STATEWIDE IMPLEMENTATION OF THE SURFACE PERFORMANCE GRADED SPECIFICATION FOR CHIP SEAL BINDERS IN TEXAS

A Thesis

by

SWATHI MAYI THEEDA

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Amy L. Epps Martin
Committee Members,	Charles J. Glover
	Maryam S. Sakhaeifar
Head of Department,	Robin Autenrieth

August 2017

Major Subject: Civil Engineering

ABSTRACT

Over the past 15 years, a Surface Performance-Graded (SPG) specification for chip seal binders was developed and validated using laboratory measurements and visual field performance of 120 highway sections (HSs). The SPG specification was established in an effort to extend the service life of chip seals by providing a binder grading system and associated selection method that: (1) accounts for differences in climate and (2) utilizes existing equipment and performance-based properties that preclude bleeding and aggregate loss in the critical first year of service after construction. The third year of implementation of the specification is ongoing and the current work is a record of the efforts during this period which involved simultaneous work on validating the existing performance parameters, educating the end users about the specification and its development, and addressing their concerns.

The improvement in the field performance correlation of the SPG parameters by considering construction factors signified the importance of the combined utilization of construction guidelines and material-related specifications. In terms of industry interaction, two round robins were conducted with TxDOT and various binder suppliers in Texas as a result of which: (a) the SPG specification was modified to incorporate offset 6^0 increments during the grading process and thus considerably reducing the number of grades in Texas and, (b) the need for a parameter that is indicative of modification was identified. On reviewing the existing phase angle threshold for its sensitivity to modification type and aging, alternative parameters were explored. Although the MSCR test parameters were not indicative of field performance, they seemed promising in terms of indicating binder modification. Based on the extensive literature review, guidelines were provided to modify the test protocol for use with chip seal binders. Further work on modifying the MSCR test protocol for chip seal applications and improving the test conditions for low temperature binder characterization were recommended.

DEDICATION

To the situations that put me out of my comfort zone.

To the people who made me push and look

beyond what I thought I could.

To the beauty of Science, Engineering and Reasoning

that helped me get out of my small world.

ACKNOWLEDGEMENTS

I am forever indebted to the kindness, grace and support of my Committee Chair, Dr. Amy Epps Martin, who looked beyond my shortcomings and believed in me. I cannot thank her enough for the opportunity with the project and I am grateful for the exposure it had given me. Her guidance, constant engagement and perseverance will always be my inspiration no matter what I do or where I go.

I thank my committee members, Dr. Glover, Dr. Newcomb, and Dr. Sakhaeifar for their guidance and support throughout the course of this research. I thank Dr. Edith Arambula for always being there and helping me understand importance of this research. I cannot be more grateful for all the time she has taken to help, guide and support me in numerous situations. I also extend my sincere gratitude to Mr. Thomas Freeman, for his dedication and tireless efforts in getting the valuable field data for the work.

Special thanks to Dr. Lorena Garcia Cucalon for her unselfish support, genuine interest with my work and never saying ‘no’ to our long discussions. Thank you for your friendship and kind encouragement with all my pursuits.

Thanks to Mr. Rick Canatella, Mr. Tony Barbosa, Mr. Ethan Karnei and Mr. Ross Taylor of the McNew lab for their helpfulness and the fun talks in the lab. Thanks also my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. Finally, thanks to my mother and father for their love and encouragement and to my brother for always being by my side.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supported by a thesis committee consisting of Dr. Amy Epps Martin and Dr. Maryam Sakhaeifar of the Department of Civil Engineering, Dr. Charles Glover of the Department of Chemical Engineering and Dr. David Newcomb of Texas A&M Transportation Institute. Constant technical guidance was received by Dr. Edith Arambula of Texas A&M Transportation Institute.

Funding Source

The funding for this work was given by Texas Department of Transportation (TxDOT) under the Project No. 5-6616-01.

NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
AADT	Annual Average Daily Traffic
BBR	Bending Beam Rheometer
DSR	Dynamic Shear Rheometer
ED	Embedment Depth
ER	Elastic Recovery
FHWA	Federal Highway Administration
FTIR	Fourier Transform Infrared Spectroscopy
HMA	Hot Mix Asphalt
HS	Highway Section
LTPP	Long Term Pavement Performance
LVE	Linear Viscoelastic Range
MSCR	Multiple Stress Creep Recovery
NCHRP	National Cooperative Highway Research Program
PAV	Pressure Aging Vessel
PG	Performance Grade
PMAB	Polymer Modified Asphalt Binder
RTFO	Rolling Thin Film Oven
SCI	Surface Condition Index
SPG	Surface Performance Grade
TRB	Transportation Research Board
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

CHAPTER I

INTRODUCTION*

In Item 316 of the Texas Department of Transportation (TxDOT) specifications, chip seals are defined as a spray application of asphalt emulsion or hot-applied asphalt binder covered with aggregate [1]. These maintenance treatments are known as chip seals or seal coats in Texas. Chip seals are popular surface maintenance treatments in Texas, covering approximately 40 percent of road surfaces in the state. TxDOT spends over $300 million every year in 25 districts on district-wide chip seal preventive maintenance programs to treat approximately 8% of the state highway system or 5000 miles. If the performance of these treatments can be improved to provide just one additional year of service life on 20% of the treated sections, approximately $9 million could be saved every year.

Toward achieving this goal, a surface performance-graded (SPG) specification for chip seal binders in service (either hot-applied asphalt binder or emulsion residue) was developed and validated over the past 15 years as part of two TxDOT research projects and an ongoing implementation project for 120 highway sections (HSs) statewide [2-11]. The specification was developed to provide a binder grading system and associated selection method that: (1) accounts for differences in climate and (2) utilizes existing equipment and performance-based properties that preclude bleeding and aggregate loss in the critical first year of service after construction. A multi-year implementation effort of this specification is currently ongoing.

The current chapter describes the motivation and evolution of the SPG specification, including the binder selection guidelines using this specification. A

*Parts of the chapter are reprinted with permission from Transportation Research Board in *Transportation Research Record: Journal of the Transportation Research Board*, No. 2632, 2017. In press. DOI: http://dx.doi.org/10.3141/2632-04 summary of the first three years of implementation and the validation efforts during the 2013-14 and 2016-17 periods are briefly described. Further, the current research problem statement along with objectives and the report outline are also provided.

SPG SPECIFICATION

Motivation

One of the primary products of the Strategic Highway Research Program (SHRP) was a performance-related specification for hot mix asphalt (HMA) binders known as the Performance-Graded or PG system [12-14]. In this system, binders are tested in three critical aging states using laboratory tests that measure properties directly related to pavement performance. The development of these tests addressed many shortcomings of the previous viscosity- or penetration-graded specification systems, including the following:

- the empirical nature of penetration and ductility tests,
- the inability to grade modified binders using viscosity tests at high temperatures,
- the absence of low-temperature characterization, and
- the lack of consideration for long-term aging.

The resulting PG binder specification is applicable to both unmodified and modified binders and employs different equipment, including the Dynamic Shear Rheometer (DSR) and the Bending Beam Rheometer (BBR), to measure performance-related properties of the binder at temperature ranges for the climate where the material will be used[13]. These properties are specified to preclude the binder's contribution to the three primary forms of distress in mixtures commonly encountered in the field: rutting caused by inadequate shear resistance under repeated load, repeated-load fatigue cracking, and low-temperature thermal cracking. The temperature range where these specified properties are met is defined as the binder PG grade, and the required properties span the range from high temperatures the binder is exposed to during production and construction to low temperatures the binder is exposed to in service. Both short- and long-term aging are considered in the PG system through the use of the

Rolling Thin Film Oven Test (RTFOT) and the Pressure Aging Vessel (PAV), respectively [13]. Climate and traffic conditions representative of those encountered by binders in mixtures are considered in the associated binder selection guidelines.

Current specifications for chip seal binders (either hot-applied asphalt binders or asphalt emulsions and their residues) (including TxDOT Item 316) also consider properties of the material during construction and in service, but the same shortcomings that existed for HMA binders prior to the development of the PG specification remain and a wide range of materials can be utilized to meet the current specified properties [1]. As shown in Table 1 for modified binders, performance in service is only accounted for by specifying penetration and viscosity for emulsion residues or the DSR and BBR PG properties at specific temperatures for hot-applied asphalt binders. Aging of emulsion residues is also not considered. Thus, a specification for chip seal binders to realize improvements similar to those for the PG specification is needed. This performance-based specification should address the same shortcomings but account for differences between chip seals and HMA in terms of distress and conditions during construction and service.

To address this need, the SPG specification for chip seal binders in service (either hot-applied asphalt binder or emulsion residue recovered by AASHTO PP 72-11 Procedure B) was developed and validated over the past 15 years as part of two TxDOT research projects and an ongoing implementation project [2-11]. The evolution of the SPG specification is described subsequently, but the 2017 version is provided in Table 2 to illustrate the similarity in structure to the PG specification and to facilitate comparison with current chip seal binder specifications and the PG specification for HMA binders. The original binder properties included for safety and sprayability in Table 2(a) are only required for hot-applied asphalt binders. Additional stability and composition properties for emulsions as listed in Table 1 are included separately as shown in Table 2(b).

Table 1. Comparison of current specifications and the SPG specification for chip seal binders for: (a) modified hot-applied asphalt binders and, (b) modified emulsions.

(a) Grade	AC-15P	AC-10-2TR	AC-20-5TR	SPG
Composition				
Polymer Required?	X	X	X	
Minimum Polymer Content?	X	X	X	
Assurance of "Modified" Behavior				
Elastic Recovery @ 50°F	X	X	X	
Phase Angle @ T_{HIGH} threshold				X
Assurance of Sprayability				
Viscosity @ 275°F	X	X	X	X @ 205°C
Resistance to Bleeding @ High Pavement Temperatures (T_{high})				
DSR @ T_{HIGH}		X @ 58°C	X @ 64°C	X @ T_{HIGH}
Viscosity @ 140°F	X	X	X	
Other Consistency				
Penetration @ 77°F	X	X	X	
Softening Point	X	X	X	
Resistance to Aggregate Loss @ Low Pavement Temperatures (T_{low}) after Aging				
PAV Aging	X w/RTFOT	X w/RTFOT	X w/RTFOT	X
BBR Stiffness @ T_{LOW}	X @ -18°C	X @ -18°C	X @ -18°C	X @ T_{low}
BBR m-value @ T_{LOW}	X @ -18°C	X @ -18°C	X @ -18°C	

(b) Grade	CRS-2P	HFRS-2P	SPG
Composition			
Polymer Required?	X	X	
Minimum Polymer Content?	X	X	
Minimum Asphalt Content?	X	X	X
Solubility?	X	X	X
Assurance of "Modified" Behavior			
Elastic Recovery @ 50°F / Ductility @ 39°F	X	X	
Phase Angle @ T_{HIGH} threshold			X
Float Test @ 140°F		X	X (for HF)
Assurance of Sprayability			
Saybolt Viscosity @ 122°F	X	X	X
Resistance to Bleeding @ High Pavement Temperatures (T_{high})			
DSR Parameter @ T_{HIGH}			X @ T_{high}
Viscosity @ 140°F	X	X	
Other Consistency			
Penetration @ 77°F	X	X	
Softening Point	X	X	
Resistance to Aggregate Loss @ Low Pavement Temperatures (T_{low}) after Aging			
PAV Aging			X
BBR Stiffness @ T_{LOW}			X @ T_{low}
Emulsion-Specific Stability Tests			
Demulsibility	X	X	X
Storage Stability	X	X	X
Sieve	**X**	**X**	**X**

Table 2. SPG Specification for Implementation in 2017 for: (A) Hot-Applied Asphalt Binders and Emulsion Residues, and (B) Emulsified Asphalt (14).

(a)

Surface Performance Grade	SPG 67				SPG 73				SPG 79			
	-13	-19	-25	-31	-13	-19	-25	-31	-13	-19	-25	-31
Average 7-day Max pavement surface design temperature, °C	<67				<73				<79			
Min pavement surface design temperature, °C	>-13	>-19	>-25	>-31	>-13	>-19	>-25	>-31	>-13	>-19	>-25	>-31
Original Binder												
Flash point temp, T 48, Min, °C	230											
Viscosity, T 316: Max 0.15 Pa*s, test temp., °C	205											
Original Performance Properties												
Dynamic Shear, T 315: G*/sin δ, Min 0.65 kPa, Test temp @ 10 rad/s, °C	67				73				79			
Phase angle (δ), Max, @ temp. where G*/sin δ = 0.65 kPa	–	80	80	80	80	80	80	80	80	80	80	80
Pressure Aging Vessel Residue (R 28)												
PAV aging temperature, °C	100				100				100			
Creep stiffness, T 313: S, Max 500 MPa, Test temp. @ 8 sec., °C	-13	-19	-25	-31	-13	-19	-25	-31	-13	-19	-25	-31

(b)

Grade	Test Procedure	HFRS-2(SPG xy[1])		CRS-2(SPG xy[1])		CHFRS-2(SPG xy[1])	
		Min	Max	Min	Max	Min	Max
Tests on emulsions:							
Viscosity, Saybolt Furol at 50°C, SFs[2]	T 72	150	400	150	400	150	400
Storage stability test, 24 h., %[2]	T 59		1		1		1
Demulsibility, 35 mL, 0.02 N $CaCl_2$, %	T 59	60					
Demulsibility, 35 mL, 0.8% dioctyl sodium sulfosuccinate, %	T 59			60		60	
Particle charge test	T 59			positive		positive	
Sieve test, %[2]	T 59		0.10		0.10		0.10
Residue recovery	PP 72, Procedure B						
Residue, %		65		65		65	
Tests on recovered residue:							
Residue properties		Meet the specified SPG grade[3], except the Max phase angle is 84					
Solubility in trichloroethylene, %	T 44	97.5		97.5			
Float test, 60°C, sec.[4]	T 50	1,200				1,200	

1. X is the average 7-day maximum pavement surface design temperature, and y is the minimum pavement surface design temperature used in SPG Specification.
2. This test requirement on representative samples is waived if successful application of the material has been achieved in the field.
3. Meet original performance properties and PAV residue requirements only
4. If Float test is less than 1,200 sec. using PP 72, Procedure B, for residue recovery, then use T 59 for residue recovery.

Comparison to Current and PG Specifications

SPG versus Current Specifications

As shown in Table 1, the SPG specification for chip seal binders addresses the majority of the same issues as current specifications, including:

- assurance of modified behavior,
- assurance of sprayability during construction,
- resistance to bleeding at high pavement temperature, and
- resistance to aggregate loss at low pavement temperature after aging.

Composition specific parameters are no longer needed in the SPG specification due to inclusion of performance-related properties. Modification in the SPG specification is controlled by phase angle measured in the DSR during high temperature grading instead of a separate elastic recovery test. Sprayability parameters remain unchanged except for a lower test temperature of 205° C for hot-applied asphalt binders. Viscosity is replaced by DSR parameters at a test temperature tied to the climate for all SPG grades, and other consistency parameters are eliminated. Low temperature stiffness measured in the BBR after only PAV aging at a test temperature tied to the climate is required for all SPG grades. Based on limited field data from chip seals with uncoated aggregates that facilitate aging evaluation, PAV aging for 20 hr at 100^0 C simulates the critical first year of service for chip seals in Texas [6].

SPG versus PG

The SPG specification utilizes the same framework and equipment as the PG specification and addresses the same shortcomings that previously existed for HMA binders, but accounts for differences between chip seals and HMA in terms of distress and conditions during construction and service. Figure 1 highlights the following differences between the SPG specification and the PG specification:

- Pavement temperatures (T_{pvmnt}) at the surface are utilized at both high temperatures (T_{high}) and low temperatures (T_{low}) for the thin chip seal applications.

- The grade temperatures at T_{high} and T_{low} are offset 3° C from those used for the PG specification to minimize confusion and accommodate the climate the SPG specification was developed for in Texas.
- The time-temperature shift at T_{low} is not utilized to capture aggregate loss at low temperatures due to traffic.
- RTFO aging is not utilized because it is not representative of conditions during construction, and there is not a performance-related property at intermediate temperatures (T_{int}).
- Only creep stiffness is determined from BBR testing, but this parameter is measured at 8 seconds to capture aggregate loss at low temperatures at the fastest reliable loading time to simulate traffic.
- A maximum phase angle is required if the useful temperature interval (UTI) is greater than or equal to 86.

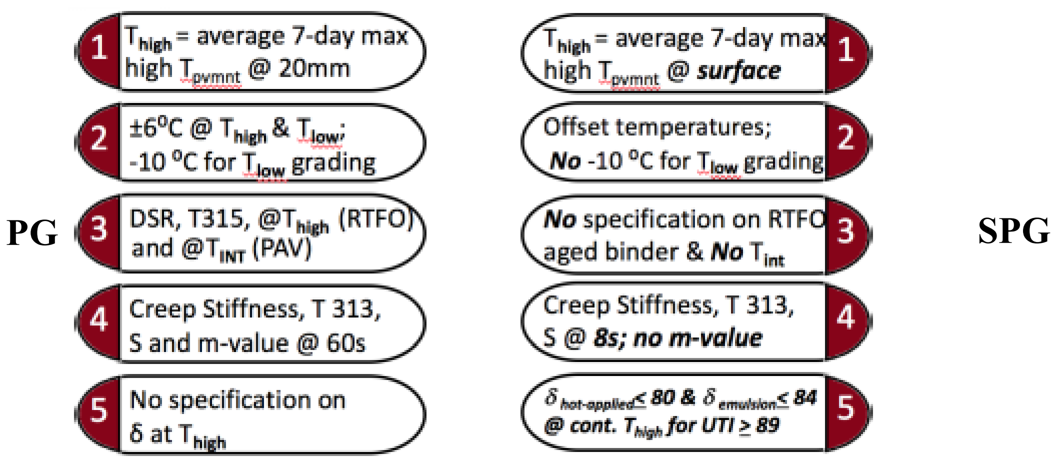


Figure 1. Comparison of PG and SPG Specifications.

Evolution of the SPG Specification

Table 3 presents the evolution of the SPG specification as documented in a series of TxDOT reports and associated TRB papers, an NCHRP report and associated TRB paper, the current published TxDOT special provision to Item 300 [15], and the recommended specification for implementation in 2017 shown in Table 2 [2-11].

Table 3. Evolution of the SPG Specification.

Equipment Test Method Temperature Aging State	Desired Performance	Performance Criteria	2001 (6, 10)	2005 (7, 8)	2010 (9, 11)	2012 (3, 4)	2015 (2)	2016 (Table 2)
DSR AASHTO T 315 High Temperature Original/Unaged	**Resistance to Bleeding**	$\frac{G^*}{\sin\delta}$ (kPa), min	0.75	0.65	0.65	0.65	0.65	0.65
	Polymer Modification	δ, max @ $\frac{G^*}{\sin\delta} = 0.65$ kPa	X	X	X	X	80 for UTI≥89	80 for UTI≥86 84 for emulsion residue
DSR AASHTO T 315 Intermediate Temperature Original/Unaged & PAV Aged	**Resistance to Aggregate Loss**	% strain, min @ $0.8G_{initial}^*$ (Original/Unaged)	X	X	25	17.5	X	X
		$G_{initial}^*$, max (PAV Aged)	X	X	2.5	2.5	X	X
BBR AASHTO T 313 Low Temperature PAV Aged	**Resistance to Aggregate Loss**	S (MPa), max @ 8 sec	500	500	500	500	500	500
	Stress Relaxation	m–value, min @ 8 sec	0.240	0.240	0.240	X	X	X

Initially, the minimum threshold value for G*/sin δ was set at 0.75 kPa based on the theoretical threshold estimate given by the Upper Bound Theorem (UBT) against aggregate loss and a qualitative field performance survey during the first TxDOT research project (10). With quantitative field performance data, this threshold was revised to 0.65 kPa and subsequent field validation with more than 120 highway sections confirmed this threshold. Researchers also considered several recovery processes for emulsions during the first TxDOT research project and selected the Texas Oven Method that became Procedure B in AASHTO PP 72-11 as the most efficient, representative, and repeatable method to recover the residue from both unmodified and modified emulsions while minimizing aging and ensuring removal of all water [3, 6, 7].

Shear strain sweep tests on both original unaged and PAV aged binders were introduced during the associated NCHRP research project and the second TxDOT research project based on research by others to evaluate strain tolerance and preclude aggregate loss. Despite one adjustment to the threshold, these parameters were removed due to lack of correlation with field performance. Most recently the phase angle parameter was added when the useful temperature interval (UTI) of the binder is greater than or equal to 86 (e.g. SPG 67-19) to ensure polymer modification and obtain adequate field performance, especially in extreme hot or cold environmental zones or under high traffic conditions. A maximum threshold of 80 degrees was chosen as it reasonably delineated the modified and unmodified binders for historically available phase angle data from TxDOT, but based on discussions with suppliers, a higher threshold of 84 degrees was selected for emulsion residues. The initial maximum threshold for stiffness (S) of 500 MPa set using a qualitative field performance survey was confirmed with quantitative field performance data from more than 120 highway sections in repeated validation efforts such as that discussed subsequently. An initial minimum threshold for m-value of 0.24 was also confirmed by field validation, but this parameter was removed from the specification in the second TxDOT research project due to a lack of relevance for chip seal performance.

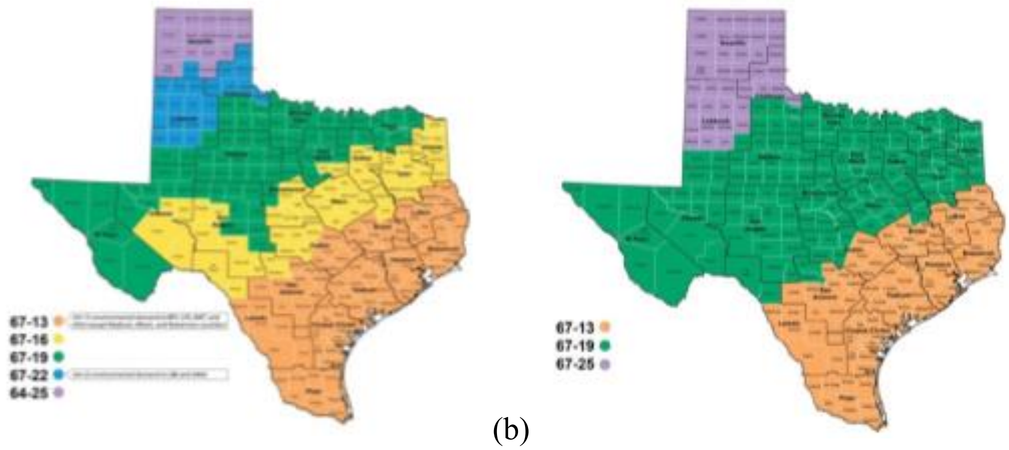
Binder Grade Selection

As a complement to the SPG grading process, the following steps are offered to select the binder SPG grade to meet climate, traffic, and other project-specific demands using the SPG specification:

1. Select a binder SPG grade using a climate-based requirement map that is color-coded by TxDOT district and county or a related and more specific TxDOT spreadsheet tool (ftp://ftp.dot.state.tx.us/pub/txdot-info/cmd/forms/docs/pg-spg-binder-climatic-grade-selection.xlsm) [16].
2. Consider adjusting the binder SPG grade for traffic or modification.
3. Select the final binder SPG grade.

The climate-based SPG map in Figure 2 or the associated TxDOT spreadsheet tool is utilized to establish the climate-based required SPG grade. This map was initially developed based on worst case surface pavement temperatures within each Texas county, starting from 95% confidence and rounding to the nearest 3° C increment (Figure 2 (a)). The majority of Texas counties require 67° C for high SPG environmental demand, and the low SPG environmental demand gets cooler moving from southeast to northwest from -13° C to -25° C.

During the 2016-17 implementation effort, a round robin program (described in Chapter V) conducted with Texas A&M Transportation Institute (TTI), TxDOT, and binder suppliers concluded that the 3^0 C increments were too tight based on the DSR precision and bias, resulting in changing the SPG binder grades to 6^0 C increments (Figure 2 (b)).



(a) (b)

Figure 2. SPG Climate-Based Requirement Map for Texas Based on (a) Initial 3^0 C and (b) Revised 6^0 C Increments.

The TxDOT spreadsheet tool utilizes location coordinates or county of interest and confidence intervals as inputs. Figure 3 (a) shows the sample input, and Figure 3 (b) shows the sample output for the spreadsheet tool. The confidence interval is the reliability level desired for the climate-based grade, and represents the likelihood that the pavement temperature will exceed the UTI in a year. Common confidence intervals are 95% and 98% and can be interpreted as a temperature excursion outside the grade limits once every 20 years and once every 50 years, respectively. The spreadsheet output provides the recommended binder SPG grade and the number and identification of the weather stations that were used in the calculation. The recommended grade is intended to encompass all the selected weather stations based on the 7-day high temperature converted to surface pavement temperature using the Superpave model [12]. The binder SPG grade is calculated from the mean and standard deviation of the surface temperature, along with the confidence interval given as input, and rounded to the 6° incremental grade that will satisfy the requirement. Larger counties may have a large variation in grades for various stations, and in that case a single station that is close to the project location may be selected.

After establishing the climate-based binder SPG grade, traffic and modification are considered. For facilities with high traffic volume or excessive truck traffic, the high-temperature SPG grade can be increased by one 6° increment. If binder modification is desired, a useful temperature interval (UTI), defined as the difference between the high-temperature and low-temperature SPG grade, of 86 or larger should be selected. After the climate and project-specific requirements have been taken into consideration, a final binder SPG grade is selected.

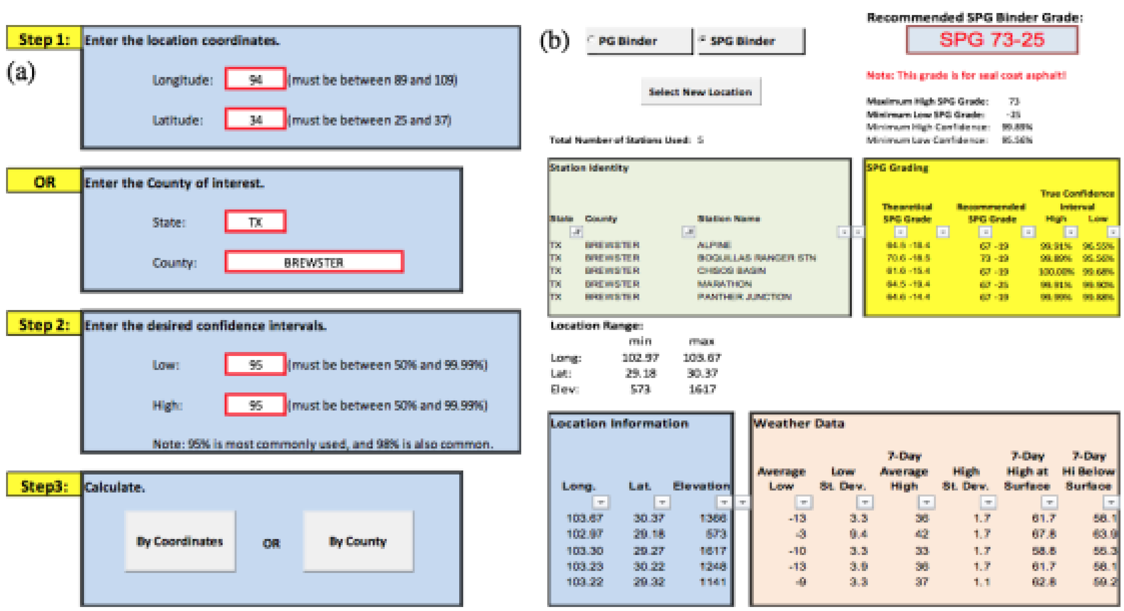


Figure 3. (a) Sample Inputs and (B) Output for the SPG Binder Grade Selection Tool Spreadsheet.

IMPLEMENTATION OF THE SPG SPECIFICATION

Implementation and Validation during 2013-14

Toward statewide implementation of the SPG specification, further field validation of the SPG parameters and the thresholds that control performance in service was completed during the first two years (2013-14) of the ongoing TxDOT implementation project (5-6616). Field performance correlation was performed on a total of 32 HSs resulting in 79% correlation of $G^*/\sin\delta$ at high temperatures and 72% correlation of the BBR Stiffness at low temperatures. The effort during this implementation period was documented as Technical Memorandum 5-6616-01-TM1 for TxDOT Project 5-6616 [2].

Apart from the implementation and validation effort during 2013-14, significant efforts were made to make the specification as practical as possible. Key highlights of the steps towards achieving practicality include the following:

- Based on the county–wise SPG grade requirements determined from the climate and calculated surface pavement temperatures, the number of SPG grades were reduced to 1-2 for each TxDOT district.
- Due to increasing use of polymer modified binders in chip seal applications, a phase angle parameter was introduced to the specification to ensure adequate modification.
- An attempt was made to replace the material and time – consuming BBR testing with the DSR frequency sweep test. Also, DSR shear strain sweep test, the then existing test method used to evaluate the intermediate temperature property of the chip seal binders was attempted to be replaced with the linear amplitude sweep (LAS) test.
- The possibility of using 4mm plate DSR testing to determine the low temperature properties (−40° C to 0° C) from frequency sweep tests was explored.

Implementation and Validation during 2016-17

The ongoing 2016-17 period marks the third year of the statewide implementation of the SPG specification. In addition to the validation effort with 14 HSs during this period, considerable effort toward educating the binder suppliers and academia and marketing the SPG specification to TxDOT districts is underway. Also, concerns regarding characterization and threshold values for ensuring the presence and quality of polymer modification are being addressed. This report documents these efforts.

PROBLEM STATEMENT

Through TxDOT Project 0-1710, NCHRP Project 14-17, and, more recently, TxDOT Project 0-6616; the SPG binder specification for chip seal binders in service was developed and validated with field performance monitoring of 75 HSs statewide. Based on field validation, given proper construction and design, the estimated SPG grades and the field performance of chip seal binders are well [3, 7].

Although most of the laboratory testing recommended in the SPG specification is consistent with the PG binder grading system, the success of its implementation requires addressing the following issues:

- Educating the industry and the potential users of the specification.
- Achieving familiarization of the specification among the binder producers and suppliers who formulate and produce the asphalt binders to meet the SPG specification.
- Gaining the confidence of the TxDOT districts to implement the specification in their future chip seal applications.
- Solving potential problems that may arise with respect to the parameters and the thresholds of the specification particularly in terms of polymer modification.
- Answering questions related to the development and the validation of the specification such as the existing field performance monitoring methodologies.

RESEARCH OBJECTIVE

The SPG specification is intended to improve the field performance of chip seals (with either hot-applied asphalt binders or emulsions) by limiting aggregate loss or bleeding distress potential. The objectives for the 2016-17 implementation period are field performance validation of the existing specification parameters, interaction with various target users of the specification through round robin programs, and evaluation of alternative testing methods, particularly MSCR test, to be indicative of polymer modification for chip seal binders.

REPORT OUTLINE

This report focuses on the third year (2016-17) of implementation of the SPG specification and is organized into six chapters. Chapter I includes the motivation and the evolution of the SPG specification along with a brief introduction to the first two years (2013-14) and ongoing implementation of the specification. The current problem statement, the research objectives, and report organization are also outlined. Chapter II is a literature review that introduces chip seal related specifications around the world, characterization of polymer modification in binders. Chapter III describes the experimental design, including the methodology and materials used. The results of laboratory evaluation and field monitoring are presented and analyzed in Chapter IV. Chapter V consists of the efforts toward making the specification more practical and addressing the identified issues during implementation. Lastly, Chapter VI summarizes the conclusions and recommendations for further research.

CHAPTER II

LITERATURE REVIEW

An extensive review of existing literature was performed, in addition to that related to the evolution of the specification, to address the following issues described in this chapter:

- In the first part, chip seal-related specifications around the world were reviewed to understand the state-of-the-art with respect to the material-related specifications in terms of parameter and threshold development.
- In the second part, various advancements and challenges in the characterization of polymer modified asphalt binders (PMABs) were studied.

DEVELOPMENT OF BINDER PERFORMANCE – BASED METRICS FOR SURFACE PRESERVATION TREATMENTS

Surface preservation treatments such as chip seals, spray seals, and microsurfacing are common, inexpensive hot mix HMA pavement maintenance solutions utilized by transportation agencies around the world. Surface treatments do not necessarily improve the structural capacity but improve the surface friction and slow down the rate of deterioration of pavements [17]. When implemented properly, these treatments prove to be effective and thus delay the need for costly reconstruction. Choosing optimum materials and ensuring good quality construction are the key to the success of these treatments.

However, the material specifications currently utilized by the departments of transportation for such applications are prescriptive and empirical in nature rather than being based on the desired performance in the field [5]. Recognizing this, government and transportation agencies around the world are increasingly streamlining their resources to develop performance tests and relevant purchase specifications to aid engineers and practitioners in choosing asphalt binders that help in precluding distresses in the field [17-23]. This section reviews the efforts in the development of performance based tests and specifications for HMA surface treatment asphalt binders around the world with a focus on chip seal binders.

Flushing Study and Performance – Based Bitumen Specification for Chip Seals in New Zealand

Herrington et al. (2015) studied various physical mechanisms that could cause flushing; flushing was defined as the loss of surface texture depth with time [19]. Their studies concluded that aggregate abrasion and breakdown, compaction and chip reorientation due to traffic, and sub-surface stripping are the major causes for flushing while the thermal expansion and viscosity of the binder and its excessive application contributed little to flushing. They suggest the use of high polymer/ crumb rubber modifiers to help minimize chip reorientation and report that thermosetting epoxy binders may be successful at resisting chip embedment. They also recommend the inclusion of a Micro-Deval (MD) test post field performance validation in a New Zealand chip seal specification as it might be able to measure chip breakdown. Intriguingly, Kim et al. report that although flushing and bleeding are used interchangeably, flushing occurs due to construction related problems where excessive binder is applied while bleeding occurs due to the viscoplastic nature of asphalt binders at high temperatures [17]. Maybe, this highlights the need to understand the mechanisms behind each of the distresses occurring in an application.

