The effect of conditioning time on Evotherm™ performance proved to be insignificant in terms of dynamic modulus (AASHTO TP79-10), flow number (AASHTO TP62-03), rutting depth (AASHTO T324), indirect tensile strength (AASHTO T322-07), and fracture energy (ASTM D7313-07a); while conditioning time had a remarkable influence on these properties for the Sasobit and the foamed mixtures.

A study at the University of Kentucky (Clements, 2011) proposed that no measures are necessarily recommended to calibrate the WMA conditioning time since no difference in flow number test (AASHTO TP62-03) and disc shaped compact tension test (ASTM D7313-07a) among WMA and HMA mixtures conditioned at different times was detected.

In general, the majority of studies that have been performed to understand the effect of conditioning prior to compaction on the performance of WMA have concluded that an increase in laboratory conditioning temperature and/or time may reduce the difference in performance between WMA and HMA. However, no standard conditioning protocol for WMA has been established to date.

3. EXPERIMENTAL DESIGN

This section first provides a review of considerations used to select WMA field projects. Next, selected field projects are introduced in detail in terms of raw materials and mix design, and protocols used to fabricate specimens in the laboratory are described. Finally, the laboratory experimental design is provided.

3.1 Field Projects

The following factors were taken into consideration in the selection of field projects to include a wide spectrum of materials and field conditions in this study: climate (wet and dry, freeze and no freeze), aggregate type, binder type, inclusion of recycled materials (recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS)), and WMA technology. Materials and cores from three field sections in Iowa, Texas, and Montana were selected based on these considerations. During construction of the Iowa and Texas field projects, raw materials and loose plant mix were acquired on-site, conditioned according to the selected protocols, and evaluated based on the selected performance parameters. Loose plant mixes were obtained for the Montana field project, and further conditioned to fabricate off-site PMLC specimens. Plant Mixed Field Compacted (PMFC) cores were obtained at all three field projects at construction and those after 6 months in service from the Iowa and Montana field projects were also acquired. All three field projects are introduced in the following subsections.

3.1.1 Iowa Field Project

The Iowa field project is near Adams County on U.S. Route 34. Five different types of aggregates from four different producers and RAP were used and combined. The gradation of the combined aggregate is presented in Figure 3.1.

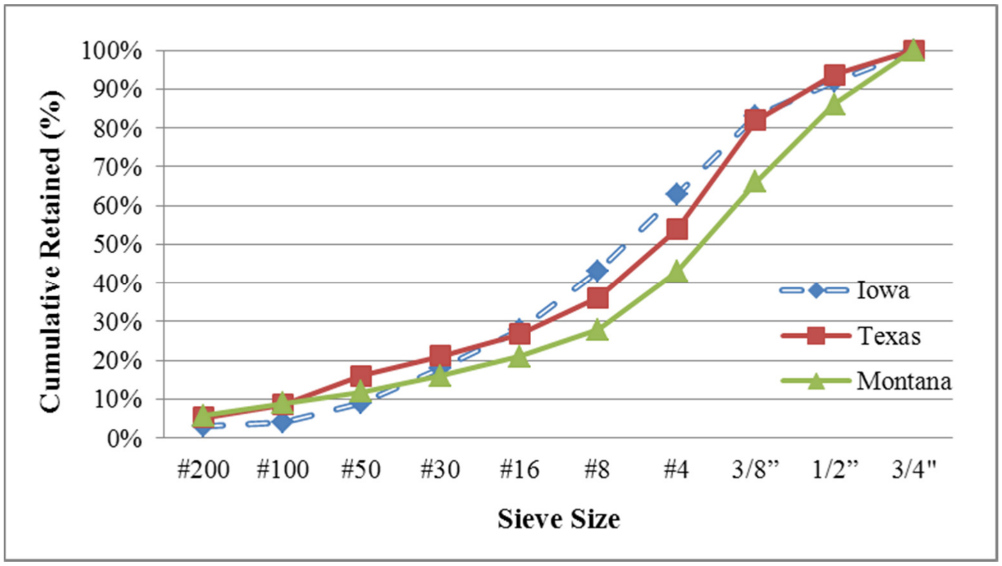


Figure 3.1. Gradation of Combined Aggregates from the Field Projects

A washed sieve analysis was conducted for combined aggregates in the laboratory. The allowable difference tolerances were ±1.0% for aggregates with sieve size bigger than #30 and ±0.5% for aggregates smaller than #30. The difference between the measured gradation from the washed sieve analysis and the given gradation in the mix design should meet the tolerance after a series of changes in the proportions of combined aggregates. Two trials with different combined proportions were conducted to meet the tolerances.

The asphalt binder used in this project was a Superpave performance-graded (PG) 58-28 binder with a specific gravity of 1.0284. The optimum binder content by the Superpave mix design process was 5.4% (by weight of the total mixture).

A third generation chemical package and a common wax additive were selected as the WMA technologies for this project. The 3rd generation chemical package is a combination of surfactants, waxes, processing aids, polymers, acids, and other materials that may provide the reduction of frictional forces between the binder and aggregate. The wax additive is a crystalline, long chain aliphatic polymethylene hydrocarbon, identical to paraffin waxes that are found in crude oil, except that it has a higher molecular weight. Due to its ability to lower the viscosity of the binder at high temperatures, this wax additive may improve the binder flow during the mixing process and during laydown operations. Both WMA additives were blended at 0.4% by weight of binder at the plant.

3.1.2 Texas Field Project

The Texas field project is on FM 973, near the Austin Bergstrom International Airport. Three rocks and two sands were used and combined. The gradation of combined aggregate is presented in Figure 3.1. A washed sieve analysis was also conducted to verify the gradation of the combined aggregates, and two trials were again used to adjust the gradation of the combined aggregates. A PG 70-22 binder with a specific gravity of 1.033 was used in this project, and the optimum binder content by the Superpave mix design process was 5.2% (by weight of the total mixture).

A second generation chemical package and a foaming process were used as WMA technologies in this field project. The chemical package has been designed to enhance coating, adhesion, and workability at lower production temperatures. In order to treat the binder with this chemical additive, the binder was heated to the mixing temperature (T_m) and the additive was blended at 5% by weight of binder. Foamed binder was produced on-site by injecting 5% water and air into the hot binder inside a special expansion chamber. In the laboratory, a foaming device that simulates the air-atomized mixing at the plant was used to produce foamed binder/mixtures with 5% water, as shown in Figure 3.2.

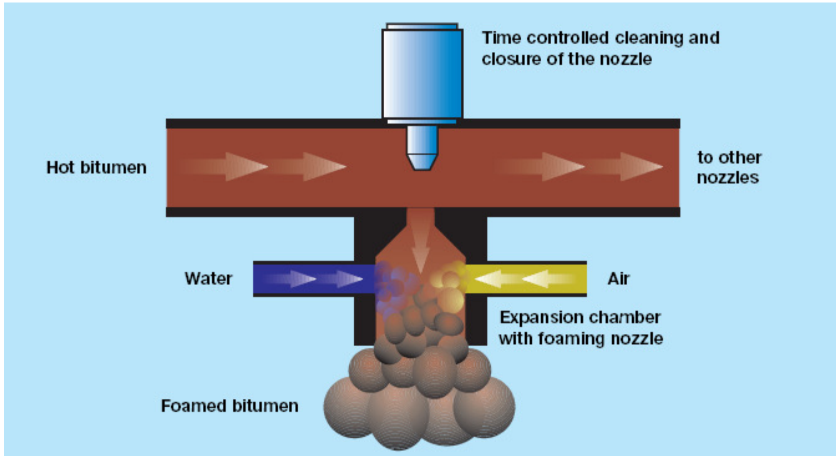


Figure 3.2. Laboratory Foaming Machine in McNew Laboratory at Texas A&M Transportation Institute (TTI) (http://www.docstoc.com/docs/79610621/FOAM-BITUMEN)

3.1.3 Montana Field Project

The Montana field project is on IH 15, near the Idaho border. Three different siliceous aggregates and lime were used and combined. The gradation of the combined aggregate is presented in Figure 3.1. A PG 70-28 binder with a specific gravity of 1.034 was used in this project, and the optimum binder content by the Superpave mix design process was 4.6% (by weight of the total mixture). A common chemical package, a wax additive, and a foaming process were used as WMA technologies in this field project. The compaction temperatures of WMA used in Montana field project are significantly higher than those in Iowa and Texas field projects. Thus, off-site PMLC specimens were fabricated following the recommended conditioning protocol proposed based on M_R data from Iowa and Texas field projects, and tested with M_R to validate the laboratory conditioning protocol.

3.1.4 Summary of Compaction Temperatures Used in the Field Projects

Compaction temperatures used in the Iowa, Texas, and Montana field projects are summarized in Table 3.1.

Table 3.1. Summary of Compaction Temperatures (T_c) Used in the Field Projects

Location and Environmental Condition	Mixture Type	Specimen Type				
		PMFC (°F)	On-Site PMLC 0-1h (°F)	On-Site PMLC 1-2h (°F)	LMLC (°F)	Off-Site PMLC (°F)
Iowa (Wet, Freeze)	HMA	295-300	N/A	295-300	295	295
	WMA with 3rd Generation CP	240-248	N/A	240-248	240	240
	WMA with Wax Additive	235-240	N/A	235-240	240	240
Texas (Wet, No-Freeze)	HMA	270-285	275	275	275	275
	WMA with 2nd Generation CP	230-235	225	225	240	240
	WMA with Foaming Process	240-250	225	250	235	275
Montana (Dry, Freeze)	HMA	310-315	N/A	315	N/A	315
	WMA with CP	270-280	N/A	275	N/A	275
	WMA with Wax Additive	275-280	N/A	279	N/A	279
	WMA with Foaming Process	270-275	N/A	271	N/A	271

CP: chemical package

3.2 Specimen Fabrication

To fabricate LMLC specimens, aggregates and binder were heated to the specified T_m independently and then mixed with a portable mixer. Afterwards, loose mixes were conditioned in the oven following a specific conditioning protocol prior to compaction with the Superpave Gyratory Compactor (SGC). Trial specimens were fabricated to assure specimens were obtained with air void contents (AV) of 7±0.5%. In total, 180 LMLC specimens with 7±0.5% AV were fabricated for the Iowa and Texas field projects that included six mixtures and five laboratory conditioning protocols described subsequently. Most LMLC specimens were tested to determine M_R approximately 2 to 3 weeks after fabrication.

To fabricate off-site PMLC specimens at the TTI laboratory, loose plant mixes were taken out of buckets and reheated in an oven to the specified conditioning temperature. After being reheated to T_c, loose mixes were further conditioned in the oven during a controlled period of time following the conditioning protocol prior to compaction. A total of 180 off-site PMLC specimens were fabricated for the Iowa, Texas, and Montana field projects that included nine mixtures and four laboratory conditioning protocols described subsequently. Loose mixes from the Iowa field project were stored for 1 to 2 months and those from the Texas field project were stored for 3 to 4 months prior to being fabricated. Most off-site PMLC specimens were tested to determine M_R approximately 2 to 3 weeks after fabrication.

For the Iowa and Montana field projects, PMFC cores were obtained at construction and after six months in service. To fabricate on-site PMLC specimens, loose mixes were taken from the trucks before leaving the plant and maintained in the oven for 1-2 hours at the specified temperature prior to compaction. Therefore, 18 PMFC cores and 9 on-site PMLC specimens from the Iowa field project and 24 PMFC cores and on-site PMLC specimens from the Montana field project were tested in this study. The placement of pavement sections in the Texas field project was completed in January 2012; therefore, only field cores at construction were included in this portion of the study. On-site PMLC specimens for the Texas field project were maintained in the oven for 0-1 hour and 1-2 hours at the specified temperature before compaction. Overall, 9 PMFC cores and 18 on-site PMLC specimens from the Texas field project were tested. PMFC cores and on-site PMLC specimens from all three field projects were tested to determine M_R after approximately 1 month and 2 months, respectively, in storage.

3.3 Laboratory Experimental Design

The goal of this study was to recommend conditioning protocols consisting of a combination of time and temperature that produce WMA LMLC and off-site PMLC specimens calibrated to field cores or PMLC specimens fabricated on-site during construction. Figure 3.3 presents the research methodology employed for this study.

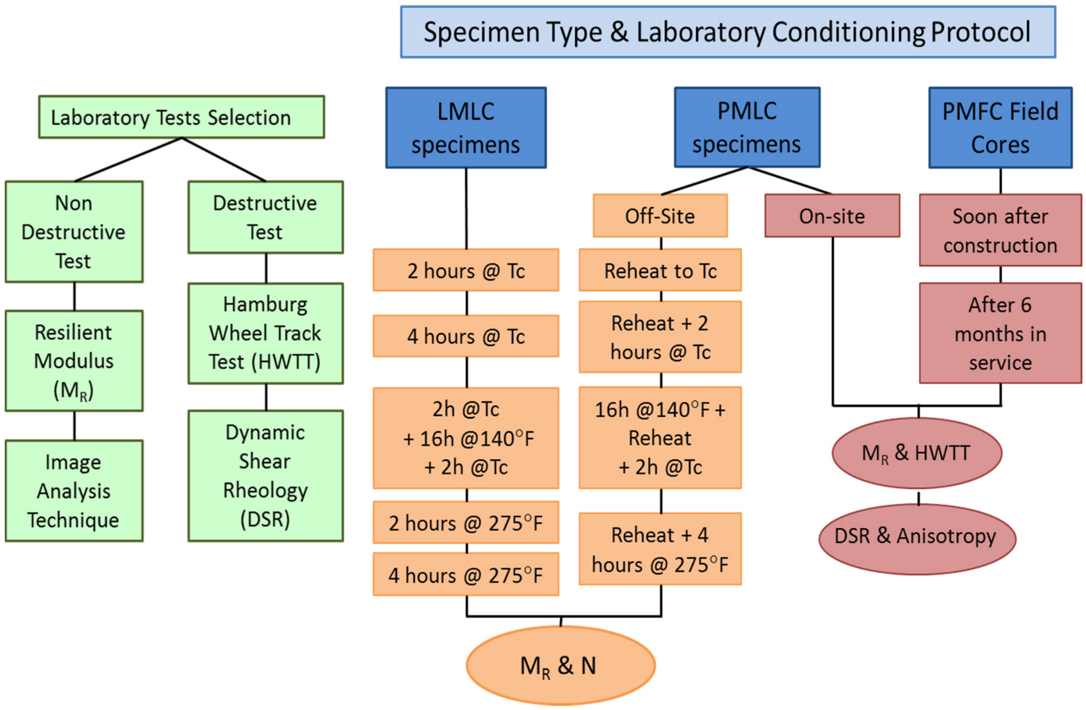


Figure 3.3. Flow Chart of the Experimental Design

3.3.1 Laboratory Test Selection

Based on previous experience with laboratory tests in evaluating asphalt mixture stiffness, one non-destructive test and one destructive test were selected to quantify the mixture stiffness in dry and wet conditions. The selected non-destructive test of choice was M_R, which is cost effective and able to provide an accurate indicator of the mixture stiffness in a dry condition at 77°F (25°C). A minimum of three replicate specimens were utilized, and each replicate was tested twice (i.e., rotating the specimen 90° after the first measurement). In addition to M_R values, the corresponding number of SGC gyrations (N) required in specimen fabrication to achieve 7±0.5% AV was used as an alternative indicator of the mixture stiffness in a dry condition and compactability. The selected destructive test was the HWTT (AASHTO T324) that considers both rutting and moisture susceptibility of the mixture. This test was proposed for capturing mixture stiffness in a wet condition. The test consists of submerging specimens in warm water (122°F (50°C)) while a loaded steel wheel passes on top of the specimen causing it to rut. The stripping inflection point (SIP) and rutting depths at certain number of passes were utilized as two test parameters.