The New Zealand Transport Agency began its work on developing performance based specification for bitumens used in chip seal applications in 2015. The specification is in the early phase of its development, and the thresholds for the suggested parameters are not yet set. The specification is aimed at assessing the performance parameters relevant to New Zealand which include compatibility of the bitumen with kerosene, its adhesion to aggregate particularly in the presence of water, and chip retention [18]. The following tests were suggested to be included in the specification to evaluate the above-mentioned performance related aspects:

- ***Compatibility of bitumen with kerosene:*** Consistency in viscosity changes when kerosene is added to the bitumen was considered important to ensure their compatibility. Conversely, it was found that the change of base bitumen had a much more predominant effect on the viscosity than the change in kerosene content in the cutback. Therefore, a parameter to ensure the compatibility was not included in the final specification.
- ***Adhesion to aggregate:*** Control of aggregate – binder adhesion was considered crucial to warrant proper aggregate surface wetting and formation of a water – resistant bond by the bitumen. However, inclusion of a test requiring both aggregates and binder such as the Vialit test was beyond the scope of an asphalt binder specification. A test to quantify chemical affinity, degradation of adhesion at high temperatures, and physical wetting of aggregate at ambient temperatures was investigated. With the premise that wetting is controlled by penetration at 25^0 C, the Multiple Stress and Creep Recovery (MSCR, AASHTO T 350-14) test at 25^0 C was proposed to be included in the specification to evaluate the binder's adhesion to the aggregate.
- ***Chip retention:*** Retention of chips under traffic loading by precluding cohesive failure at very high or very low temperatures (range of temperatures) was judged to be a important component of a chip seal binder specification. A tensile test along the lines of a ductility test at a temperature of interest was proposed to specify a minimum fracture or yield stress indicative of sufficient cohesion energy for chip retention. But, at low test temperatures (-10^0 C to 0^0 C), the binder is brittle while at temperatures above 50^0 C, the binder is too viscous to conduct the test. Therefore, MSCR test at 55^0 C was proposed to balance the binder's resistance to deformation and elastic recovery.

This specification attempts to ensure good chip seal performance by safeguarding the aggregate – binder bond at different temperatures and addressing binder composition-based issues.

Australian Polymer Modified Binder (PMB) Specification

Polymer modified binders (PMBs) were specified in Australia through maximum allowable stiffness at 15^0 C for spray applications and at 25^0 C for HMA. Urquhart (2015) investigated the possible inclusion of ARRB (Australian Road Research Board) elastometer in the Australian PMB specification to rank the low temperature cracking resistance of PMBs used in HMA and spray applications [21]. Although good correlation between number of oscillation cycles to 50% reduction in binder stiffness in the DSR and the fatigue life was reported, the possibility of utilizing the DSR for this purpose was eliminated due to prolonged testing time. Further, the potential use of a force ductilometer test for ranking thermal cracking resistance of PMBs was disregarded due to the lack of availability of the equipment in Australia to perform the test. The ARRB extensiometer (or elastometer) was eventually chosen due to equipment availability and the reported good correlation between force ratio and fatigue life at 10^0 C from earlier studies. While the study by Urquhart (2015) also showed good correlation between the extensiometer's force ratio and fatigue life, it was proposed that the relevant test conditions be developed to rank hard PMBs.

Note that importance was given to the practicality of testing in terms of the test time and the availability of the equipment in Australia prior to considering the test to be included in a specification.

Chip Seal Tests and Specifications in the United States

Emulsion Performance Grade (EPG) Specification for Surface Treatments

The Emulsion Performance Grade (EPG) Specification was developed for pavement surface treatments including chip seals, spray seals, and microsurfacing as part of National Cooperative Highway Research Project (NCHRP) 9-50 Performance-Related Specifications for Emulsified Asphaltic Binders Used in Preservation Surface Treatments [17]. The specification, as the name suggests, was developed for emulsions used in spray surface applications through understanding of mechanisms of material – related distresses for each of the treatments and establishing and validating threshold limits for parameters measured in relevant performance – based test methods. Only chip seal related testing and parameter thresholds are discussed in this section.

In the development of the EPG specification for chip seals, the researchers identified raveling, bleeding, and rutting in multilayered seals as the critical distresses. Three types of raveling were defined for chip seals: (a) early raveling, which was attributed to opening the chip seal section to traffic before emulsion curing is complete, (b) late raveling, which was attributed to the effect of traffic in the long term at intermediate (loss of aggregate – binder bond) and low (brittle asphalt) temperatures, and (c) wet raveling, induced by moisture damage that causes the emulsion residue-aggregate bond to fail. However, the researchers highlight that only low temperature raveling was addressed in the specification although it was recommended that the other two types of raveling also be considered during mix design. Interestingly, bleeding was addressed as an after – effect of raveling where the binder that is no longer holding the chips together was considered to contribute to bleeding.

Test Methods and Development of Parameters in the Specification

The EPG specification summarized in

Table **4** contains test methods that help in specifying the required properties in fresh emulsions (storage and constructability) as well the mixture performance of the pavement surface treatment. A typical binder grade in the EPG specification is CRS-EPG 67-19M, where CRS denotes the emulsifier charge and set rate, 69-19 represent the high and low temperature emulsion grade as per EPG thresholds, and M indicates the traffic volume. The traffic levels designated for the specification in terms of Annual Average Daily Traffic (AADT) which are defined are as follows:

- Low: 0 – 500 AADT
- Medium: 501 – 2,500 AADT
- High: 2,501 – 20,000 AADT

Table 4. Properties Evaluated and Used for Performance Related Specification by Kim et al. (2017).

Binder state	Test	Parameter measured	Property evaluated	Specification
Residue	DSR, Temp-Freq Sweep	G* at Critical phase angle	Low temp. aggregate loss	Max
	MSCR	J_{nr}	Bleeding and rutting	Max
Fresh emulsion	Rotational viscometer	Sprayability, drain out, storage stability, Separation	Workability & stability	Min

AASHTO T59 was utilized in the specification to assess the fresh emulsion, while AASHTO PP 72 Method was proposed for residue recovery. The specification thresholds for the proposed parameters for the residue were set based on laboratory testing on binder for permanent deformation (MSCR) and on laboratory fabricated chip seal specimens for aggregate loss (Vialit and the Third Scale Model Mobile Loading Simulator (MMLS3) tests). For high temperature grading, the parameter J_{nr} (non-recoverable creep compliance) from the MSCR test at 3.2 kPa was proposed to capture the polymer network and the binder's resistance to permanent deformation. A DSR frequency sweep test from 5^0 C to 15^0 C was proposed to measure the low temperature binder fracture resistance through G* at a critical phase angle. It was reported that the low temperature aggregate loss was due to cohesive failure of the binder rather than adhesive failure of the aggregate – binder bond which showed a strong relationship with crossover modulus (G_c*). As the G_c* (with phase angle 45^0) is indicative of the balance between elastic and viscous behavior of binders, an increase in G_c* (with decrease in temperature) makes the binder susceptible to cracking. However, as G_c* is a temperature independent parameter, it was incorporated into the temperature based EPG specification through critical phase angle. Correlating the aggregate loss to temperature and G* values corresponding to varying phase angles to obtain a temperature independent relationship between aggregate loss and G*, critical phase angles were defined for various low temperature EPG grades. Although considered in the development phase, thresholds at intermediate temperatures were not established due to the inability of the chosen parameter to delineate modified and unmodified binders and its poor correlation with aggregate loss measured in chip seal mixture testing.

Chip Seal Bleeding Test

Attempts have been made by some researchers to develop testing equipment for chip seals by modifying the existing equipment used for HMA. One such attempt was the Modified Loaded Wheel Test (LWT) developed by Chaturabong et al. at the University of Wisconsin – Madison [23]. This equipment was chosen by the researchers because it was a less expensive piece of equipment and more widely available. The group developed new sample preparation, testing procedure, and analysis framework for this purpose.

They made changes to the equipment and the test procedure to simulate the field bleeding phenomenon. One reason for bleeding in chip seals is due to embedment of the chips into the binder layer. To simulate this, the researchers used neoprene pads between the sample, and a steel plate was used to support the sample in the original device. The original test runs at ambient temperatures whereas bleeding occurs at high temperature. So, the test was carried out at higher temperatures by insulating the sample, and a temperature control unit was placed to control the temperature. Another modification made to the equipment to avoid unrealistic and excessive raveling in the sample was done by replacing the steel wheel with a rubber tire. Also, the dimensions of the simple were increased to align with the sample size for the sweep test (ASTM D7000). The final test equipment is as shown in the Figure 4 (reprinted from [23]).

Figure 4. Final Modified Loaded Wheel Test Equipment, Reprinted From [23].

With this equipment, bleeding was assessed as a percentage of asphalt on the surface through surface texture measurements and Image Processing Analysis Software (IPAS). The surface texture was measured using a modified sand patch test as the surface of the chip seal is not microtextured to enable high speed data collection with a laser. The IPAS uses the threshold intensity of a bare aggregate piece and compares the specimen before and after testing to quantify bleeding.

It was reported that the modified LWT could quantify bleeding potential and bleeding development of laboratory prepared chip seal samples. Temperature, number of loading cycles, and contact stress affect bleeding. Bleeding increases with an increase in all of these factors. It was also reported that texture loss and % bleeding were moderately related from IPAS analysis. However, some validation effort showed that texture loss could be indicative of bleeding.

Chaturabong, in his MS Thesis, also investigated the relationship between emulsion residue performance as measured by the MSCR test and chip seal bleeding resistance as measured by the LWT to evaluate the factors that are related to bleeding performance to prevent bleeding in the field [22]. It was reported that MSCR could possibly be used in evaluating the emulsion residue performance as it was found that it could differentiate between emulsion chemistry and modification while being sensitive to temperature and stress. Attempts to quantify the benefits of emulsion modification was made by comparing the specimens prepared with modified and unmodified binders. It was concluded that modification gave higher creep compliance at higher temperatures which is positive for better performance.

Summary

Need for performance based material specifications has become paramount in the pavement industry to ensure longevity and delay costly reconstruction. After the dawn of Superpave Performance Grade (PG) specification for binders used in HMA pavements, transportation agencies around the world are recognizing the need to move away from empirical and prescriptive specifications. In this part of the chapter, various efforts on developing asphalt binder tests and specifications for chip seal applications in New Zealand, Australia and the United States are described briefly. The significance of these efforts is the importance given to the relevance of the specification parameters to preclude material related failure in the field, the ease and availability to perform the test protocols and making the test procedures appropriate for chip seal applications. Undoubtedly, these are some of the factors that must be considered at grass root level in the process of developing a performance based material specification.

CHARACTERIZATION OF PMABS

The ever-increasing traffic volumes and loads coupled with more extreme weather conditions in recent years resulted in increased use of polymer modified asphalt binders (PMABs) by highway agencies to increase the durability and improve the performance of HMA pavements [21, 24-27]. While modification can make the binders almost twice as expensive as unmodified binders, nearly 15% of the total annual tonnage of asphalt binder used in the United States was modified as of 2001 [28].Various reasons for modification include widening the UTI defined as the range between the high and low temperature binder performance grade (PG)) or attaining specific material properties such as withstanding slow-moving traffic [12, 14]. Although the experience with the use of PMABs has been largely positive, the characterization of such binders has become a major challenge from both research and implementation perspectives [25, 28].

Need for New Parameters to Characterize PMABs

The current PG specification in AASHTO M320 was originally developed based on unmodified or traditional binders with test conditions in the LVE range [25]. The initial success of the high temperature rutting parameter of the specification, G*/ sin δ, in correlating with rutting performance of the HMA pavements (i.e. predicting the permanent deformation in the binder despite the test conditions being in the LVE range) can be attributed to the largely viscous nature of traditional binders which exhibit very low recovery in deformation post loading. However, polymer modification changes binder morphology by inducing a larger elastic component to the binders, allowing them to perform well in higher or slow moving traffic conditions. Considering the nature of the test conditions utilized while measuring the G*/ sin δ parameter where the loading is completely reversed (shown in Figure 5 (a)), the permanent deformation caused by the viscous component is cancelled out. Therefore, unidirectional loading (Figure 5(b)) that can clearly delineate the elastic and delayed elastic response (recoverable component of strain) and the viscous component (permanent strain) was suggested to characterize PMABs (reprinted from [29]).

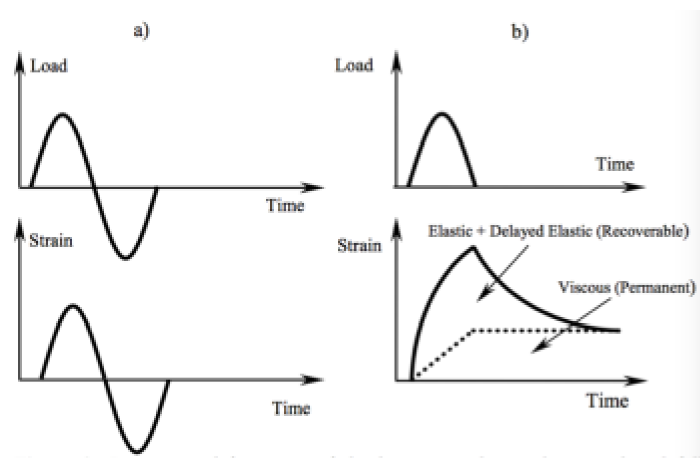


Figure 5. Comparison of Permanent Deformation of Binders Caused by (A) Fully Reversed Loading And (B) Unidirectional Loading, Reprinted From [29].

Moreover, asphalt binders in HMA pavements typically experience localized stresses beyond their LVE range [30]. PMABs are sensitive to the applied stress levels and exhibit non-linear behavior at higher stress levels, whereas unmodified or neat binders have linear flow and are insensitive to the stress levels used in AASHTO T315 to characterize these materials at high and intermediate temperatures in the DSR (Figure 6, reprinted from [25]) [24, 25, 31]. G*/ sin δ is measured at low stress levels in the LVE range where the polymer network may not be activated and hence, the advantage of modification is not completely captured [27]. This adds to the complexity associated with PMAB characterization.

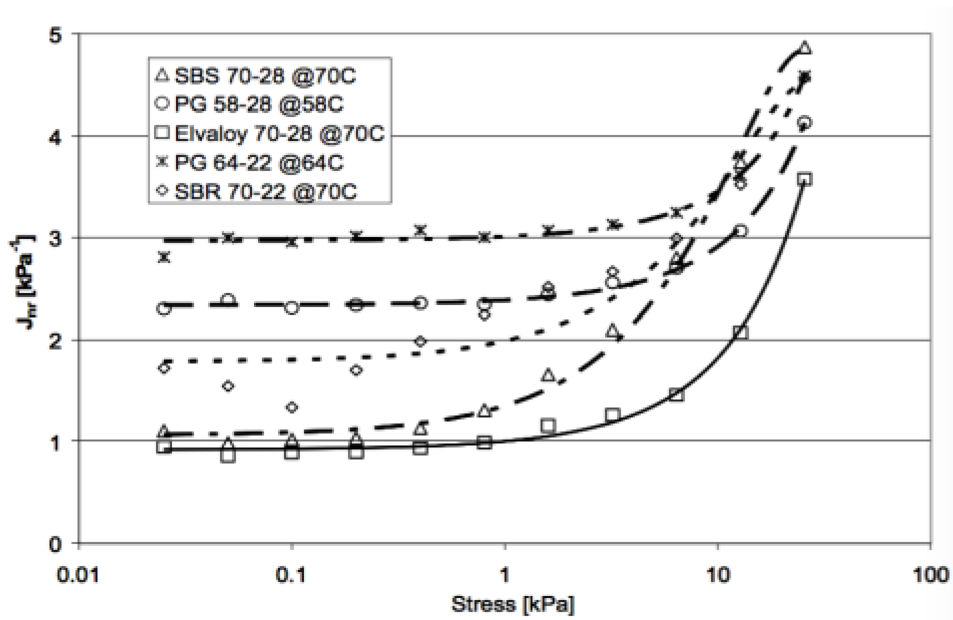


Figure 6. Data Supporting the Stress Sensitivity of Modified Binders, Reprinted From [25].

The adequacy of the G*/ sin δ to characterize PMABs has been questioned by both the research community and public agencies, which increased the need for a new parameter that is both performance based and insensitive to modification type [25, 26, 28, 32-34]. Some of the factors that need to be captured by a performance based test for PMABs are the following:

- ***Type of Modifier:*** Hossain et al. (2016) report the dependency of binder performance on the type of modifier [24]. Li et al. (2011) reported that PPA modified binders exhibited the worst performance while PPA + Elvaloy and SBS + PPA combination modifiers gave the best performance in terms of having high recovery and low accumulated creep strain in the MSCR test. Similarly, it was also reported that the MSCR test could differentiate the rheology of rubber modified asphalt binders [35]. Another study as shown in Figure 7 (reprinted from [17]) reports the ability of the MSCR test to clearly delineate PMABs from neat binders as well as the different modifiers in the PMABs [17].

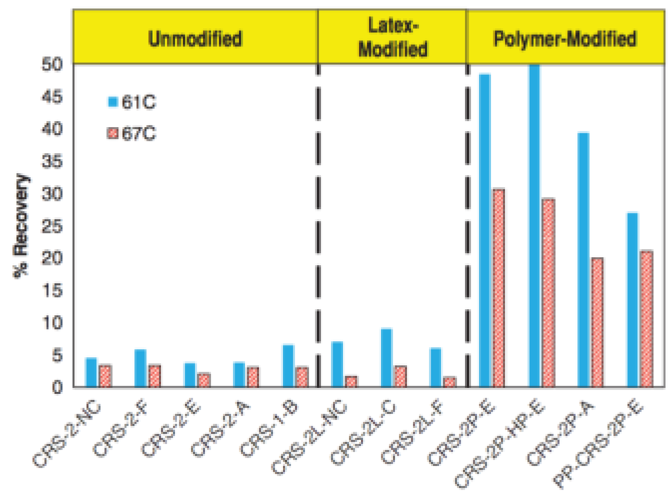


Figure 7. A Study Reporting the Ability of MSCR Test to Delineate PMABs from Neat Binders and the Modifiers in PMABs, Reprinted From [17].

- ***Formulation of the Asphalt Binders:*** D'Angelo and Dongre (2009) report the sensitivity of binders modified by SBS polymers to polymer content, amount of cross-linking agent, and additives such as polyphosphoric acid (PPA). The compatibility of the base binder and the modifier also plays a huge role in the optimum dispersion of SBS [36].
- ***Blending Conditions:*** The performance of the binders was also reported to be affected by blending time and the temperature of SBS modifier [36].

Status of PMAB Characterization

The state departments of transportation (DOTs) adopted additional "PG Plus" tests such as elastic recovery (ER), force ductility, or toughness or phase angle to combat the issue of inadequate PMAB characterization (Figure 8, reprinted from [27]). However, some of these tests pose fundamental issues such as change in the specimen geometry while testing and the lack of consideration for the strain rate dependency of viscoelastic materials (modified vs. unmodified) [31]. Moreover, these tests are time consuming, expensive, sensitive to modifier type, empirical, and most importantly, do not correlate to field performance [24-29, 31].

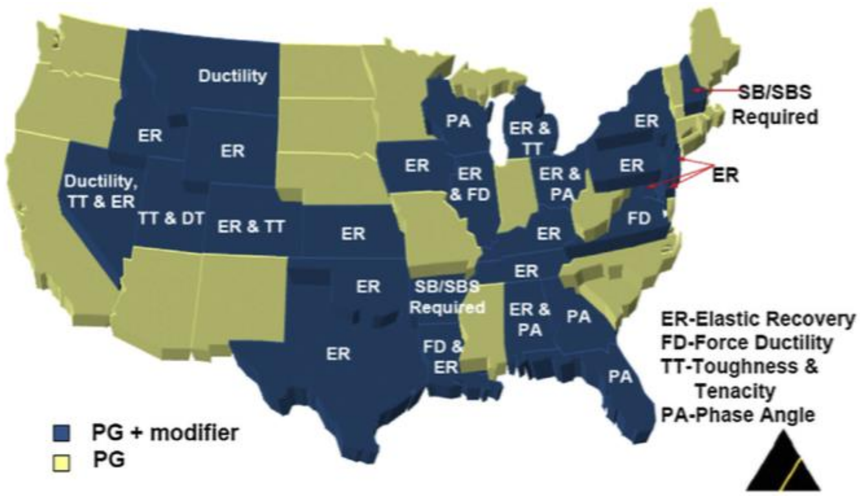


Figure 8. Map Showing the Use of PG Plus Tests by Various State DOTs in the United States, Reprinted From [27].

Responding to the growing need to accurately characterize PMABs, NCHRP 9-10 Superpave Protocols for Modified Asphalt Binders was conducted where a repeated creep recovery test (RCRT) was first developed which was eventually modified to the Multiple Stress Creep and Recovery Test (MSCR) by the Federal Highway Administration (FHWA) through evaluation of both modified and unmodified (neat) binders as discussed subsequently.

The MSCR test may be implemented partially where the test method is used along with AASHTO M320; or fully, where the test method and the corresponding specification in AASHTO MP19 with modified grading system completely based on climate and loading are used together without grade bumping [24, 37]. Asphalt Institute (AI) suggests that using the MSCR test with AASHTO M320 provides better high temperature performance – related binder characterization and also provides guidance on their combined use to eventually do away with the empirical PG Plus test methods [37].

A typical binder grade with full implementation of the MSCR test is PG 64-22H where 'H' indicates that the binder exhibits low residual strain as discussed subsequently for use in heavy traffic conditions. Note that the binder grade implies that the MSCR testing was performed at 64^0 C (PG T_{high}) and no grade bumping was performed i.e. to PG 70-22. Studies report that full implementation of MSCR is being considered for implementation by some state DOTs, while it is already adopted by four states in United States and the asphalt user/ producer groups have performed interlaboratory studies to determine the precision of the MSCR test [26, 27, 33, 38-40]. The current status of MSCR implementation in the United States as reported by the AI is shown in Figure 9.

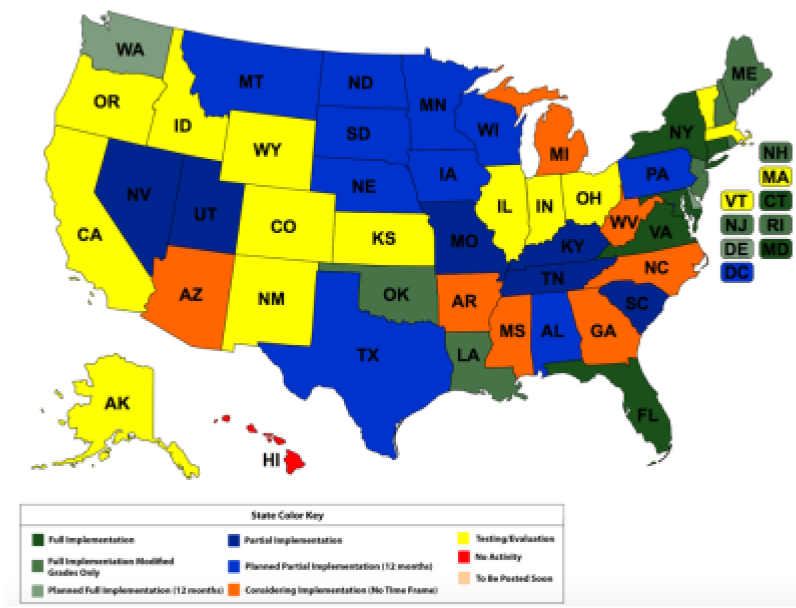


Figure 9. Status of MSCR Implementation in the United States, as Reported by AI.

Efforts towards PMAB Characterization - Introduction of the MSCR Test

After considering various parameters, a RCRT test was developed as an outcome of NCHRP 9-10. The principle used in the development of the test was to truly replicate the cyclic non-reversible loading representing real traffic conditions instead of cyclic reversible loading which is the concept behind the derivation of $G^*/\sin \delta$. This helps in measuring the damage induced in the binder due to viscoplastic flow and helps in completely characterizing PMABs as discussed previously. It was hypothesized that the permanent deformation is associated with nonlinear viscoelastic properties and hence, the stress levels applied and the residual strains observed are crucial to understanding the binder rutting behavior [34]. In this direction, the viscous component of the binder stiffness, G_v (sensitive to aging) was measured in the RCRT test that exhibited high variability depending on the modification type [29]. Sensitivity to aging was likely the reason this parameter was abandoned in subsequent work. However, it may be noted that this aging sensitivity could be a result of degradation of polymer chains or other modifiers with aging [41].

The RCRT test later formed the basis for the development of the MSCR test. The MSCR test, performed on rolling thin-film oven-aged (RTFO) binder, is described in AASHTO TP70 with an associated PG Plus specification in AASHTO MP19 [42, 43]. The idea behind this test is to be able to run the test at multiple stress levels on the widely available DSR and hence, characterize the stress dependency of PMABs [25, 26]. As it was developed to replace or supplement the $G^*/\sin\delta$ paramter, it was originally intended to capture the rutting performance of HMA pavements while being blind to the type of modification and hence, avoid the use of PG Plus tests to identify the presence of polymers [26, 27, 29, 32, 35, 44, 45].

Development of the Multiple Stress Creep and Recovery (MSCR) Test

The genesis of the MSCR test lie with the RCRT test proposed during NCHRP Project 9-10. Originally, the test was performed at stress levels ranging from 0.025 to 25.6 kPa on individual samples where at least 100 cycles were performed at each stress level [46]. Performing the test on individual samples at each stress level for several cycles meant a large sample size requirement and long testing periods for one binder. Therefore, in the initial development phases of the MSCR test, a single sample for all the stress levels with fewer cycles was utilized. A total of 11 stress levels including 0.025, 0.05, 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, 12.8, and 25.6 kPa were proposed to be performed for ten cycles each before moving to the next higher stress level on a single sample. For each cycle, a loading time of 1 sec followed by a rest period of 9 secs was used [25, 34].

These stress levels closely represent actual traffic loading and thereby help to characterize PMAB stress dependency [26].

The current MSCR test is performed on RTFO aged binders at only two stress levels (0.1 and 3.2 kPa) for ten cycles each with each cycle corresponding to the sequence of 1 sec loading and 9 secs rest period. Also, a ten cycle conditioning sequence with ten cycles at 0.1 kPa stress level has to be performed at the start of each test per AASHTO TP70 [43]. A schematic of the MSCR test loading sequence and the various parameters obtained from the test data analysis are as shown in Figure 10 and Figure 11 (reprinted respectively from [36] and [26]). The key parameters obtained from the MSCR testing are % recovery (%R) and non-recoverable creep compliance (Jnr). The calculations to determine these parameters are described in Chapter III. It should however be noted that binders with higher %R and lower Jnr are considered good quality binders.

(a) (b)

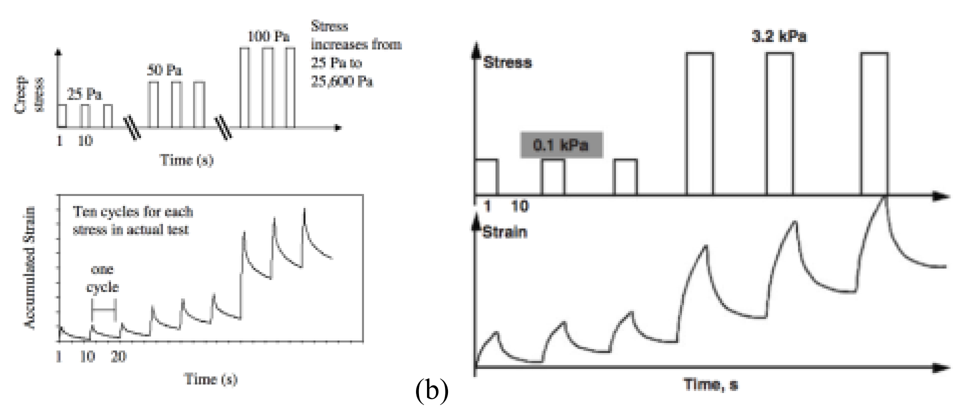


Figure 10. (a) Schematic of Initial MSCR Test Loading Sequence, [47] and, (b) the Current MSCR Test Loading Sequence, Reprinted From [36].

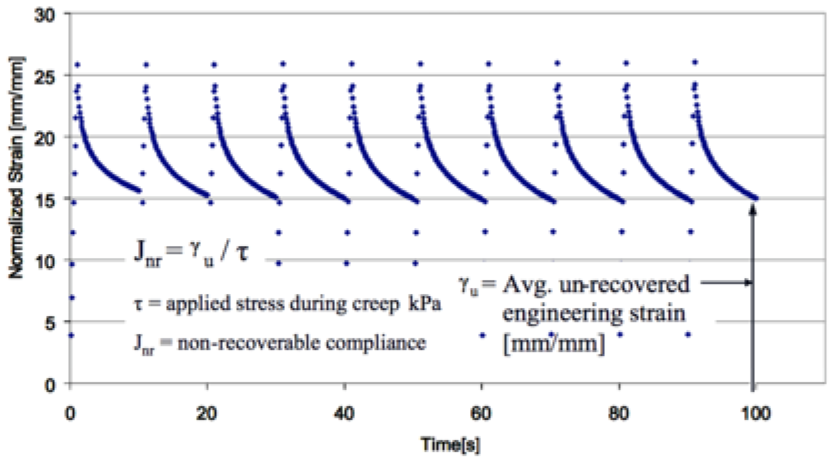


Figure 11. Typical Creep and Recovery Data Obtained During MSCR Test and the Parameters Calculated from the Data, Reprinted From [26].

From the extensive testing performed during the development of the MSCR test, it was concluded that the MSCR testing could delineate different modifiers, and the neat binders exhibited Jnr value of about 0.3 consistently at different grading temperatures suggesting their stress insensitivity. D'Angelo and Dongre report that the MSCR test was able to differentiate between the poorly and well dispersed SBS in the base binder and they suggest that the test protocol should be utilized to ensure optimum modifier blending in PMABs [36].

Methods of Analyzing MSCR Test Results

There is a reasonable amount of literature that provides guidance or different methods of analyzing the MSCR test results, some of which are summarized as follows:

- AI mandates performing the MSCR test on RTFO aged binders and recommends the test temperatures based on Long Term Pavement Performance Bind (LTTPBind) climatic conditions for various locations in the United States [37]. The plot of MSCR % R vs J_{nr} at 3.2 kPa as shown in Figure 12 (reprinted from [37]) can be utilized to check if the binder exhibits sufficient MSCR %R where the data points above the curve indicate binders that are modified with elastomeric polymers and have high elasticity; the data points falling below the curve indicate poor modification and the binders would exhibit poor elasticity.

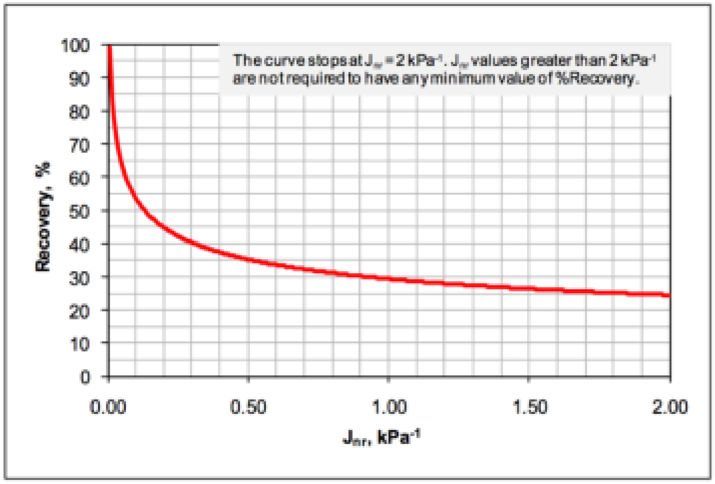


Figure 12. Jnr vs. Recovery Plot to be Utilized to Determine the Sufficiency of Delayed Elastic Response, Reprinted From [37].

AI also suggests the utilization of the stress sensitivity parameter, $J_{nr,\ diff}$, calculated as the ratio of difference between $J_{nr,\ 3.2\ kPa}$ and $J_{nr,\ 0.1\ kPa}$ to $J_{nr,\ 0.1\ kPa}$ as follows (Equation 1):

$$\mathbf{J_{nr,diff}} = \frac{\mathbf{J_{nr,3.2\ kPa}} - \mathbf{J_{nr,0.1\ kPa}}}{\mathbf{J_{nr,0.1\ kPa}}} \qquad \text{Equation 1}$$

It was suggested that the binder can be considered stress sensitive if the $J_{nr,\ diff} >$ 0.75 and a $J_{nr,\ diff}$ value threshold of 0.75 was set if MSCR is utilized with AASHTO M320.

- Hossain et al. (2016) utilized two methods to analyze the MSCR data: (a) the Polymer Method and (b) the Quadrant Method. The basis for analysis using the Polymer method is the same as that suggested by AI which uses Figure 12 to determine whether the binder has sufficient delayed elastic response. In the case of the Quadrant Method, four quadrants as shown in Figure 13 (reprinted from [24]) are plotted using MSCR % R values at 3.2 kPa and elastic recovery (ER) or phase angle with their corresponding set thresholds. A binder that fails to meet the MSCR % R threshold but passes the ER threshold implies that the binder may not have been sufficiently modified and hence, puts the supplier at risk. The basis for forming the quadrants is to balance the user and the supplier risk. This method is also useful in establishing the threshold for %MSCR recovery at 3.2 kPa [24].

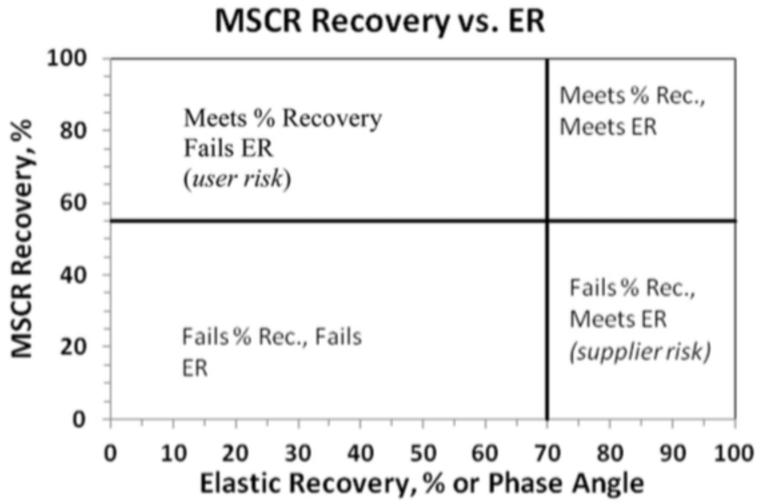


Figure 13. Graph Showing the Quadrant Method Utilized by Hossain et al. (2015) (Reprinted From [24]).

Critical Examination of the MSCR Test Protocol

Although considerable effort has been taken up to develop, validate, and correlate the MSCR test procedure to field performance (rutting in particular), several researchers highlight and emphasize the need to carefully evaluate the stress levels, geometry, and temperatures utilized for performing the test [48]. In this section, an attempt was made to understand the shortcomings of the MSCR test protocol from this perspective as reported by various researchers. Further, based on the arguments made from this section, the possibility of utilizing or modifying the test protocol to effectively characterize the PMABs for chip seal applications will be explored in the subsequent section.

Effect of Polymer Content

In contrast to several findings that supported the utilization of MSCR test parameters to be indicative of the rutting performance of HMA pavements, a study on highly modified asphalt binders in Australia (typical polymer content of 4-8% as against 2-4% in the United States) reported poor correlation of the MSCR test parameters with rutting and shear flow studies [49]. Suggestions to include higher stress levels and longer recovery periods (>9 secs) to accommodate the increased delayed elastic response due to high modification and to utilize a stress level higher than the existing 0.1 kPa to avoid very high stress sensitivity of highly modified PMABs at such low stresses were made. There was an emphasis that the MSCR test protocol be suitably investigated and adjusted based on the application of the binder (i.e. chip seal vs. HMA), location of implementation, and the type of materials used [49].

Effect of Number of Cycles and Loading Time

Different studies championed the need to increase the number of loading cycles prescribed the MSCR test protocol to allow the binders to reach the steady state. Bahia et al. (2006) suggest a minimum of 50 cycles while Golalipur et al. (2017) recommended 30 cycles at each stress level [28, 29, 46]. Figure 14 (reprinted from [46]) shows the effect of the number of cycles on the Jnr values at 0.1 and 3.2 kPa as reported by Golalipur et al. (2017). It indicates that at 10 cycles, there could still be high variability in the results, particularly for binders with higher delayed elastic response. In addition to revising the MSCR test protocol to attain steady state, utilization of last five cycles to calculate Jnr instead of all the cycles was recommended to reduce the variability of the MSCR parameters.

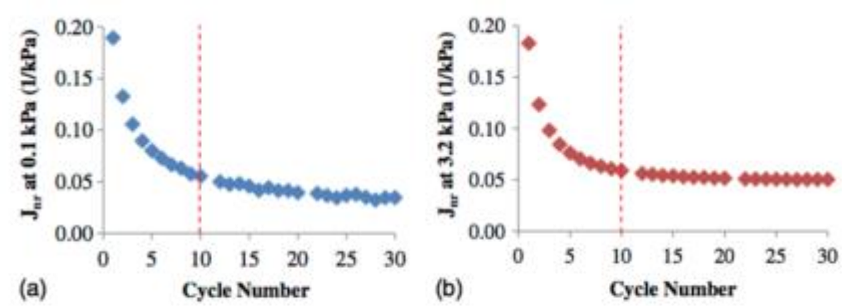


Figure 14. Effect of Number of Cycles for Binder with High Delayed Elasticity at 0.1 and 3.2 kPa, Reprinted From [46].

Mohseni and Azari (2014) also report that the current 10 loading cycles may not allow PMABs, particularly highly modified ones, to reach the steady state at temperatures lower than their PG_{high} causing unstable permanent strains or attainment of tertiary flow even before the test completes resulting in high test variability [40]. The authors performed incremental repeated load permanent deformation (iRLPD) test on RTFO aged highly modified asphalt binders at PG-6^0 C, PG, and PG+6^0 C, and three stress levels, 0.1, 3.2, and 5.0 kPa, with 20 cycles each. The loading sequence required 0.1 sec loading and 0.9 secs rest period resulting in a total test time of 60 secs against 300 secs of MSCR test. Attainment of tertiary flow was reported with MSCR testing while no tertiary flow was reported with iRLPD testing at all three test temperatures. Negative MSCR % R values in neat binders were attributed to the internal binder failure that does not allow the binder to reach steady state in ten cycles and the coupling effect of high stress (3.2 kPa) and longer loading times (1 sec). The permanent strain in MSCR at 3.2 kPa was reported to be much higher than that of iRLPD with the iRLPD strain rate reaching a steady state at each stress level increment. The variability of iRLPD test was reported to be lower in comparison to that of MSCR test even for highly modified binders.

Although iRLPD test seems to be a promising alternative to MSCR testing, the loading and rest periods could be not very practical considering the capabilities of the rheometers. Achieving stress levels as high as 5 kPa in time as low as 0.1 sec could lead to erroneous results. However, utilization of a higher stress level and increasing the number of cycles could make the test protocol better.

Effect of Stress Levels

PG specification takes into effect the slow and high traffic by bumping up the PG_{high} of the binders. However, grade bumping was criticized by researchers as different modifiers exhibit different levels of sensitivity to change in loading time and temperature [27, 29]. This is illustrated in Figure 15 (reprinted from [29]) where differently modified binders with same PG grade exhibited different amounts of permanent strain.

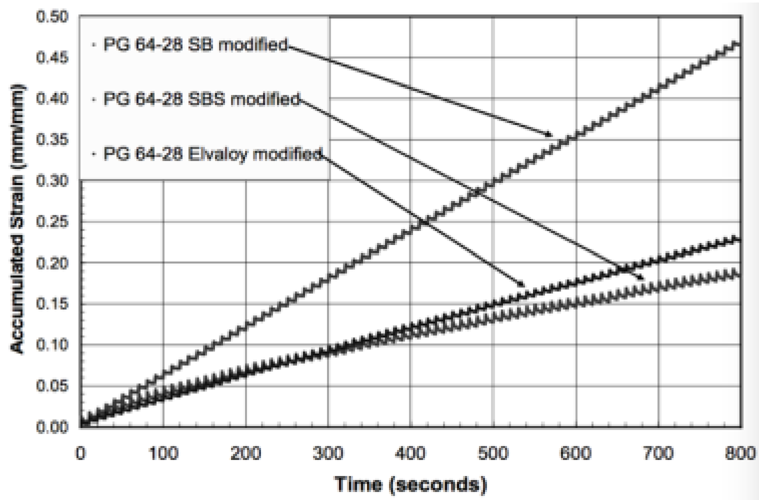


Figure 15. Difference in the Behavior of Binders with Same PG Grade Under Cyclic Creep Loading, Reprinted From [29].

Similarly, another study by Jafari et al. (2015) also reported difference in the response of binders with same continuous PG_{high} (i.e. similar behavior in LVE) but with different modifiers at stress levels greater than 3.2 kPa [34]. The test included an additional stress level of 12.8 kPa and was performed on SBS and PPA modified binders at 55^0 C and 70^0 C (shown in Figure 16, reprinted from [34]). The %R and Jnr values for each stress cycle were calculated. SBS modified binder exhibited better behavior in terms of lower sensitivity and permanent deformation at higher stress levels and PPA modified binders exhibited sudden high sensitivity after 3.2 kPa making such binders unsuitable for unexpected traffic loading. If the test was performed only up to 3.2 kPa, this difference wouldn't have been observed as the both the SBS and PPA modified binders would behave similarly due to their equivalent continuous PG_{high} grades.

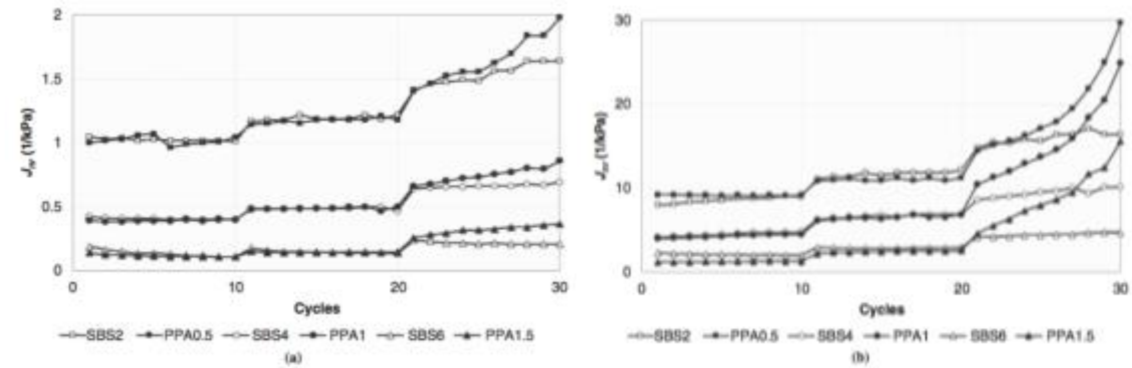


Figure 16. Jnr Values in Each Cycle of SBS and PPA Modified Binders with the Same Continuous PG Grade (i.e. Different Proportions of Modifiers) (a) at 55^0 C and (b) at 70^0 C, Reprinted From [34].

Golalipur et al. (2017) reported similar results with their test protocol that included a stress level of 10 kPa that was representative of the average shear stress in the binder phase of HMA pavements when a standard load of 80 kN single-axle load is applied through a 150 mm diameter circular tire contact area [46].

Jafari et al. (2015) and Golalipur et al. (2017) recommend the addition of a higher stress level to completely map the stress sensitivity of the binders as well as their nonlinear behavior. To avoid tertiary flow and high variability, Jafari et al. (2015) recommended the usage of lower stress levels (<3.2 kPa) at temperatures greater than the binder's PG_{high} to avoid negative recovery values and higher stress levels (>3.2 kPa) at temperatures less than the binder's PG_{high} to discern the elasticity imparted by different modifiers to the binder. However, a stress level >3.2 kPa depending on the test temperature was strongly recommended to be added to the MSCR test protocol to measure the nonlinearity of particularly modified binders.

Effect of Test Geometry

Motamed and Bahia (2011) studied the effect of various MSCR test conditions such as test geometry, temperature, stress level, and loading duration through a laboratory study [48]. The effect of each of the parameters was studied by analyzing the recoverable and permanent strains. They report that the 1 mm gap currently used with the parallel plate geometry could allow the unstable binder to flow causing change in specimen geometry during the test as shown in Figure 17 (reprinted from [48]); this binder response was reported to be inaccurately captured by the parallel plate geometry in the form of high permanent deformations caused by the binder dilation. It was stated that the unstable tertiary-like binder flow is often misunderstood as tertiary flow. Though the authors deliberate reducing the gap to 0.275 mm, increase in confining stress was pointed out as an issue. Instead, use of cone and plate geometry with 1^0 angle was highly suggested as tertiary-like flow is imminent at high stress level, load durations and temperatures, and the parallel plate geometry would give high permanent deformation values at such conditions.

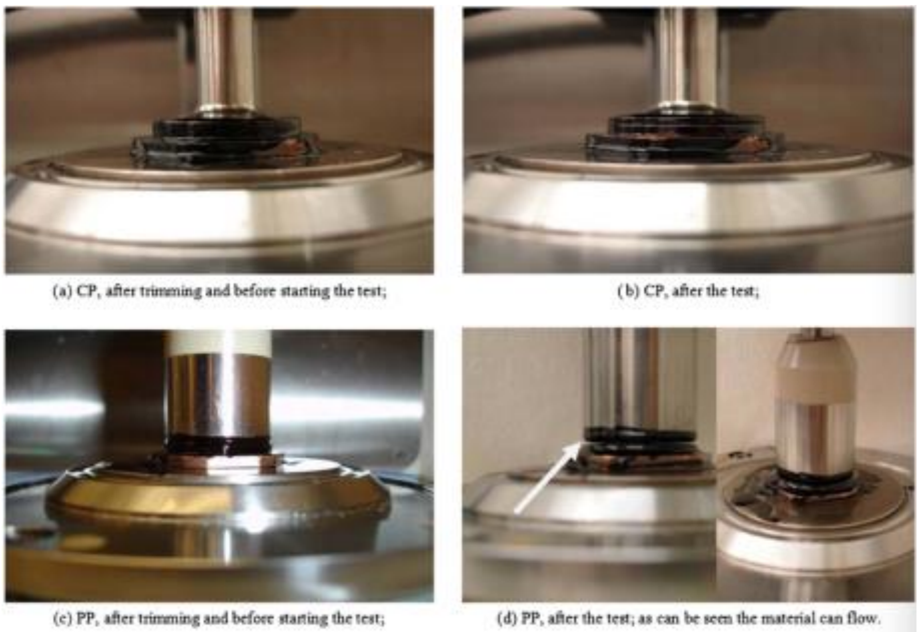


Figure 17. Effect of Plate Geometry i.e. Cone and Plate (CP) and Parallel Plate (PP) on the Binder Geometry During the MSCR Testing, Reprinted From [48].

Relevance of MSCR Test Protocol for Chip Seal Applications

Based on the literature reviewed on polymer modification and the MSCR test protocol, consideration should be given to the following:

- Increasing traffic and vehicular loading are mandating the utilization of PMABs to maximize the performance that can be obtained from asphalt binders. The employment of PMABs has been rising even in the case of chip seal applications.

This certainly necessitates the exploration of parameters to accurately characterize PMABs.

- One recent development that is being popularly considered regarding PMAB characterization is the MSCR test where the creep loading and rest period are applied on the binder in a cyclic fashion on a DSR at the temperatures corresponding to the LTPPBind climatic conditions. This parameter was validated in the laboratory to correlate to the rutting performance of the binder in HMA applications.
- The principle behind the development of the MSCR test protocol (i.e. unidirectional loading) and its familiarity among the asphalt user groups and state highway agencies due to implementation of AASHTO M320 makes it an appealing alternative to consider while pursuing the challenge of characterizing PMABs.
- The development of the MSCR test took place in stages where stress levels ranging from 0.025 to 25 kPa for over 100 cycles were utilized on different samples. Based on practicality, the test protocol was reduced to two stress levels and 10 cycles to be performed on a single sample.
- Some researchers did not agree with the test protocol in terms of its relevance to highly modified binders that have a higher elastic component and larger delayed elastic response and the test conditions such as the stress levels applied, duration of loading and rest periods, total number of cycles applied, and the test geometry. In addition, the initiation of tertiary flow in the binder due to high stress levels or high number of loading cycles results in negative MSCR % R values and high variability in the results particularly at 3.2 kPa is also a major concern.
- Researchers made the following suggestions to improve the test protocol with respect to the binders used for HMA pavements:
    - Increase the number of loading and unloading cycles to attain steady state and reduce variability in the test parameters.

- Increase the rest period to accommodate the larger delayed response of highly modified binders.
- Increase the lower stress level (0.1 kPa) to reduce variability in the parameters.
- Include a higher stress level to simulate the stresses caused by traffic in the binder phase and to completely map the stress sensitivity of different modifiers that may exhibit similar behavior in the LVE range and at stress levels up to 3.2 kPa.
- Avoid tertiary flow either by changing the plate geometry or by using the proper combination of test temperatures and stress levels.
- Use the test data from the last or the last few cycles to avoid possibly variable data or develop alternative parameters to understand the binder behavior subjected to the MSCR test protocol.

These issues are crucial to understanding the relevance of the MSCR test protocol to characterizing PMABs used for chip seal applications. They serve as the basis and guidelines to develop a test protocol that is in line with the principles of MSCR testing but suitable for chip seals binders. In the current work, the MSCR test was performed on unaged binders although the test standard prescribes RTFO aged binders, since RTFO aging is not relevant for chip seal applications [6, 7]. Based on the discussion of the MSCR test results and the issues highlighted, a framework for developing a test protocol to characterize PMABs appropriate for chip seal applications is provided in chapter V.

Summary

The inability of the LVE parameter G*/ sin δ to accurately characterize PMABs is an increasing concern. Several researchers and state DOTs have been attempting to move toward a test method that yields parameters insensitive to modification type while being able to differentiate the quality of modification. The need for such a test along with some crucial aspects of polymer modification to be captured including optimum blending conditions were discussed. The process of development and implementation of the MSCR test was briefly reviewed.

Further, the effect of loading time, stress levels, temperature, and plate geometry on the MSCR test results based on various studies were discussed. Most of the studies suggest the utilization of higher stress levels, change in loading and rest times, careful consideration of test temperatures and sometimes, change in the parameters considered from MSCR analysis particularly when the test method is utilized for characterizing high polymer content binders. In addition, the test and its parameters must be carefully set based on the binder application and conditions, and by performing extensive laboratory and field validation studies. Regarding the applicability of the test methodology to chip seals, all the above conditions must be prudently selected with careful consideration.

SUMMARY

In this chapter, a comprehensive review of the state-of-the-art work in developing test protocols and performance-based specifications for binders utilized in the chip seal applications were discussed. The progress in this area all around the world show the importance of such specifications and the need to move forward. Further, the advancements in the characterization of PMABs and the MSCR test protocol were extensively discussed with critical examination of the possible challenges. Additionally, issues in evaluating the relevance of the protocol to the binders used in chip seal applications were brought forward.

CHAPTER III

EXPERIMENTAL DESIGN

Following the success of the validation and implementation effort of the SPG specification during 2013-14, a third year of implementation was continued in 2016. Figure 18 shows the various major tasks involved in the implementation and the validation of the SPG specification.

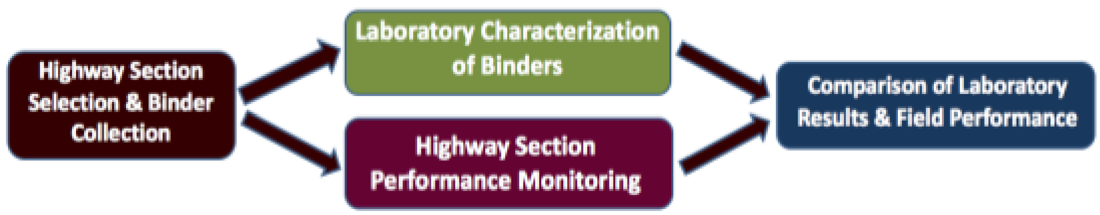


Figure 18. Major Steps Involved in the Implementation and the Validation of the SPG Specification.

The validation methodology begins with the identification of highway sections (HSs) in the TxDOT districts that are part of the district-wide chip seal programs and meet criteria discussed subsequently. The next steps include binder collection from corresponding established test sections; characterization of the chip seal binders in the laboratory; performance monitoring by pre-construction, post-construction, and 1-year visual distress surveys in the field; and comparison of the laboratory results with field performance. The experimental design involved with these steps are discussed in detail in the subsequent parts of this chapter.

HIGHWAY SECTION SELECTION & BINDER COLLECTION

Highway Section Selection

This section discusses the highway section selection procedure used during the 2016-17 implementation period. As shown in Table 5, fourteen chip seal HSs in six TxDOT districts (Abilene [ABL], Amarillo [AMA], Austin [AUS], Brownwood [BWD], Corpus Christi [CRP], and Paris [PAR]) built in 2016 were selected to cover a wide range of materials, environments, and traffic conditions representative of the variety of conditions prevalent in Texas.

Table 5. Selected HSs Built in 2016.

<table>
<tr><th rowspan="2">District</th><th rowspan="2">Code</th><th rowspan="2">County</th><th rowspan="2">Hwy</th><th rowspan="2">Construction Date</th><th rowspan="2">Weather During Construction</th><th rowspan="2">Binder Type</th><th rowspan="2">Binder Rate (Gal/ SY)</th><th rowspan="2">Agg. Type</th><th rowspan="2">Agg. Rate (SY/ CY)</th><th rowspan="2">Time Between Binder & Rock Application (min)</th><th rowspan="2">Time to First Roll since Binder Application (min)</th><th rowspan="2">2016 AADT & Level</th><th rowspan="2">% Truck</th><th colspan="2">Pre- Construction Embedment Depth (%)</th></tr>
<tr><th>Wheel Path (WP)</th><th>Between WP</th></tr>
<tr><td rowspan="2">Abilene</td><td>ABL-1</td><td>Howard</td><td>BI 0020 G</td><td>5/9/2016</td><td>Hot, 100° F</td><td rowspan="2">SPG 73-19</td><td>0.36</td><td>PC Gr 4</td><td>115</td><td>-</td><td>-</td><td>3700, M</td><td>45</td><td>95</td><td>80</td></tr>
<tr><td>ABL-2</td><td>Jones</td><td>SH0092</td><td>8/1/2016</td><td>Windy, 95° F</td><td>0.38</td><td>PB Gr 4</td><td>115</td><td>SH0092-1| 3:55
SH0092-2| 8:34
SH0092-3| 8:42
SH0092-4| 3:33/6:04</td><td>SH0092-1| 6:07
SH0092-2| 11:57
SH0092-3| 12:55
SH0092-4| 10:12</td><td>2500, M</td><td>30</td><td>SH0092-1| 95
SH0092-2| 95
SH0092-3| 95
SH0092-4| 95</td><td>SH0092-1| 50
SH0092-2| 90
SH0092-3| 95
SH0092-4| 95</td></tr>
<tr><td rowspan="2">Amarillo</td><td>AMA-1</td><td>Ochiltree</td><td>US0083X</td><td>8/1/2016</td><td>Hot, 100° F</td><td rowspan="2">SPG 64-25</td><td>0.45</td><td>PC Gr 3/4</td><td>100</td><td>-</td><td>-</td><td>3500, M</td><td>28</td><td>75</td><td>75</td></tr>
<tr><td>AMA-2</td><td>Hartley</td><td>FM0281</td><td>8/15/2016</td><td>Windy, 85° F</td><td>0.41</td><td>PC Gr 4</td><td>110</td><td>FM0281-1| 5:53
FM0281-2| 5:04
FM0281-3| 3:34
FM0281-4| 4:12</td><td>FM0281-1| 7:03
FM0281-2| 7:50
FM0281-3| 5:04
FM0281-4| 8:46</td><td>2627, M</td><td>42.9</td><td>FM0281-1| 75
FM0281-2| 75
FM0281-3| 75
FM0281-4| NA</td><td>FM0281-1| 75
FM0281-2| 85
FM0281-3| 85
FM0281-4| NA</td></tr>
<tr><td rowspan="3">Austin</td><td>AUS-1</td><td>Mason</td><td>US0087</td><td>7/19/2016</td><td>Hot, windy, 95° F</td><td rowspan="3">SPG 70-19</td><td>US0087-1| 0.31
US0087-2| 0.31
US0087-3| 0.31
US0087-4| 0.32</td><td>PC Gr 4</td><td>US0087-1| 110
US0087-2| 110
US0087-3| 110
US0087-4| 120</td><td>US0087-1| 2:23
US0087-2| 2:15
US0087-3| 2:45
US0087-4| 3:10</td><td>US0087-1| 7:01
US0087-2| 7:03
US0087-3| 3:47
US0087-4| 3:46</td><td>4995, M</td><td>17.7</td><td>US0087-1| 25
US0087-2| 35
US0087-3| 85
US0087-4| 90</td><td>US0087-1| 25
US0087-2| 25
US0087-3| 50
US0087-4| 80</td></tr>
<tr><td>AUS-2</td><td>Mason</td><td>SH0029 (1-4)</td><td>7/19/2016</td><td>Light wind, 90° F</td><td>0.32</td><td>PC Gr 4</td><td>120</td><td>SH0029-1| 3:08
SH0029-2| 0:41
SH0029-3| 3:05
SH0029-4| 0:33</td><td>SH0029-1| 6:47
SH0029-2| 2:29
SH0029-3| 5:31
SH0029-4| 1:25</td><td>1100, M</td><td>16.6</td><td>95</td><td>95</td></tr>
<tr><td>AUS-3</td><td>Llano</td><td>SH0029 (5-6)</td><td>7/19/2016</td><td>Hot, windy, 100° F</td><td>0.33</td><td>PC Gr 4</td><td>121</td><td>SH0029-5| 3:08
SH0029-6| 0:41</td><td>SH0029-5| 6:47
SH0029-6| 2:29</td><td>4995, M</td><td>17.7</td><td>95</td><td>95</td></tr>
<tr><td rowspan="2">Brownwood</td><td>BWD-1</td><td rowspan="2">Coleman</td><td>US0084</td><td>7/15/2016</td><td>Light wind, 96° F</td><td>CRS-2P</td><td>0.38</td><td>GR 4</td><td>120</td><td>9:50</td><td>16:40</td><td>3300, M</td><td>11.7</td><td>50</td><td>40</td></tr>
<tr><td>BWD-2</td><td>US0084</td><td>7/12/2016</td><td>Light wind, 85° & 96° F</td><td>SPG 67-22</td><td>0.42</td><td>Lime Gr 4</td><td>120</td><td>US0084-1| 12:56
US0084-2| 7:29
US0084-3| 11:10
US0084-4| 8:01</td><td>US0084-1| 15:57
US0084-2| 12:32
US0084-3| 13:18
US0084-4| 10:38</td><td>3300, M</td><td>11.7</td><td>US0084-1| 95
US0084-2| 90
US0084-3| 95
US0084-4| 80</td><td>US0084-1| 90
US0084-2| 90
US0084-3| 95
US0084-4| 100</td></tr>
<tr><td rowspan="2">Corpus Christi</td><td>CRP-1</td><td>Jim Wells</td><td>FM3376</td><td>9/17/2016</td><td>Hot, humid, 99° F</td><td rowspan="2">SPG 70-19</td><td>0.35</td><td>PC GR 4</td><td>110</td><td>FM3376-1| 2:22
FM3376-2| 2:59
FM3376-3| -
FM3376-4| -</td><td>FM3376-1| 3:02
FM3376-2| 6:45
FM3376-3| -
FM3376-4| -</td><td>3000, M</td><td>10</td><td>FM3376-1| 90
FM3376-2| 95
FM3376-3| 75
FM3376-4| 75</td><td>FM3376-1| 90
FM3376-2| 95
FM3376-3| 75
FM3376-4| 75</td></tr>
<tr><td>CRP-2</td><td>Nueces</td><td>FM0665</td><td>FM0665-1| 9/19/16
FM0665-2| 9/19/16
FM0665-3| 9/19/16
FM0665-4| 9/20/16</td><td>FM0665-1| Light wind, 98°F
FM0665-2| Still, 74° F
FM0665-3| Steady wind, 96° F
FM0665-4| Steady wind, 92° F</td><td>0.35</td><td>PC 45, B</td><td>110</td><td>FM0665-1| 2:04
FM0665-2| 1:59
FM0665-3| 4:41
FM0665-4| 4:35</td><td>FM0665-1| 9:22
FM0665-2| 6:24
FM0665-3| 8:03
FM0665-4| 6:35</td><td>3500, M</td><td>8</td><td>FM0665-1| 80
FM0665-2| 75
FM0665-3| 80
FM0665-4| 75</td><td>FM0665-1| 75
FM0665-2| 75
FM0665-3| 80
FM0665-4| 75</td></tr>
<tr><td rowspan="3">Paris</td><td>PAR-1</td><td>Hunt</td><td>FM0035</td><td>7/7/2016</td><td>Hot, 95° F</td><td rowspan="3">SPG 70-22</td><td>0.32</td><td>PC Gr 4</td><td>130</td><td>FM0035-1| -
FM0035-2| -
FM0035-3| 4:50
FM0035-4| 2:40</td><td>FM0035-1| -
FM0035-2| -
FM0035-3| 5:46
FM0035-4| 7:27</td><td>4147, M</td><td>9.1</td><td>FM0035-1| 75
FM0035-2| 90
FM0035-3| 90
FM0035-4| 95</td><td>FM0035-1| 40
FM0035-2| 40
FM0035-3| 40
FM0035-4| 40</td></tr>
<tr><td>PAR-2</td><td>Fannin</td><td>US0069</td><td>8/26/2016</td><td>Cloudy, 84° F</td><td>0.32</td><td>PC GR 4 B</td><td>140</td><td>US0069-1| 4:02
US0069-2| 1:29
US0069-3| -
US0069-4| -</td><td>US0069-1| 6:40
US0069-2| 4:30
US0069-3| -
US0069-4| -</td><td>3300, M</td><td>15.5</td><td>US0069-1| 80
US0069-2| 75
US0069-3| 75
US0069-4| 75</td><td>US0069-1| 60
US0069-2| 40
US0069-3| 40
US0069-4| 40</td></tr>
<tr><td>PAR-3</td><td>Grayson</td><td>SH0289</td><td>9/9/16</td><td>SH0289-1| Windy, 84° F
SH0289-2| Windy, 82° F
SH0289-3| Windy, 84° F
SH0289-4| Windy, 85° F</td><td>SH0289-1| 0.32
SH0289-2| 0.32
SH0289-3| 0.36
SH0289-4| 0.36</td><td>PC GR 4</td><td>140</td><td>SH0289-1| 0:45
SH0289-2| 2:02
SH0289-3| 1:02
SH0289-4| 2:28</td><td>SH0289-1| 2:29
SH0289-2| 3:31
SH0289-3| 1:45
SH0289-4| 6:03</td><td>2500, M</td><td>30</td><td>SH0289-1| 80
SH0289-2| 80
SH0289-3| 90
SH0289-4| 90</td><td>SH0289-1| 80
SH0289-2| 80
SH0289-3| 90
SH0289-4| 90</td></tr>
</table>

The factors considered in selecting these HSs were the traffic volume, aggregate type, and SPG climate zones. As the binders utilized for this project (except BWD-1) were specified based on the SPG specification from the second TxDOT research project (4) labeled 2012 in

Table **3** i.e. as SPG XX-XX, there was no control over choosing the binders based on the modifier or the type. However, all the binders were identified to be polymer modified based on Fourier Transform Infrared (FTIR) spectroscopy as described subsequently.

Traffic Volume Consideration

The traffic parameter considered in the experimental design was volume in terms of the annual average daily traffic (AADT), which is consistent with the TxDOT chip seal design procedure in terms of the binder and aggregate application rates. AADT was categorized into three tiers: high (T1), medium (T2), and low (T3). The threshold values for each group are shown in Table 6. Note that the upper traffic threshold value of the tier T3 was reduced to 500 as against the previously utilized value of 1000 and similarly, the lower threshold value for the T2 tier was revised to 500.

Table 6. Traffic Tiers.

Traffic Tier	Thresholds
T1	AADT>5000
T2	500≤AADT≤5000
T3	AADT<500

Aggregate Types

The aggregate types in this project were defined by TxDOT Item 302—Aggregates for Chip Seals—as shown in Table 7. The aggregate gradation was also recorded in this project based on aggregate gradation requirements provided by TxDOT Item 302, as shown in Table 8.

Table 7. Aggregate Types.

Type	Material
A	Gravel, crushed slag, crushed stone, or limestone rock asphalt (LRA)
B	Crushed gravel, crushed slag, crushed stone, or LRA
C	Gravel, crushed slag, or crushed stone
D	Crushed gravel, crushed slag, or crushed stone
E	Aggregate as shown on plans
L	Lightweight Aggregate
PA	Precoated gravel, crushed slag, crushed stone, or LRA
PB	Precoated crushed gravel, crushed slag, crushed stone, or LRA
PC	Precoated gravel, crushed slag, or crushed stone
PD	Precoated crushed gravel, crushed slag, crushed stone
PE	Precoated aggregate as shown on the plans
PL	Precoated lightweight aggregate

Table 8. Aggregate Gradation Requirements (Cumulative Percent Retained[1]).

Sieve	Grade								
	1	2	3S[2]	3		4S[2]	4	5S[2]	5
				Non-lightweight	Lightweight				
1"	–	–	–	–	–	–	–	–	–
7/8"	0–2	0	–	–	–	–	–	–	–
3/4"	20–35	0–2	0	0	0	–	–	–	–
5/8"	85–100	20–40	0–5	0–2	0–2	0	0	–	–
1/2"	–	80–100	55–85	20–40	10–25	0–5	0–5	0	0
3/8"	95–100	95–100	95–100	80–100	60–80	60–85	20–40	0–5	0–5
1/4"	–	–	–	95–100	95–100	–	–	65–85	–
#4	–	–	–	–	–	95–100	95–100	95–100	50–80
#8	99–100	99–100	99–100	99–100	98–100	98–100	98–100	98–100	98–100

1. Round test results to the nearest whole number.
2. Single-size gradation.

Binder Collection

The binders reported in this section were collected from the 2016 statewide chip seal implementation program. As mentioned earlier, all the binders in this project except BWD-1 were specified based on the SPG specification from the second TxDOT research project (4) labeled 2012 in

Table **3**. The binder for the HS in BWD on US0084 was initially specified as SPG 67-22, but due to construction issues, CRS 2P was later supplied to complete the project. In addition to the climate-based requirement of the SPG specification, local conditions such as traffic were considered to eventually specify the SPG binder grade for a given HS. The SPG grades specified for the six TxDOT districts in the 2016-17 implementation period along with the traditional binder types utilized in these districts based on the data from 2013-14 implementation period are summarized in Table 9.