3.3.2 Laboratory Conditioning Protocol Selection

As shown in Tables 3.2 and 3.3, five different conditioning protocols were selected for LMLC specimens prior to compaction and four different ones were applied to off-site PMLC specimens after reheating to the specified conditioning temperature. For LMLC specimens, the conditioning protocol of 2 hours at T_c for was proposed since it was recommended by the recently completed NCHRP Project 9-43, and 4 hours at 275°F (135°C) was proposed because it is the current standard in the state of Texas. The comprehensive conditioning protocol of 2 hours at T_c followed by 16 hours at 140°F (60°C) and 2 hours at T_c was proposed during a WMA workshop (Harrigan, 2012) held in May 2011, in Irvine, California. The other two protocols utilized were derived by combining common conditioning temperatures and times. For off-site PMLC specimens, the conditioning protocol of reheating to T_c was proposed as the least amount of conditioning time/temperature possible prior to compaction. Additionally, three protocols proposed for LMLC specimens were also used to prepare off-site PMLC specimens. The recommended laboratory conditioning protocol for off-site PMLC specimens was proposed based on M_R data from the Iowa and Texas field projects. Since the Montana compaction temperatures for both HMA and WMA were significantly higher than those for Iowa and Texas, off-site PMLC specimens from the Montana field project were fabricated following the recommended protocol as well as the one consisting of the same conditioning time at T_c, and tested with M_R to validate the recommended protocol. Volumetrics of LMLC specimens and on-site PMLC specimens were calculated and compared in terms of binder absorption and film thickness (STP 204-19).

Field cores and on-site PMLC specimens were expected to have similar stiffnesses as they experienced approximately the same level of binder aging. However, their performance in M_R tests was significantly different as described subsequently and thus binder was extracted and recovered from these specimens to measure the difference in binder stiffness with the Dynamic Shear Rheometer (DSR). In addition, images were acquired from the same specimens through a novel method (Zhang et al., 2011) to evaluate the effect of aggregate orientation by different compaction methods on mixture stiffness.

Table 3.2. Laboratory Conditioning Test Plan for M_R and N to 7% AV for LMLC Specimens

Location and Environmental Condition	Mixture Type	Laboratory Conditioning Protocols				
		2h@T_c	2h@275°F	4h@T_c	2h@T_c+16h@140°F+2h@T_c	4h@275°F
Iowa (Wet, Freeze)	HMA	X	X	X	X	X
	WMA with 3rd Generation CP	X	X	X	X	X
	WMA with Wax Additive	X	X	X	X	X
Texas (Wet, No-Freeze)	HMA	X	X	X	X	X
	WMA with 2nd Generation CP	X	X	X	X	X
	WMA with Foaming	X	X	X	X	X

CP: chemical package
h: hour(s)

Table 3.3. Laboratory Conditioning Test Plan for M_R and N to 7% AV for Off-Site PMLC Specimens

Location and Environmental Condition	Mixture Type	Laboratory Conditioning Protocols			
		R	R+2h@T_c	R+16h@140°F+2h @T_c	R+4h@275 °F
Iowa (Wet, Freeze)	HMA	X	X	X	X
	WMA with 3rd Generation CP	X	X	X	X
	WMA with Wax Additive	X	X	X	X
Texas (Wet, No-Freeze)	HMA	X	X	X	X
	WMA with 2nd Generation CP	X	X	X	X
	WMA with Foaming	X	X	X	X
Montana (Dry, Freeze)	HMA	Recommended Protocol (w/ normal WMA T_c)			Recommended Protocol (w/ high WMA T_c)
	WMA with 2nd Generation CP				
	WMA with Wax Additive				
	WMA with Foaming Process				

CP: chemical package
R: reheat
h: hour(s)

4. TEST RESULTS AND DATA ANALYSIS

This chapter provides the test results for HMA and WMA following different conditioning protocols used in this study. Volumetrics, M_R stiffness, binder stiffness, aggregate orientation, N to 7% AV, and HWTT results are shown and analyzed.

4.1 Mixture Volumetrics

Table 4.1 presents the comparison of volumetrics of LMLC and on-site PMLC specimens maintained in the oven for 1-2 hours at the specified temperature prior to compaction from the Iowa and Texas field projects in terms of rice specific gravity (G_{mm}), percentage of absorbed binder (P_{ba}), and effective binder film thickness (FT). They are calculated based on aggregate gradation, percentage of binder in the mixture, and G_{mm}.

Table 4.1. Volumetrics of Different Asphalt Mixtures in the Iowa and Texas Field Projects

Location and Environmental Condition	Mixture Type	Specimen Type	G_{mm}	P_{ba} (%)	FT (µm)
Iowa	HMA	LMLC	2.415	0.82	13.2
		On-Site PMLC 1-2h	2.443	1.32	11.9
	WMA with 3rd Generation Chemical Package	LMLC	2.400	0.53	14.0
		On-Site PMLC 1-2h	2.434	1.17	12.3
	WMA with Wax Additive	LMLC	2.374	0.04	15.3
		On-Site PMLC 1-2h	2.438	1.24	12.1
Texas	HMA	LMLC	2.397	0.10	12.5
		On-Site PMLC 1-2h	2.420	0.53	11.5
	WMA with 2nd Generation Chemical Package	LMLC	2.399	0.13	12.4
		On-Site PMLC 1-2h	2.408	0.30	12.0
	WMA with Foaming Process	LMLC	2.407	0.28	12.1
		On-Site PMLC 1-2h	2.400	0.15	12.4

The comparison among different specimen types shows that all LMLC specimens (except for foamed WMA from the Texas field project) had lower G_{mm}, lower

P_{ba}, and higher FT than corresponding on-site PMLC specimens. These results reveal that on-site PMLC specimens experienced more conditioning prior to compaction. Additionally, all WMA mixtures from the Iowa field project had lower G_{mm} and P_{ba} and larger FT than the corresponding control HMA for a given specimen type, which might be caused by the lower production temperature for WMA. A similar trend was observed for on-site PMLC specimens from the Texas field project while volumetrics of HMA and WMA LMLC specimens were opposite. The lower P_{ba} for WMA might decrease the bonding strength between aggregates and binders, making WMA more susceptible to moisture and subsequent stripping. Differences in volumetrics were also evident for WMA with different technologies.

4.2 Resilient Modulus (M_R)

The M_R test is conducted through repetitive applications of compressive loads in a haversine waveform along a vertical diametral plane of cylindrical asphalt concrete specimens. The resulting horizontal deformations of the specimen are measured by two linear variable differential transducers (LVDT) aligned along the horizontal diametral plane. M_R of the specimen is calculated based on vertical load, horizontal deformation, and the asphalt mixture's Poisson's ratio at the test temperature. The M_R test equipment used to perform the measurements is shown in Figure 4.1. LMLC and off-site PMLC specimens with different conditioning protocols, PMFC cores, and on-site PMLC specimens were tested to determine M_R in accordance with the current ASTM D-7369 with a modification consisting of replacing the on-specimen LVDTs with LVDTs aligned along the horizontal diametral plane (i.e., gauge length as a fraction of diameter of the specimen = 1.00).

(a) (b) (c)

Figure 4.1. M_R Test Equipment; (a) Loading Frame and Data Acquisition System, (b) Specimen with Mounted LVDTs, (c) Specimen Setup in Loading Frame

4.2.1 Laboratory Conditioning Protocols for LMLC Specimens

Figure 4.2 and Figure 4.3 present M_R results of PMFC cores, on-site PMLC specimens, and LMLC specimens for the Iowa and Texas field projects, respectively. In each graph, PMFC cores and on-site PMLC specimens are presented on the left and the LMLC specimens with different conditioning protocols are shown on the right. Each bar in Figures 4.2 and 4.3 represents the average value of three replicate specimens, and the error bars represent ± one standard deviation from the average value.

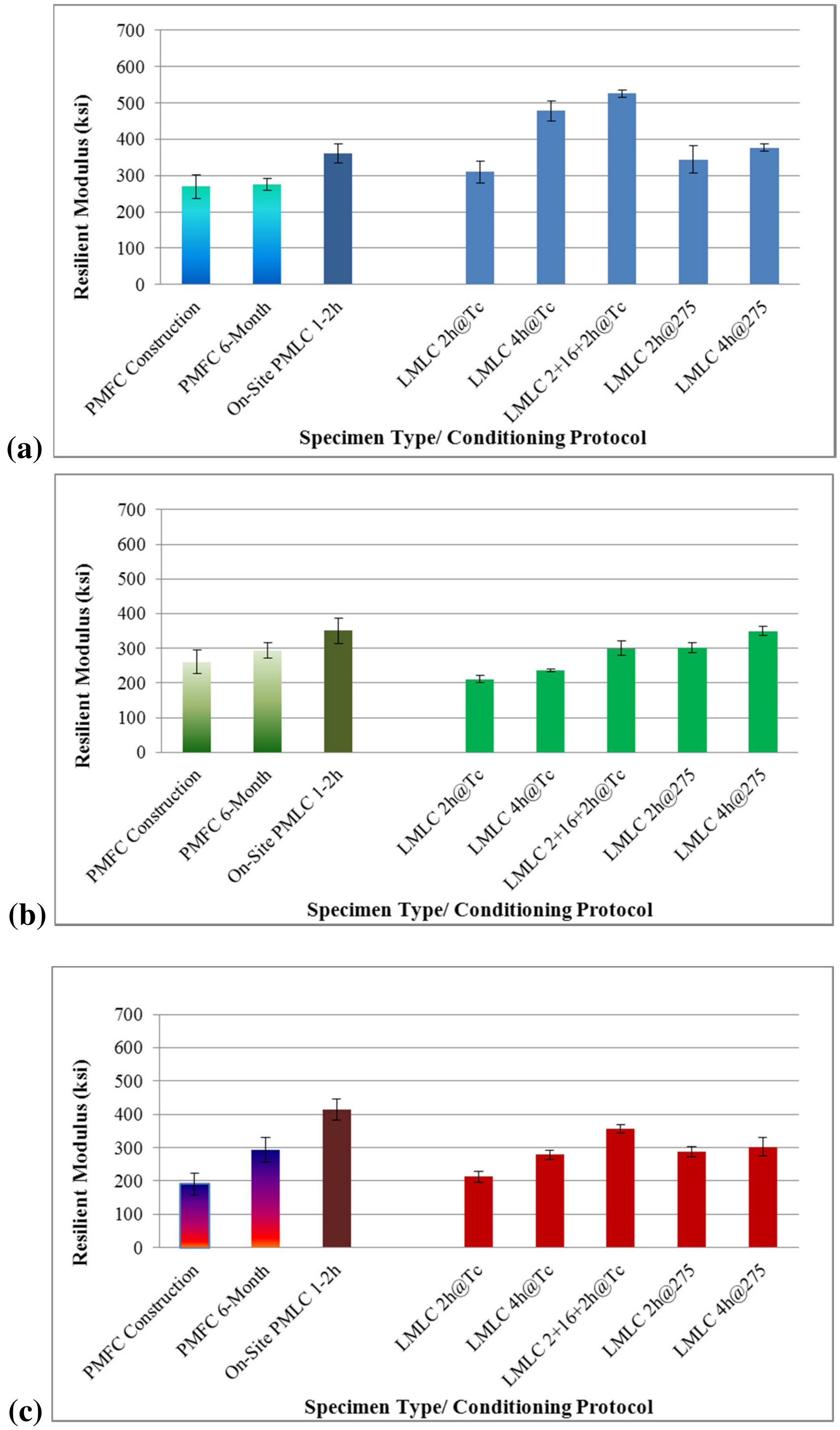


Figure 4.2. Comparison of Iowa PMFC and On-Site PMLC Specimens with LMLC Specimens with Different Conditioning Protocols in Terms of M_R; (a) HMA, (b) WMA with 3rd Generation Chemical Package, (c) WMA with Wax Additive