Table 9. Specified SPG Binder Grades and the Corresponding Traditionally Specified Binder Types for the 2016 TxDOT Districts.

TxDOT District	Specified SPG Grade in 2016	Traditional Binder Types
Abilene	SPG 73-19	-
Amarillo	SPG 64-25	AC10, AC10-2TR, AC20-5TR
Austin	SPG 70-19	-
Brownwood	CRS 2P, SPG 67-22	AC10-2TR
Corpus Christi	SPG 70-19	CRS 2, AC 15P
Paris	SPG 70-22	AC20-5TR

Information Collected

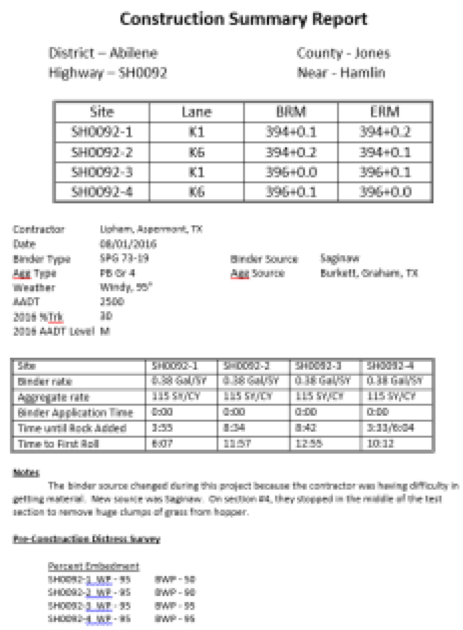
Altogether, the following information including pictures and videos of the HSs before and after construction was collected for each HS and documented as district-wide construction reports:

- Material-related
  - Binder type and application rate
  - Aggregate type, gradation, and application rate
- Traffic-related

    - 2016 Average Annual Daily Traffic (AADT) and 2016 Truck %
- Construction-related
    - Date of construction
    - Weather and temperature during construction
    - Time between the binder and aggregate application
    - Time between binder application and rolling
- Pavement surface condition-related
    - Embedment depth (ED) in and between wheel path pre-construction and post construction (not presented in Table 5)
    - Other surface distresses on the pavement (not presented in Table 5)
    - Pictures and videos

A typical construction report is as shown in Figure 19.

Additional notes on construction factors specific to the HS are also included in the construction summary reports. This information is helpful in understanding and identifying the role of construction factors on the performance of a chip seal and to explain any differences between the predicted field performance of the chip seals based on laboratory characterization and the actual field performance observed.



Construction Summary Report

District – Abilene | County - Jones
Highway – SH0092 | Near - Hamlin

Site	Lane	BRM	ERM
SH0092-1	K1	394+0.1	394+0.2
SH0092-2	K6	394+0.2	394+0.1
SH0092-3	K1	396+0.0	396+0.1
SH0092-4	K6	396+0.1	396+0.0

Contractor Upham, Aspermont, TX
Date 08/01/2016
Binder Type SPG 73-19 Binder Source Saginaw
Agg Type PB Gr 4 Agg Source Burkett, Graham, TX
Weather Windy, 95°
AADT 2500
2016 %Trk 30
2016 AADT Level M

Site	SH0092-1	SH0092-2	SH0092-3	SH0092-4
Binder rate	0.38 Gal/SY	0.38 Gal/SY	0.38 Gal/SY	0.38 Gal/SY
Aggregate rate	115 SY/CY	115 SY/CY	115 SY/CY	115 SY/CY
Binder Application Time	0:00	0:00	0:00	0:00
Time until Rock Added	3:55	8:34	8:42	3:33/6:04
Time to First Roll	6:07	11:57	12:55	10:12

Notes
The binder source changed during this project because the contractor was having difficulty in getting material. New source was Saginaw. On section #4, they stopped in the middle of the test section to remove huge clumps of grass from hopper.

Pre-Construction Distress Survey

Percent Embedment
SH0092-1 WP - 95 BWP - 50
SH0092-2 WP - 95 BWP - 90
SH0092-3 WP - 95 BWP - 95
SH0092-4 WP - 95 BWP - 95

Figure 19. Typical Construction Summary Report.

LABORATORY CHARACTERIZATION OF BINDERS

The 2016 binders (either hot-applied asphalt binder or recovered emulsion residue) were tested and characterized in accordance with the SPG specification from the second TxDOT research project (4) labeled 2012 in

Table **3**. Accordingly, SPG tests and other rheological tests to characterize the binders at low temperatures and possible polymer modification were performed on the collected chip seal binders. Table 10 shows the details of the laboratory evaluation carried out as part of this project.

AASHTO T313 and AASHTO T315 are the standard high and low temperature SPG binder grading tests [50, 51]. The FTIR spectroscopy test was performed on the original binders to check for the presence of polymers and on the aged binders to quantify the increase in carbonyl area after PAV aging. The MSCR and ER tests were performed to explore the possibility of characterizing polymer modification in the binders in addition to or as an alternative to the existing phase angle threshold [43, 52]. The 4mm frequency sweeps at low temperatures were performed to develop master curves and to further investigate the resulting parameters to possibly replace the use of creep stiffness from the BBR test. Along with these test methods, the emulsion residue recovery method and the aging protocols for the SPG binders are discussed further in this chapter.

Table 10. Test Plan.

	Test	Conditions	Result Recorded
Original Binder	DSR - Dynamic Shear, AASHTO T315	3° C increments at high temp; 10 rad/sec	G*/sin δ and Phase angle (δ)
	DSR - Multiple Stress and Creep Recovery (MSCR), AASHTO TP70	55° C, 61° C and 67° C; @0.1 kPa - 20 cycles of 1 sec loading and 9 sec unloading, @ 3.2 kPa - 10 cycles of 1 sec loading and 9 sec unloading	Jnr and % Recovery at test temperatures
	Ductilometer - Elastic Recovery (ER), Tex-539-C	10° C; 50 mm/ min strain rate for 4 minutes; specimen is held at 200 mm for 5 minutes and is cut at the center; allowed to recover for 1 hr	Elongation of the specimen in mm; calculate elastic recovery
	Fourier Transform Infrared (FTIR) Spectroscopy		Presence of polymer
PAV @ 100°C, 20 hr	DSR - Dynamic Shear, AASHTO T315	At passing and failing T_{high} of the original binder; 10 rad/sec	Phase angle (δ)
	DSR - Frequency Sweep with 4 mm Plate	-36⁰ C, -30⁰ C, -27⁰ C, -24⁰ C, -21⁰ C, -18⁰ C, -12⁰ C, -6⁰ C and 0⁰ C; 15 frequencies between 100 – 0.2 rad/s	G*, G' and G"
	FTIR Spectroscopy		Increase in carbonyl area
	BBR - Low-Temperature Creep Stiffness, AASHTO T313	Low temp; 8 sec loading time	Stiffness, S and m-value

Emulsion Residue Recovery Method

The Texas Oven method is Procedure B in AASHTO PP 72-11 and was recommended for emulsion residue recovery during TxDOT Project 0-6616 [3]. It was concluded that this method best simulates the residue obtained in the field and that the procedure is relatively fast and allows for recovery of large quantities of emulsion residue.

In this procedure, the emulsion is poured onto a silicone mat and in one continuous motion spread evenly with a wet film applicator to obtain a wet film thickness of 0.381 mm. The silicone mat was then placed in a 60° C forced draft oven for 6 hr. The mat was allowed to cool for 15 minutes at room temperature prior to emulsion residue removal. The recovered emulsion residue was removed from the mat by peeling using a uniform rolling motion with a metal rod. The recovered residue was then shaped appropriately for chemical or rheological testing.

Binder Aging

RTFO test aging was not performed on the binder in the SPG specification because chip seal binders are not exposed to high production and construction temperature during application. Before determination of the low-temperature properties, the binders, both hot-applied asphalt binder and emulsion residues were aged in the PAV for 20 hr at 100° C to simulate approximately 1 year of environmental exposure for chip seals in Texas [53].This 1-year time period is critical to ensure adequate performance for chip seal binders [54].

SPG Binder Grading Tests

High Temperature Grading

According to the SPG specification, the high temperature SPG grade of a hot-applied asphalt binder or emulsion residue is the warmest test temperature at which $G^*/\sin\delta > 0.65$ kPa as measured in the DSR by AASHTO T315 on the original unaged material. Therefore, to report the high temperature SPG grade, the participants must provide a test temperature (T^0 C) at which $G^*/\sin\delta > 0.65$ kPa (Pass) and another test temperature ((T+6) ^{0}C) at which $G^*/\sin\delta < 0.65$ kPa (Fail). With one pass and one fail test temperature, the high temperature SPG grade is reported as T ^{0}C. Figure 20 provides the procedure to be followed for high temperature SPG grading of a hot-applied asphalt binder or emulsion residue.

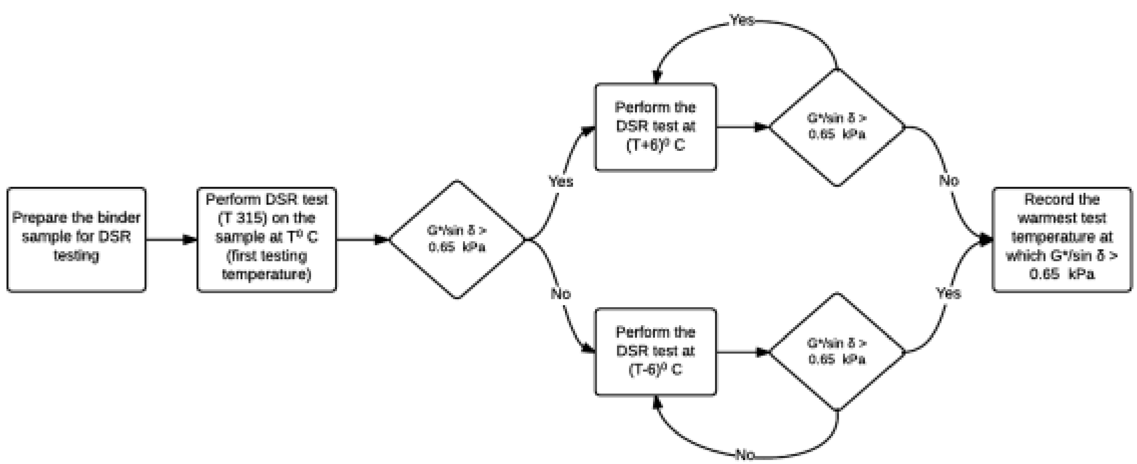


Figure 20. SPG High Temperature Grading of Hot-Applied Asphalt Binders and Emulsion Residues.

Low Temperature Grading

According to the SPG specification, the low temperature SPG grade of a hot-applied asphalt binder or emulsion residue is the coldest test temperature at which S < 500 MPa at 8 seconds as measured in the BBR by AASHTO T313 on the PAV aged material at the actual low temperature SPG grade (without a 10^0 C shift). Therefore, to report the low temperature SPG grade, the participants must provide a test temperature (T^0 C) at which S < 500 MPa (Pass) and another test temperature ($(T-6)^0$ C) at which S > 500 MPa (Fail). With one pass and one fail test temperature, the low temperature SPG grade is reported as T^0 C. Figure 21 provides the procedure to be followed for low temperature SPG grading of a hot-applied asphalt binder or emulsion residue.

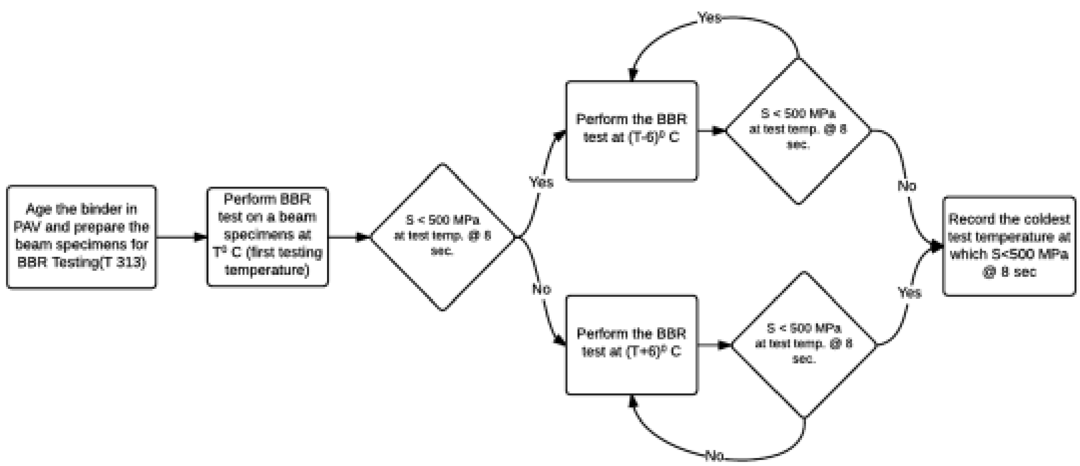


Figure 21. SPG Low Temperature Grading of Hot-Applied Asphalt Binders and Emulsion Residues.

Polymer Modification-Related Tests

FTIR Testing

FTIR spectroscopy was performed on the original binder to identify the presence of polymers in the binder samples. The test is performed by first cleaning the surface of the FTIR using a mild solvent like varsol followed by acetone. The binder is locally heated and a small amount is mounted on the FTIR surface using a spatula to run the FTIR analysis. This exercise is repeated to have data for three replicates. The presence of polymers is then determined based on the peak near the frequency of 967 cm^{-1}[55-57]. If a peak is present, then the binder is concluded to have polymer in it. It is important to note that the FTIR analysis is only qualitative but not quantitative with regard to the presence of polymer.

FTIR analysis can also be utilized to determine the carbonyl area defined as the area under the absorbance band between the frequencies 1,650 cm^{-1} to 1820 cm^{-1}. This area can be calculated for both unaged and aged binders, and the change in the carbonyl area can be used to quantify aging in binders.

Elastic Recovery

The elastic recovery (ER) test was performed on the unaged binder to determine the presence of the polymer modifiers in the binder and its quality. It was performed at 10^0 C on a ductilometer in accordance with AASHTO T51 for the apparatus preparation and Tex-539-C for the actual test procedure. The binder is poured into the ER molds in between clips and is conditioned as required by AASHTO T51. The sample clips are then attached to the ductilometer and are pulled at 50 mm/min till the sample reaches 200 mm. The sample is held at 200 mm for five minutes and is cut at its approximate center to let it relax for one hour. The clips are moved together so that the sample's cut ends meet and the elongation (E_f) is measured and recorded in mm. The ER is calculated using Equation 2.

$$ER = \frac{200 - E_f}{200} X100 \qquad \text{Equation 2}$$

MSCR Test

The MSCR test was performed on unaged material to determine the % recovery and non-recoverable creep compliance of the binders under shear creep and recovery at two stress levels (0.1 kPa and 3.2 kPa). The test was performed at three temperatures (55^0 C, 61^0 C, and 67^0 C) using the Malvern DSR Kinexus-II and the same configuration and sample size (with 25 mm plates and 1 mm gap) as in the high-temperature DSR test. The samples were loaded at constant stress for 1 s then allowed to recover for 9 s. Twenty creep and recovery cycles were run at a creep stress of 0.1 kPa followed by 10 creep and recovery cycles at a creep stress of 3.2 kPa.

The strain accumulated at the end of the creep and recovery portions was recorded and used to estimate the average percent recovery and the non-recoverable creep compliance (J_{nr}) of the binder. J_{nr} is the ratio of the maximum accumulated strain at the end of the test to the maximum stress level applied to the binder. The percent recovery of binders determined in this test is dependent on the extent of modification of the binder and can be used to determine if modified binders offer a better elastomeric response. J_{nr} might be an indicator of the binder's resistance to bleeding under repeated loading.

Percent recovery, ε_r (100, N) for N = 1 to 10 is obtained from Equation 3:

$$\varepsilon_r(100, N) = \frac{\varepsilon_{10} - \varepsilon_1}{\varepsilon_1} X100 \qquad \text{Equation 3}$$

where ε_{10} is the adjusted strain value at the end of recovery portion of each cycle and ε_1 is the adjusted strain value at the end of creep portion of each cycle.

The non-recoverable compliance J_{nr} (σ, N) for N = 1 to 10 is obtained from Equation 4:

$$J_{nr}(\sigma, N) = \frac{\varepsilon_{10}}{\sigma} \qquad \text{Equation 4}$$

where ε_{10} is the adjusted strain value at the end of recovery portion of each cycle and σ is the applied stress.

HIGHWAY SECTION PERFORMANCE MONITORING

Field performance monitoring data was collected prior to construction, post construction, and after the first winter post-construction of chip seals and includes aggregate loss, bleeding, and ED information. The HSs were monitored using a visual survey technique from the long-term pavement performance (LTPP) distress identification manual and analyzed to determine SCI score by the specific procedure developed in TxDOT Project 0-1710 [7, 8, 58].

Test Section Selection

Consistent with the previous TxDOT Projects 0-1710, 0-6616, and 5-6616, a test section was defined as a representative subsection of a field section with an area of approximately 5,000 to 7,000 ft^2 for which performance monitoring was conducted. Characteristics of a test section were as follows:

- Each test section was 500 ft long and 10 to 14 ft wide (equivalent highway lane width).
- Two to four test sections were established, depending on the length of the chip seal project. Overall performance of the field section was taken as the average of the performance of the individual test sections.
- Multiple test sections were used for each field section to avoid the possibility of overrating or underrating performance due to the absence or presence of localized distresses or geometric features such as turns or changes in surface elevation.
- Data were collected from the outside lane only. This practice increases safety. The survey was conducted from the shoulder or edge of the pavement to make traffic control not necessary.
- Intersections, access road junctions, grades, and curves were avoided to minimize the effects of extremely slow and turning traffic, which could exaggerate distress, as well as for safety reasons.
- Test sections were marked using existing reference points or objects such as road mile marker signs. New test sections were marked using reference spikes (cotton gin spindle) driven into the pavement at the start and stop of the field section, along with spray-painted markings. Global positioning system (GPS) coordinates and Texas reference markers were also gathered and tabulated for each field section.

Distresses Monitored in the Field

Each test section was monitored for aggregate loss, bleeding, and ED.

Aggregate Loss

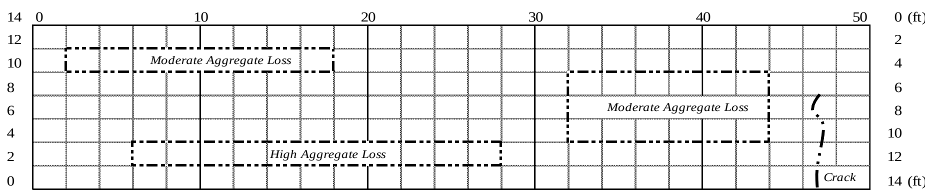
Aggregate loss or raveling is the principal distress associated with chip seals and controlled by the SPG specification system. This distress results as aggregates are dislodged from the surface of the pavement downward.

The aggregate loss, in terms of square feet of affected surface area at each severity level, was recorded on a field performance monitoring survey sheet as shown in the example in Figure 22.

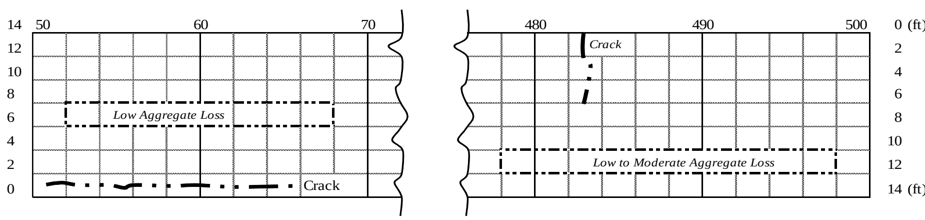
COMPLETED FIELD PERFORMANCE MONITORING SURVEY

VISUAL DISTRESS SURVEY SHEET

Hwy Section: *HS P3* Inspection No. *3*
Date: *9/5/2002* Time: *1.00PM* Weather: *Sunny*
Test Sction No. *1* Start: *196 K6* End: *196 K6 + 500 miles*



Comment: *Aggregate embedment = approximately 65% in wheel path, and about 30 to 40 % between wheel path*



Comment: *Evidence of aggregate loss. Some transverse cracks from underlying structure. Generally - inadequate performance (aggregate loss)*

Surveyed by: *Tom Freeman*

Example of Distress Observations:
Consider for example, the following field survey observations on a particular highway section:

Aggregate Loss
Area coverage on 4 test sections: ***20%, 5%, 10%, and 3%***
Mean area coverage on 4 test sections: ***9.5%***
SCI score for distress area coverage (DAC): ***72%***
Severity levels for 4 test sections: ***Low to moderate, low to moderate, low, & low***
Percent severity on each test section is thus: ***10% 10%, 5%, & 5%***
Mean percent severity: ***7.5%***
SCI score for degree of severity of aggregate loss (DSD): ***80%***

Cracking: ***Transverse cracking observed on some parts of the highway section***

Bleeding
Area coverage on 4 test sections: ***15%, 5%, 10%, & 10%***
Mean area coverage on 4 test sections: ***10%***
SCI score for distress area coverage (DAC): ***70%***
Severity levels for 4 test sections: ***High, low, moderate to high, & moderate to high***
Percent severity on each test section is thus: ***95%, 5%, 50%, & 50%***
Mean percent severity: ***50%***
SCI score for degree of severity of bleeding (DS ***300%***

Aggregate Embedment: ***60-90 % in wheel path***
30-50 % between wheel path

Figure 22. Example Field Performance Monitoring Survey Sheet.

Table 11. Severity Levels for Aggregate Loss.

#	Level	Description
1	Low	Aggregate has begun to ravel off but has not significantly progressed. Evidence of loss of some fine aggregate.
2	Moderate	Surface texture is becoming rough and pitted; loose particles generally exist; loss of fine and some coarse aggregates.
3	High	Surface texture is very rough and pitted; loss of coarse aggregates.

Bleeding

Bleeding occurs as a shiny, black, or glasslike reflective surface caused by liquid binder migrating to the pavement surface, often in the wheel paths. It can also be defined as a film of excess binder occurring on the pavement surface. The result can be a dangerous, slippery pavement due to decreased frictional characteristics between the tire and pavement surface. Often, bleeding occurs at high pavement temperatures due to high binder content (associated with design and construction), low binder viscosity, use of very small aggregates and excessive embedment, inadequate and/or loss of aggregates, excessive compaction during construction, and high traffic.

Like aggregate loss, bleeding was defined and recorded in square feet of affected surface area at each of three severity levels (low, moderate, and high), consistent with the SHRP distress identification manual (FHWA 2003), as described in Table 12.

Embedment Depth

Embedment of the aggregates into the asphalt layer is important information collected pre-construction, post construction, and one year after the construction.

Table 12. Severity Levels for Bleeding.

#	Level	Description
1	Low	An area of pavement surface discolored (black) relative to the remainder of the pavement.
2	Moderate	Distinctive black appearance and loss of surface texture due to free excess binder.
3	High	Wet-black shiny appearance on the pavement surface due to excess binder; excess binder may obscure aggregates; tire marks may be evident in warm weather.

Performance Evaluation and Rating Criteria

The SCI methodology and criterion was consistent for the most part across TxDOT Project 0-1710 and TxDOT Project 0-6616. This performance index is based on calculated SCI scores, which range from 0.0 percent (very poor performance) to 100 percent (perfect performance). For each distress, the SCI score was calculated as an equal weighted function of the distress area coverage (DAC) and the degree of severity of distress (DSD), expressed as a percentage, as shown in Equation 5:

$$SCI_{Distress}=0.5(P_{DAC}+P_{DSD}) \quad \text{Equation 5}$$

Where:

$SCI_{Distress}$ = SCI score as a percentage for a given distress
P_{DAC} = distress area coverage as a percentage
P_{DSD} = degree of severity of a distress in percentage

In TxDOT Project 0-1710 and TxDOT Project 0-6616, the SCI scores for P_{DAC} and P_{DSD} were determined by a severity level scale, as shown in Figure 23 and Figure 24. However, the % Area and % Severity in those scales are determined by personal judgment, which results in subjective PDAC and PDSD scores. To avoid this issue, a quantitative approach to determine the % Area and % Severity for each distress based on the field evaluation data was developed during the 2013-14 implementation period, as shown in Equation 6 and Equation 7. This approach enabled the evaluation of field performance to be more objective and consistent.

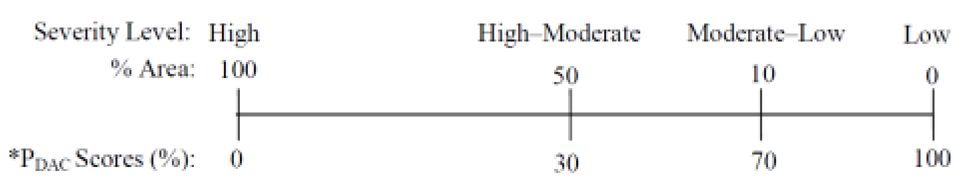


Figure 23. SCI Distress Evaluation and Scores—Distress Area Coverage (DAC).

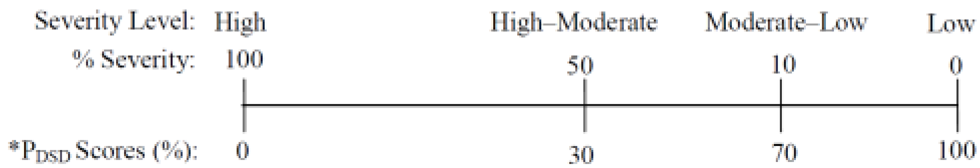


Figure 24. SCI Distress Evaluation and Scores—Degree of Severity of Distress (DSD).

$$\%\text{Area} = \frac{\text{Area}_{\text{Low}} + \text{Area}_{\text{Medium}} + \text{Area}_{\text{High}}}{\text{Area}_{\text{Total}}} \qquad \text{Equation 6}$$

$$\%\text{Severity} = \frac{\text{Area}_{\text{Low}}}{\text{Area}_{\text{Dis}}} \times \left(\frac{\text{Area}_{\text{Low}}}{\text{Area}_{\text{Total}}} \times 10 + 0\right) + \frac{\text{Area}_{\text{Medium}}}{\text{Area}_{\text{Dis}}} \times \left(\frac{\text{Area}_{\text{Medium}}}{\text{Area}_{\text{Total}}} \times 40 + 10\right) + \frac{\text{Area}_{\text{High}}}{\text{Area}_{\text{Dis}}} \times \left(\frac{\text{Area}_{\text{High}}}{\text{Area}_{\text{Total}}} \times 50 + 50\right)$$

Equation 7

where:

%Area = the percentage of area for a given distress in evaluation section.
%Severity = the percentage of severity for a given distress in evaluation section.
Area_{Low} = the area of low severity for a given distress in evaluation section.
$\text{Area}_{\text{Medium}}$ = the area of medium severity for a given distress in evaluation section.
$\text{Area}_{\text{High}}$ = the area of high severity for a given distress in evaluation section.
Area_{Dis} = the total area for a given distress in evaluation section.
$\text{Area}_{\text{Total}}$ = the total area in evaluation section.

As shown in Equation 8 and Figure 25 (reprinted from [8]), the $\text{SCI}_{\text{overall}}$ is a weighted average of the individual SCI scores for aggregate loss and bleeding, SCI_{AL} and SCI_{BL}, respectively, with relative weights of 80 percent for aggregate loss and 20 percent for bleeding. Cracking and other distresses were not considered as principal distresses for chip seals in this project, as illustrated in Equation 8 and Equation 9. As shown in Table 13, field performance results were categorized based on SCI scores with a threshold of 70 percent (SCI ≥ 70 percent for adequate overall performance [$\text{Pass}_{\text{Field}}$] and SCI < 70 percent for inadequate overall performance [$\text{Fail}_{\text{Field}}$]). SCI scores for individual distresses were also used with the same threshold of 70 percent. Due to variability in field performance evaluation as calculated from three subsections per HS, some HSs with SCI scores between 70 percent and 75 percent were tentatively classified as “pass” to indicate marginal performance.

$$\mathrm{SCI} = [\alpha_{\mathrm{AL}}\mathrm{SCI}_{\mathrm{AL}}] + [\alpha_{\mathrm{BL}}\mathrm{SCI}_{\mathrm{BL}}] + \cdots + [\alpha_{\mathrm{distress}}\mathrm{SCI}_{\mathrm{distress}}] \qquad \text{Equation 8}$$

$$\alpha_{\mathrm{AL}} + \alpha_{\mathrm{BL}} + \cdots + \alpha_{\mathrm{Distress}} = 1.00 \qquad \text{Equation 9}$$

Where:

SCI = Overall field section SCI score as a percentage.

$\mathrm{SCI}_{\mathrm{AL}}$ = SCI score for aggregate loss as a percentage.

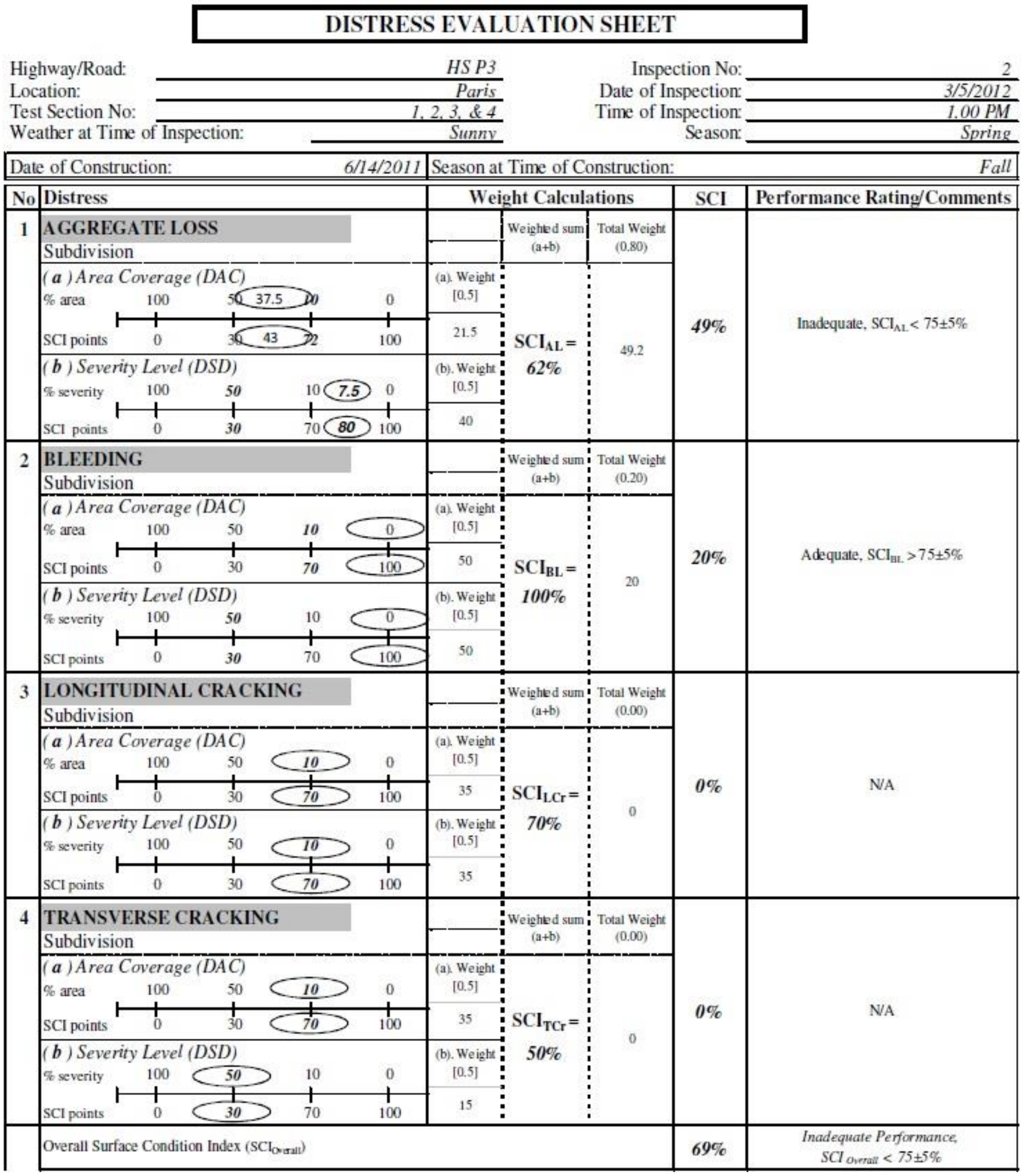
$\mathrm{SCI}_{\mathrm{BL}}$ = SCI score for bleeding as a percentage.

$\mathrm{SCI}_{\mathrm{Distress}}$ = SCI score for other distresses as a percentage.

α_{AL} = Distress weighting factor for aggregate loss (~0.80).

α_{BL} = Distress weighting factor for bleeding (~0.20).

$\alpha_{\mathrm{Distress}}$ = Distress weighting factors for other distresses (~0.00).