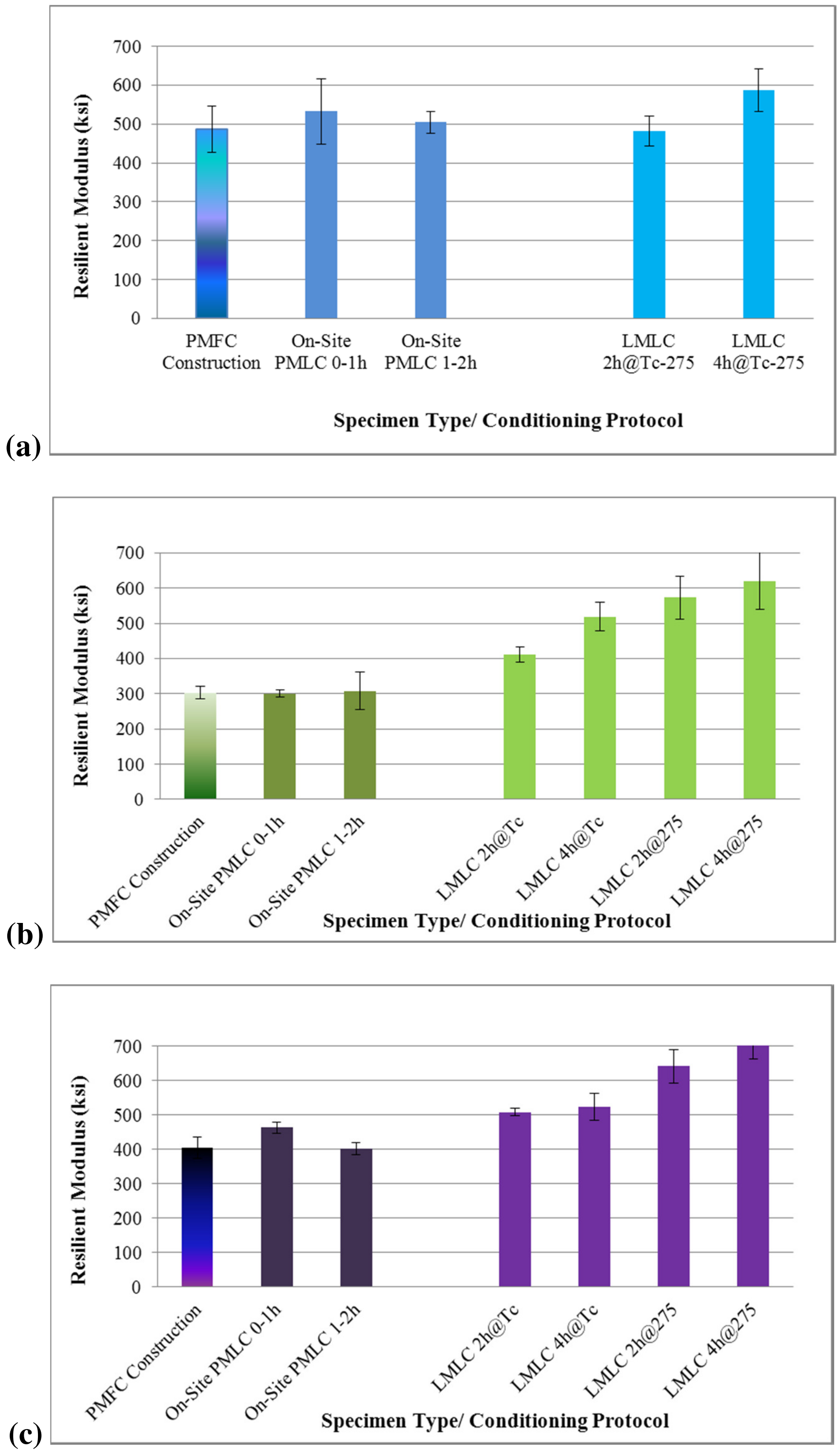


Figure 4.3. Comparison of Texas PMFC and On-Site PMLC Specimens with LMLC Specimens with Different Conditioning Protocols in Terms of M_R; (a) HMA, (b) WMA with 2nd Generation Chemical Package, (c) WMA with Foaming Process

As illustrated in Figure 4.2 for Iowa, HMA and WMA on-site PMLC specimens had higher stiffnesses as compared to the PMFC cores after construction and after six months in-service. The stiffness of the HMA and WMA with 3rd generation chemical package PMFC cores increased slightly after six months in service, while PMFC cores of WMA with wax additive increased significantly. In addition, the longer conditioning protocols for LMLC specimens resulted in specimens with stiffnesses equivalent to or beyond the M_R values measured in the early life of the pavement. Among the five conditioning protocols applied to LMLC specimens, 2 hours at T_c and 2 hours at 275°F (135°C) produced enough aging such that the stiffness of the specimens was equivalent to the stiffness of PMFC cores at construction. Additionally, WMA specimens conditioned with 2 hours at 275°F (135°C) had significantly higher stiffnesses than those conditioned with 2 hours at T_c, while WMA specimens conditioned with 2 hours and 4 hours at T_c had similar stiffnesses. Thus, it can be inferred that WMA specimens are more susceptible to conditioning temperature rather than conditioning time in terms of changes in M_R.

Comparison of M_R results for the PMFC cores and on-site PMLC specimens from the Texas field project showed that there was no increase in stiffness for on-site PMLC specimens conditioned with 1-2 hours at T_c as compared to those conditioned with 0-1 hour at the same temperature (Figure 4.3). In addition, on-site PMLC specimens and PMFC cores had similar stiffness values. The conditioning protocol of 2 hours at T_c followed by 16 hours at 140°F (60°C) and 2 hours at T_c was not performed on LMLC specimens from the Texas field project given the high stiffness values obtained for the same protocol in the Iowa field project and the more impractical nature of this protocol. Among four conditioning protocols applied to the LMLC specimens, 2 hours at T_c more closely represented the stiffness of the pavement in its early life. Similar trends to the ones obtained for the Iowa field project were observed with the stiffness increasing with higher conditioning temperature and longer conditioning time, and the stiffness of the mixtures being more sensitive to conditioning temperature versus conditioning time (Figure 4.3).

Based on the results shown, 2 hours at T_c and 2 hours at 275°F (135°C) are the recommended conditioning protocols for LMLC specimens to simulate the stiffness of WMA and HMA pavements in their early life, respectively. A statistical analysis was completed to further justify this recommendation and account for the variability in the M_R results. Analysis of Variance (ANOVA) and Tukey-Kramer Honestly Significant Difference (Tukey's HSD) tests were conducted with a 95% confidence level to verify the difference in M_R between the conditioned LMLC specimens versus the PMFC cores and on-site PMLC specimens. Initially, in addition to the main factor of interest Conditioning Protocol, the effect of Orientation (i.e., rotating the specimen 90^o after the first the measurement) as well as the interaction effect between Orientation and Conditioning Protocol was also tested by utilizing a more sophisticated ANOVA analysis (a split plot design analysis). It was confirmed from the split plot design analysis that neither the effect of interaction between Orientation and Conditioning Protocol nor the main effect of Orientation was statistically significant for any of the mixtures considered. The effect of Conditioning Protocol was statistically significant for all mixtures except for Texas HMA. The general results of Tukey's HSD test on Conditioning Protocol are shown in Figure 4.4 and 3.5 with different capital letters above the M_R results. The M_R values decrease as letters change from *A* to *E*. Conditioning protocols with different letters have M_R values that are significantly different from each other. A detailed comparison for all conditioning protocols versus PMFC cores and on-site PMLC specimens is summarized in Table 4.2. As shown, 2 hours at 275°F (135°C) resulted in HMA LMLC specimens with stiffnesses that were statistically equivalent to PMFC cores and on-site PMLC specimens. For all WMA mixtures except those with the 3rd generation chemical package from the Iowa field project, LMLC specimens conditioned with 2 hours at T_c had stiffnesses statistically equivalent to corresponding PMFC cores and/or on-site PMLC specimens.

As shown in Figure 4.4 and 4.5, equivalent stiffness between HMA LMLC specimens conditioned at 2 hours at 275°F (135°C) and PMFC cores and/or on-site PMLC specimens were verified by the outcome of the statistical analysis. For Iowa

WMA with wax additive and Texas foamed WMA, the conditioning protocol of 2 hours at T_c was able to simulate the stiffness of PMFC cores at construction and on-site PMLC specimens, respectively, as indicated by the same statistical grouping. For Texas WMA with the 2nd generation chemical, the conditioning protocol of 2 hours at T_c was able to simulate mixture stiffness for both PMFC cores at construction and on-site PMLC specimens. For Iowa WMA with the 3rd generation chemical package, 2 hours at T_c represented more closely the stiffness of PMFC cores at construction while 2 hours at 275°F (135°C) was able to simulate the stiffness of pavements at all conditions in their early life. Nevertheless, a single conditioning protocol for preparing WMA LMLC specimens consisting of 2 hours at T_c is desirable.

However, in most instances T_c is not specified in the mix design and it is sometimes arbitrarily selected, with different values used for LMLC specimens, on-site PMLC specimens, and placement temperatures during pavement construction. As highlighted in Table 3.1, T_c for most LMLC and off-site PMLC WMA mixtures was approximately 240°F (116°C) with the exception of the foaming mixture in the Texas field project. Therefore, it is ultimately recommended that 2 hours at 240°F (116°C) and 2 hours at 275°F (135°C) be used as standard laboratory conditioning protocols for WMA and HMA, respectively.

Table 4.2. Summary of Statistical Analysis Results of Difference between Different Laboratory Conditioning Protocols for LMLC Specimens and PMFC cores and On-Site PMLC Specimens in M_R

Mixture Type		Conditioning Protocols for Preparing LMLC Specimens				
		$2h@T_c$	$4h@T_c$	$2+16+2h@T_c$	2h@275	4h@275
Iowa	HMA	PMFC PMFC 6-M On-Site PMLC	High	High	PMFC 6-M On-Site PMLC	On-Site PMLC
	WMA with 3rd Generation CP	Low	PMFC PMFC 6-M	PMFC PMFC 6-M On-Site PMLC	PMFC PMFC 6-M On-Site PMLC	PMFC 6-M On-Site PMLC
	WMA with Wax Additive	PMFC	PMFC 6-M	PMFC 6-M On-Site PMLC	PMFC 6-M	PMFC 6-M
Texas	HMA	PMFC On-Site PMLC	PMFC On-Site PMLC		PMFC On-Site PMLC	PMFC On-Site PMLC
	WMA with 2nd Generation CP	PMFC On-Site PMLC	High		High	High
	WMA with Foaming	On-Site PMLC	On-Site PMLC		High	High

CP: chemical package
h: hour(s)

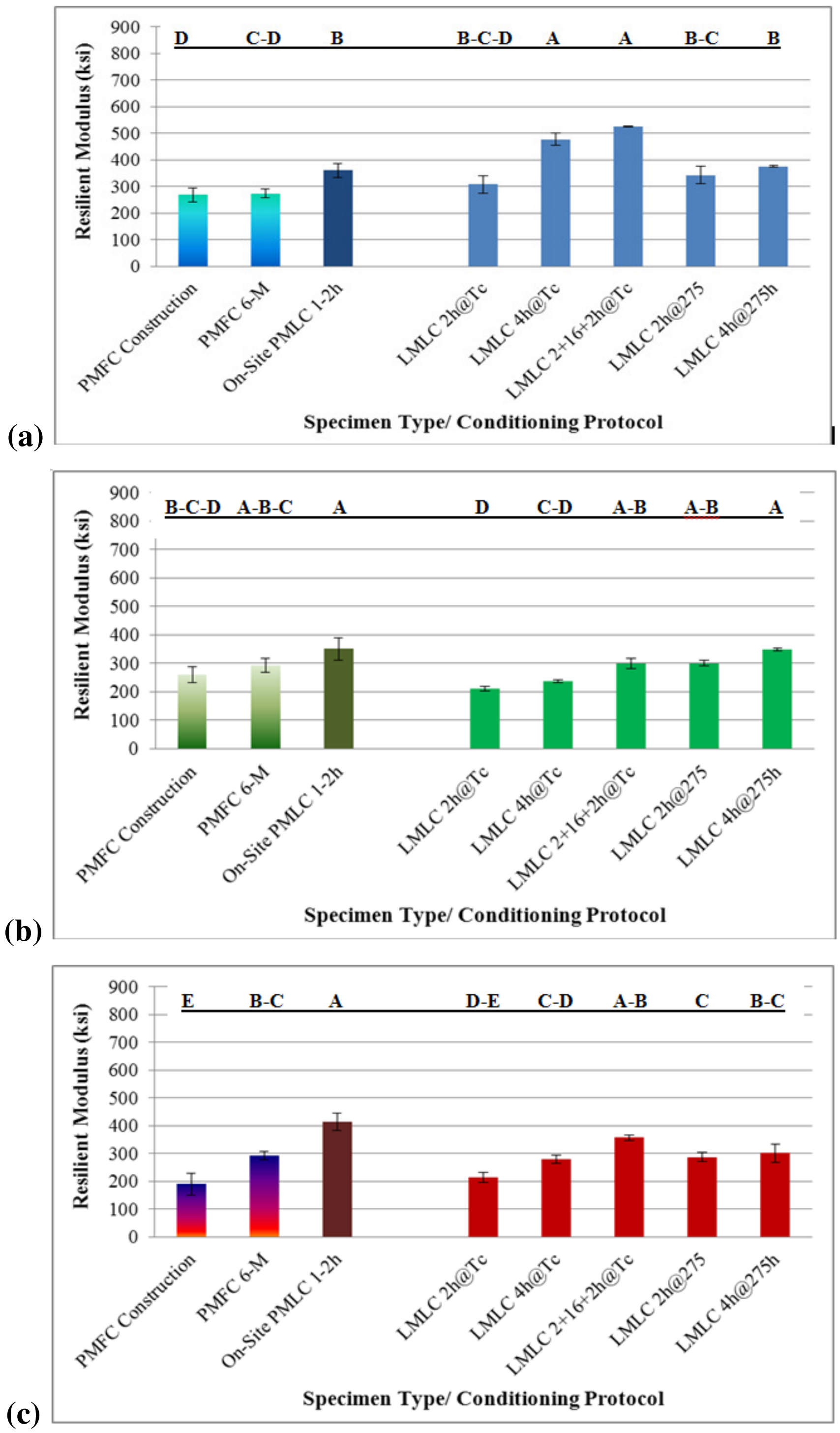


Figure 4.4. Statistical Analysis Results in Terms of Comparison of Iowa PMFC and On-Site PMLC Specimens with LMLC Specimens with Different Conditioning Protocols in M_R; (a) HMA, (b) WMA with 3rd Generation Chemical Package, (c) WMA with Wax Additive

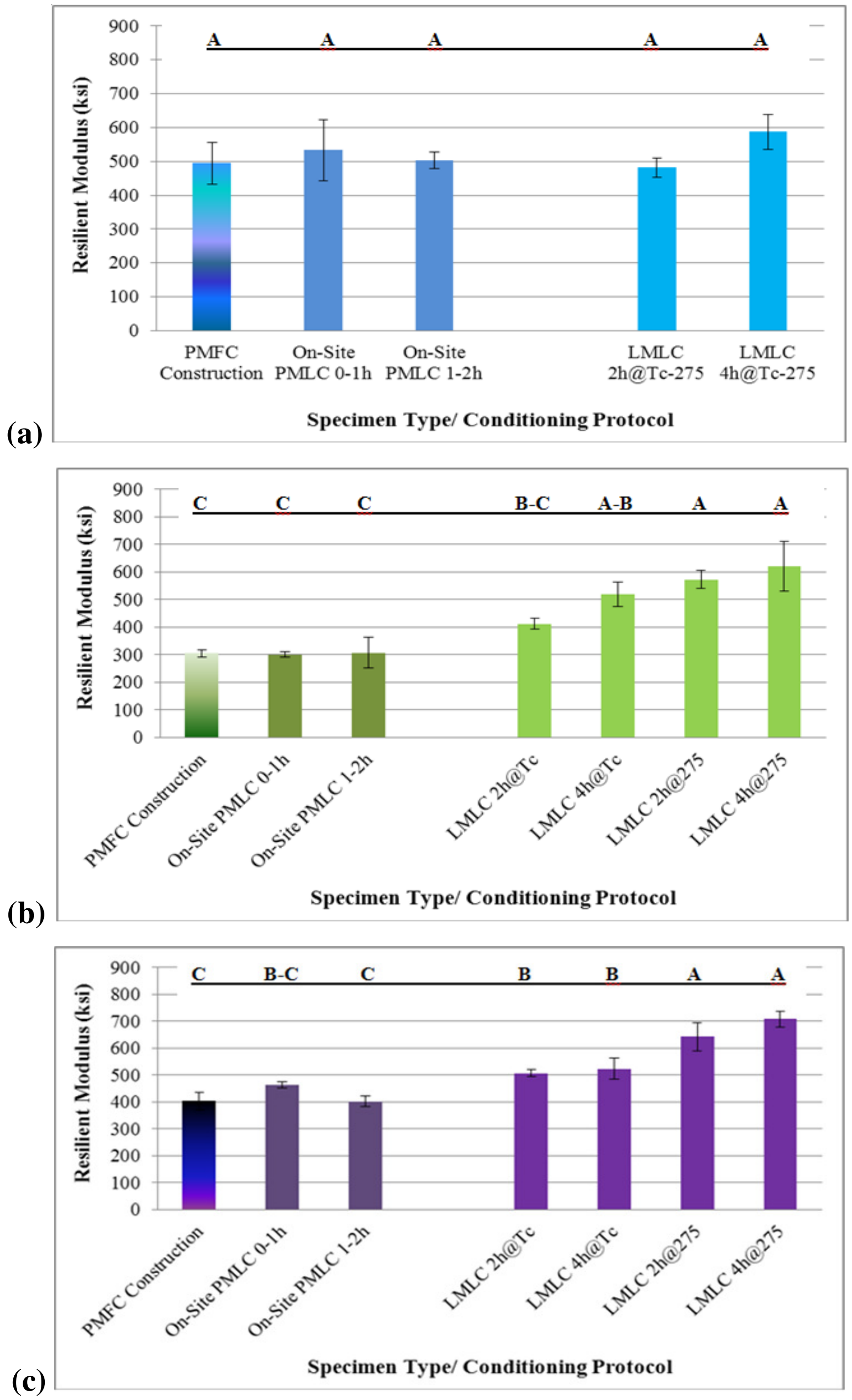
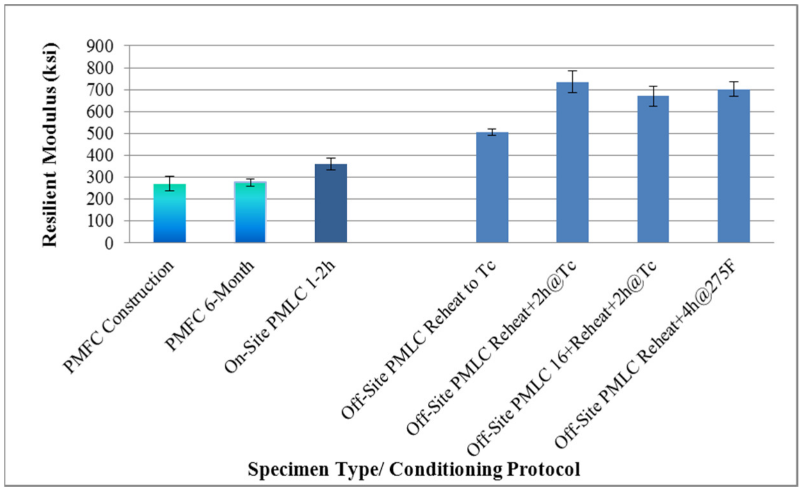


Figure 4.5. Statistical Analysis Results in Terms of Comparison of Texas PMFC and On-Site PMLC Specimens with LMLC Specimens with Different Conditioning Protocols in M_R; (a) HMA, (b) WMA with 2^{nd} Generation Chemical Package, (c) WMA with Foaming Process

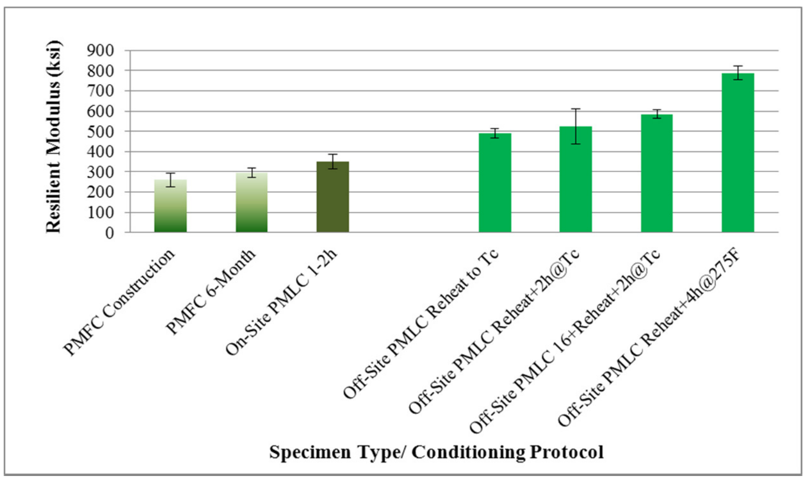
4.2.2 Laboratory Conditioning Protocols for Off-Site PMLC Specimens

Figures 4.6 and 4.7 present the M_R results for PMFC cores, on-site PMLC specimens, and off-site PMLC specimens for the Iowa and Texas field projects, respectively. In each graph, PMFC cores and on-site PMLC specimens are located on the left and off-site PMLC specimens subjected to different conditioning protocols are shown on the right. Each bar in Figures 4.6 and 4.7 represents the average value of three replicate specimens, and the error bars represent ± one standard deviation from the average value.

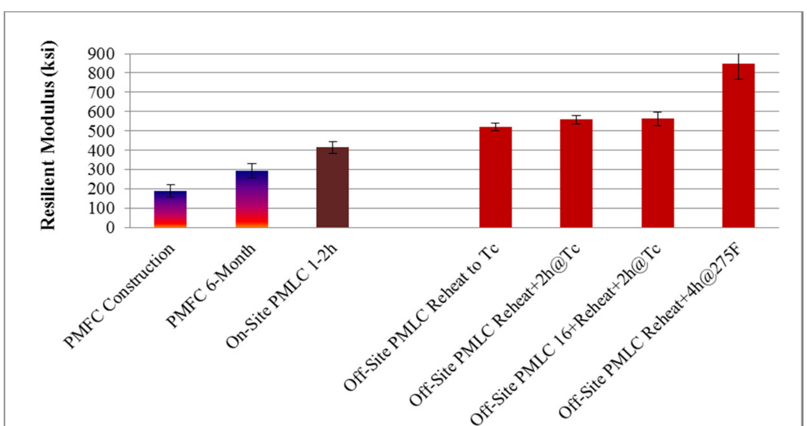
Figure 4.6 and Figure 4.7 show that off-site PMLC specimens conditioned with all laboratory conditioning protocols had significantly higher stiffness as compared to PMFC cores or on-site PMLC specimens for all mixtures except Texas HMA. In addition, the stiffness of off-site PMLC specimens increased or was equivalent to those with higher conditioning temperature and/or longer conditioning time. From these trends, it is apparent that the process of reheating loose mix significantly increases its stiffness. The smallest difference in stiffness values between PMFC cores or on-site PMLC specimens versus off-site PMLC specimens corresponded to the conditioning/curing protocol of reheating to T_c. Therefore, reheating to T_c is the best candidate for a standard laboratory conditioning protocol for preparing WMA off-site PMLC specimens made with additives. Foamed WMA, on the other hand, requires a different conditioning protocol since the foaming effect during production is lost after mixing and cooling of the loose mix. Table 3.1 shows that the Iowa field project HMA T_c was 295°F (146°C) and T_c used in the Texas field project was 275°F (135°C). However, the conditioning protocol of reheating to 275°F (135°C) was able to provide enough compactability for the loose HMA from both field projects. Based on these results, reheating to 275°F (135°C) is recommended as the standard conditioning protocol for HMA and foamed WMA off-site PMLC specimens.



(a)

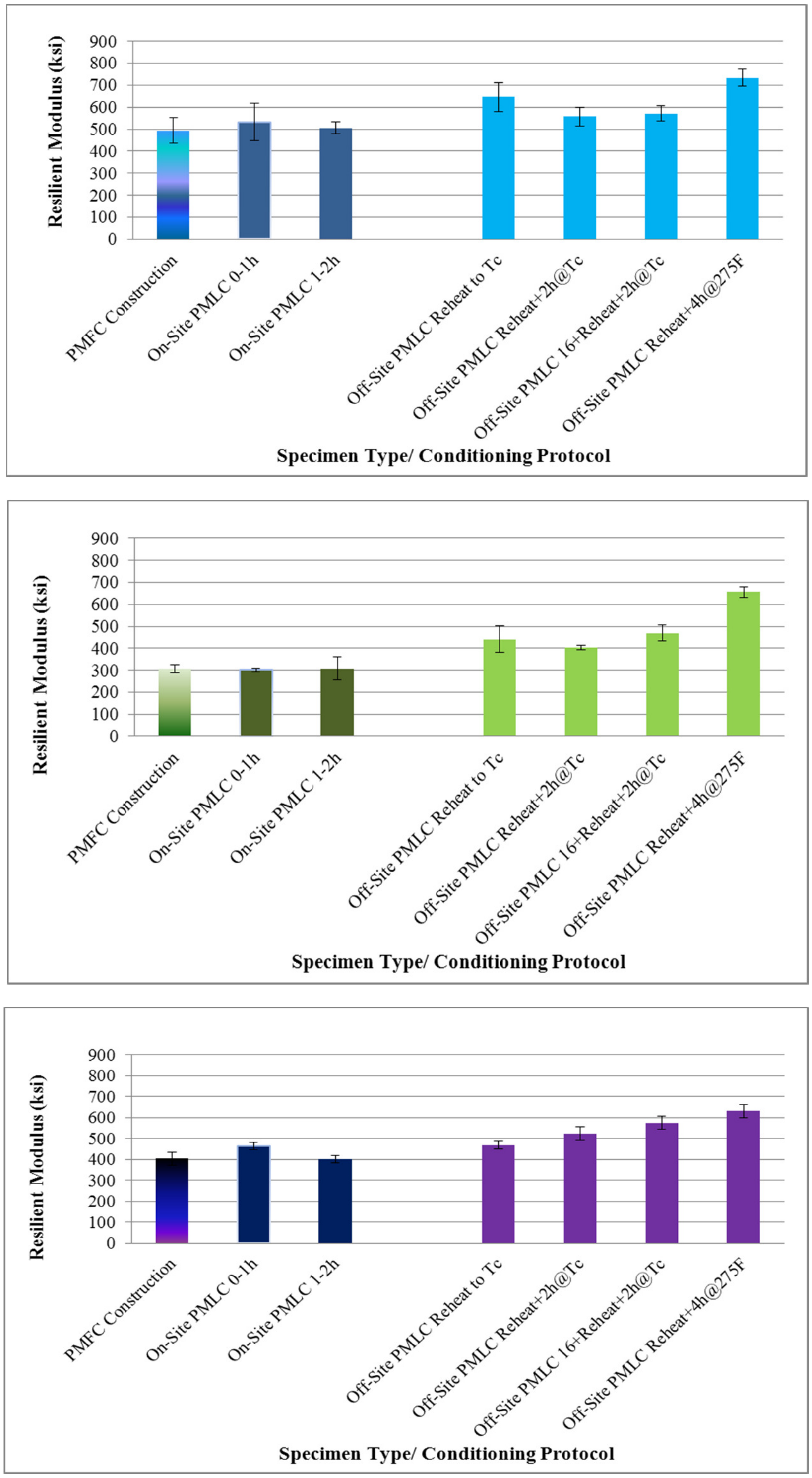


(b)



(c)

Figure 4.6. Comparison of Texas PMFC and On-Site PMLC Specimens with Off-Site PMLC Specimens with Different Conditioning Protocols in Terms of M_R; (a) HMA, (b) WMA with 3rd Generation Chemical Package, (c) WMA with Wax Additive



(a) **(b)** **(c)**

Figure 4.7. Comparison of Texas PMFC and On-Site PMLC Specimens with LMLC Specimens with Different Conditioning Protocols in Terms of M_R; (a) HMA, (b) WMA with 2nd Generation Chemical Package, (c) WMA with Foaming Process

Statistical analysis similar to that used for the LMLC specimens was utilized to verify the difference in M_R between PMFC cores and on-site PMLC specimens versus off-site PMLC specimens subjected to the different conditioning protocols. The interaction effect between Conditioning Protocol and Orientation was statistically insignificant for all mixtures. The main effect Orientation was statistically insignificant for all mixtures except for Texas WMA with the 2nd generation Chemical Package but the difference was practically insignificant. The effect of Conditioning Protocol was statistically significant for all mixtures. The general results of Tukey's HSD test are shown in Figures 4.8 and 4.9 in capital letters above the bars. Conditioning protocols with different letters have M_R values that are significantly different from each other. A detailed comparison for all conditioning protocols versus PMFC cores and on-site PMLC specimens is summarized in Table 4.3. As shown, for all Iowa mixtures, all selected conditioning protocols yielded off-site PMLC specimens with statistically higher stiffness values as compared to either PMFC cores or on-site PMLC specimens. The smallest difference in terms of M_R between PMFC cores or on-site PMLC specimens versus off-site PMLC specimens for these mixtures was found after reheating to T_c prior to compaction, and this protocol also resulted in statistically equivalent stiffnesses to Texas foamed WMA on-site PMLC specimens and Texas HMA PMFC cores and on-site PMLC specimens.