DISTRESS EVALUATION SHEET

Highway/Road: HS P3 | Inspection No: 2
Location: Paris | Date of Inspection: 3/5/2012
Test Section No: 1, 2, 3, & 4 | Time of Inspection: 1.00 PM
Weather at Time of Inspection: Sunny | Season: Spring

Date of Construction: 6/14/2011 | Season at Time of Construction: Fall

No	Distress	Weight Calculations			SCI	Performance Rating/Comments
1	AGGREGATE LOSS – Subdivision: (a) Area Coverage (DAC) % area 100, 50, 37.5, 20, 0; SCI points 0, 30, 43, 72, 100; (b) Severity Level (DSD) % severity 100, 50, 10, 7.5, 0; SCI points 0, 30, 70, 80, 100	(a). Weight [0.5] 21.5; (b). Weight [0.5] 40	Weighted sum (a+b): SCI_{AL} = 62%	Total Weight (0.80): 49.2	49%	Inadequate, SCI_{AL} < 75±5%
2	BLEEDING – Subdivision: (a) Area Coverage (DAC) % area 100, 50, 10, 0; SCI points 0, 30, 70, 100; (b) Severity Level (DSD) % severity 100, 50, 10, 0; SCI points 0, 30, 70, 100	(a). Weight [0.5] 50; (b). Weight [0.5] 50	Weighted sum (a+b): SCI_{BL} = 100%	Total Weight (0.20): 20	20%	Adequate, SCI_{BL} > 75±5%
3	LONGITUDINAL CRACKING – Subdivision: (a) Area Coverage (DAC) % area 100, 50, 10, 0; SCI points 0, 30, 70, 100; (b) Severity Level (DSD) % severity 100, 50, 10, 0; SCI points 0, 30, 70, 100	(a). Weight [0.5] 35; (b). Weight [0.5] 35	Weighted sum (a+b): SCI_{LCr} = 70%	Total Weight (0.00): 0	0%	N/A
4	TRANSVERSE CRACKING – Subdivision: (a) Area Coverage (DAC) % area 100, 50, 10, 0; SCI points 0, 30, 70, 100; (b) Severity Level (DSD) % severity 100, 50, 10, 0; SCI points 0, 30, 70, 100	(a). Weight [0.5] 35; (b). Weight [0.5] 15	Weighted sum (a+b): SCI_{TCr} = 50%	Total Weight (0.00): 0	0%	N/A
	Overall Surface Condition Index ($SCI_{Overall}$)				69%	Inadequate Performance, $SCI_{Overall}$ < 75±5%

Figure 25. Example Distress Evaluation Sheet (Reprinted From [8]).

Table 13. SCI Threshold Values and Overall Performance Rating Criteria.

SCI Threshold Value	SPG Validation
SCI ≥ 75%	$Pass_{Field}$ (Adequate Performance)
70% ≤ SCI < 75%	Tentatively $Pass_{Field}$ (Adequate Performance)
SCI < 70%	$Fail_{Field}$ (Inadequate Performance)

COMPARISON OF LABORATORY RESULTS & FIELD PERFORMANCE

The predicted field performance from the laboratory results and the actual measured field performance were compared to validate the SPG parameter thresholds. Due to the way the binder grades are specified for the 2016 HSs, the way the field performance is predicted based on laboratory results differs from the earlier validation and implementation efforts in TxDOT Projects 0-1710-2 and 0-6616-1 and the first two years of 5-6616-1 [2-9, 11]. In these projects, the binder is expected to fail in the field if it doesn't meet the SPG climate based requirements. However, for the current implementation period, the binder is expected to fail if it doesn't meet the SPG binder grade specified by the engineer for a given chip seal project. For instance, if the binder grade specified for a HS was SPG 67-19 and the binder was characterized as SPG 64-19 or SPG 70-16 or if the phase angle threshold was not met at the continuous high temperature grade, in other words, $Fail_{Lab}$, the binder is expected to fail in the field (SCI < 70). If the same binder was graded as SPG 70-19 or SPG 67-22 or SPG 73-22, the binder is said to have passed in the laboratory ($Pass_{Lab}$) and is expected to pass in the field (SCI ≥ 70).

Therefore, Table 14 is used to check the correlation between the expected performance from laboratory results and the observed field performance. In addition, the SPG parameter thresholds are validated using this table if better correlations are found.

Table 14. Laboratory vs. Field Performance Correlation Table.

Laboratory Results	Field Performance	Correlation
$Pass_{Lab}$	$Pass_{Field}$	Yes
$Pass_{Lab}$	$Fail_{Field}$	No
$Fail_{Lab}$	$Pass_{Field}$	No
$Fail_{Lab}$	$Fail_{Field}$	Yes

SUMMARY

In this chapter, the experimental methods and the analysis methodologies involved in each of the steps during the implementation and the validation of the SPG specification were discussed. Highway section (HS) selection based on traffic and aggregates, and collection of binders and construction information were presented. Laboratory test methods including emulsion residue recovery, binder aging, SPG binder grading, and additional tests to characterize polymer modification and low temperature binder properties were described. Test section selection, surface distress measurement, and SCI score calculation were included along with the basis for laboratory and field performance comparison. The field performance monitoring and laboratory results obtained using these methods are analyzed and discussed in chapter IV. The results corresponding to the non-SPG grading related testing are described in chapter V.

CHAPTER IV

LABORATORY EVALUATION & FIELD PERFORMANCE MONITORING

The laboratory evaluation results of the binders collected from the 14 chip seal HSs selected as described in chapter III and their pre-and post-construction field performance are presented and compared in this section. Only the laboratory test results relevant to the field performance correlation of the thresholds (i.e. SPG grading) are discussed. The results corresponding to the other test methods described in chapter III are discussed in chapter V to address issues and concerns regarding the SPG specification.

SPG GRADING RESULTS

The SPG grading results of the chip seal binders collected during the 2016-17 implementation period of the specification for the HSs built in 2016 are summarized in Table 15. Binders that meet the specified SPG grade are supposed to exhibit adequate performance in the field with respect to aggregate loss and bleeding, while those that fail in the laboratory are expected to demonstrate inadequate performance in the field. All of the binders (14 of 14) met the required environmental SPG grade, while two binders (14%, 16-AUS-2 and 16-AUS-3) failed to meet the specified SPG grade of the material supplied at the high temperature end. This could mean that the binders might perform poorly in terms of bleeding.

Three binders (21%, 16-BWD-2, 16-CRP-1 and 16-CRP-2) failed to meet the phase angle maximum threshold of 80^0 specified by the SPG specification. This could indicate inadequate polymer modification. However, all of the binders utilized during the 2016-17 SPG implementation period were found to be polymer modified by FTIR spectroscopy results as shown subsequently. Therefore, the phase angle threshold did not indicate the presence of polymers in the three binders. Possibly the modification was insufficient or compatibility between the base binder and the additives was poor. Depending on the type of modifier (plastomer/ elastomer), this could adversely affect the performance either in terms of bleeding (plastomer) or both bleeding and aggregate loss (elastomer).

Table 15. SPG Grading Results of the HSs Built in 2016.

District	Code	SPG Environmental Required Grade	Material Supplied/ Specified	Continuous High temp. grade	Continuous Low temp. grade	SPG Grade Measured	Phase Angle @ continuous SPG Grade (°)
Abilene	16-ABL-1	67-19	SPG 73-19	76.63	-23.84	76-22	70.26
	16-ABL-2			80.93	-23.36	79-22	76.42
Amarillo	16-AMA-1	64-25	SPG 64-25	64.39	-35.19	64-34	77.99
	16-AMA-2			66.36	-33.59	64-31	73.66
Austin	16-AUS-1	67-16	SPG 70-19	74.64	-24.27	73-22	51.99
	16-AUS-2			69.11	-24.06	67-22	76.41
	16-AUS-3			69.20	-24.15	67-22	77.87
Brownwood	16-BWD-1	67-19	CRS 2P	72.34	-24.37	70-22	79.57
	16-BWD-2		SPG 67-22	68.17	-25.53	67-25	81.12
Corpus	16-CRP-1	67-13	SPG 70-19	73.23	-24.35	73-22	82.10
	16-CRP-2			74.90	-24.16	73-22	80.31
Paris	16-PAR-1	67-19	SPG 70-22	72.90	-22.47	70-22	79.28
	16-PAR-2			72.19	-25.60	70-25	78.61
	16-PAR-3			78.75	-22.06	76-22	72.67

NOTE: Values in shaded cells correspond to failure in the laboratory test in the form of noncompliance with the standard thresholds or failure to meet the specified SPG grade of the material supplied.

FIELD PERFORMANCE MONITORING RESULTS

Per the guidelines described in chapter III, a total of 19 HSs with multiple test sections were initially established to monitor field performance and utilize the associated distress data to validate the SPG threshold values from the second TxDOT research project (4) labeled 2012 in

Table **3** (i.e. G*/sin δ, phase angle (δ) and stiffness (S)). The field performance monitoring data was collected prior to construction, post construction, and after the first winter in service. While the binders supplied for 14 of the selected test sections (as shown in Table 15) were collected during construction, the remaining five binders could not be collected by the TTI personnel due to communication and scheduling issues. Therefore, although field performance data was collected for 19 test sections, the validation of the SPG parameters was discussed with regard to the 14 test sections for which the associated laboratory binder characterization results were available.

Pre-Construction Field Performance Data

Table 16 shows the field performance data of the HSs prior to construction in terms of SCI_{AL}, SCI_{BL}, and the overall SCI as defined in chapter III. Cells marked in grey indicate failure in the field. Four HSs exhibited poor bleeding performance, whereas two HSs performed poorly in terms of aggregate loss prior to construction. Due to the higher weight (0.8) corresponding to aggregate loss in the overall SCI calculation, the HSs with poor SCI_{AL} had poor overall SCI as well. Although for some HSs high embedment depth (ED) was captured through poor SCI_{BL}; some HSs with high EDs such as 16-AUS-2, 16-AUS-3, 16-CRP-1, and 16-CRP-3 had high SCI_{BL} scores.

Although most HSs had pre-construction SCI values greater than 70, chip seals were still applied. There could be various reasons for this including the following:

- Bleeding (low SCI_{BL}, not necessarily low SCI) could have impacted the road surface texture of certain HSs adversely necessitating the chip seal treatment to improve the skid resistance.
- SCI by its definition does not capture cracking distress as the field performance monitoring program for SPG implementation included the collection of bleeding, aggregate loss, and ED only. The districts may have made the decision to treat some HSs with chip seals based on inadequate cracking performance.
- Construction scheduling may have been cost effective if some of the sections (even with SCI = 100) were treated with chip seals at the time along with other HSs that needed the chip seal treatment.

Table 16. Field Performance Monitoring of the HSs Built in 2016 Prior to Construction.

Code	Highway	Embedment Depth (%)		SCI_{BL}	SCI_{AL}	SCI
		Wheel Path (WP)	Between Wheel Path (BWP)			
16-ABL-1	BI0020G	95	80	60	100	92
16-ABL-2	SH0092	95	83	69	100	94
16-AMA-1	US83	75	75	100	100	100
16-AMA-2	FM0281	75	82	100	100	100
16-AMA-3	FM1541	98	79	45	100	89
16-AUS-1	US0087	59	45	93	60	67
16-AUS-2	SH0029	95	95	100	100	100
16-AUS-3	SH0029	95	95	-	-	-
16-BWD-1	US0084	90	94	-	-	-
16-BWD-2	US0084	50	40	87	100	97
16-CRP-1	FM3376	84	84	100	100	100
16-CRP-2	FM0665	78	76	100	100	100
16-CRP-3	FM0351	99	99	100	100	100
16-PAR-1	FM0035	88	40	56	100	91
16-PAR-2	US0069	76	45	100	51	61
16-PAR-3	SH0289	85	85	100	100	100

NOTE: Values in shaded cells correspond to failure in the field i.e. SCI < 70.

Post-Construction Field Performance Data

The only information collected after construction was ED, as the other distresses were not seen immediately after construction. ED is greatly affected by the traffic type and volume which make the initial ED right after the construction crucial to the performance of the chip seals [9]. Generally, chip seal design requires 40-50% initial ED (depending on the chip shape, size, and gradation) during construction so that a target ED of 50-65% is achieved after two years in service. To reduce the risk of vehicle damage and noise post construction, smaller chips are often preferred for chip seal construction. However, the binder application rate should be carefully selected to achieve the desired ED and to avoid chip loss caused by small initial EDs or flushing that results in high initial ED.

Table 17 compares the ED of the HSs prior to and post construction. Multiple ED values for a given HS indicate individual results for test sections. For instance, two ED values for a given HS indicates that two test sections were established to perform the field performance distress survey for that HS. These ED values were averaged over all test sections and a single value was utilized for the entire HS. However, individual ED values are considered for the current analysis to study the effect and quality of chip seal construction. Clearly, uniform embedment was not achieved throughout the entire HS, stressing the need for good construction practices and appropriate quality control.

Table 17. Comparison of the Embedment Depth Values of the HSs Pre-and Post-Construction.

Code	Traffic (AADT)	% Truck	Traffic Tier	Embedment Depth (%)			
				Pre-Construction		Post-Construction	
				Wheel Path (WP)	Between Wheel Path (BWP)	Wheel Path (WP)	Between Wheel Path (BWP)
16-ABL-1	3700	45	T2	95, 95	80, 80	95, 95	80, 80
16-ABL-2	2500	30	T2	95, 95, 95, 95	50, 90, 95, 95	75, 50, 35, 30	40, 30, 15, 10
16-AMA-1	3500	28	T2	75, 75, 75, 75	75, 75, 75, 75	25, 20, 20, 20	10, 10, 10, 10
16-AMA-2	2627	42.9	T2	75, 75, 75	75, 85, 85	50, 25, 30, 15	15, 15, 15, 10
16-AUS-1	4995	17.7	T2	25, 35, 85, 90	25, 25, 50, 80	20, 20, 25, 20	10, 10, 15, 10
16-AUS-2	1100	16.6	T2	95, 95, 95, 95	95, 95, 95, 95	40, 80, 60, 80	10, 15, 10, 10
16-AUS-3	4995	17.7	T2	95, 95	95, 95	95, 95	20, 20
16-BWD-1	3300	11.7	T2	95, 90, 95, 80	90, 90, 95, 100	40, 50, 35, 50	15, 75, 15, 10
16-BWD-2	3300	11.7	T2	50	40	20	10
16-CRP-1	3000	10	T2	90, 95, 75, 75	90, 95, 75, 75	20, 20, 10, 10	10, 10, 10, 20
16-CRP-2	3500	8	T2	80, 75, 80, 75	75, 75, 80, 75	20, 25, 30, 30	10, 10, 15, 10
16-PAR-1	4147	9.1	T2	75, 90, 90, 95	40, 40, 40, 40	80, 80, 75, 65	30, 20, 30, 20
16-PAR-2	3300	15.5	T2	80, 75, 75, 75	60, 40, 40, 40	75, 90, 75, 70	60, 60, 60, 40
16-PAR-3	2500	30	T2	80, 80, 90, 90	80, 80, 90, 90	20, 20, 30, 10	10, 10, 10, 10

Analysis of High EDs

During construction, high ED values could be a result of excessive binder application or high construction temperatures that cause flushing (a construction-related problem) while accelerated or slow traffic could potentially displace and disorient the chips in service resulting in bleeding (a performance-related problem) [17]. This means that high ED values observed in HSs prior to construction could be the combined effect of possible flushing during construction and bleeding due to high traffic volumes experienced by the HSs. The high ED values observed in the HSs post construction are due to flushing.

Pre-Construction High EDs

From Table 17, all of the HSs were in traffic tier T2 as defined in chapter III, although some HSs had high % trucks. Also, most HSs (except 16-AUS-1) had high ED values close to 100% prior to construction. This could be the reason for bumping up the high temperature grade of the binders specified for HSs in ABL, AMA, AUS, CRP, and PAR although they did not necessarily exhibit poor bleeding performance. For instance, the SPG climatic requirement for ABL is SPG 67-13 while the district specified a SPG binder grade of SPG 73-19. This was probably done considering the high levels of ED observed in the ABL HSs particularly due to high % trucks.

Post-Construction High EDs

Post-construction high ED values are a result of flushing due to high binder application rates, high construction temperatures or immediate opening to the traffic. The HSs that experienced flushing post construction include 16-ABL-1, 16-AUS-2, 16-AUS-3, 16-PAR-1 and 16-PAR-2 as shown in Figure 26. While the binder application rates for these HSs were not exceptionally high ranging from 0.32 to 0.36 Gal/SY, the temperatures during construction were high. The temperatures during construction for these HSs ranged from 84° F to 100° F where most HSs except 16-PAR-2 (84°) were constructed at a temperature greater than 95° F. This possibly explains high EDs for these HSs.

Figure 26. Pictures Depicting Flushing in HSs That Exhibited High ED Post-Construction.

Analysis of Low EDs

Largely, the HSs exhibited ED values greater than 50% prior to the chip seal construction. Post-construction, low ED values could be the result of dusty aggregates, low construction temperatures or long time gaps between the time of binder spraying and aggregate application or the time of aggregate application and the first rolling. Sometimes, low aggregate application rates result in large amounts of daylight (empty regions without aggregate) around the aggregate. This could be interpreted as aggregate loss or low ED.

Pre-Construction Low EDs

The HSs that didn't exhibit high ED values prior to construction had EDs varying from 40-75%. These values are not extremely high and are reasonably within the target ED range of 50-65%. However, these values were observed in the BWP region where the traffic loading is low.

Post-Construction Low EDs

Post construction, most HSs had ED values less than 50% ranging anywhere from 10-40%. The very low ED values were particularly observed BWP while some HSs including 16-AMA-1, 16-AMA-2 (some test sections), 16-AUS-1, 16-BWD-2, 16-CRP-1, 16-CRP-2, 16-CRP-3, and 16-PAR-3 had very low EDs even in the WP (some of which are shown in Figure 27). In most cases except 16-BWD-2, low construction temperatures accompanied by low aggregate application rates caused daylight resulting in low ED values. Long time gaps between the binder and aggregate application (3-11 minutes) or between the binder application and the first roll (6-15 minutes) also could have aggravated the poor embedment issue. With regard to 16-BWD-2, dusty aggregates in a windy construction environment as shown in Figure 27 caused poor aggregate embedment.

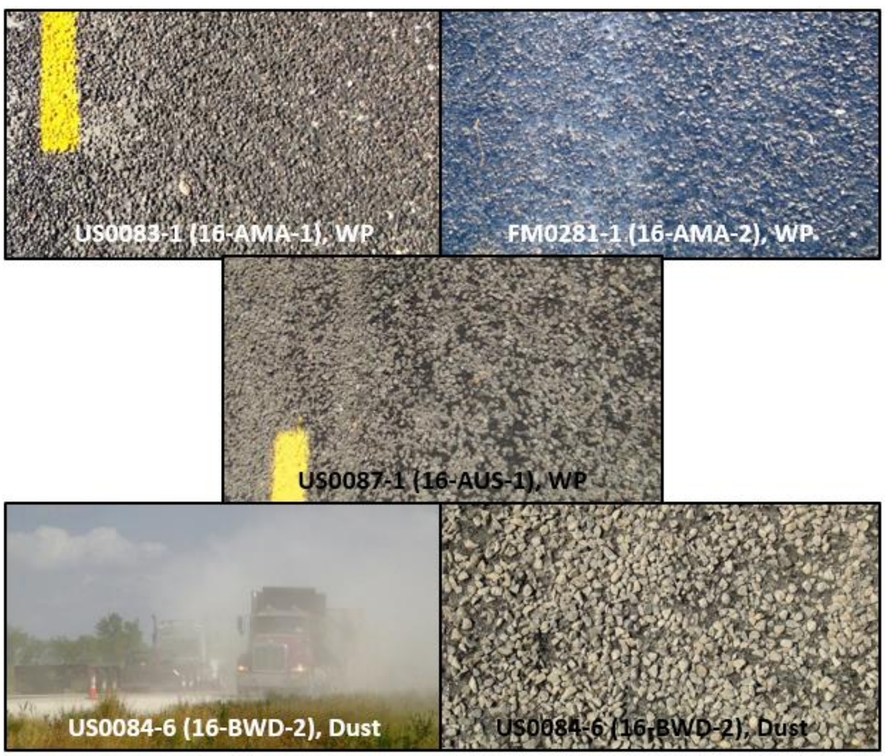


Figure 27. Pictures Depicting Poor Aggregate Embedment in Few HSs.

Conclusions

In conclusion, construction factors significantly influence chip seal performance. Proper materials selection should be accompanied by good construction practices with suitable quality control while taking into account the construction environment holistically to ensure good performance of a chip seal.

Post First Winter Field Performance Data

The field performance of the HSs was monitored after the critical first winter (Table 18). At this time two HSs, 16-ABL-1 and 16-PAR-1, showed inadequate field performance in terms of bleeding. Based on the post-construction field information, flushing was observed (ED > 80) in the test sections corresponding to these HSs due to construction temperatures greater than 95° F. Clearly, construction factors greatly impact the performance of the HSs. Similarly, four HSs; 16-AUS-1, 16-BWD-2, 16-CRP-1, and 16-CRP-2 exhibited poor performance in terms of aggregate loss. These four HSs exhibited very low ED values immediately after construction due to low aggregate application rate (daylight), low construction temperatures, long time gaps between binder and aggregate application and the first roll, and dusty aggregates (16-BWD-2). The initial poor embedment could have dislocated the aggregates when the road was opened to traffic. In addition, the binders corresponding to 3 out of the 4 HSs including 16-BWD-2, 16-CRP-1, and 16-CRP-2 did not meet the phase angle requirement. Perhaps poor modification (material-related factor) in addition to the construction factors resulted in the poor performance of these HSs. Again, due to more weight given to the aggregate loss (0.8) when calculating the overall SCI, three of these HSs also failed in terms of overall SCI score and one HS only passed tentatively with SCI = 72.

Table 18. Laboratory and Field Performance Monitoring Results for HSs Built During 2016-17 period.

HS	Traffic (AADT)	Binder Specified	SPG Climatic Requirement	SPG Grade Measured	δ @ Cont. SPG Grade	Embedment Depth		Performance after 1st Winter		
						WP	BWP	SCI_{BL}	SCI_{AL}	SCI
16-ABL-1	3700	SPG 73-19	SPG 67-13	SPG 76-22	70.3	79	55	55	100	91
16-ABL-2	2500			SPG 79-22	76.4	45	18	95	92	93
16-AMA-1	3500	SPG 64-25	SPG 64-25	SPG 64-34	78.0	28	12	100	96	97
16-AMA-2	2627			SPG 64-31	73.7	34	13	96	92	93
16-AUS-1	4995	SPG 70-19	SPG 67-16	SPG 73-22	52.0	26	12	91	61	67
16-AUS-2	1100			SPG 67-22	76.4	64	11	77	87	85
16-AUS-3	4995			SPG 67-22	77.9	83	58	73	100	95
16-BWD-1	3300	CRS 2P	SPG 67-19	SPG 70-22	79.6	23	10	78	81	80
16-BWD-2	3300	SPG 67-22	SPG 67-19	SPG 67-25	81.1	60	46	89	68	72
16-CRP-1	3000	SPG 70-19	SPG 67-13	SPG 73-22	82.1	20	13	100	56	65
16-CRP-2	3500			SPG 73-22	80.3	31	11	100	57	65
16-PAR-1	4147	SPG 70-22	SPG 67-19	SPG 70-22	79.3	75	28	66	100	93
16-PAR-2	3300			SPG 70-25	78.6	64	39	89	82	83
16-PAR-3	2500			SPG 76-22	72.7	20	13	100	86	89

NOTE: Values in shaded cells (SPG grades) correspond to failure in the laboratory test in the form of noncompliance with the standard thresholds or failure to meet the specified SPG grade of the material supplied. Values in the shaded cells corresponding to field performance mean failure in the field i.e. SCI < 70.

FIELD PERFORMANCE CORRELATION OF SPG PARAMETERS

The SPG laboratory characterization results and binder properties (G*/sin δ from the DSR and S from the BBR) were initially correlated with the overall field performance (overall SCI score) in previous research [3]. However, this correlation was considered inappropriate in this project because these properties are designed to correlate to specific distresses for chip seals (bleeding or aggregate loss, respectively). Therefore, since the beginning of the SPG implementation in 2013, each binder property was compared to the SCI for the corresponding individual distresses. G*/sin δ from the DSR at high temperatures was correlated with SCI_{BL} because this property was used to specifically evaluate the resistance to aggregate retention and bleeding in chip seal binders at high temperatures. In addition, S from the BBR at low temperatures was correlated with SCI_{AL} to evaluate the strain susceptibility and resistance to aggregate loss.

Example of Adequate Performance, SCI ≥ 70 Percent

An example of adequate field performance is shown in Figure 28 for HS 16-AMA-1 after the first winter post construction. This section is located on US83 in Ochiltree County, AMA District. The SPG climatic requirement in that county is 64-25, and the binder supplied for construction was SPG 64-25. The binder utilized for construction was graded as SPG 64-34 with the continuous phase angle meeting the SPG threshold value of less than 80°. The 2016 AADT was approximately 3500 on this section with 28% trucks. Consistent with digital pictures, as shown in Figure 28, this section exhibited adequate performance in terms of aggregate loss, bleeding, and overall combined distress. The SCI_{AL}, SCI_{BL}, and SCI values were 100, 96, and 97, respectively.

Figure 28. Example of Adequate Performance—16-AMA-1, Post First Winter.

Example of Inadequate Performance, SCI < 70 Percent

Figure 29 shows an example of inadequate performance for HS 16-CRP-2 after the first winter post construction. This section is located on FM0665 in Nueces County, CRP District. The inadequate performance for aggregate loss (SCI_{AL} = 57) and overall (SCI = 65) is reflected in the digital pictures (Figure 29). This section received a chip seal with SPG 70-19 binder. The 2016 AADT on this section was recorded at approximately 3500 with 8% trucks. The SPG climate requirement is SPG 67-13, and the binder was graded as SPG 73-22 while it failed to meet the SPG phase angle threshold at the continuous T_{high}.

Figure 29. Example of Inadequate Performance— 16-CRP-2, Post First Winter.

Field Performance Correlation of G*/sin δ at T_{high}

The field performance parameter used to validate the G*/sin δ threshold at T_{high} was SCI_{BL} that is indicative of bleeding performance. Figure 30 shows the plot of G*/sin δ values measured at T_{high} on the binders collected during the 2016-17 SPG implementation period with SCI scores represented as different colors to indicate individual field performance. The 2016 AADT values for each HS are printed above each data point.

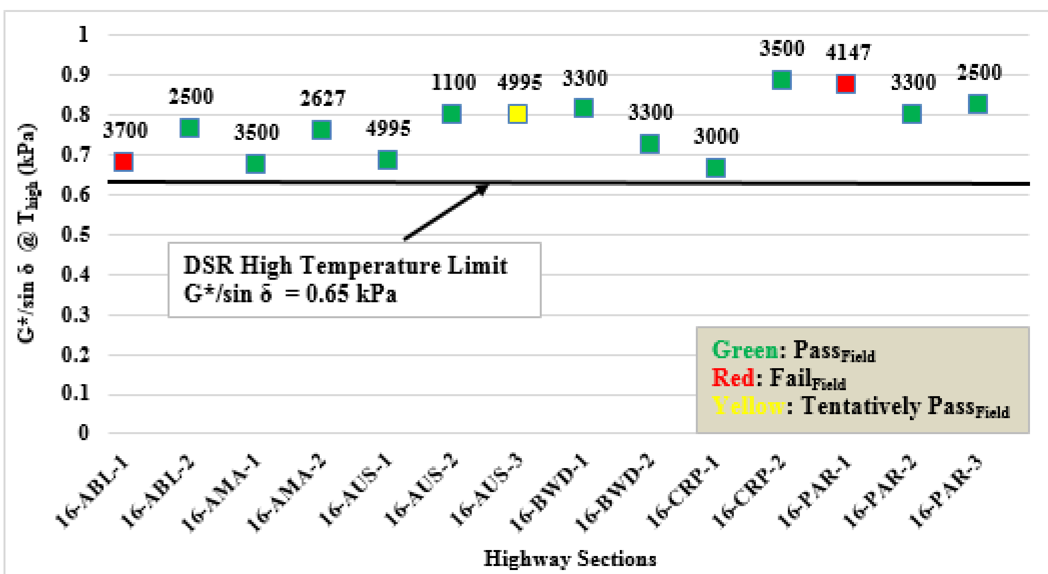


Figure 30. Plot of G*/sin δ Measured At T_{high} (with Traffic Volume above Each Data Point) for the Binders Collected During the 2016-17 Period; SCI_{BL} Scores were Color-Represented.

$G^*/\sin\delta$ at T_{high} was above 0.65 kPa for all HSs. This indicates that from the climatic requirement standpoint, all the binders were expected to perform adequately in the field with $SCI_{BL} > 70$. However, for the current period of implementation as the binders were specified in terms of SPG grade, failure to meet the specified grade results in the prediction of poor field performance ($Fail_{lab}$). As 16-AUS-2 and 16-AUS-3 did not meet their specified SPG grade ($Fail_{lab}$), they were expected to exhibit poor bleeding performance. However, 16-AUS-3 tentatively passed in the field with SCI_{BL} of 73 (tentative $Pass_{Field}$) while16-AUS-2 had just adequate bleeding performance with SCI_{BL} of 77 ($Pass_{Field}$). This could be because both the binders met their climatic SPG grade and the grade bumping was not necessary; or, the huge difference between the AADTs experienced by the two HSs could have caused 16-AUS-2 (AADT of 1100) to perform adequately and 16-AUS-3 (AADT of 4995) to tentatively fail. 16-ABL-1 and 16-PAR-1 could have failed in the field due to construction issues discussed previously. This analysis resulted in a field performance correlation of 71% (10 out of 14) for the $G^*/\sin\delta$ parameter without the consideration of construction factors. Factoring in the construction factors will result in a correlation value of 83% (10 out of 12).

Field Performance Correlation of Stiffness, S at T_{low}

The field performance parameter used to validate the stiffness parameter, S threshold at T_{low} was SCI_{AL} that is indicative of aggregate loss of the HS. Figure 31 shows the plot of stiffness, S values measured at T_{low} on the binders collected during the 2016-17 SPG implementation period with SCI scores represented as different colors to indicate individual field performance. The 2016 AADT values for each HS are printed above each data point.

At T_{low}, all the binders had stiffness less than the specified 500 MPa resulting in the prediction of good field performance in terms of aggregate loss for all the HSs from the climatic requirement perspective. All the binders met the low temperature grade specified for their corresponding HSs as well. Yet, four binders; 16-AUS-1. 16-BWD-2, 16-CRP-1, and 16-CRP-2; showed inadequate chip retention due to construction issues discussed previously and possibly the failure to meet the phase angle threshold. This comparison resulted in a 71% (10 out of 14) field performance correlation for the stiffness parameter without consideration of construction factors. Considering the construction factors resulted in a 100% (10 out of 10) field performance correlation.

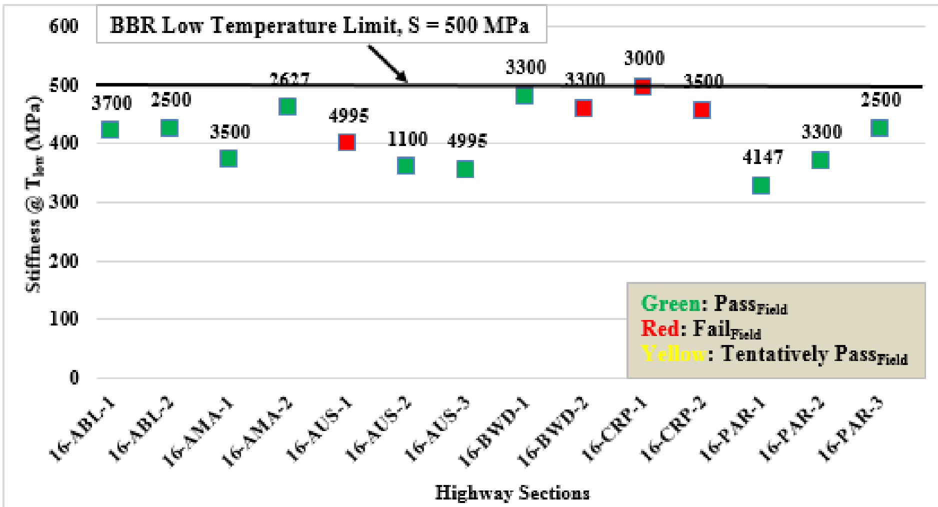


Figure 31. Plot of Stiffness, S Measured at T_{high} (With Traffic Volume Above Each Data Point) for the Binders Collected During the 2016-17 Period; SCI_{AL} Scores Were Color-Represented.

Summary of the Field Performance Correlation Study

Construction factors need to be considered when comparing field performance to laboratory performance to understand the exclusive contribution of material-related factors to failure. Based on this, a summary of the correlation between laboratory and field performance results with and without considering construction factors is presented in Table 19.

Table 19. Correlation Between Laboratory and Field Performance Results, with and Without Considering Construction Factors.