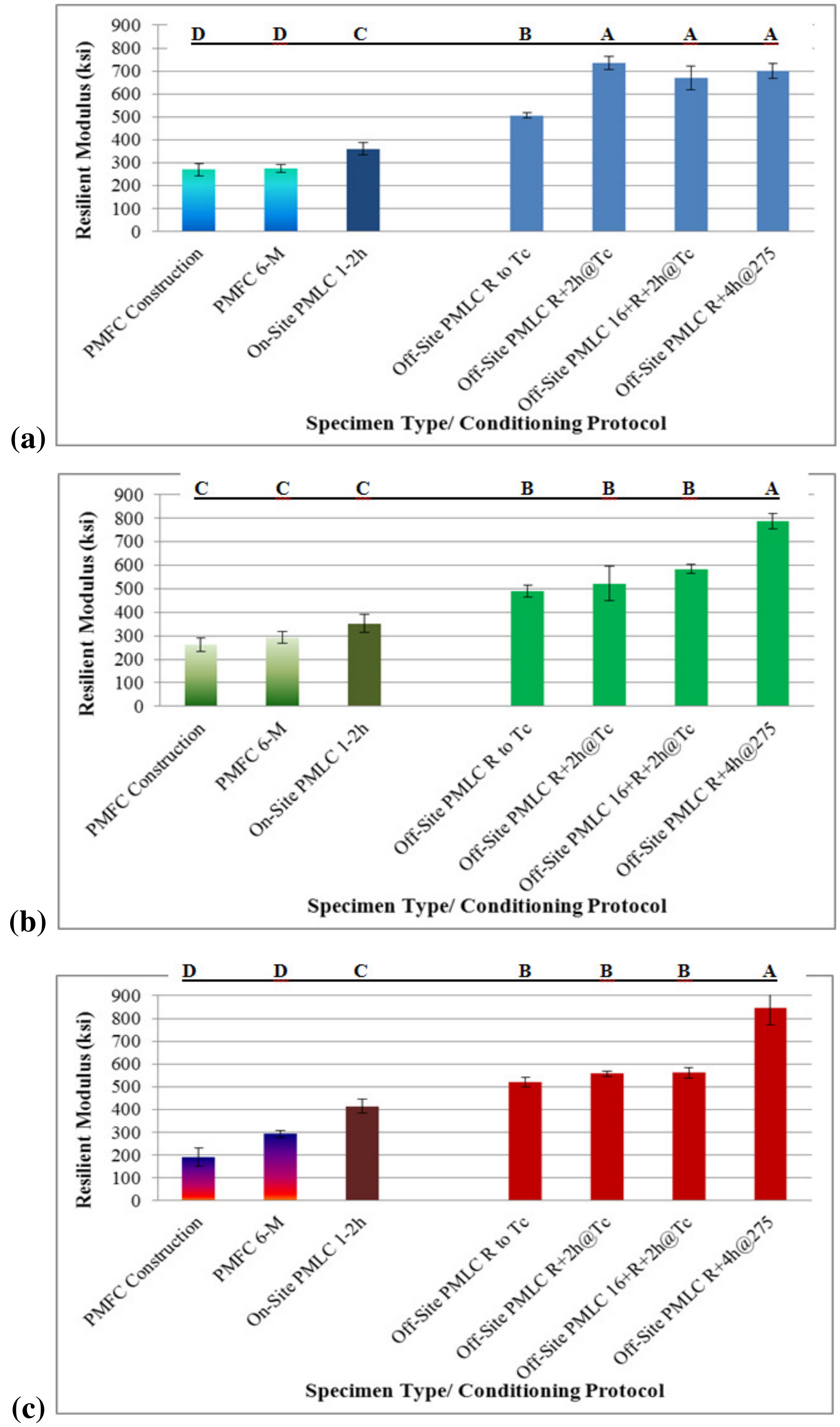


Figure 4.8. Statistical Analysis Results in Terms of Comparison of Iowa PMFC and On-Site PMLC Specimens with Off-Site PMLC Specimens with Different Conditioning Protocols in M_R; (a) HMA, (b) WMA with 3rd Generation Chemical Package, (c) WMA with Wax Additive

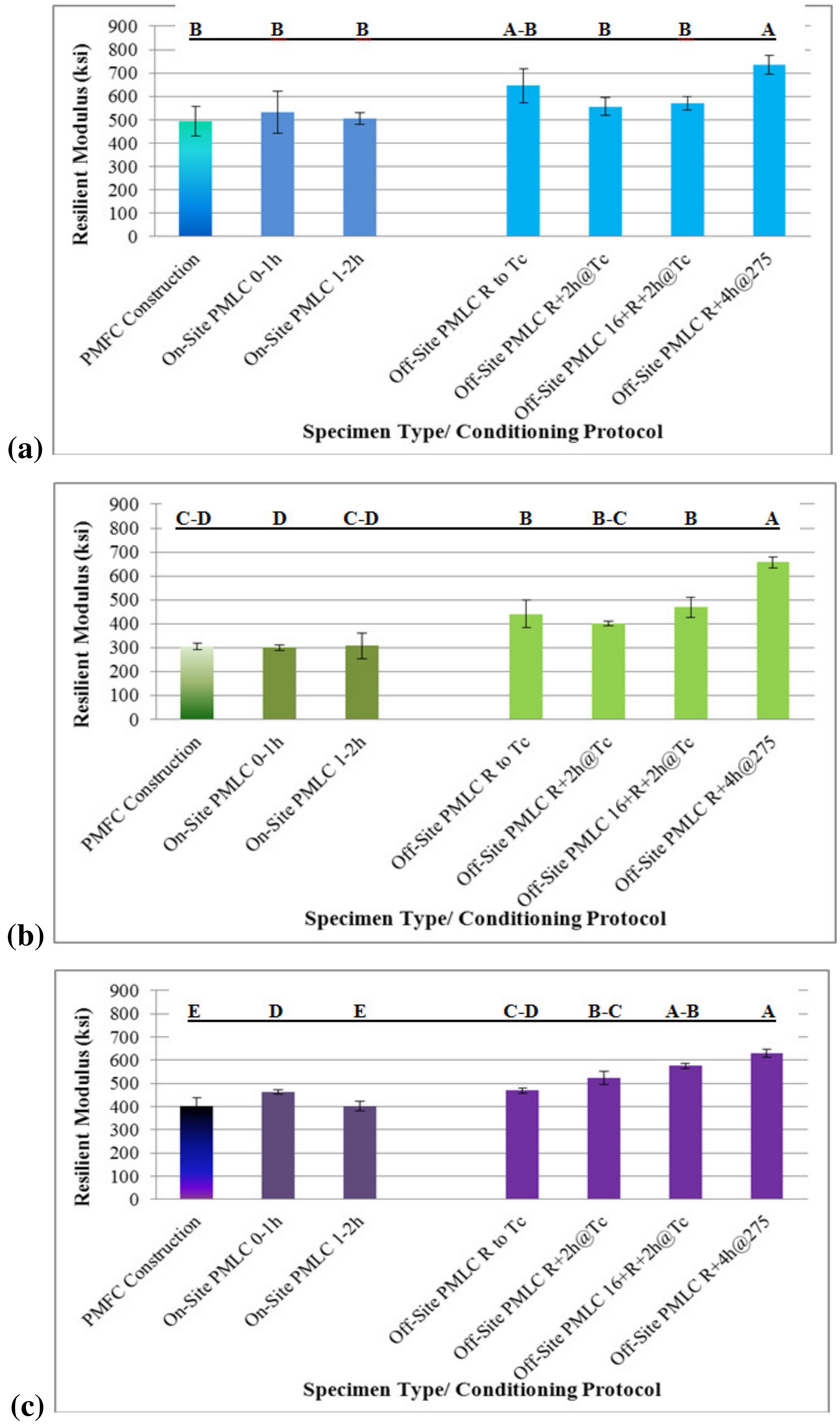


Figure 4.9. Statistical Analysis Results in Terms of Comparison of Texas PMFC and On-Site PMLC Specimens with Off-Site PMLC Specimens with Different Conditioning Protocols in M_R; (a) HMA, (b) WMA with 2nd Generation Chemical Package, (c) WMA with Foaming Process

As previously mentioned, most Tc for WMA from the Iowa and Texas field projects were approximately 240°F (116°C). Therefore, the conditioning protocols recommended for preparing off-site PMLC specimens are more likely to be (1) reheat to 240°F (116°C) for WMA with additives and (2) reheat to 275°F (135°C) for HMA and foamed WMA. Compaction temperatures for WMA from the Montana field project were significantly higher than those from the Iowa and Texas field projects. To further validate the recommended conditioning protocol, the off-site PMLC specimens were fabricated following the recommended protocol as well as reheating to real compaction temperature of 315°F (157°C) for HMA and 275°F (135°C) for WMA with additives prior to compaction and then tested to determine MR. MR results are shown in Figure 4.10, together with the same statistical analysis used for LMLC and off-site PMLC specimens from the Iowa and Texas field projects. The general results of Tukey's HSD test are shown in Figure 4.10 with capital letters above the bars. Conditioning protocols with different letters have MR values that are significantly different from each other. A detailed comparison for all conditioning protocols versus PMFC cores and on-site PMLC specimens is summarized in Table 4.3. As illustrated in the table, all three mixtures conditioned with the recommended conditioning protocols were able to simulate the stiffness of corresponding pavements in their early life based on the comparison with both PMFC cores and on-site PMLC specimens. Therefore, the recommended conditioning protocols of reheating to 275°F (135°C) for HMA and foamed WMA and 240°F (116°C) for WMA except foamed WMA were verified.

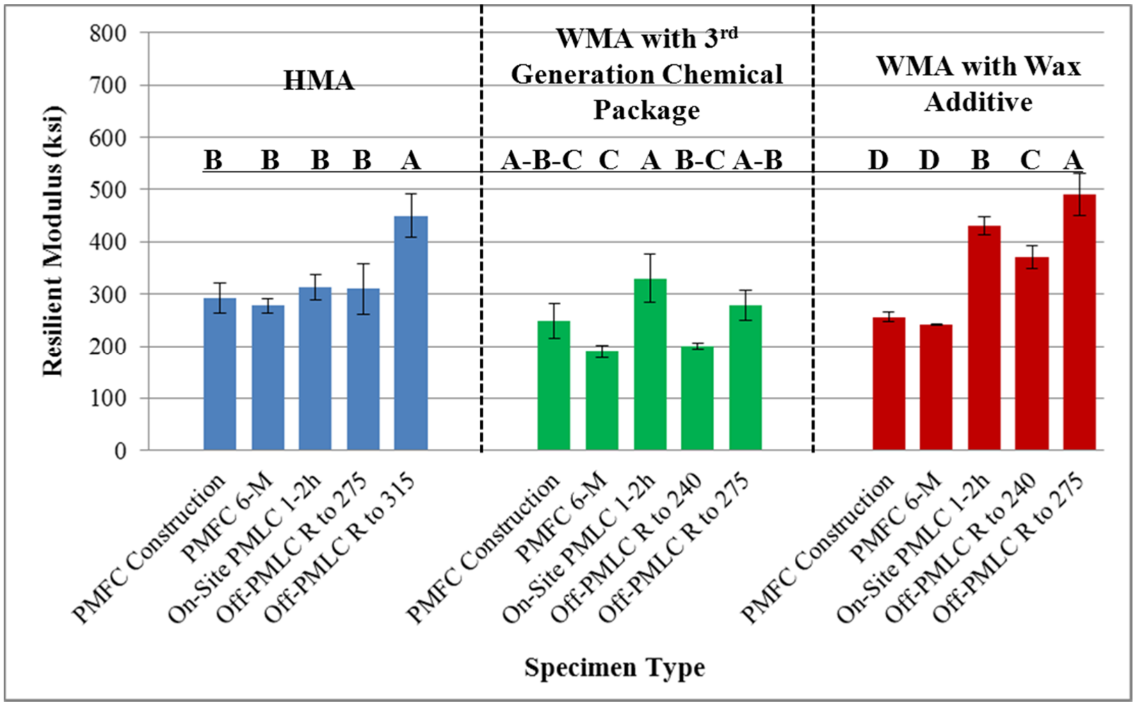


Figure 4.10. Comparison of Montana PMFC and On-Site PMLC Specimens with Off-Site PMLC Specimens with Different Conditioning Protocols in Terms of M_R Together with Statistical Analysis Results

Table 4.3. Summary of Statistical Analysis Results of Difference between Different Laboratory Conditioning Protocols for Off-Site PMLC Specimens and PMFC cores and On-Site PMLC Specimens in M_R

Mixture Type		Conditioning Protocols for Preparing Off-Site PMLC Specimens			
		R to T_c	**R+2h@T_c**	**16+R+2h@T_c**	**R+4h@275**
Iowa	HMA	High Least Difference	High	High	High
	WMA with 3rd Generation CP	High Least Difference	High Least Difference	High Least Difference	High
	WMA with Wax Additive	High Least Difference	High Least Difference	High Least Difference	High
Texas	HMA	PMFC On-Site PMLC	PMFC On-Site PMLC	PMFC On-Site PMLC	High
	WMA with 2nd Generation CP	High	PMFC On-Site PMLC	High	High
	WMA with Foaming	On-Site PMLC	High	High	High
		Conditioning Protocols for Preparing Off-PMLC Specimens			
		Recommended Protocol		**R to T_c**	
Montana	HMA	PMFC PMFC 6-M On-Site PMLC		High	
	WMA with CP	PMFC PMFC 6-M		PMFC On-Site PMLC	
	WMA with Wax Additive	> PMFC Cores < On-Site PMLC		High	

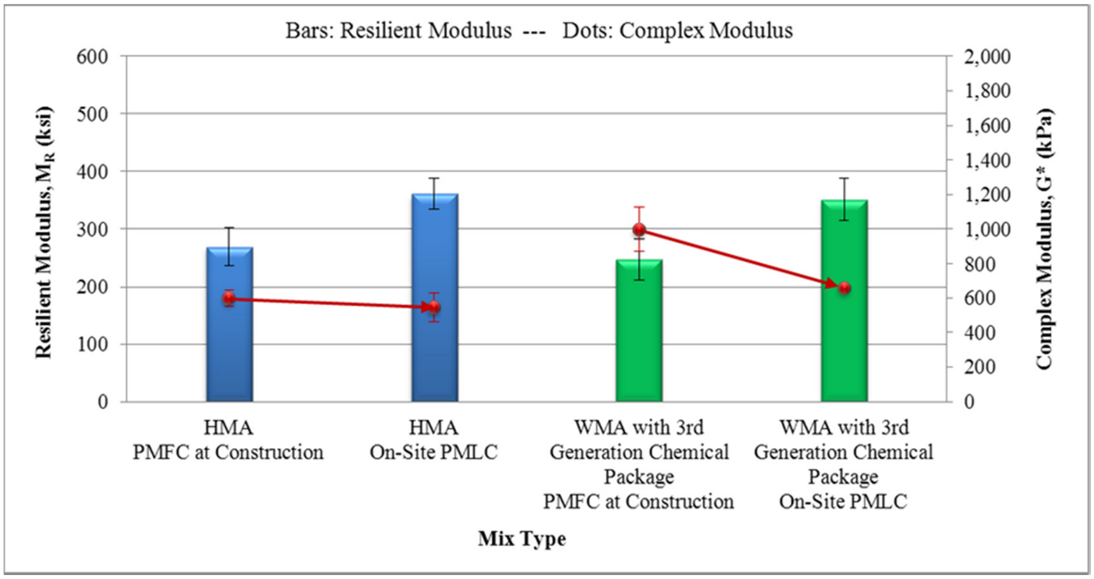
CP: chemical package
R: reheat
h: hour(s)