Parameter	Existing SPG Limit	Without Construction Factors Laboratory vs. Field Results		With Construction Factors Laboratory vs. Field Results	
DSR G*/sin δ T_{high}	Min 0.65kPa	Correlated $Pass_{LAB}$–$Pass_{FIELD}$: 10 $Fail_{LAB}$–$Fail_{FIELD}$: 0	71%	Correlated $Pass_{LAB}$–$Pass_{FIELD}$: 10 $Fail_{LAB}$–$Fail_{FIELD}$: 0	83%
		Uncorrelated $Pass_{LAB}$–$Fail_{FIELD}$: 2 $Fail_{LAB}$–$Pass_{FIELD}$: 2	29%	Uncorrelated $Pass_{LAB}$–$Fail_{FIELD}$: 0 $Fail_{LAB}$–$Pass_{FIELD}$: 2	17%
BBR S @ 8 s, T_{low}	Max 500 MPa	Correlated $Pass_{LAB}$–$Pass_{FIELD}$: 10 $Fail_{LAB}$–$Fail_{FIELD}$: 0	71%	Correlated $Pass_{LAB}$–$Pass_{FIELD}$: 10 $Fail_{LAB}$–$Fail_{FIELD}$: 0	100%
		Uncorrelated $Pass_{LAB}$–$Fail_{FIELD}$: 4 $Fail_{LAB}$–$Pass_{FIELD}$: 0	29%	Uncorrelated $Pass_{LAB}$–$Fail_{FIELD}$: 0 $Fail_{LAB}$–$Pass_{FIELD}$: 0	0%

CONCLUSIONS

In this chapter, SPG grading results of the binders collected during the 2016-17 implementation period; field performance monitoring of the associated HSs pre-, post- and the first winter after construction; and the field performance correlation of the SPG parameters were discussed. All binders met the environmentally required SPG grade, while most binders met their specified SPG grade with some binders not meeting the phase angle requirement. Pre-construction field performance monitoring scores indicated the possible reasons for the construction of chip seals on the HSs selected for the project. Construction factors such as high (or low) construction temperatures, large time gaps between the binder – aggregate application or binder application – first roll etc. helped in understanding the ED values observed post construction. While evaluating the correlation of the SPG parameters to the field performance data after the first winter post construction, it was found that the construction factors did play a large role in the performance of the HSs even after the construction. Considering the construction factors improved the correlation of the high temperature parameter (G*/sin δ) from 71% to 83%

and that of the low temperature parameter (stiffness, S) from 71% to 100%. Based on this correlation study, selecting binders based on the SPG specification prior to construction minimized premature failure of the selected chip seal HSs due to material failure. This necessitates the need for the combined use of construction-related specifications such as the maximum time gap allowed prior to aggregate application after binder application along with material specifications (such as SPG) to ensure good chip seal performance.

CHAPTER V

INDUSTRY INTERACTION

In addition to the efforts in ongoing validation and implementation of the SPG specification, several proactive initiatives were completed in this project to make the specification more practical. These initiatives include:

- Educating the potential users of the specification such as the TxDOT districts, binder suppliers, academia, and industry asphalt user-producer groups on the SPG specification through technical briefings and update presentations in addition to technical memorandums, a revised chip seal binder selection table, and technical reports.
- Interacting and collaborating with the industry in the form of multiple round robin testing programs to achieve a certain level of comfort among the suppliers using the specification.
- Evaluating the empiricism involved with field distress data collection by visual inspection.
- Addressing the issues and concerns raised regarding the specification including:
    - Sensitivity of the existing phase angle threshold to the type of modification and stiffer aged binders
    - Exploration of a new parameter or test method to ensure polymer modification

Each of the above initiatives are discussed in detail in this chapter.

ROUND ROBIN PROGRAMS

Toward statewide implementation of the SPG specification, two round robin programs were conducted with the help of TxDOT. The first round robin was aimed at improving consistency in test methods for chip seal binder SPG specification. The second robin was aimed at further exploring parameters other than phase angle at the high temperature threshold to ensure polymer modification in addition to achieving consistency in the specification's test methods.

For each of the round robin programs, a commonly used hot-applied asphalt binder and a typical emulsion were supplied to each of the participating laboratories by TxDOT. Testing and reporting guidelines were also provided for both round robin programs as shown in Appendix A. The participants were required to recover the emulsion by AASHTO PP 72 Method B prior to performing any SPG tests or any other tests prescribed in the guidelines. The results were reported to TTI by all the participants which were then further compiled and analyzed statistically. This section describes both round robin programs, the results of the analyses, and the conclusions.

Round Robin I

TxDOT distributed samples of a typical emulsion (CRS 2P) and a commonly used hot-applied asphalt binder (AC 15P) to each participating laboratory that included five suppliers, TxDOT, and TTI. Testing guidelines included an evaluation of the effects of reheating emulsion residue prior to DSR testing. Each participant was required to recover the emulsion by AASHTO PP 72 Method B and use SPG tests to characterize the chip seal binders based on the SPG specification labeled as 2015 in

Table **3** (i.e. TxDOT Item 300) [15].

Results and Discussions

Results reported by the seven participants are summarized and presented in Figure 32. The values in the parenthesis below each participant's name indicates the SPG grade of the sample. The bars in the graphs represent continuous SPG grades defined as the temperature in 1° C increments where the parameter meets the threshold, i.e. where $G^*/\sin\delta = 0.65$ kPa and $S = 500$ MPa.

For the AC 15P, five out of seven participants reported a T_{high} of 67^0 C showing good repeatability with only two participants reporting 70^0 C and 73^0 C (Figure 32 (a)). However, all the participants were within 3^0 C of each other's continuous T_{high} i.e. 67^0 C to 70^0 C except Participants G and D, who reported high temperature grades 2^0 C higher than 70^0 C. All the participants reported a low temperature grade of -25^0 C showing very good agreement.

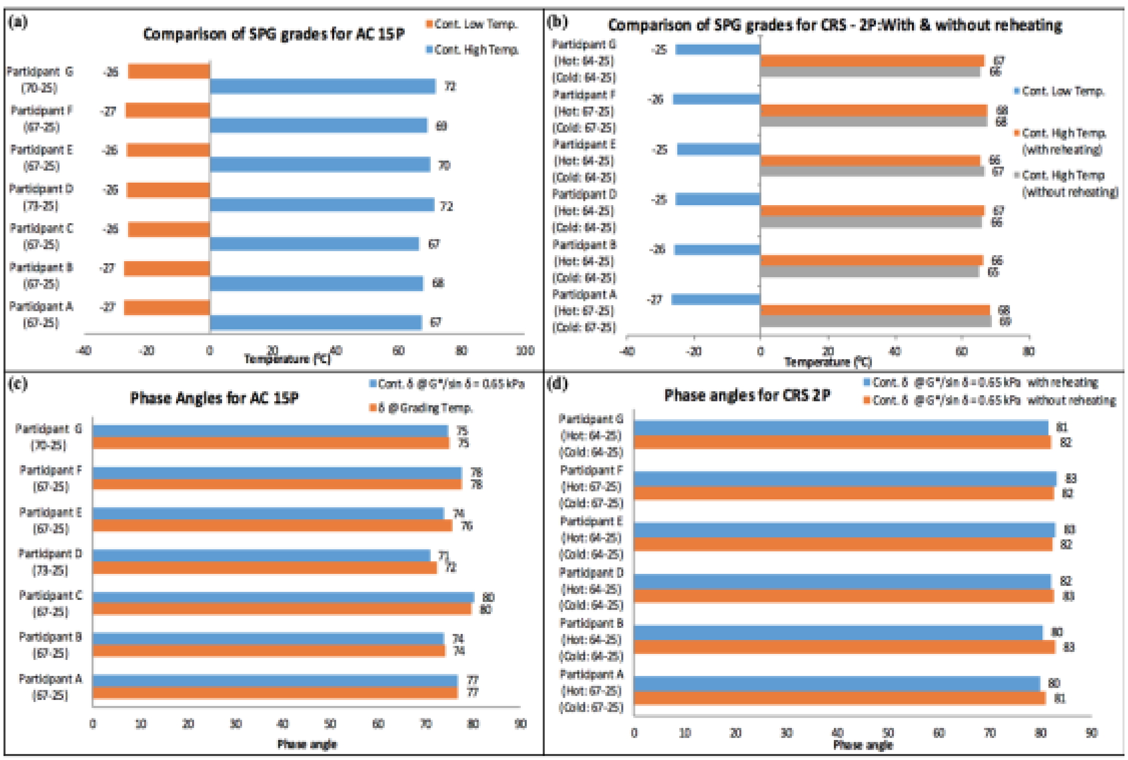


Figure 32. Comparison of SPG Grades for (a) AC15P and (b) CRS 2P With and Without Reheating and Phase Angles for (c) AC15P and (d) CRS 2P.

For the CRS 2P, the high temperature grades were within 1^0 C of each other irrespective of reheating prior to DSR testing (Figure 32 (b)). Four out of six participants (with one supplier not participating) reported a T_{high} of 67^0 C while two other participants reported 64^0 C. Again, all the participants reported a low temperature grade of -25^0 C showing very good agreement.

The phase angles at G*/sinδ = 0.65 kPa reported for the AC 15P varied from about 71^0 to 80^0 which is below the phase angle threshold of 80^0 (Figure 32 (c)). For the CRS 2P, the phase angles at G*/sinδ = 0.65 kPa were within 3^0 of each other irrespective of reheating prior to DSR testing but were higher than the threshold of 80^0 (Figure 32 (d)).

One supplier suggested that it is more practical to have the phase angle requirement at the grading temperature to reduce interpolation errors. Thus the phase angles for both conditions were compared (Figure 32 (c)). For five out of seven participants, there was no change in phase angle. Only Participants D and E showed 1^0 and 2^0 higher phase angles at the grading temperature.

Statistical Analysis

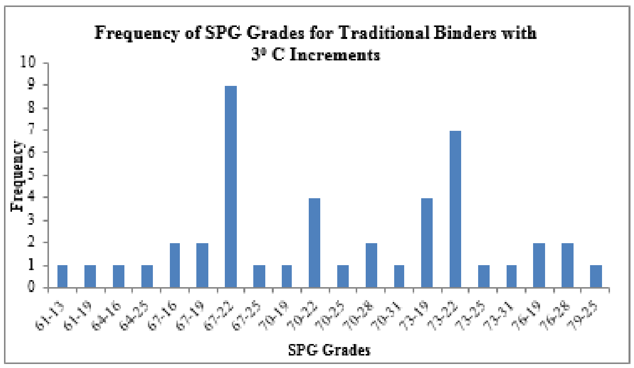
A statistical analysis was also performed on the round robin results using the precision and bias estimates provided in AASHTO T 315 and T 313 for DSR and BBR tests, respectively [50, 51]. For multi – laboratory precision, results from two different laboratories can be expected to differ by the acceptable range of test results (%d2s value) calculated as follows:

$$\%\text{d2s} = \frac{\text{Difference in two test results}}{\text{Mean of the two test results}} * 100$$

The multi-laboratory precision %d2s value for DSR and BBR test results is 17.0 and 17.8, respectively. The following three temperatures where data was available for all participants were used in this analysis: 70^0 C for AC 15P, 67^0 C for CRS 2P, and -25^0 C for both materials. The %d2s values were then calculated for each pair of participants and compared to the allowable %d2s. Then the difference in the continuous SPG grades was determined.

Conclusions

Based on statistical analysis, a difference of $2\text{-}3^0$ C between the continuous high temperature grades was found to be reasonable between two different laboratories resulting in the conclusion that the 3^0 C SPG increment is too tight. However, at low temperatures, the 3^0 C SPG increment is acceptable. Therefore, considering practicality, 6^0 C increments at both high and low temperatures but offset to capture the statewide 67-19 climate in Texas and avoid confusion with PG grades was proposed. This would make the SPG grades unique as shown in Figure 33, fewer in number, and possibly decrease the adjustments needed from the climate-based requirement due to high traffic or the need for modification.



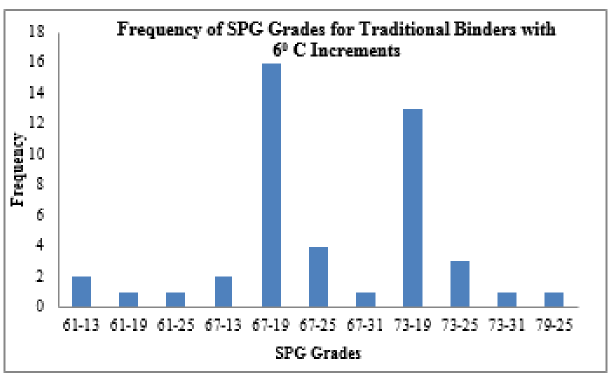


Figure 33. Frequency of Number of SPG Grades in Texas for Traditional Binders With 3^0 C, and 6^0 C Increments.

Round Robin II

Following the success of Round Robin – I, a second round robin program was completed. Initially, TxDOT distributed samples of a typical emulsion and a commonly used hot-applied asphalt binder, both with SPG grades, to each participating laboratory that included ten suppliers, TxDOT, and TTI. However, due to inconsistent results at the high temperature, a total of three different hot-applied asphalt binder samples were distributed to the participants.

Testing and reporting guidelines shown in Appendix A were also provided wherein each participant was required to recover the emulsion by AASHTO PP 72 Method B and use SPG tests to characterize the chip seal binders using the revised SPG specification that utilizes 6^0 C increments offset by 3^0 C from those used in the PG specification. For high temperature grading, two measurements (replicates) on the same sample without additional conditioning time before changing the test temperature for subsequent measurements were requested.

In addition to the SPG tests required by specification, the participants were requested to perform the ER by Tex-539-C and the MSCR by AASHTO TP 70 on the original unaged material on both binder samples for information only to provide additional data toward selection of an appropriate parameter to ensure polymer modification. The m-value was also requested for each cold temperature for information only.

SPG Binder Grading Results

Hot-Applied Asphalt Binder

As mentioned previously, a total of three different hot-applied asphalt binder samples were distributed to the participants due to inconsistent results at high temperature. Figure 34 summarizes the SPG binder grading results of the three hot-applied asphalt binders, namely, hot-applied asphalt binder 1 (HAA 1), hot-applied asphalt binder 2 (HAA 2), and hot-applied asphalt binder 3 (HAA 3). The values in the parenthesis below each participant's name indicates the SPG grade of the sample whereas the bars represent continuous SPG grades defined as the temperature in 1° C increments where the parameter meets the threshold.

Four different SPG grades were reported for HAA 1– four out of eleven participants reported a T_{high} of 73^0 C, two reported 79^0 C, three reported 85^0 C, and two reported 91^0 C. However, on the low temperature end, all the participants were within

4^0C of each other's continuous low temperature grade i.e. -21^{0}C to - 25^{0}C with a reported low temperature grade of -19^0 C, showing good agreement. Although most participants reported phase angles in the range 41^0 to 47^0, participants F, I and one replicate each of B and G reported phase angles ≥ 55^0. Clearly, the binder grading results of HAA 1 were highly variable and thus necessitated that another sample be provided and characterized.

In the case of HAA 2, two out of seven participants reported a continuous T_{high} of 73^0 C, three reported 85^0 C, and two reported 91^0 C – a total of three different SPG grades. At low temperatures, all the participants reported -19^0 C with their continuous low temperature grade ranging from -19^0 C to -21^0 C (with one exception at -23^0 C). Similar to HAA 1, most participants reported phase angles in the range 41^0 to 47^0, but participants A and F reported phase angles ≥ 60^0. Three different SPG grades for the same binder were still unacceptably inconsistent; therefore, a third hot-applied asphalt binder was again distributed to the participants. In addition, for most participants, the two replicates of HAA 1 and HAA 2 were very different from each other.

For the third hot-applied asphalt binder HAA 3, all six participants were in very good agreement with each other with respect to both the continuous high and low temperature grades and the phase angles. All the participants reported one grade (SPG 79-19) and were within 1^0 C of each other's high and low temperature grades. Possible reasons for the inconsistency at high temperatures for HAA 1 and 2 include:

- Improper blending of the base binder and the polymers/ rubbers/ other additives in the binder.
- Poor compatibility between the base binder and the additives present in the binder.

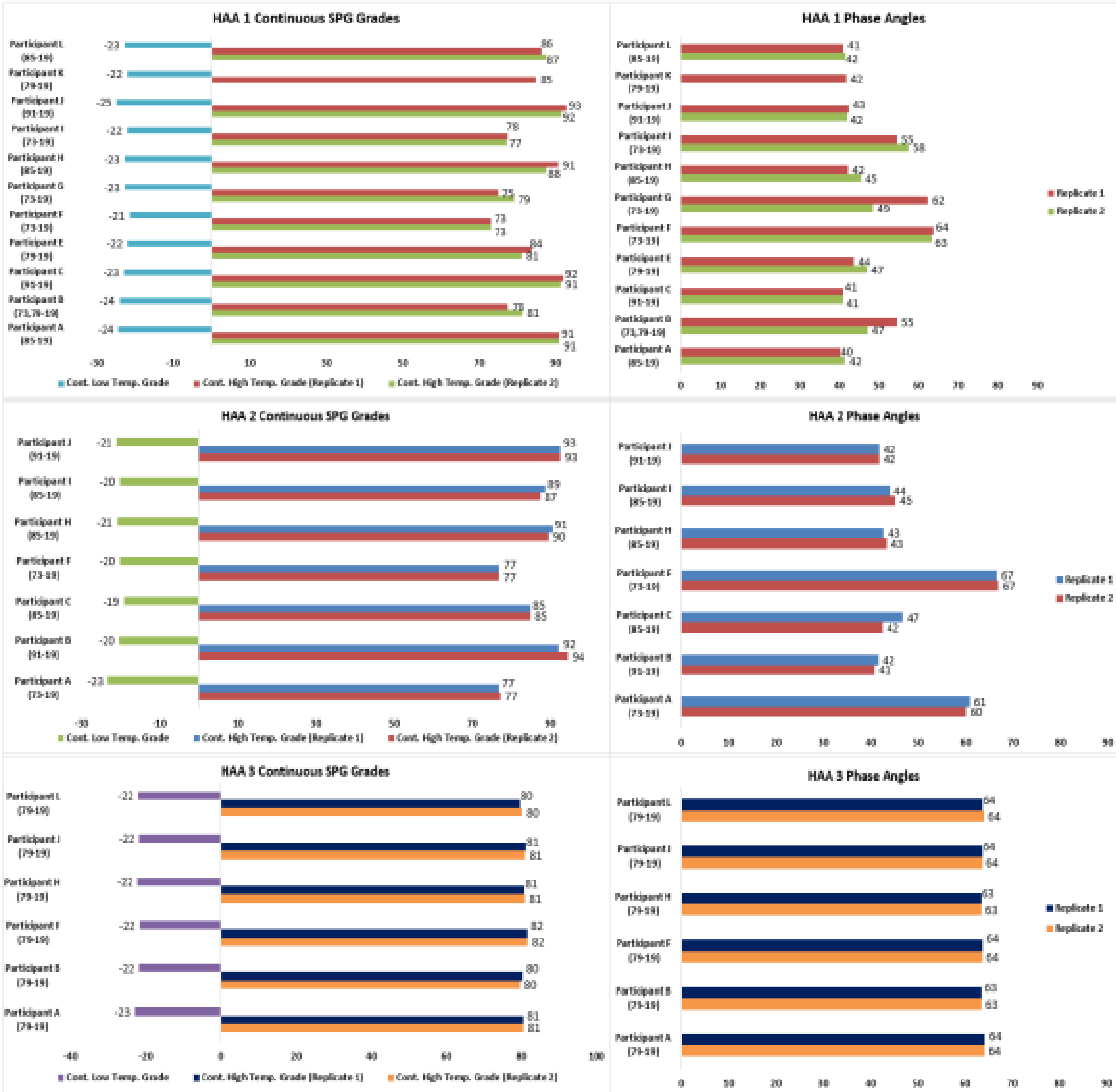


Figure 34. SPG Grading Results of the Round Robin 2 Hot-Applied Asphalt Binders, HAA 1, HAA 2 & HAA 3 Results.

Emulsion

The SPG grading results of the emulsion sample are shown in Figure 35. Four out of eight participants reported a T_{high} of 67^0 C, and the remaining four reported 73^0 C. However, except Participant G, all the participants' continuous high temperature grades were within 5^0 C ranging from 71^0 C to 76^0 C. In addition, the continuous low temperature grades (-22^0 C to -24^0 C) and the phase angles (79^0 to 82^0) were in very good agreement with each other.

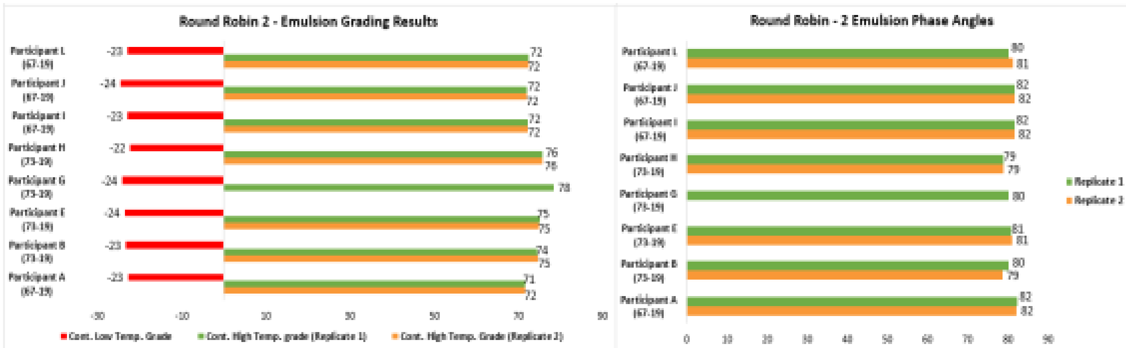


Figure 35. SPG Grading Results of the Round Robin 2 Emulsion

Statistical Analysis of the SPG Binder Grading Results

A statistical analysis was also performed on the round robin results using the precision and bias estimates provided in AASHTO T 315 and T 313 for DSR and BBR tests (18), respectively. For multi – laboratory precision, results from two different laboratories can be expected to differ by the acceptable range of test results (%d2s value) calculated as follows:

$$\%\text{d2s} = \frac{\text{Difference in two test results}}{\text{Mean of the two test results}} * 100$$

The multi-laboratory precision %d2s value for DSR and BBR test results is 17.0 and 17.8, respectively. The following three temperatures where data was available for all participants were used in this analysis: 79^0C (both replicates) for HAA 3, 73^0C (both replicates) for emulsion, and -19^0C for both materials. The %d2s values were then calculated for each pair of participants and compared to the allowable %d2s.

The %d2s values for HAA 3 indicate that the results of all of the participants were equivalent. In the case of the emulsion, the %d2s values at high temperatures indicated that two sets of participants are equivalent – participants A, I, J, and L (SPG 67-19) and participants B, E, and H (SPG 73-19); Participant G was an outlier. At low temperatures, all the participants were equivalent except B & J and B & L; Participant G was again an outlier. Similarly, ANOVA on replicates 1 and 2 of HAA 3 showed that at 99% confidence, the mean of G*/sin δ at 79^0 C of all six participants were equal.

ANOVA on replicates 1 and 2 of the emulsion showed that at 99% confidence, A & I were equal and at 95% confidence, A & J; B & E, I & J, I & L, and J & L were not significantly different from each other. Overall, the %d2s and ANOVA analyses agree with each other in terms of pairing the equivalent results.

Additional Test Results

Elastic Recovery

The statistics of the %ER reported for HAA 3 and the emulsion are shown in Table 20. In general, the % ER reported for the HAA 3, as observed from SPG binder grading results, is less variable when compared to that of the emulsion. Also, as indicated by the lower phase angle of the HAA 3, its % ER is very high (82.8); the emulsion, whose phase angle ranged from 79^0 to 82^0 exhibited a relatively low % ER of 52.8.

Table 20: Statistics of %ER Reported for HAA 3 and the Emulsion.

	No. of reported results	%ER		Without Outliers	
		Average	Std. Dev.	Average	Std. Dev.
HAA 3	5	84.3	3.8	82.8	2.4
Emulsion	7	59.1	13	52.8	5.3

MSCR Results

The % recovery values of HAA 3 and the emulsion at 55^0 C and 61^0 C are as shown in Figure 36. Similar to the SPG binder grading and the % ER results, HAA 3 exhibited very consistent results whereas the emulsion's % R values were variable. The %d2s analysis performed (using thresholds from a SEAUPG Inter Laboratory Study) on the % R values showed that for HAA 3, the % R values @ 0.1 kPa and 3.2 kPa at 55^0 C and @ 3.2 kPa at 61^0 C are equivalent whereas the corresponding values @ 0.1 kPa at 61^0 C are not [38]. For the emulsion, none of the % R values were statistically equivalent.

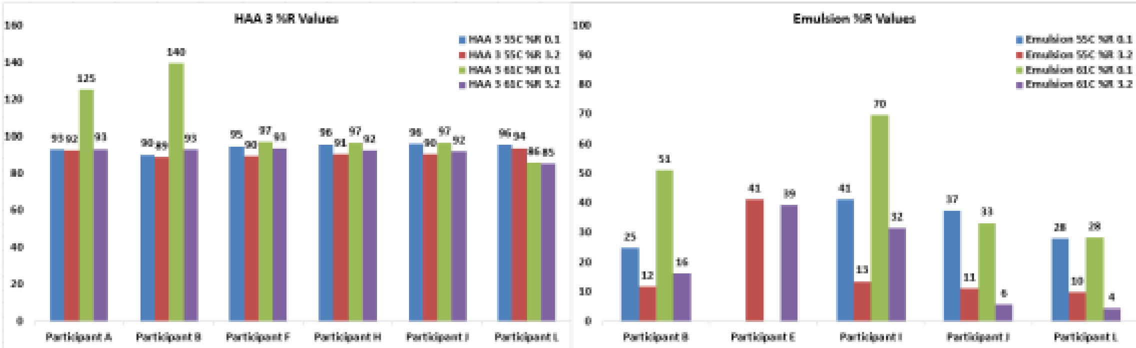


Figure 36. Graphs Showing % R and Jnr at 0.1 and 3.3 kPa and 55^0 C and 61^0 C for HAA 3 and the Emulsion.

Conclusions

Following are conclusions from the second round robin:

- The third hot-applied asphalt binder (HAA 3) gave highly consistent results across all the participants with respect to T_{high} and T_{low}, phase angles, %ER, and the % R values. The emulsion exhibited reasonably consistent results with respect to T_{HIGH} and T_{LOW}, phase angles, and %ER, but the %R values were variable.
- The first and the second hot-applied asphalt binders (HAA 1 and 2) exhibited high variability at high temperatures, possibly due to improper blending or poor compatibility between the base binder and the polymers/ rubbers/ other additives. Parameters and corresponding threshold values to separate these types of binders should be explored.

VISUAL FIELD INSPECTION

In multiple TxDOT research projects (0-1710, 0-6616, and 5-6616) related to the development and implementation of the SPG specification, field evaluation of embedment depth (ED) was done by experienced TTI personnel through visual observation [2, 3, 8]. However, concerns were raised regarding the empiricism involved with visual distress survey and data collection. Suggestions were received to use more mechanistic, quantitative, and automated field distress evaluation methods. In order to address this concern, a study was conducted to compare the embedment depth (ED) collected by visual inspection and ED calculated from the Mean Profile Depth (MPD) surface texture measurement [59]. This section describes this small study and its outcomes.

Embedment Depth (ED) Study

The SPG specification is aimed at precluding the two primary types of distress in chip seal applications – aggregate loss and bleeding. Proper embedment of aggregates in chip seals is crucial to prevent these distresses, and thus embedment depth was used as a measure of chip seal performance during the validation of the specification [2-11]. A small embedment depth study estimated ED from the MPD surface texture data and compared the estimated value to that collected by visual inspection.

One of TxDOT's recent developments is the high-speed 3D texture measurement device, which is capable of capturing the pavement's longitudinal profile through MPD surface texture measurements (1). By utilizing a representative aggregate size in the chip seal, ED can possibly be estimated.

To evaluate if this is possible, TxDOT provided MPD data acquired with the 3D texture measurement device from two field sections located in the BRY (FM 2000) and WAC (FM 0487) districts. These sections were used as part of the TxDOT 5-6616 implementation project. Since the aggregates used in these field sections were not collected at construction, certain assumptions had to be made.

Visual Evaluation vs. 3D Texture Measurement Device

The 3D texture measurement device collects the MPD data at three different locations, Outside Wheel Path (OWP), Center Wheel Path (CWP), and Inside Wheel Path (IWP), while the visual inspection is done at two locations, wheel path and between wheel path along each lane. Figure 37 shows the data collection locations for both methods.

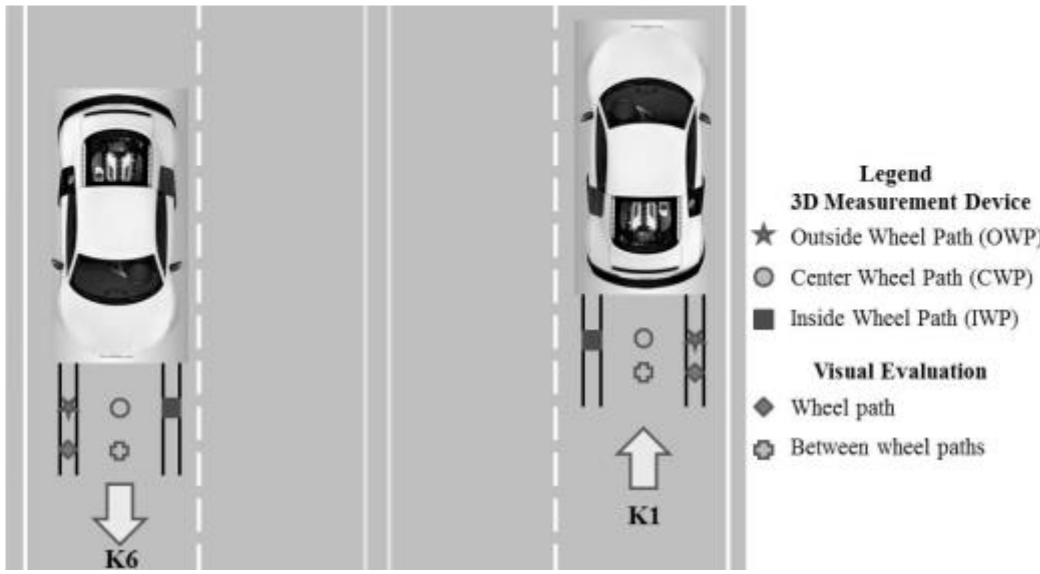


Figure 37. Locations for 3D Texture Measurements and Visual Observations.

MPD data is collected over 550 ft of the highway section, and the visual inspection is typically done along a strip of about 5 ft near the beginning of the test section. Due to these differences, all the three measurement locations of the automated method were considered for the analysis; however, only two measurement locations (OWP and CWP) in the first 5 ft. were considered for comparison with the visual inspection.

Data Analysis

MPD data is a collection of distinct peaks and troughs reported every 0.2 ft (61 mm). Typical MPD data is as shown in Figure 38 where the MPD data for FM 2000 (BRY) for the three regions of measurement along K1 lane is presented. For the estimation of ED, only the peaks of the MPD data were considered, assuming they represented the largest aggregate particles above the surface of the pavement. Also, to eliminate outliers, peak points above the 98^{th} percentile of the MPD data were not considered.

The aggregates used in the FM 2000 and FM 0487 field sections were both Grade 4, which according to TxDOT specifications has 95-100% passing the #4 (4.75 mm) sieve (2). This aggregate size was selected as representative to compare against the MPD peaks. The ED was then calculated (using MATLAB) by subtracting the representative aggregate size (4.75 mm) from the peak points, and then dividing by the predominant aggregate size.

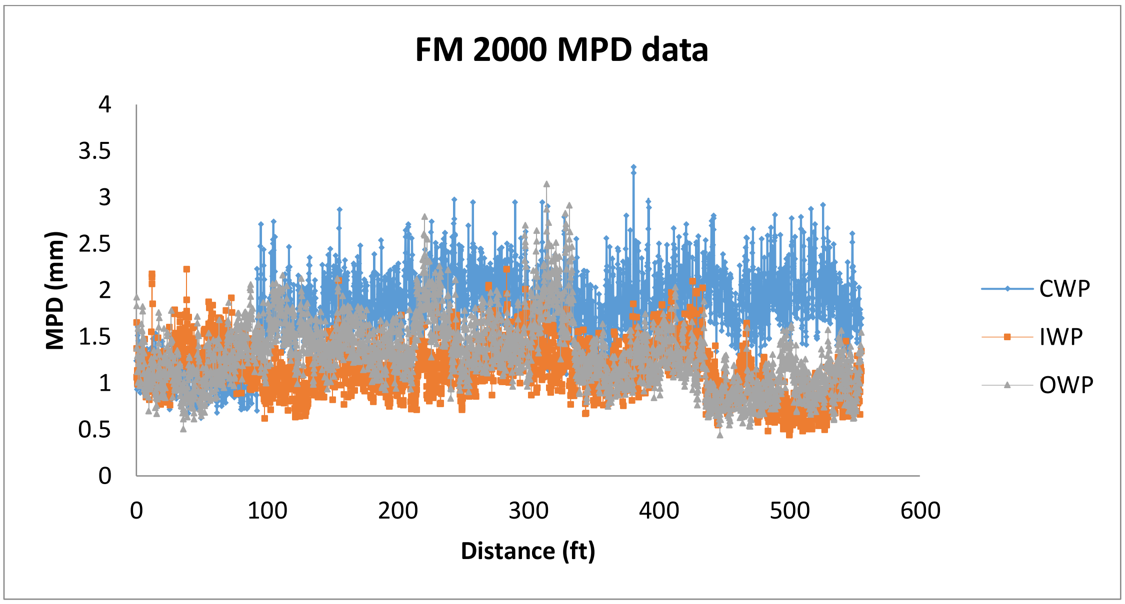


Figure 38. Graph Showing MPD Data for Different Regions in FM 2000, K1 Lane.

Comparison of Automated versus Visual Observation

The EDs estimated using the MPD data for all locations along the FM 2000 and FM 0487 field sections are shown in Table 21 and are compared against the visual observation estimates in Figure 39. With respect to the measurement locations, OWP for the automated procedure was compared to the Wheel Path (WP) for the visual observation and CWP for the automated procedure was compared to Between Wheel Path (BWP) for the visual observation.

Table 21. Variation in Embedment Depth at Different Locations along the Field Sections.

Highway Section	Lane	Region of measurement	Manual ED (%)	Overall Automated ED (%)	Embedment Depth (ED, %) 0-5 ft	100-105 ft	200-205 ft	500-505 ft
FM 2000	K1	CWP (BWP)	10	59.2	69.9	57.0	59.4	53.2
		IWP	-	73.9	74.0	77.3	72.8	83.8
		OWP (WP)	58	70.5	69.5	63.1	69.1	71.2
	K6	CWP (BWP)	10	56.9	49.8	54.0	47.8	58.4
		IWP	-	79.6	83.7	78.3	72.8	75.4
		OWP (WP)	70	79.5	86.6	-	71.3	72.5
FM 0487	K1	CWP (BWP)	20	45.9	77.3	37.2	45.4	42.6
		IWP	-	60.9	52.8	58.8	64.2	63.6
		OWP (WP)	40	58.8	46.3	59.6	58.1	62.6
	K6	CWP (BWP)	10	43.1	42.6	44.5	45.2	43.0
		IWP	-	60.6	62.7	58.5	63.6	62.4
		OWP (WP)	20	60.6	62.7	58.5	63.6	62.4

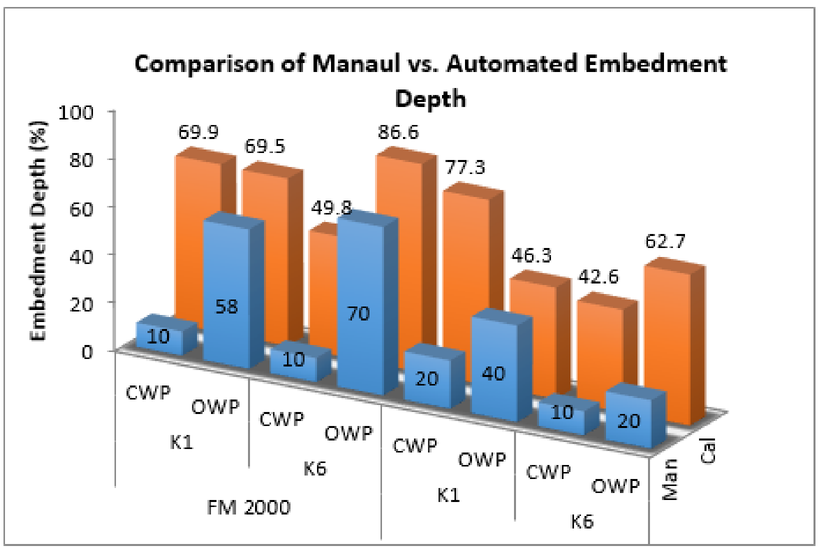


Figure 39. Comparison of Automated Versus Manual Embedment Depths.

In the CWP location, the ED estimated from the MPD data was remarkably higher than the ED obtained via visual observation for unknown reasons. However, in the OWP location, the automated and visual EDs were comparable. While the automated method provides objective and continuous data along the length of the section that may be useful in a forensic evaluation, the manual observation of ED is sufficient to identify if there is a problem and/or provide a reason for uncorrelated field performance and that expected based on the SPG grade of the chip seal binder.

ADDRESSING THE ISSUE WITH PMAB CHARACTERIZATION

For UTI > 86^0 C, a phase angle threshold of 80^0 (max.) at the continuous high SPG grade was introduced in the SPG specification to ensure adequate polymer modification [2]. However, concern regarding the ability of the phase angle threshold to capture all types of modifiers was raised by one of the binder suppliers in Texas. The supplier supplied asphalt binders modified with latex which consistently exhibited phase angles greater than the existing threshold of 80^0 resulting in the failure of the binder to meet the SPG specification.

Although poor modification in the form of less than adequate polymer content, incompatibility of the modifier with base binder, insufficient cross – linker content, etc. could be the reason for the latex modified binders to not to meet the phase angle specification; the existing threshold was reviewed to check if it can capture the polymer modification in the binders [24]. This section describes the efforts to address this concern.

Review of Existing Phase Angle Threshold for PMABs

The following two sets of data, as shown in Figure 40 were utilized to review the current phase angle threshold:

- Historically available phase angle data from 2004 supplied by TxDOT and
- Phase angle data of the binders used during the first two years of implementation of the specification in 2013 and 2014 [2]

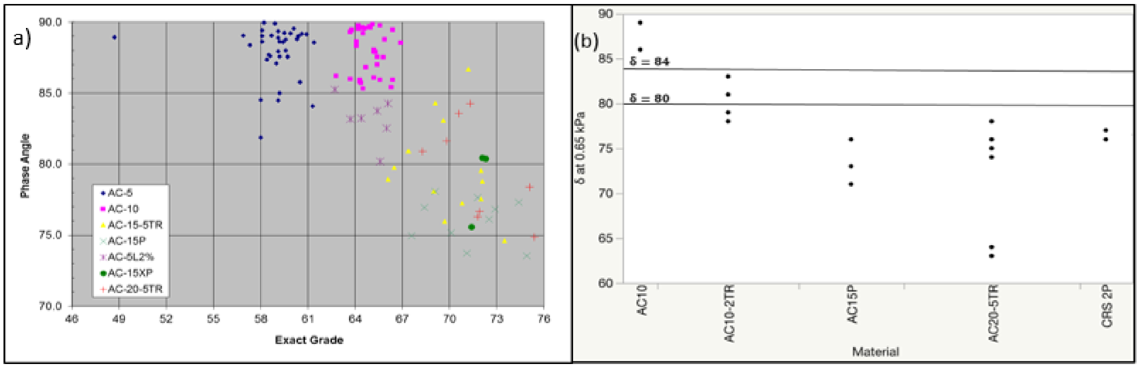


Figure 40. (a) Historically Available Phase Angle Data from 2004 (b) Phase angles by Material for 2013/14 Binders from the TxDOT Project 5-6616.

Figure 40 (a) shows that the unmodified binders AC-5 and AC-10 exhibited phase angles well above 80^0, where most of the binders fell in the range of [85^0, 90^0), which confirms the expectation that unmodified binders tend to have higher phase angles (more viscous behavior). The modified binders AC15-5TR and AC-15P generally had phase angles < 80^0, and the maximum phase angle exhibited was 84^0 (excluding an outlier). However, the binder modified with latex, AC-5L2%, consistently exhibited phase angles > 80^0, mostly falling within the range (80^0, 85^0).

Figure 40 (b) shows the range of phase angles by material and clearly, the usage of unmodified binders declined considerably from 2004 to 2013. However, AC10 was still used in two highway sections (13-AMA-2 and 14-SAT-1) in 2013 and 2014 and both the binders exhibited phase angles much higher than 80^0 within the same range as exhibited by the 2004 binders i.e. (85^0, 90^0). The modified binders, except for two cases with AC10-2TR, in general had phase angles less than 80^0. The maximum phase angle observed with the modified binders was 84^0. Clearly, the 2013-14 binder data agrees very well with the 2004 data.

As the objective of establishing the phase angle threshold was to ensure adequate polymer modification, the threshold had to at least be greater than the typical phase angles exhibited by the modified binders. This discussion results in the conclusion that modified binders typically exhibit phase angles < 84^0. Therefore, the acceptable range of phase angle values that can potentially differentiate modified binders from unmodified binders is [80^0, 84^0].

Conclusions

In this section, the sensitivity of the existing phase angle threshold was evaluated utilizing the historical phase angle data from TxDOT and the phase angle data of the asphalt binders from 2013-14 implementation of the SPG specification. The following conclusions can be drawn from this small study:

- The acceptable range of phase angle values that can potentially delineate modified binders from unmodified binders is [80^0, 84^0].
- The current phase angle threshold is on the lower end of this range and hence, it may not capture certain modified binders not necessarily modified with latex that fall within this range. If the threshold were to be raised to 84^0, there is increased risk of accepting unmodified or poorly modified binders.
- This calls for the need to explore a parameter or a test that is sensitive to polymer modification but blind to the type of modifier.

Sensitivity of Phase Angle to Stiffer Binders

Stiffer or aged binders generally have phase angles lower than that of their corresponding base binders. This might cause such binders to pass the phase angle threshold. To check this possibility preliminarily, the phase angle data of original and RTFO aged samples from TxDOT was utilized (Figure 41).

The highlighted box shows that the majority of the RTFO aged binders with phase angles close to 80^0 had phase angles falling in the range [80^0, 84^0] in their original state. Excluding an outlier, the change in the phase angle from original to RTFO aged state ranged from [0.7^0, 5.6^0] for the same sample. This means that binders that are unmodified or poorly modified may pass the phase angle threshold if stiffened or aged. However, such binders may be captured by the low temperature threshold of the SPG specification. In order to further confirm the stiffening/ aging effect on the phase angle and to explore the ability of the low temperature threshold to capture stiff/ aged binders, a small study was conducted as described further in this section.

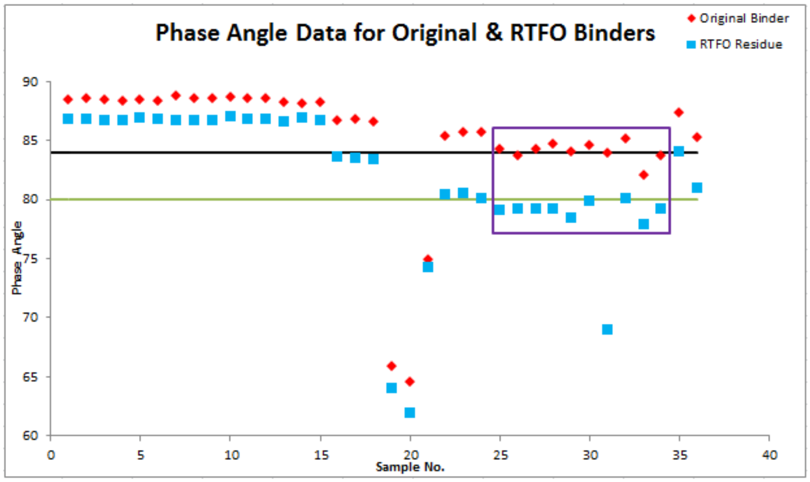


Figure 41. Phase Angle Data of Original and RTFO Aged Binders, Source: TxDOT.

To determine the effect of aging on phase angle, two unmodified binder samples from 2013 and 2014, 13-AMA and 14-SAT, both AC10, were chosen. Unmodified binders were chosen for the study to check the possibility of unmodified binders passing the phase angle threshold with aging. Both the binders were tested according to AASHTO T315 at three different aging states - original, RTFO aged, and RTFO+PAV aged. The binders were tested at 3^0 C increments until the high temperature threshold was met as specified by the current TxDOT SPG specification [5].

Figure 42 shows the change in phase angles with aging for both unmodified binders. Phase angles measured on both the binders in their original state when initially received (in 2013 and 2014) are also included. Clearly, aging reduced the phase angle exhibited by both the binders with the reduction being more predominant in the 14-SAT AC 10 sample. Comparing the initial and current results, there was no significant difference in the continuous phase angles exhibited by both the binders in their original state.

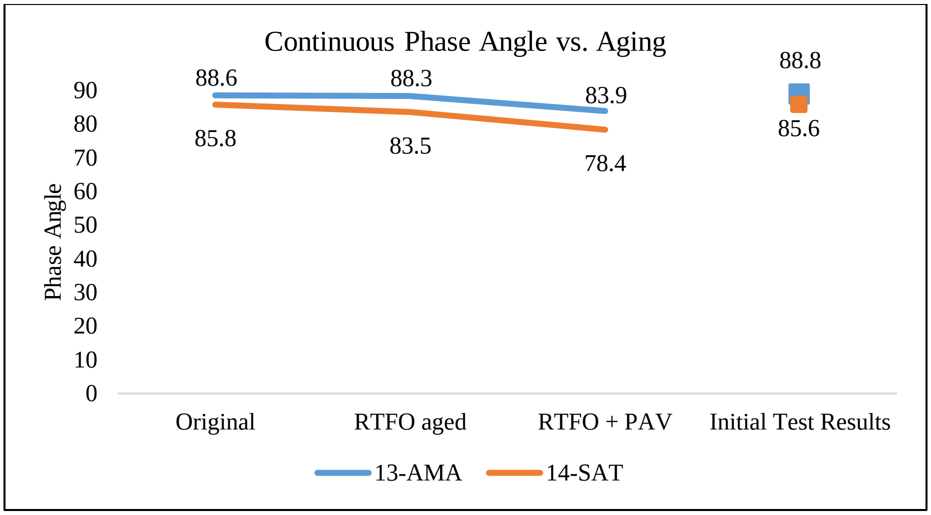


Figure 42: Change in Continuous Phase Angle (δ at 0.65 kPa) with Aging.

Both the original binders exhibited phase angles greater than the critical 84^0 and their corresponding RTFO aged binders' phase angles did not go below the existing threshold of 80^0. The 13-AMA binder, whose original binder's phase angle was close to 90^0 had a phase angle greater than 80^0 upon RTFO+PAV aging while the 14-SAT binder, whose original binder's phase angle was close to 84^0 had a phase angle less than 80^0 upon RTFO+PAV aging. This might be an indication that binders with unaged phase angles greater than but close to 84^0 may still end up passing the phase angle threshold upon prolonged aging.

The final SPG continuous and 6^0 C grades for the three aging states used to simulate a supplier providing an aged unmodified binder are as shown in Table 22.

Table 22. Final SPG Continuous and 6^0 C Grades for the Three Aging States.

Aging State (+PAV for SPG_{low})	13-AMA	14-SAT
Unaged	63-21 (SPG 61-19)	64-29 (SPG 61-25)
RTFO	68-20 (SPG 67-19)	72-28 (SPG 67-25)
RTFO+PAV	75-20 (SPG 73-19)	80-29 (SPG 73-25)

This data confirms the scenario where unmodified binders might be aged to meet the phase angle requirement and yet have no change in low temperature grade.

Conclusions

Some key conclusions from this preliminary study with TxDOT data and the experimental data from the test plan described in this section are as follows:

- Aging increased the high temperature grade of both unmodified binders studied, while the phase angle decreased with aging.
- From the limited data, the original binders with phase angles falling in the range [80^0, 84^0] have the possibility of passing the phase angle specification after stiffening or aging. Such binders in their stiffened/ aged state may still pass the threshold at low temperature.
- The low temperature SPG test (BBR) was unable to capture the difference between original and stiff binders. So, an alternate parameter may be explored for this purpose.
- The binders in their stiff/ aged state would eventually meet the specification at some temperature which again calls for the need to explore parameters or test methods to capture aging in the binders.

Exploration of a New Parameter to Ensure Polymer Modification

The existing phase angle threshold specified to ensure polymer modification did not seem to delineate the modified binders with values between 80^0 and 84^0, and the parameter was not robust with aging. Therefore, alternate parameters were explored to supplement or replace the phase angle threshold as described in this section.

FTIR Spectroscopy

As the binders collected during the 2016-17 implementation period were specified using SPG grades, it was initially unclear whether the binders were modified. FTIR spectroscopy was performed on original and PAV aged binders to evaluate the presence of presence of polymers in the binders along with the increase in carbonyl area with aging. The presence of a peak near a frequency 967 cm^{-1} was used as an indication of polymer in the binder. However, the conclusions could only be qualitative as the height of the peak does not indicate the amount of polymer present in the binder. Figure

43 shows the FTIR spectroscopy test results on the 14 original binders collected during 2016-17 period. All of the binders showed a peak at 967 cm^{-1} and are thus designated as polymer modified.

Further, FTIR spectroscopy was also performed on PAV aged binders to determine the increase in carbonyl area defined as the area under the absorbance band between the frequencies 1,650 cm^{-1} to 1820 cm^{-1}. Note that the magnitude of the carbonyl area does not indicate the age of the specimen, but the change in the carbonyl area quantifies the magnitude of aging in binders. This exercise was performed to explore the possible relationship between the increase in carbonyl area and the corresponding change in phase angle at the passing T_{high} of the binders. Figure 44 shows the change in carbonyl area and Figure 45 shows a plot of change in carbonyl area and the change in phase angle at the passing T_{high} with PAV aging.

All binders showed an increase in carbonyl area with PAV aging, as expected. Two binders exhibited an increase in phase angle with aging. Figure 45 shows that similar increases in carbonyl area did not result in similar decreases in phase angle. Some binders exhibited a larger decrease in phase angle for the same increase in carbonyl area, highlighting that different binders respond differently when subjected to similar conditions. These results agree with those of Islam et al. (2015) who reported that PAV aging simulated 3-4 years of field aging in hot-applied asphalt binders and less than 3 years for the emulsion and caused differences in their rheology [60]. The quality of base binder and modification, compatibility between base binder and the modifier, and the chemical composition of the base binder and the modifier dictate the way the binder responds to the conditions it is subjected to (environmental and traffic loading).

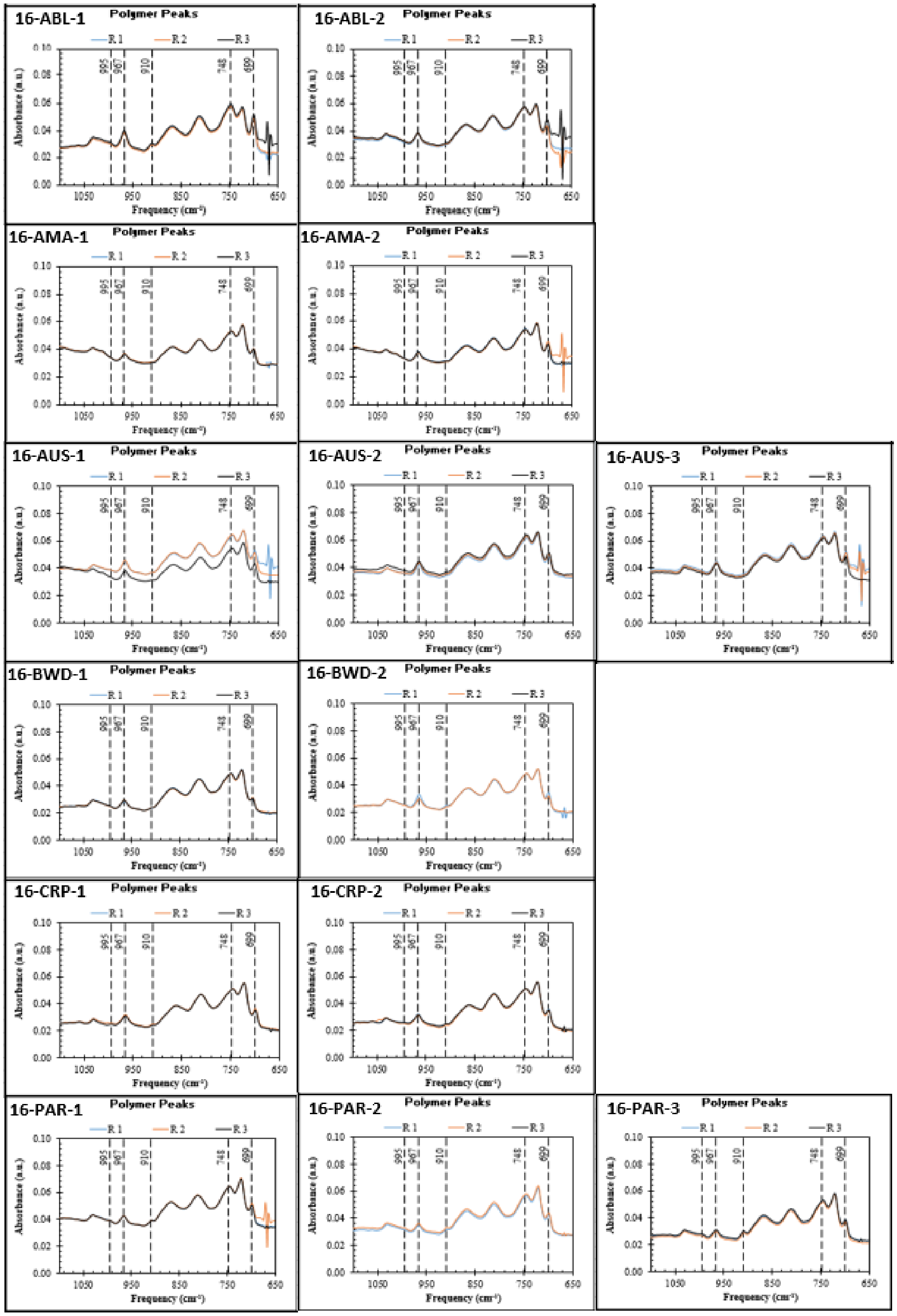


Figure 43. FTIR Spectroscopy Results on Original Binders Collected During 2016-17 Implementation Period.

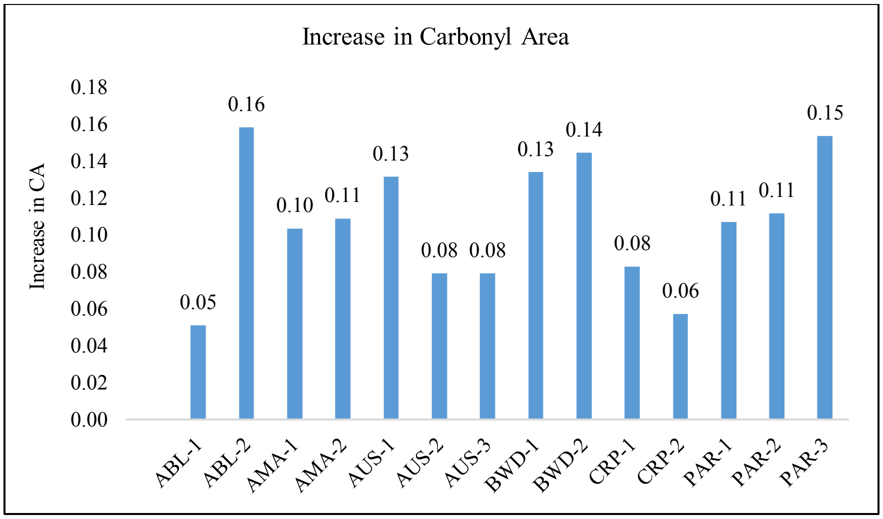


Figure 44. Increase in Carbonyl Area with PAV Aging in Binders Collected During 2016-17 Period.

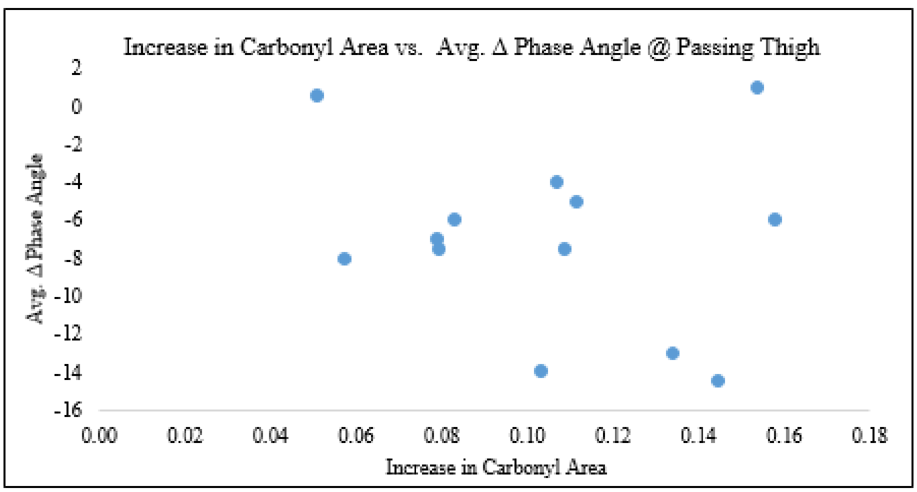


Figure 45. Increase in Carbonyl Area versus Change in Phase Angle at Passing T_{high} with PAV Aging.

Phase Angles of PAV Aged Binders

Phase angles of PAV aged binders from the 2016-17 implementation period were measured at the passing T_{high} of the unaged binders per AASHTO T315, and the results are presented in Figure 46. As expected, the phase angles of the PAV aged binders were lower than those of their corresponding original binders with one exception. However, there was no clear delineation between the original binders with phase angles in the range (80^0, 84^0) and those with phase angles less than 80^0 after aging, possibly due to the compositional differences and different responses to aging as mentioned previously. Therefore, this parameter was not explored further.

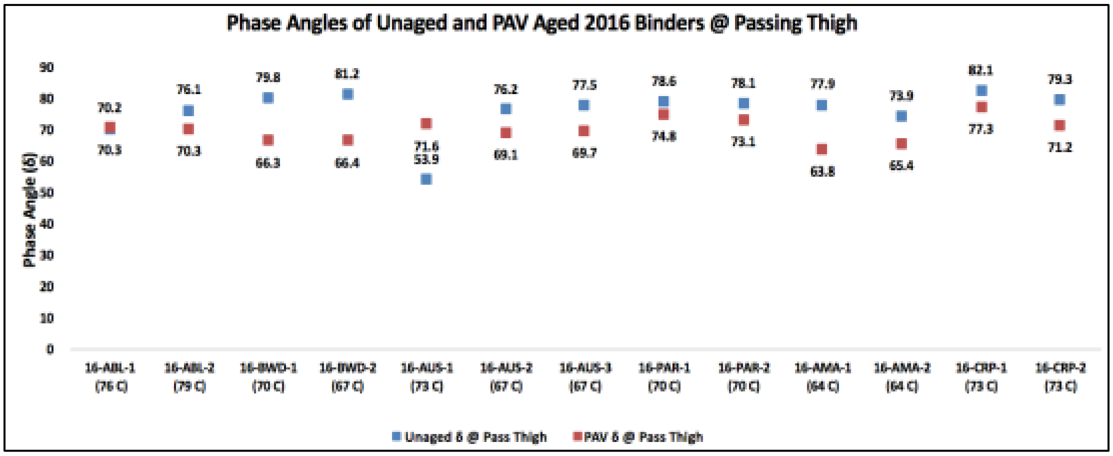


Figure 46. Phase Angles of the Unaged and PAV Aged Binders @ Passing T_{high} of the Unaged Binders.

Elastic Recovery

Elastic recovery (ER) is one of the PG Plus tests utilized by the state highway agencies to ensure polymer modification. The ER test was performed on unaged binders to determine the presence and quality of polymer modifiers in the binders. The test was performed at 10^0 C on a ductilometer in accordance with AASHTO T51 for the apparatus preparation and Tex-539-C for the actual test procedure. Figure 47 shows the plot of the force exerted as displacement is applied on the 2016-17 binders. Table 23 shows the %ER at 10^0 C, and the peak forces. Additionally, the post peak behaviors of the binders were qualitatively described by comparing the F_{200mm} (i.e. magnitude of force at 200mm) and $F_{min, post peak}$ (i.e. minimum force exhibited by the binder post peak).

In general, similar binders seemed to have been supplied to a given TXDOT district except for ABL and PAR as the force-displacement graphs of the binders from a given district almost completely overlapped. Binders exhibited peak forces ranging from 2N to 13N with different post peak behaviors. Some binders had recovering behavior with $F_{200mm} > F_{min, post peak}$ while some binders continue to fail with $F_{200mm} < F_{min, post peak}$.

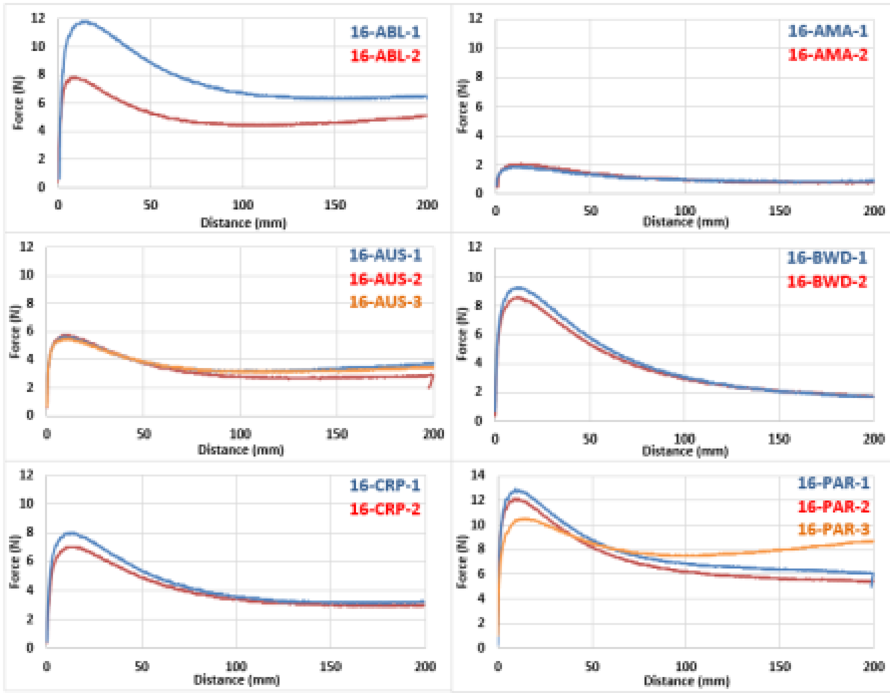


Figure 47. Force vs. Displacement Graphs for Binders Collected During 2016-17 Period in the ER Test.

Table 23. Table Showing Different Parameters Obtained During ER Test.

	% ER @ 10^0 C	**Peak Force (N)**	$F_{200mm} > F_{min, post\ peak}$?
16-ABL-1	88	7.8	Yes
16-ABL-2	56	11.8	Yes
16-AMA-1	59	2.1	No
16-AMA-2	71	1.9	No
16-AUS-1	73	5.7	Yes
16-AUS-2	72	5.8	Yes
16-AUS-3	72	5.5	Yes
16-BWD-1	55	9.3	No
16-BWD-2	52	8.6	No
16-CRP-1	81	8	Constant
16-CRP-2	83	7	Constant
16-PAR-1	60	13	No
16-PAR-2	40	12.2	No
16-PAR-3	73	10.5	Yes

From Table 23, the %ER values were not indicative of the post beak behavior of the binder nor were they of the peak forces exerted by the binders. For instance, 16-AMA-2 with a peak load of 1.9N and declining post peak behavior ($F_{200mm} < F_{min, post peak}$) had almost equivalent %ER value as that of 16-AUS-1 with a peak load of 5.7N and recovering post peak behavior ($F_{200mm} > F_{min, post peak}$). Perhaps higher peak load does not mean the binder exhibited good recovery behavior. For ABL binders, 16-ABL-2 with 56% ER seemed to show better recovery properties than 16-ABL-1 with 88% ER which again seems counterintuitive. However, %ER values clearly delineated the behaviors of the three binders from PAR where 16-PAR-3 exhibited the best recovery behavior and had the highest %ER value followed by 16-PAR-1 and 16-PAR-2.

Overall, the ER test was not the best alternative to characterize polymer modification due to the inconsistent conclusions as discussed. In addition, the test temperature (10^0 C) was not representative of the field conditions, the sample size for one replicate was about 20g and the total test time for each sample was about 5 hours. Therefore, utilization of the ER test to ensure polymer modification was not pursued further.

MSCR Test

The MSCR test is the most recent advancement in characterizing PMABs and was thus performed on the 2016-17 binders at 55^0 C, 61^0 C, and 67^0 C.

Correlating MSCR Parameters with Field Performance

The MSCR test measures permanent deformation, and thus it was utilized to explore correlation with bleeding (i.e. SCI_{BL}) as shown in Figure 48. The results showed that there was an increase in the magnitude of Jnr and a decrease in MSCR %R values with increasing temperature that indicated an increase in the viscous component for all binders at higher temperatures. Unfortunately, the MSCR parameters did not delineate the good and bad performance of binders at any of the three test temperatures. For example, 16-ABL-1 performed well with the smallest Jnr and the largest MSCR %R at the three test temperatures, but it had the lowest SCI_{AL}. Similarly, although 16-PAR-1 and 16-AUS-3 exhibited reasonably good MSCR results, the binders exhibited inadequate or marginal resistance to bleeding, respectively. Overall, no clear conclusion could be drawn from the results at any of the three test temperatures, possibly due to the shortcomings of the MSCR test as discussed previously including the need to increase the number of stress levels and adjusting the stress levels based on the temperature of measurement.