4.2.3 Other Factors Affecting Mixture Stiffness

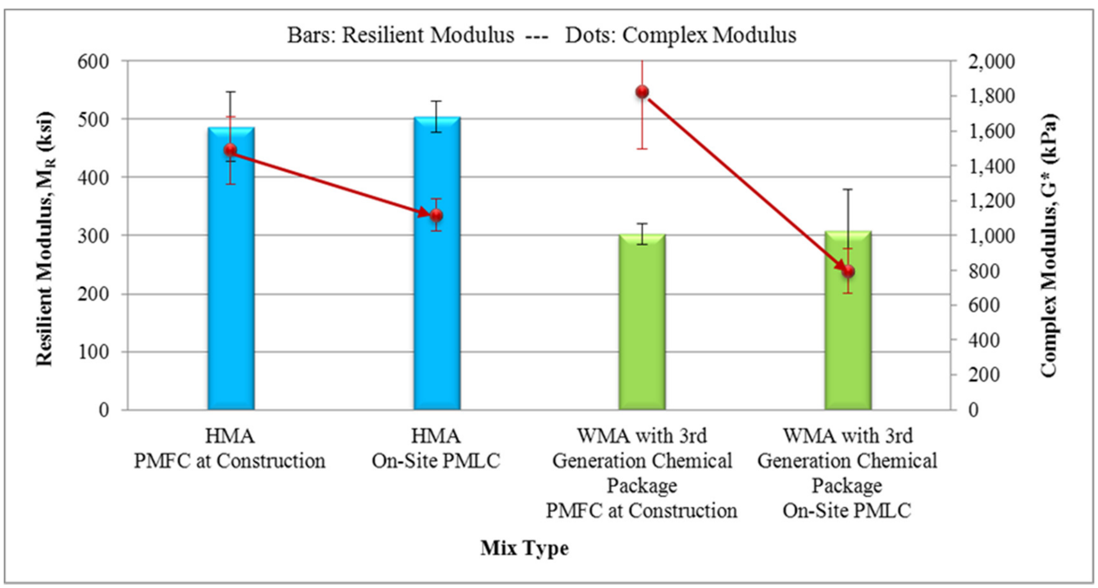
On-site PMLC specimens and PMFC cores taken at construction were expected to have similar mixture stiffnesses as they experienced approximately the same level of binder aging, with the PMFC cores possibly aging more during transportation to the pavement site. M_R results from the Texas field project verified this expected behavior, while M_R results from the Iowa field project showed a different trend. For the Iowa field project, the on-site PMLC specimens showed higher stiffnesses as compared to the PMFC cores at construction. To evaluate these differences with respect to binder stiffness and aggregate orientation, binders were extracted and recovered from HMA and WMA with 2nd and 3rd generation chemical package on-site PMLC specimens and PMFC cores obtained from both projects. The stiffness of the extracted binders was then evaluated with the DSR. In addition, the effect of the aggregate orientation was estimated via image analysis techniques.

DSR tests were performed on the extracted and recovered binders in accordance with AASHTO T315 at 77°F (25°C) to match the M_R test temperature. The binder complex modulus (G*) was selected as test parameters. DSR and M_R results of PMFC cores at construction and on-site PMLC specimens from both projects are summarized in Figure 4.11. The bars in Figure 4.11 represent the average M_R of three replicate specimens, the dots the average complex modulus of three measurements, and the error bars ± one standard deviation from the average values.

The results show that all PMFC cores had higher G* values than corresponding on-site PMLC specimens. Therefore, PMFC specimens were expected to be stiffer as compared to on-site PMLC specimens, assuming that the aggregate orientation is equivalent. However, M_R results showed significantly opposite trends, as illustrated in Figure 4.11. M_R results indicate that the mixture stiffnesses of PMFC cores are lower or equivalent to that of corresponding on-site PMLC specimens. Therefore, factors other than binder aging such as different compaction methods and different specimen AV are more likely affecting the stiffness of the mixture.



(a)



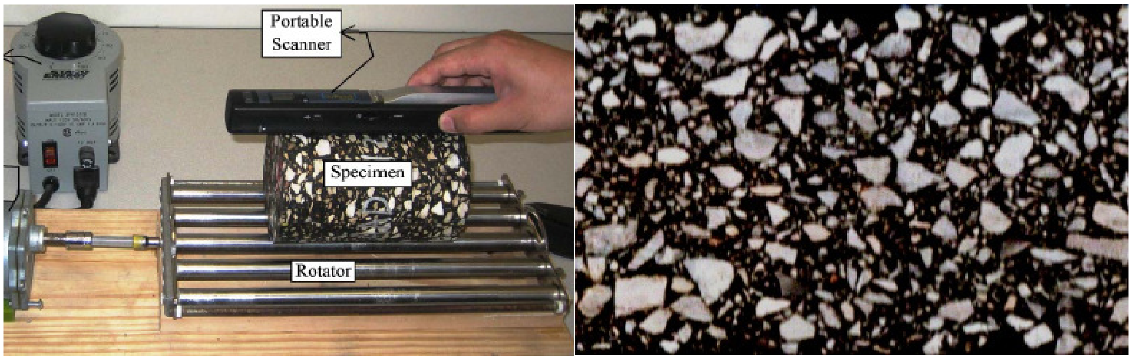
(b)

Figure 4.11. M_R and DSR Results of On-Site PMLC and PMFC Specimens at 77°F (25°C); (a) Iowa Field Project, (b) Texas Field Project

A previous study (Richard et al, 1992) indicated that different compaction methods may induce differences in specimen anisotropy and aggregate interlock and that both factors may have significant effects on mixture stiffness. Specifically, field compaction is expected to give rise to cross-anisotropic materials, indicating that most aggregates orient along the horizontal direction in the field. These cross-anistropic materials will exhibit lower M_R values when tested in the horizontal direction than isotropic ones due to this aggregate orientation.

The difference in aggregate orientation was evaluated via image analysis techniques using a portable scanner to capture a continuous image of the lateral surface of the specimen as shown in Figure 4.12. Four on-site PMLC specimens and PMFC cores from the Iowa and Texas field projects were scanned. The specimens were laid horizontally on an automatic constant speed rotator while the portable scanner was placed on top of the specimen to scan its lateral surface. Using image analysis software, several aggregate characteristics including the inclination angle, cutting surface area, and aspect ratio were measured and used in a modified vector magnitude, Δ', to evaluate the overall aggregate orientation of the asphalt mixture (Zhang et al., 2011). The parameter Δ' has a range from zero to 1 with 0 indicating full isotropy (i.e., complete random distribution of particles) and larger values indicating more anisotropy (i.e., preferential orientation of the long dimension of the aggregates in the horizontal direction, which is perpendicular to the direction of compaction).

The results for the on-site PMLC specimens and PMFC cores from the Iowa and Texas field projects are summarized in Figure 4.13. As expected, the Δ' parameter for the PMFC cores were higher than those for on-site PMLC specimens, indicating higher anisotropy in the horizontal direction. Therefore, PMFC cores may have less resistance to the diametral load in the M_R test in this direction.



(a) **(b)**

Figure 4.12. Image Analysis Techniques in the McNew Laboratory at TTI; (a) Test Equipment, (b) Scanned Image of Lateral Surface of Asphalt Mixture Sample

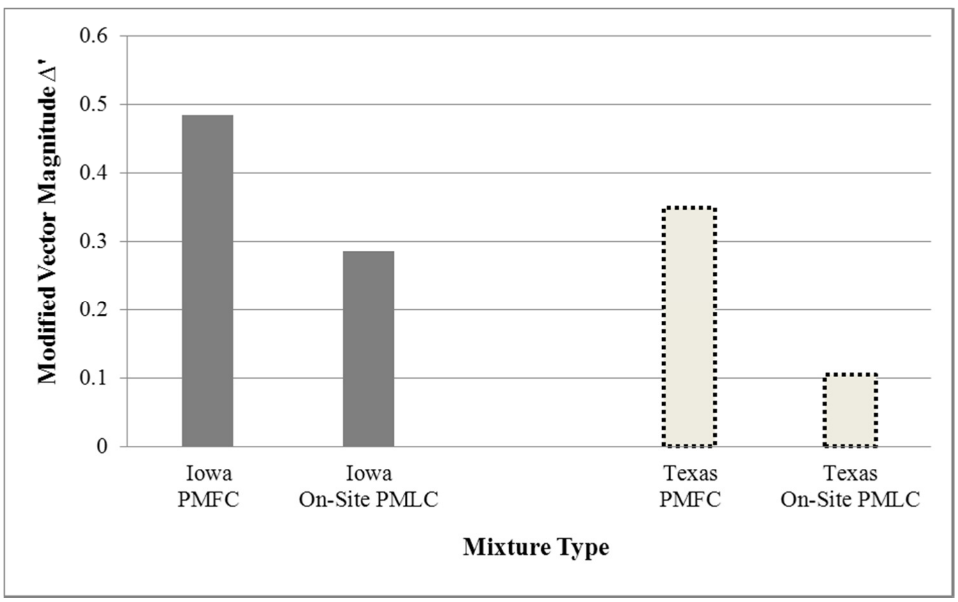


Figure 4.13. Overall Aggregate Orientation of On-Site PMLC and PMFC Cores from the Iowa and Texas Field Projects

Another factor to consider in the comparison of mixture properties conditioned using the selected protocols is AV. It is well known that AV have a significant effect on mixture stiffness. In this study, all laboratory fabricated specimens (LMLC and off-site PMLC) had a target AV of 7± 0.5% while the PMFC cores had a higher AV, in the range of 7% to 9%. To evaluate the effect of AV in stiffness, several LMLC specimens of WMA with wax additives with AV ranging from 5% to 9% were fabricated and tested to determine M_R. Test results presented in Figure 4.14 show that mixture stiffness reduced significantly as AV increased from 5% to 9%, while the M_R value was stable for specimens with AV between 5% and 6% AV. Therefore, the higher AV of PMFC cores may explain some of the differences in mixture stiffness as compared to the on-site PMLC specimens.

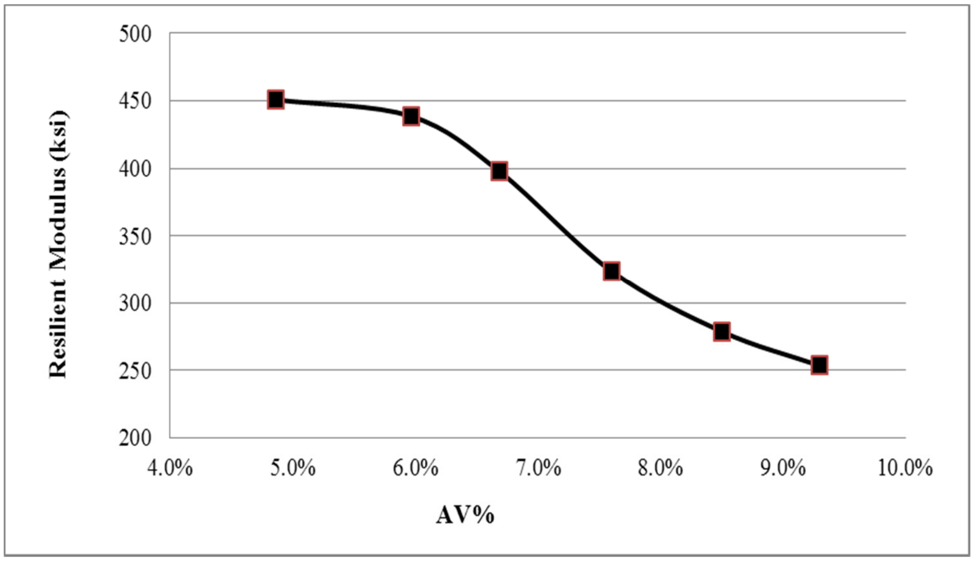
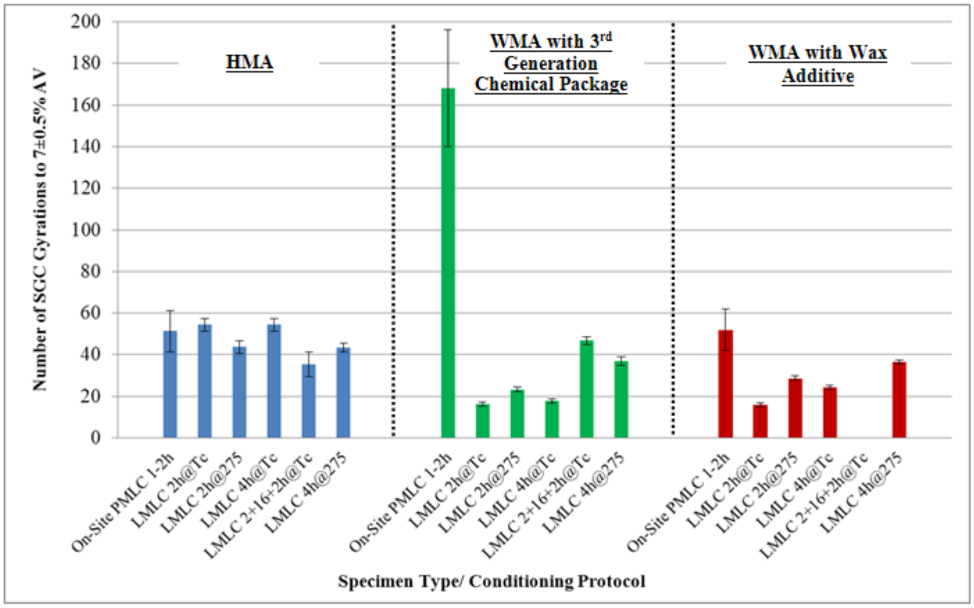


Figure 4.14. AV Effect on Mixture Stiffness (Iowa WMA with Wax Additive LMLC Specimens)

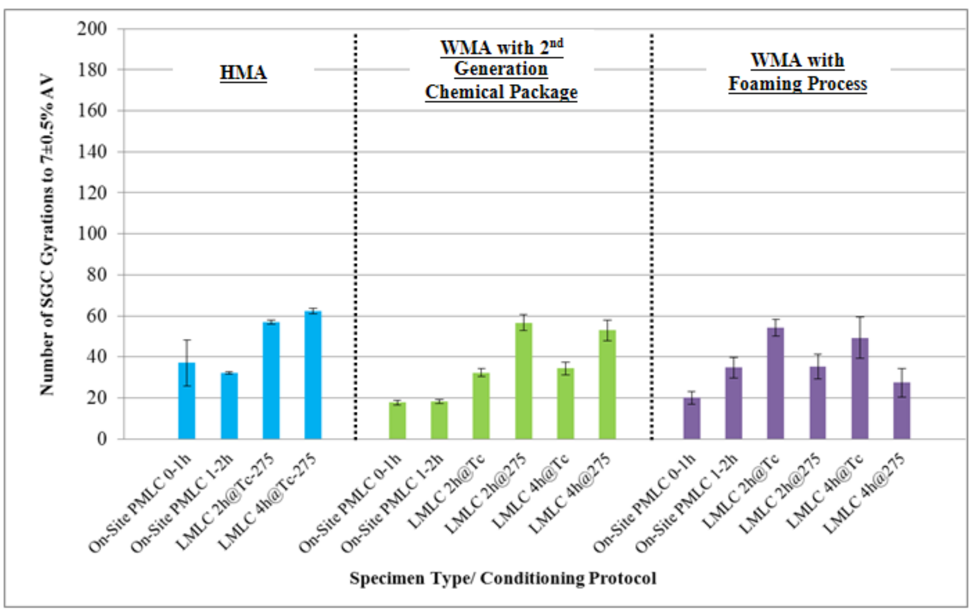
In general for the HMA and WMA evaluated, both compaction method (i.e., anisotropy) and overall AV had a significant effect on mixture stiffness that could help explain the discrepancy in the mixture and binder stiffnesses observed between on-site PMLC specimens versus PMFC cores (Figure 4.11).

4.3 Number of Gyrations (N)

Figures 4.15 and 4.16 present the comparison between LMLC and off-site PMLC specimens versus. On-site PMLC specimens in terms of N to 7±0.5% AV from the Iowa and Texas field projects. Each bar in Figures 4.15 and 4.16 represents the average value of three replicate specimens, and the error bars represent ± one standard deviation from the average value.

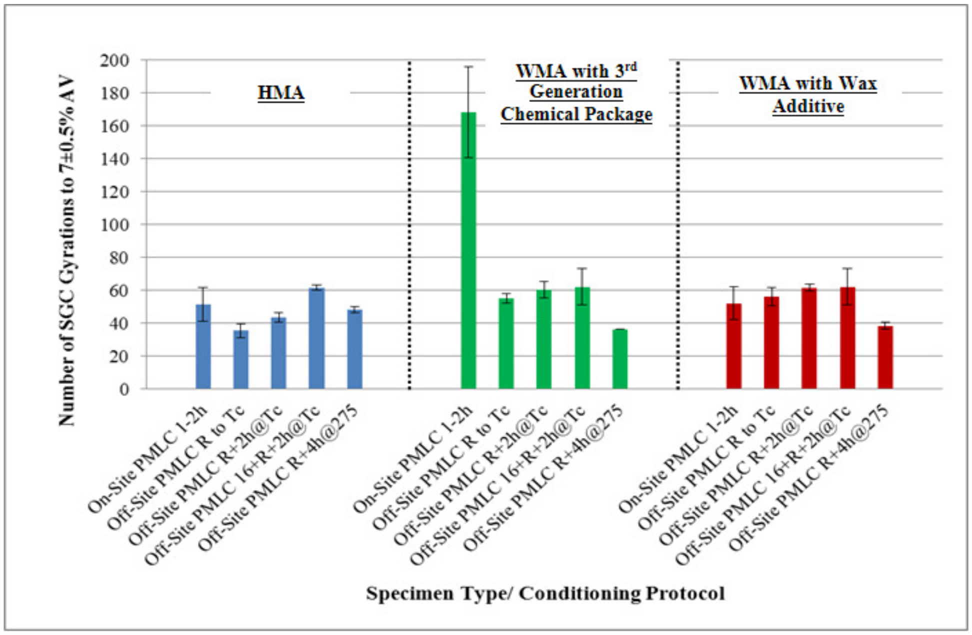


(a)

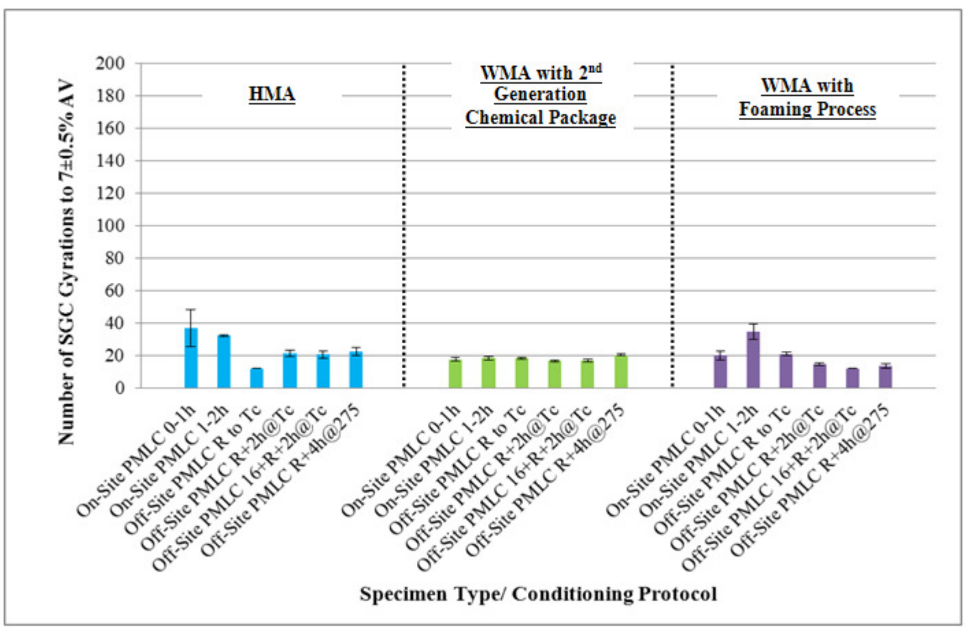


(b)

Figure 4.15. Comparison of HMA and WMA On-Site PMLC Specimens with LMLC Specimens with Different Conditioning Protocols in Terms of N; (a) Iowa Field Project, (b) Texas Field Project



(a)



(b)

Figure 4.16. Comparison of HMA and WMA On-Site PMLC Specimens with Off-Site PMLC Specimens with Different Conditioning Protocols in Terms of N; (a) Iowa Field Project, (b) Texas Field Project

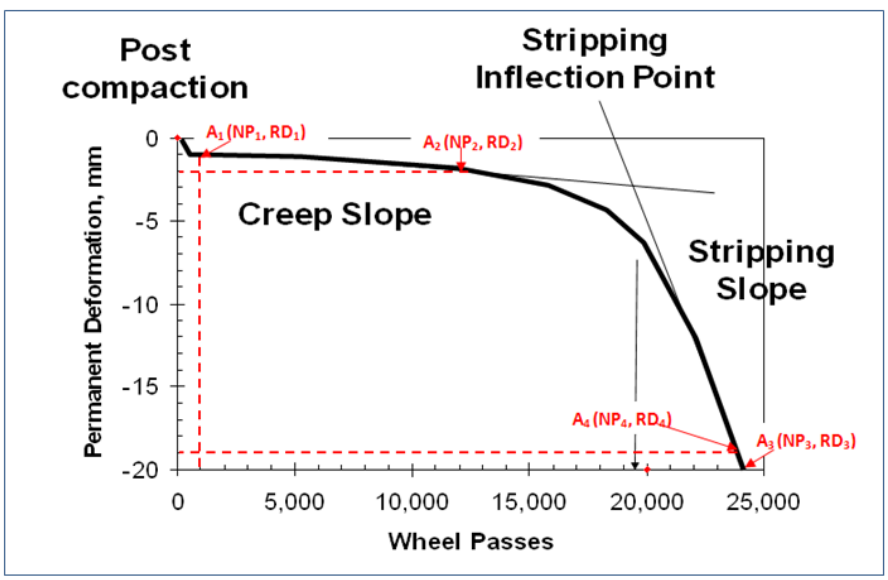
As illustrated in Figure 4.15, for all HMA and WMA mixtures except Texas foamed WMA, N increased as the laboratory conditioning temperature and/or time increased, which verified the trend between M_R and different conditioning protocols. A different trend was shown by Texas foamed WMA; higher conditioning temperature and longer conditioning time resulted in smaller N values that might be caused by partial loss of the foaming effects during conditioning prior to compaction. The comparison between HMA and WMA indicated that more gyrations (higher N) are required to compact HMA to the target AV range as compared to WMA, which is likely caused by lower production temperatures of WMA. Additionally, for the comparison between on-site PMLC specimens and LMLC specimens, the SGCs were different. This may have contributed to the larger difference for Iowa WMA mixtures. As shown in Figure 4.16, for the majority of mixtures, the difference in N values of HMA and WMA off-site PMLC specimens conditioned with different protocols was not remarkable, which might be caused by over aging of loose mix during reheating. This result agrees with the M_R results, which indicates that reheating loose mix significantly increases the mixture stiffness, more than the additional conditioning after reheating. In addition, equivalent N values were observed between on-site PMLC and off-site PMLC specimens of HMA and WMA with wax additive from the Iowa field project and WMA with 2nd generation chemical package and foaming process from the Texas field project. N values of on-site PMLC specimens were higher than those corresponding to off-site PMLC specimens for WMA with 3rd generation chemical package from the Iowa field project and HMA from the Texas field project.

In general, an increase in laboratory conditioning temperature and/or time may significantly increase the stiffness of the mixture and therefore, a greater number of gyrations (higher N values) is required to achieve the same AV level. The results shown in Figure 4.15 and 4.16 agree with those for the M_R results. Therefore, the N value is able to help compare the stiffness of HMA and WMA LMLC and off-site PMLC specimens conditioned with different protocols.

4.4 Hamburg Wheel-Track Testing (HWTT)

HWTT is a laboratory test that utilizes repetitive loading in the presence of water and measures combined mixture resistance to moisture susceptibility and rutting. As shown in Figure 4.17 (a), specimens are submerged in warm water at 122°F (50°C) and subjected to 52 passes of a steel wheel per minute. Each sample is loaded for a maximum of 20,000 passes or until 0.8in (20mm) of deformation occurs.

(a)



(b)

Figure 4.17. Hamburg Wheel-Track Testing Equipment; (a) Submerged Specimens (Solaimanian et al., 2007), (b) Typical Deformation Behavior with Load Passes

Test results include creep slope, stripping slope, and stripping inflection point (SIP), as shown in Figure 4.17 (b). The SIP occurs where the line of the creep slope and the line of the stripping slope intersect, and it is defined as the number of load passes at that location. To obtain the equations for the creep slope, two points in the deformation curve were identified. The first point was located after the post compaction phase of 1000 load passes, while the second point was positioned where the deformation was 1-mm larger than the first point. These points were labeled A_1 (NP_1, RD_1) and A_2 (NP_2, RD_2), where NP stood for the number of load passes and RD for the rutting depth. The line representing the creep slope was then determined by the following equation:

$$RD_C = \frac{RD_2 - RD_1}{NP_2 - NP_1} NP_c + RD_1 = \frac{-1}{NP_2 - 1000}(NP - 1000) + RD_1$$

Equation 4.1

The stripping slope was calculated by first fitting a polynomial function to the data (F_{poly}) in order to minimize the noise that was often encountered towards the end of the test (and data outliers were also removed). Then, two points were again identified along the deformation curve. The first point was located at the end of the test and the second point was situated where the deformation was 1-mm smaller than the first point. The points were labeled A_3 (NP_3, RD_3) and A_4 (NP_4, RD_4), where $RD_3 = F_{poly}$ (NP_3) and $RD_4 = F_{Poly}$ (NP_4). The line for the stripping slope was then calculated using the following equation:

$$RD_S = \frac{RD_3 - RD_4}{NP_3 - NP_4} NP_s + RD_3 = \frac{1}{NP_3 - NP_4}(NP - NP_3) + RD_3$$

Equation 4.2

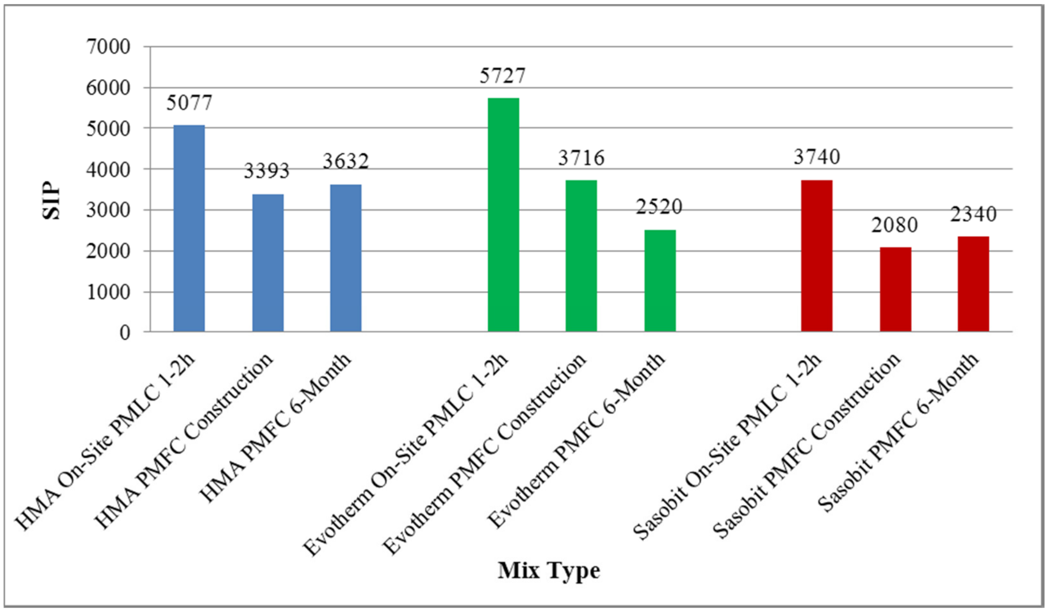
The SIP was obtained by setting equations 1 and 2 equal, in other words where RD_c equaled RD_s corresponded to the number of load passes (NP) for the SIP.

Figures 4.18 and 4.19 present HWTT results for on-site PMLC specimens and PMFC cores from the Iowa and Texas field projects in terms of two test parameters: SIP and rut depth at a specific number of passes. SIP reflects mixture moisture susceptibility, and rut depth at a specific number of passes indicates mixture stiffness in terms of rutting resistance in a wet condition.

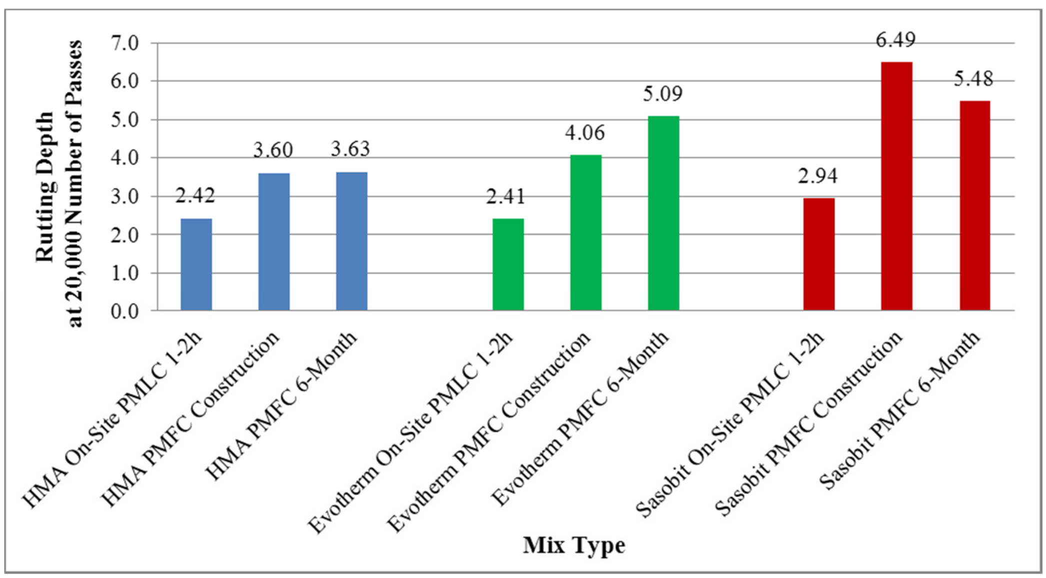
As shown in Figure 4.18, all on-site PMLC specimens had higher SIPs and smaller rut depths at 2,000 passes than the corresponding PMFC cores, indicating better resistance to moisture damage and rutting, respectively. This observation agrees with that obtained from the M_R results. The comparison between PMFC cores at construction and after 6 months in service showed that PMFC cores at construction for HMA and WMA with wax additive had similar SIPs and rut depths at 2,000 passes for both ages, while PMFC cores at construction for WMA with a chemical package had worse resistance to moisture damage and rutting as compared to PMFC cores after 6 months in service. WMA with a chemical package had better performance than WMA with a wax additive, and this behavior might be attributed to anti-stripping agents included in the chemical package.

Opposite observations are shown in Figure 4.19; PMFC cores for HMA and WMA with a chemical package at construction had better performance as compared to on-site PMLC specimens conditioned at two different times. PMFC cores of foamed WMA had similar SIPs and rut depths at 2,000 passes as on-site PMLC specimens conditioned for 0-1 hour at T_c, while on-site PMLC specimens conditioned for longer times performed substantially better. Partial evaporation of water and the lost effect of foaming properties during the extended conditioning process may have significantly stiffened the foamed loose mix and thus, resulted in better performance in the HWTT.

As expected, increased moisture susceptibility and rutting of WMA as compared to HMA was observed in Figures 4.18 and 4.19, which is likely caused by the lower production temperatures of WMA. The incorporation of anti-stripping agents and increased time or temperature in the conditioning protocol may increase the mixture stiffness in a wet condition and improve the mixture resistance to moisture damage.

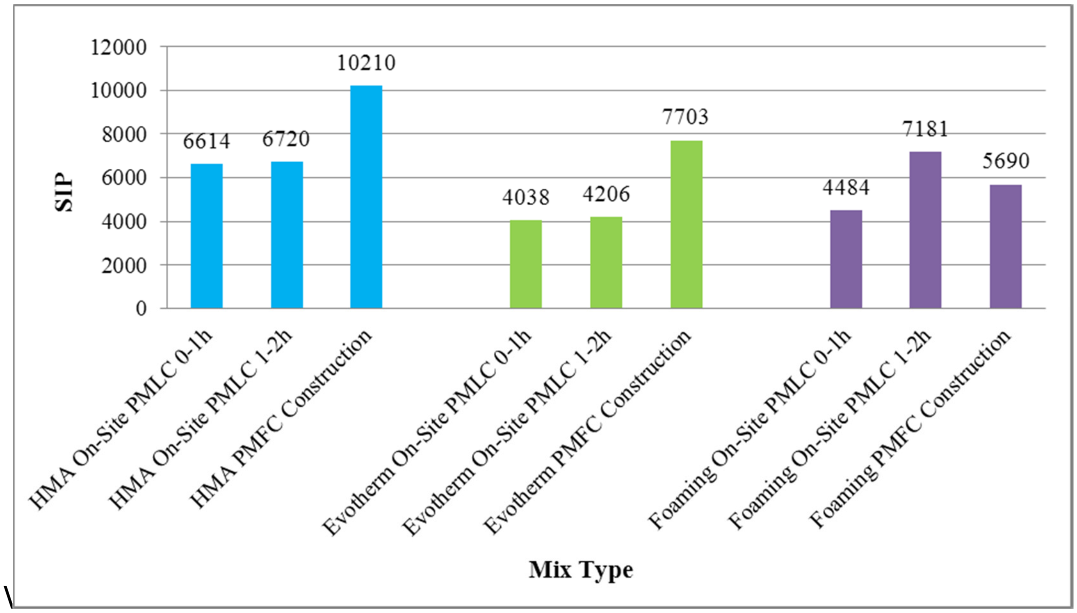


(a)

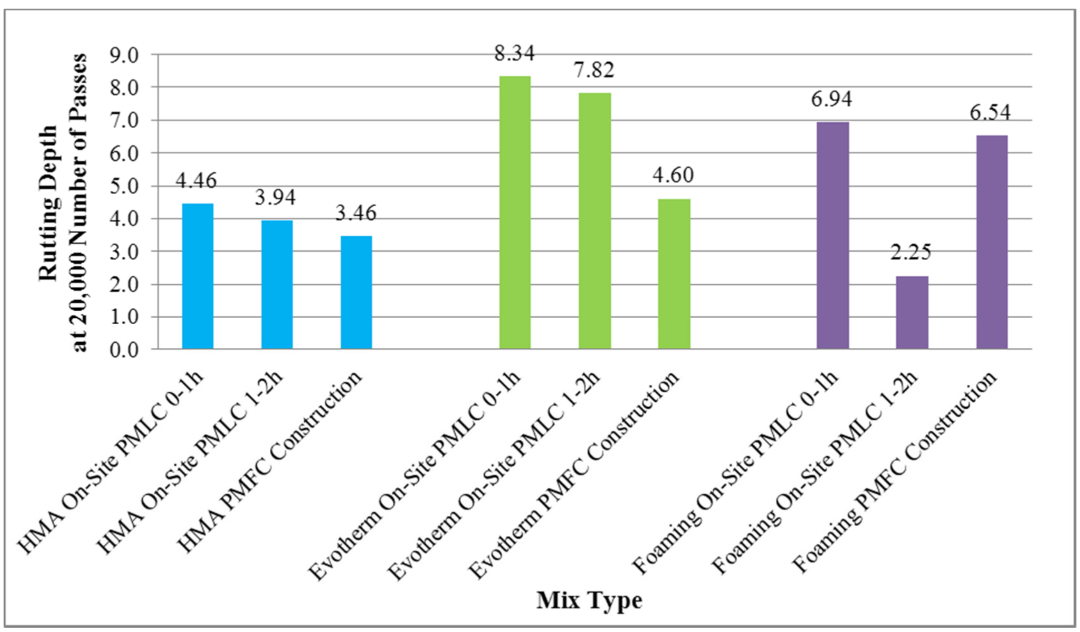


(b)

Figure 4.18. HWTT Results of On-Site PMLC and PMFC Specimens from the Iowa Field Project; (a) SIP, (b) Rutting Depth at 2,000 Passes



(a)



(b)

Figure 4.19. HWTT Results of On-Site PMLC and PMFC Specimens from the Texas Field Project; (a) SIP, (b) Rutting Depth at 2,000 Passes

5. CONCLUSIONS AND FUTURE RESEARCH

The objective of this study was to recommend standard laboratory conditioning protocols for WMA specimens for performance testing. These protocols are intended to be used as part of the WMA mix design procedure or the quality control/quality assurance program for WMA. Different conditioning protocols were selected for fabricating WMA LMLC and off-site PMLC specimens, and these specimens were tested to determine the effect of the conditioning protocol on the stiffness of the mixture (M_R). PMFC cores at construction and after six months in-service and on-site PMLC specimens were also incorporated in the experimental design to represent HMA and WMA pavements in their early life. Volumetrics, mixture stiffness, binder stiffness, aggregate orientation, and mixture compactability (N to 7%AV) of different HMA and WMA specimens were evaluated. The following specific conclusions can be made based on this study:

1. Comparison of volumetrics between LMLC and on-site PMLC specimens indicated that all on-site PMLC specimens (except for foamed WMA from the Texas field project) have higher G_{mm} values and binder absorption (P_{ba}) and lower effective binder FT. Thus the loose plant mix experienced more conditioning prior to compaction than those mixed in the laboratory. The reduction in mixing and compaction temperatures (T_m and T_c) and the incorporation of WMA additives resulted in lower G_{mm} values and lower binder absorption as compared to HMA which may reduce the bonding strength between aggregates and binders, making WMA more susceptible to early age distress such as moisture damage and rutting.

2. M_R results showed that stiffnesses of LMLC specimens increased with higher conditioning temperatures and longer conditioning time and that WMA was more

sensitive to conditioning temperature than conditioning time. Among five selected conditioning protocols for LMLC specimens, 2 hours at 275°F (135°C) and 2 hours at T_c were more representative in terms of stiffnesses of HMA and WMA pavements, respectively, in their early life. Considering the difficulty in accurately defining T_c in the field and the common range of T_c for WMA, 2 hours at 240°F (116°C) instead of 2 hours at T_c is recommended as the standard laboratory conditioning protocol for WMA LMLC specimens. For HMA LMLC specimens, 2 hours at 275°F (135°C) is recommended prior to compaction.

3. Reheating loose mix had a significant effect on the stiffness of off-site PMLC specimens. Even in the case of HMA and WMA with only reheating to T_c, the stiffness was higher than the stiffness of PMFC cores or on-site PMLC specimens. Therefore, reheating to 240°F (116°C) is recommended as the standard laboratory conditioning protocol for WMA with additives. Considering the evaporation of water in foamed mixtures and the lost effect of foaming properties when reheating, conditioning of off-site PMLC specimens of foamed WMA must follow the same protocol as that for HMA. Reheating to 275°F (135°C) is recommended as the standard laboratory conditioning protocol for HMA and WMA produced with the foaming process.

4. The stiffness of the binder extracted from PMFC cores at construction was higher than the stiffness of the binder extracted from on-site PMLC specimens, as indicated by DSR testing. The discrepancy in mixture and binder stiffness between PMFC cores at construction and on-site PMLC specimens is likely due to mixture anisotropy induced by different compaction methods and different AV. Based on image analysis techniques, the on-site PMLC specimens showed less anisotropy as compared to PMFC cores at construction, resulting in less resistance to the diametral load in M_R test. Higher AV may also significantly reduce the mixture stiffness in terms of M_R. Therefore, mixture anisotropy and

overall AV have a greater effect on mixture stiffness than increasing binder stiffness.

5. Number of SGC gyrations data indicated that more gyrations are required to achieve the same AV level during compaction for laboratory fabricated specimens conditioned with protocols with longer time at higher temperature, which agreed with M_R results. Therefore, the N value is able to help compare the stiffness of HMA and WMA LMLC and off-site PMLC specimens conditioned with different protocols.

6. HWTT results of PMFC cores and on-site PMLC specimens from the Iowa and Texas field projects agree with corresponding observations based on M_R tests. Therefore, there may be a strong correlation between mixture stiffness in dry and wet conditions. HMA specimens exhibited better performance than WMA, and WMA with different additives showed differences in performance in the HWTT. WMA with the 3rd generation chemical package from the Iowa field project had better resistance to rutting and moisture damage as compared to WMA with a wax additive likely due to the presence of an anti-stripping agent. Conditioning for longer periods of time substantially improved the resistance of on-site PMLC specimens of foamed WMA from the Texas field project to moisture damage and rutting. Therefore, the incorporation of anti-stripping agents and increased time or temperature in a conditioning protocol can improve the performance of WMA in the HWTT.

Based on the study, recommendations for the future research can be made:

1. In this study, standard laboratory conditioning protocols to prepare LMLC specimens and off-site PMLC specimens for performance tests were proposed

based on M_R results. Additional mixture properties need to be considered for validation.

2. Among those conditioning protocols proposed for preparing LMLC specimens, 2 hours at 275°F (135°C) was able to simulate the pavement stiffness in its early life for all asphalt mixtures except WMA from the Texas field project. Therefore, it should be evaluated further to allow for the possibility of a single conditioning protocol for both HMA and WMA.

3. The effect of the total AV in the asphalt mixture specimen on mixture stiffness was verified in this study using LMLC specimens of a single WMA technology prepared with one specific conditioning protocol. Future research into the comprehensive effects of AV on the stiffness of asphalt mixtures prepared with various WMA technologies is necessary, with a particular emphasis on exploring the difference in AV between PMFC cores and LMLC specimens and off-site PMLC specimens.

4. A number of WMA additives are available to reduce the production temperature of asphalt mixtures. In this study, commonly used WMA additives were used and evaluated. Future research may include other WMA technologies and verify the standard conditioning protocols proposed in this study.

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