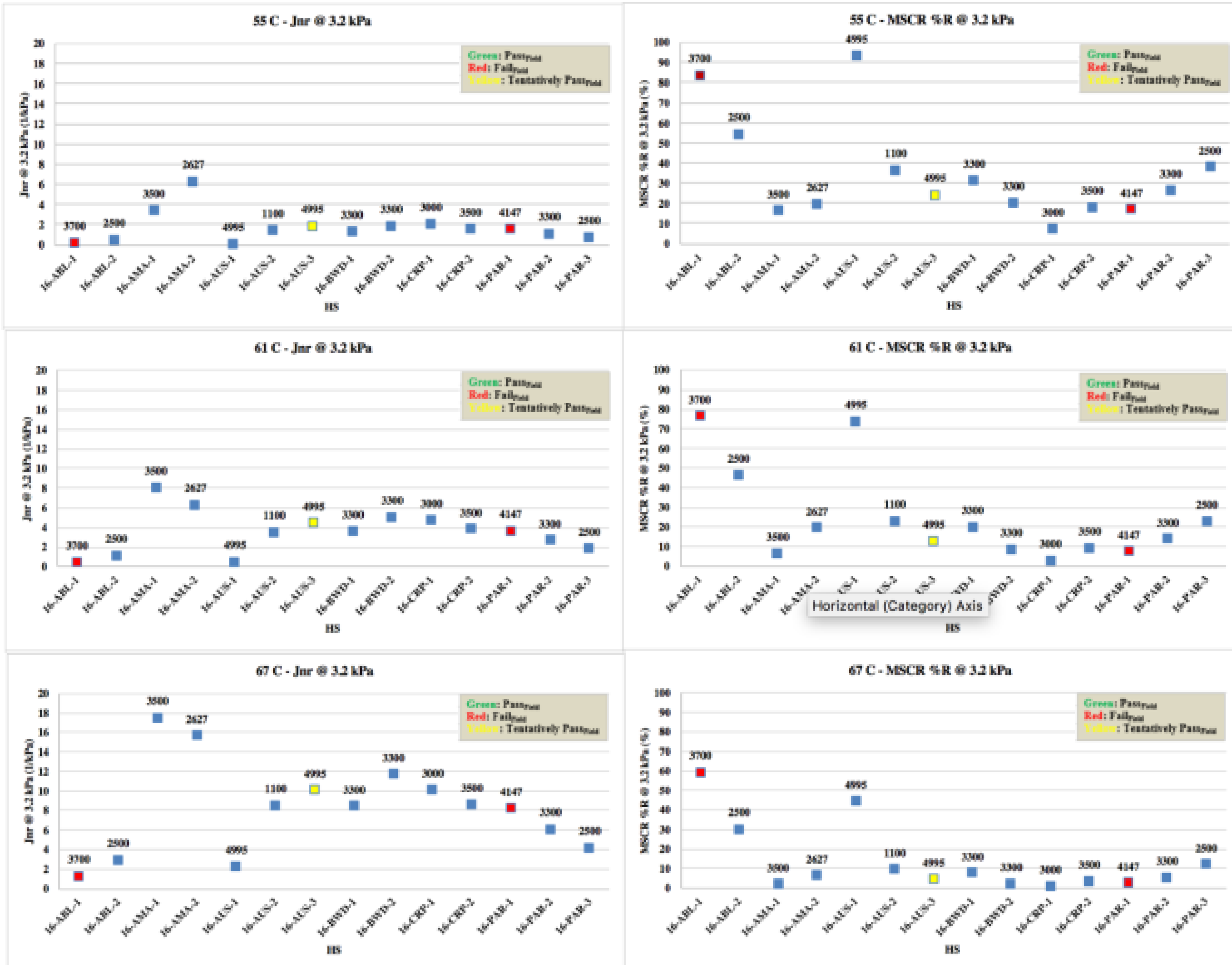


Figure 48. MSCR Test Results of the 2016-17 Binders at 55^{0} C, 61^{0} C, 67

Determining Sufficiency of Modification Using Polymer Curve Method

The MSCR results of each binder were also analyzed based on AI's polymer curve method with a plot of MSCR % R and Jnr at 3.2 kPa at the three test temperatures as presented in Figure 49. As per AI's recommendations, binders that lie above the polymer curve (indicated in red) are expected to have sufficient polymer modification with good delayed elastic response. For a given stress level, as the temperature increases, the viscous component of the binder dominates its response, i.e. it exhibits higher permanent deformation. Therefore, with an increase in temperature, the magnitude of the binder's delayed elastic response reduces causing it to move toward the lower side of the polymer curve. This implies that that the sufficiency of the modification can only be relatively defined based on the temperature and the stress levels at which the binder is expected to perform.

In Figure 49, for each binder, the highest point indicates the test results at 55^0 C, the middle point shows behavior at 61^0 C, while the lowest point was measured at 67^0 C. The slope of the lines joining these points are different for each binder indicating differences in their stress sensitivities. The steeper the lines joining these points, the faster the increase in viscous behavior or faster the deterioration of polymer networks in the binders.

Except the ABL binders and a binder from AUS, none of the binders exhibited sufficient delayed elastic response at any of the three temperatures. Although the FTIR spectroscopy results indicated that all of the binders were modified, most binders were below the polymer curve, even at 55^0 C. Thus according to this analysis, only the binders from ABL and one from AUS seem to be satisfactory in terms of the sufficiency of modification and delayed elastic response.

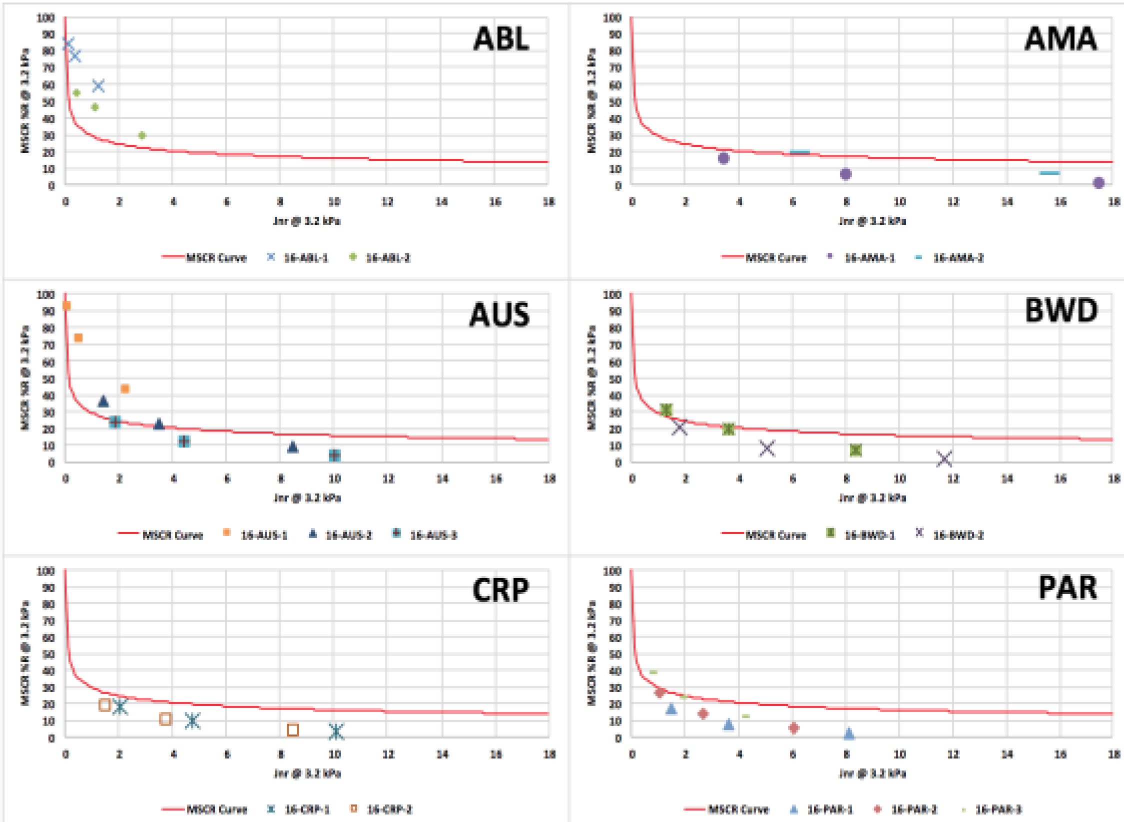


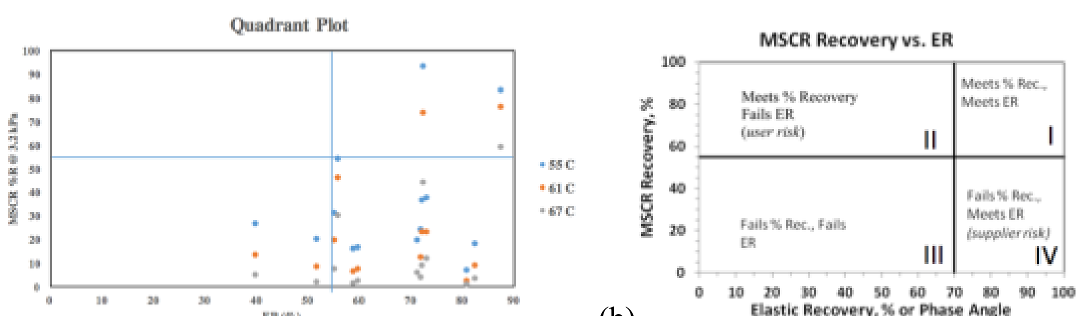
Figure 49. MSCR Test Results of Binders at 55^0 C, 61^0 C and 67^0 C Analyzed Using the Polymer Method

Recalling the phase angle values (the existing SPG parameter for ensuring polymer modification), the binders with continuous phase angles > 78^0 (close to the existing threshold of 80^0) were 16-BWD-1, 16-BWD-2, 16-PAR-1, 16-PAR-2, 16-CRP-1, and 16-CRP-2; while those that failed the threshold were 16-BWD-2, 16-CRP-1, and 16-CRP-2. Except in the case of AMA and AUS binders, the binder phase angles and inferences from the polymer curve method seem to agree with each other with binders that almost failed or failed the phase angle threshold also indicated as insufficiently modified binders, at all the three test temperatures.

Although the MSCR parameters did not correlate with bleeding in the field, they may be useful to indicate polymer modification. This could be due to utilization of inappropriate or inadequate stress levels or attainment of tertiary flow at the stress levels considered. Further exploration of MSCR test parameters and modification of the test protocol to suit the conditions and failure mechanisms relevant to chip seals could help in effectively utilizing the MSCR test protocol i.e. unidirectional loading that can clearly delineate the elastic and delayed elastic response and the viscous component (discussed in chapter II).

Analyzing MSCR Parameters Using Quadrant Method

The MSCR parameters were analyzed using the quadrant method reviewed in Chapter II. The quadrant plot for the 2016-17 binders is as shown in Figure 50 (a) at the three test temperatures. As suggested by Hossain et al. (2016), the quadrants were plotted based on the typical existing %ER threshold for PMABs and modified PG binders as specified by TxDOT [15, 24]. To make the supplier risk equal to the user risk and for the analysis purposes, the MSCR %R threshold was set as 55%. An ideally modified binder would lie in quadrant I where the binder meets both the MSCR %R and %ER thresholds. A binder in quadrant II puts the user at risk as it does not meet the %ER threshold while a binder in quadrant IV puts the supplier at risk as it does not meet the MSCR %R. A binder in quadrant III indicates the failure to meet both %ER and MSCR %R.



(a) (b)

Figure 50. Quadrant Plot for the MSCR Test Results at 55⁰ C, 61⁰ C, and 67⁰ C

Based on this analysis, none of the binders put the users at risk at any of the test temperatures. However, the majority of the binders would put the suppliers at risk for not meeting the set MSCR %R threshold, indicating insufficient or poor modification. These results agree with the conclusions from the polymer curve method where majority of the binders were shown to have insufficient modification.

Conclusions on the New Parameters Considered to Ensure Polymer Modification

Based on the limited studies performed on the sensitivity of phase angle to modification and aging, attempts were made to supplement or replace this parameter. Different parameters including phase angles after PAV aging, elastic recovery, and MSCR %R or Jnr were considered. On critically analyzing these parameters with respect to the binders from 2016-17 (which were found to be modified based on FTIR spectroscopy) to be indicative of polymer modification, the following conclusions can be made:

- Based on FTIR spectroscopy studies and AASHTO T315 testing on unaged and PAV aged binders, binders (modified or unmodified) subjected to similar conditions age differently. This means that PAV aging need not be indicative of 1 year field aging for all the binders.
- Phase angles of PAV aged binders did not delineate unmodified and modified binders based on the existing phase angle threshold making it an inappropriate parameter to ensure polymer modification.
- The ER tests results were not indicative of the binder's strength nor their ability to recover post peak. Moreover, the amount of sample and the time required for running a single test made it an unattractive alternative.
- Regarding MSCR test results, there was no correlation of the parameters with bleeding performance exhibited by the binders in the field. However, further analysis of the parameters using polymer curve and quadrant methods gave conclusions in agreement with the existing phase angle threshold, i.e. the parameters indicated insufficient modification for binders with phase angles greater than 78^0 (close to the existing threshold of 80^0).

These conclusions with MSCR test results and the thorough literature review presented on the MSCR test protocol suggest that the test is promising in terms of characterizing PMABs.

Recommendations on Modifying the MSCR Test Protocol for Chip Seal Binders

Prior to approaching the task of modifying the MSCR test protocol, it is important to determine the purpose of utilizing the test in the context of chip seal binders. Recall that the SPG specification is a performance based specification intended to preclude the predominant distresses of aggregate loss and bleeding in chip seals. Based on previous work and the SCI scoring methodology, aggregate loss is considered more critical to chip seal performance [2-11].

However, PMABs are intended to improve both the high and low temperature properties of the binders. Lee and Kim (2010) report that utilization of polymer-modified emulsions will be cost-effective only if they can extend the service life of chip seals from a typical 5 years to 7 years [61]. To make the most use of polymer modification, the amendments suggested to the test protocol must be able to characterize the PMABs at stresses causing chip seal failure in terms of bleeding and aggregate loss at the corresponding critical temperatures.

In addition to the test geometry, loading and rest periods, number of cycles, and the binder aging state; the most critical parameters for MSCR test protocol are the stress levels and the testing temperatures. The current MSCR stress levels were suggested for binders in HMA pavements. Therefore, it is necessary to tailor the test protocol to suit chip seal applications. Suggested modifications to each of the parameters based on the results presented are as follows.

- ***Test Geometry:*** Test geometry becomes crucial to avoiding negative MSCR %R values due to attainment of tertiary flow. Although Golalipur et al. (2017) suggest the utilization of a cone and plate geometry at 0.275 mm, but this is not practical considering that the asphalt laboratories typically work with parallel plate geometries [46]. For the stress levels and number of loading cycles chosen for chip seal binders (final protocol), if binder flow is observed, utilizing a lower plate gap could be a possible alternative although particle size distribution of the binders could make this unfeasible (especially if tire or crumb rubber is the modifier).

- ***Loading and Rest Periods:*** The current loading period of 1 sec seems to be reasonable. However, if a higher stress level is chosen for the test protocol, the capacity of the rheometer to attain that higher stress level in 1 sec must be checked. In addition, the rest period should be long enough to sufficiently characterize the delayed elastic response of the binders. Different loading and rest periods could be chosen for different stress levels and the proposed loading to rest period ratio could be along the lines of the existing MSCR protocol (i.e. 1:9 or higher).
- ***Number of cycles:*** This parameter should be fixed based on the requirements to: (a) achieve steady state in the binder, (b) avoid unstable permanent strains, and (c) preclude tertiary flow at a given stress level. The methodology employed by Golalipur et al. (2017) to determine the optimum number of cycles could be utilized [46]. Perhaps the number of cycles could be different for each stress level as the number of cycles to reach steady state could be higher for higher stress levels.
- ***Binder Aging State:*** The aging state of the binder for which the test protocol is to be modified depends on the worst-case binder age – distress scenario. For instance, aggregate loss is predominant with aged binders. Therefore, it is suggested to perform the test protocol corresponding to aggregate loss on PAV aged binders. Similarly, bleeding is greater with softer binders. Hence, the test protocol for bleeding is more relevant for unaged binders. In addition, testing the PMABs before and after aging may help in identifying the deterioration in polymer networks induced by the aging process.
- ***Stress Levels:*** The stress levels utilized for PMAB characterization are extremely important because binders that exhibit similar properties in the LVE range (i.e. in terms of $G^*/\sin\delta$) could exhibit completely different properties once outside of this range due to their inherent stress sensitivities [25, 29, 34]. However, choosing the stress levels requires consideration of two important factors: (a) the stress levels should fall in the region where the PMABs exhibit stress sensitivity (i.e.

beyond LVE regime), and (b) the stress levels must be representative of the stresses that cause cohesive and adhesive failures in the binder. The typical ranges of LVE regime for binders can be obtained from the literature or, to specifically determine this range for chip seal binders, simple linear amplitude sweeps could be performed to determine the binder yield stress or the methodology described in chapter II could also be adopted [62]. It is important to consider that the stress levels causing failure in the field are temperature dependent [34]. Mechanistic modeling is a crucial step in determining the stresses corresponding to field failure. Gerber and Jenkins (2017) developed a finite element model for chip seals with the major failure mechanisms taking into consideration the binder properties at 25^0 C and the standard 80 kN wheel load at 80 km/hr [63]. They reported the shear stresses at failure from the model along with those from literature in Figure 51 (reprinted from [63]). Based on further exploration of the validity of the models presented in Figure 51, the stress levels reported could be utilized as the starting point for the exploring the parameters for a modified MSCR test protocol.

	Adhesive zone	Bitumen	
Previous works[a]	Shear stress	Shear stress	95 Percentile von Mises
Henderson et al. (2006)	–	–	320 kPa
Milne (2004)		10–300 kPa	–
Huurman (2010)	120–330 kPa	–	–
Current paper	80–160 kPa	50–120 kPa	200–250 kPa

[a]Bitumen: 70–100 or 80–100 penetration grades; 25°C; 80 kN axle loads at 80 km/h.

Note: Current Paper - [63]

Figure 51. Shear Stresses in the Binders for Adhesive and Cohesive Failures, Reported by [63]

- ***Test Temperatures:*** The test temperatures should be representative of the critical temperatures at which the binders fail in the field. For instance, climate-based T_{high} for bleeding. However, it is important to consider that stress levels and the test temperatures are inter-related as high stress levels cannot be applied at high temperatures due to the higher viscous component in the binder at such temperatures.

These recommendations are only guidelines and must be investigated for a wide range of materials.

CONCLUSIONS

This chapter discussed the various efforts undertaken to make the implementation of the SPG specification as practical as possible. A summary of these efforts are as follows:

- Significant industry interaction was achieved through the two round robin programs, the outcomes of which resulted in moving to offset 6^0 C increments in the SPG grading process and identifying the need to accurately characterize the polymer modification in binders utilized for chip seal applications.
- The study to compare the ED values reported by the TTI personnel through visual field inspection and the EDs calculated from the MPD measured using TxDOT's 3D texture device resulted in the conclusion that the visual observation of ED is sufficient to identify if there is a problem and/or provide a reason for uncorrelated field performance and that expected based on the SPG grade of the chip seal binder.
- Studies to evaluate the sensitivity of the phase angle parameter to modification and aging showed that the threshold did not seem to delineate the modified binders that fell in the range of 80^0 to 84^0 and was not robust against aging, calling for the need to explore an alternate parameter to supplement or replace the phase angle and ensure polymer modification.
- Different alternative parameters were explored to capture modification. FTIR spectroscopy studies and phase angles of PAV aged binders showed that different binders subjected to the same conditions aged differently. ER studies gave inconsistent results regarding the capacity of the binder to recover post loading and the actual % ER values. The large sample size requirement and long testing times made ER test an unattractive alternative to phase angle.

- Further, MSCR test results on the 2016-17 binders did not show field performance correlation in terms of bleeding; however, the test protocol seems promising in terms of capturing the polymer modification. The lack of field performance correlation was attributed to the unsuitability of the standard protocol to chip seal applications. Based on the extensive literature review and the objectives of characterizing polymer modification with regard to major distresses in chip seals, guidelines towards modifying the test protocol were proposed.

CHAPTER VI

CONCLUSIONS

This report is a summary of the efforts completed during the third-year (2016-17) implementation of SPG specification for chip seal binders in Texas. The first part of the work involved continuing the field performance correlation of the already existing parameters of the specification i.e. $G^*/\sin\delta$ and the phase angle δ at high temperature and the stiffness S at low temperatures. Keeping in mind that the binders for this period were specified using the SPG specification, significant consideration was given to the effect of construction factors on field performance. This process yielded a field performance correlation of 71% for both $G^*/\sin\delta$ and S without considering the construction factors; however, including them resulted in a correlation of 81% for $G^*/\sin\delta$ and 100% for S. This clearly highlights the need for the combined use of good construction practices and material-related specifications to achieve adequate field performance.

The second part of the work was the actual implementation effort involved with the end users of the specification, addressing their concerns and making the specification as practical as possible. Two round robins were conducted with TTI, TxDOT, and various suppliers in Texas to eventually move to offset 6^0 C increments in the SPG specification and identify the need to accurately characterize the PMABs. After reviewing the existing phase angle to be indicative of polymer modification and evaluating its sensitivity to aging, various parameters were explored to supplement or replace the existing phase angle. Finally, it was concluded that although the MSCR parameters did not correlate with field performance, the principle utilized in the test protocol to characterize PMABs seemed promising. Using the discussions from the literature review and considering the field distresses, guidelines were given to move forward with the test protocol modification to suit chip seal applications.

Overall, these efforts advanced the SPG specification to the next level where the failures in the field caused by the materials can be reduced. The need for a parameter to characterize PMABs arose due to the changes in material composition over time to accommodate the increasing traffic and preclude premature failure. However, changes in the materials and their formulations will continue to happen and the specifications with a strong mechanistic foundation and reflective of field performance will continue to stand through the test of time.

RECOMMENDATIONS FOR FUTURE WORK

Based on the conclusions of the current work, the following are some of the areas that could potentially be explored in the future.

- Further evaluation of the guidelines recommended to modify the MSCR test protocol is needed.
- Based on the conclusions of the evaluation, parameters and thresholds must be established using the modified protocol for binders utilized in chip seal applications.

REFERENCES

1. TxDOT, *STANDARD SPECIFICATIONS FOR CONSTRUCTION AND MAINTENANCE OF HIGHWAYS, STREETS, AND BRIDGES*, in *Item 300*. 2004.
2. Chang, S. and A.E. Martin, *Toward Statewide Implementation of the Surface Performance Graded Specification for Chip Seal Binders.* . 2015: [College Station, Texas] : [Texas A & M University], [2015].
3. Vijaykumar, A., et al., *Revision and further validation of surface-performance graded specification for surface treatment binders. by Aishwarya Vijaykumar, Edith Arambula, Thomas J. Freeman and Amy Epps Martin*. Report: 6616-1. 2013: College Station, Tex. : Texas A&M Transportation Institute, 2013.
4. Vijaykumar, A. and A. Epps Martin, *Validation of surface performance-graded specification for surface treatment binders*. 2012: [College Station, Tex.] : [Texas A&M University], [2012].
5. Epps Martin, A., et al., *Evolution of the Surface Performance-Graded (SPG) Specification for Chip Seal Binders (Accepted).* TRANSPORTATION RESEARCH RECORD, United States, Washington, DC, National Academy Press, 2017.
6. Martin, A.E., C.J. Glover, and R. Barcena, *A performance-graded binder specification for surface treatments. by Amy L. Epps, Charles J. Glover and Roberto Barcena*. Report: 1710-1. 2001: College Station, Tex. : Texas Transportation Institute, The Texas A&M University System ; Springfield, Va. : Available through the National Technical Information Service, [2001].
7. Walubita, L.F. and A.E. Martin, *Development and initial validation of a surface performance-graded binder specification. authors, Lubinda F. Walubita and Amy*

Epps Martin. Project summary report: 0-1710-S. 2005: College Station, Tex. : Texas Transportation Institute, the Texas A & M University System, [2005].

8. Walubita, L.F., A.E. Martin, and C.J. Glover, *A surface performance-graded (SPG) specification for surface treatment binders : development and initial validation. Lubinda F. Walubita, Amy Epps Martin and Charles J. Glover*. Technical report / Texas Transportation Institute: 0-1710-2. 2005: College Station, Tex. : Texas Transportation Institute, Texas A&M University System ; [Springfield, Va.] : [Available through the National Technical Information Service], [2005].
9. Shuler, S., *Manual for emulsion-based chip seals for pavement preservation. Scott Shuler [and others]*. NCHRP report: 680. 2011: Washington, D.C. : Transportation Research Board, 2011.
10. Barcena, R., A.E. Martin, and D. Hazlett, *Performance-graded binder specification for surface treatments.* BITUMINOUS BINDERS 2002, 2002(1810): p. 63-71.
11. Hoyt, D., A.E. Martin, and S. Shuler, *Surface performance-grading system to grade chip seal emulsion residues*. Transportation Research Record. 2010. 63-69.
12. Anderson, D.A. and T.W. Kennedy, *Development of SHRP Binder Specification.* Journal of Association of Asphalt Paving Technologists, 1993. **62**: p. 481-507.
13. AI, *SP-1 Superpave Performance Graded Asphalt Binder Specifications and Testing*. 2003, Asphalt Institute.
14. McGennis, R., S. Shuler, and H. Bahia, *BACKGROUND OF SUPERPAVE ASPHALT BINDER TEST METHODS. FINAL REPORT*. 1994.
15. TxDOT, *Special Provision: Asphalts, Oils and Emulsions*, in *Item No. 300-011*. Austin, TX.
16. *PG and SPG Binder Grade Selection Tool*. ftp://ftp.dot.state.tx.us/pub/txdot-info/cmd/forms/docs/pg-spg-binder-climatic-grade-selection.xlsm 2016 [cited 2017 May].

17. Kim, Y.R., et al., *Performance-Related Specifications for Emulsified Asphaltic Binders Used in Preservation Surface Treatments*, in *NCHRP 09-50*. 2017, National Cooperative Highway Research Program.

18. Herrington, P., J. Wu, and G. Bentley, *Bitumen performance tests*. 2016, Opus Research: New Zealand Transport Agency.

19. Herrington, P., S. Kodippily, and T. Henning, *Flushing in chipseals*. 2015, Opus Research and University of Auckland: New Zealand Transport Agency.

20. Kim, Y.R. and J.D. Clark, *Performance‐Related Specifications for Chip Seals.* North Carolina State University, 2015.

21. Urquhart, R., *Development of a Binder Test to Rank the Low Temperature Cracking Resistance of Polymer Modified Binders: Technical Report AP-T299-15*. 2015, Austroads.

22. Chaturabong, P., *Development of the Loaded Wheel Tracking Test (LWT) for Evaluating Bleeding In Chip Seals and Relationship to Emulsion Residue Rheology.* UNIVERSITY OF WISCONSIN – MADISON, 2014.

23. Chaturabong, P., A.J. Hanz, and H.U. Bahia, *Development of Loaded Wheel Test for Evaluating Bleeding in Chip Seals.* Transportation Research Record: Journal of the Transportation Research Board, 2015: p. 48-55.

24. Hossain, Z., et al., *Use of the Multiple Stress Creep Recovery (MSCR) Test Method to Characterize Polymer-Modified Asphalt Binders.* Journal of Testing and Evaluation, 2016. **44**(1): p. 507–520.

25. D'Angelo, J., *New High-Temperature Binder Specification Using Multistress Creep and Recovery*. Development in Asphalt Binder Specifications. 2010: National Academies of Sciences, Engineering, and Medicine.

26. D'Angelo J., et al., *Revision of the Superpave High Temperature Binder Specification: The Multiple Stress Creep Recovery Test.* Journal of Association of Asphalt Paving Technologists, 2007. **67**(Association of Asphalt Paving Technologists, Minnesota).

27. DuBois, E., D.Y. Mehta, and A. Nolan, *Correlation between multiple stress creep recovery (MSCR) results and polymer modification of binder.* Construction and Building Materials, 2014. **65**: p. 184-190.

28. Bahia, H.U., et al., *Characterization of Modified Asphalt Binders in Superpave Mix Design*. NCHRP report: 459. 2001: Washington, D.C. : Transportation Research Board, 2001.

29. Delgadillo, R., K. Nam, and H. Bahia, *Why do we need to change G*/sin delta and how?* ROAD MATERIALS AND PAVEMENT DESIGN, 2006. **7**(1): p. 7-27.

30. Motamed, A., A. Bhasin, and K.M. Liechti, *Interaction nonlinearity in asphalt binders.* MECHANICS OF TIME-DEPENDENT MATERIALS, 2012. **16**(2): p. 145-167.

31. Tabatabaee, H.A., et al., *Critical Problems with Using the Asphalt Ductility Test as a Performance Index for Modified Binders.* TRANSPORTATION RESEARCH RECORD, 2013(2370): p. 84-91.

32. FHWA-HIF-11-038, *THE MULTIPLE STRESS CREEP RECOVERY (MSCR) PROCEDURE.* Federal Highway Administration, US Department of Transportation, 2011.

33. Behnood, A., et al., *High-Temperature properties of asphalt binders*. Transportation Research Record. Vol. 2574. 2016: National Research Council. 131-143.

34. Jafari, M., A. Babazadeh, and S. Aflaki, *Effects of stress levels on creep and recovery behavior of modified asphalt binders with the same continuous performance grades*. Transportation Research Record. Vol. 2505. 2015: National Research Council. 15-23.

35. Domingos, M.D.I. and A.L. Faxina, *Susceptibility of asphalt binders to rutting: Literature review.* Journal of Materials in Civil Engineering, 2016. **28**(2).

36. D'Angelo, J. and R. Dongré, *Practical use of multiple stress creep and recovery test: Characterization of styrene-butadiene-styrene dispersion and other*

additives in polymer-modified asphalt binders. Transportation Research Record. 2009. 73-82.

37. AI, *Guidance on the Use of the MSCR Test with the AASHTO M320 Specification*, in *Asphalt Institute, Lexington, KY*. 2010, Asphalt Institute Technical Advisory Committee.

38. Anderson, R.M., *Southeast Asphalt User-Producer Group Interlaboratory Study to Determine the Precision of AASHTO TP70 – the Multiple- Stress Creep-Recovery (MSCR) Test*. 2012, Asphalt Institute.

39. Stevens, R., et al., *Evaluation of Multiple Stress Creep and Recovery (MSCR) Data for Arizona.* International Journal of Pavement Research & Technology, 2015. **8**(5): p. 337-345.

40. Mohseni, A. and H. Azari, *High-Temperature Characterization of Highly Modified Asphalt Binders and Mixtures.* TRANSPORTATION RESEARCH RECORD, 2014(2444): p. 38-51.

41. Woo, W.J. and C.J. Glover, *Development of a long-term durability specification for polymer modified asphalt. by Won Jun Woo*. 2010: [College Station, Tex.] : [Texas A&M University], [2010].

42. AASHTO, *AASHTO MP 19:2010 Specification For Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test* 2010, American Association of State and Highway Transportation Officials.

43. AASHTO, *AASHTO TP 70 : Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*. 2016, American Association of State and Highway Transportation Officials.

44. Saboo, N. and P. Kumar, *Analysis of different test methods for quantifying rutting susceptibility of asphalt binders.* Journal of Materials in Civil Engineering, 2016. **28**(7).

45. D'Angelo, J.A., *The Relationship of the MSCR Test to Rutting.* Road Materials and Pavement Design, 2009. **10**: p. 61-80.

46. Golalipour, A., H.U. Bahia, and H.A. Tabatabaee, *Critical considerations toward better implementation of the multiple stress creep and recovery test.* Journal of Materials in Civil Engineering, 2017. **29**(5).
47. Wasage, T.L.J., J. Stastna, and L. Zanzotto, *Rheological analysis of multi-stress creep recovery (MSCR) test.* International Journal of Pavement Engineering, 2011. **12**(6): p. 561-568.
48. Motamed, A. and H.U. Bahia, *Influence of Test Geometry, Temperature, Stress Level, and Loading Duration on Binder Properties Measured Using DSR.* Journal of Materials in Civil Engineering, 2011. **23**(10): p. 1422-1432.
49. White, G., *Grading highly modified binders by multiple stress creep recovery.* Road Materials and Pavement Design, 2016: p. 1-16.
50. AASHTO, *AASHTO T 313-10: Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)*. 2010, American Association of State and Highway Transportation Officials.
51. AASHTO, *AASHTO T 315-12: Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*. 2012, American Association of State and Highway Transportation Officials.
52. TxDOT, *Tex-539-C: Measurement of Elastic Recovery of Tensile Deformation Using a Ductilometer*. 2014, Texas Department of Transportation, Austin, TX.
53. Senadheera, S., D. Gransberg, and T. Kologlu, *Chip Seal Field Manual*. 2001, Texas Tech University, Lubbock.
54. Estakhri, C. and S. Senadheera, *The Updated TxDOT Chip Seal and Surface Treatment Manual – Summary*. 2003, Texas Transportation Institute, College Station.
55. Cortizo, M.S., et al., *Effect of the thermal degradation of SBS copolymers during the ageing of modified asphalts.* Polymer Degradation and Stability, 2004. **86**(2): p. 275-282.
56. Isacsson, U. and X. Lu, *Characterization of bitumens modified with SEBS, EVA and EBA polymers.* Journal of Materials Science, 1999. **34**(15): p. 3737-3745.

57. Larsen, D.O., et al., *Micro-structural and rheological characteristics of SBS-asphalt blends during their manufacturing.* Construction and Building Materials, 2009. **23**(8): p. 2769-2774.
58. Miller, J.S. and W.Y. Bellinger, *Distress Identification Manual for the Long-Term Pavement Performance Program (Fourth Revised Edition)*, in *FHWA-RD-03-031*. 2003, Federal Highway Administration, Washington, D.C.
59. Huang, Y., et al., *Development of Texture Measurement System Based on Continuous Profiles from Three-Dimensional Scanning System.* TRANSPORTATION RESEARCH RECORD, 2013(2367): p. 13-22.
60. Islam, R.M., W.B. King Jr, and N.M. Wasiuddin, *Correlating Long-Term Chip Seals Performance and Rheological Properties of Aged Asphalt Binders.* Journal of Materials in Civil Engineering, 2016. **28**(5): p. 1-9.
61. Lee, J. and Y.R. Kim, *Evaluation of performance and cost-effectiveness of polymer-modified chip seals*. Transportation Research Record. 2010. 79-86.
62. Marasteanu, M.O. and D.A. Anderson, *Establishing linear viscoelastic conditions for asphalt binders.* ASPHALT BINDERS 2000, 2000(1728): p. 1-6.
63. Gerber, J. and K. Jenkins, *Finite element modelling and damage quantification of chip seals*. Road Materials and Pavement Design, 2016. **18**(2): p. 350-361.

APPENDIX – A: ROUND ROBIN-I GUIDELINES

ROUND ROBIN – I

Thank you for your participation in a round-robin program as part of the Texas Department of Transportation (TxDOT) implementation of the seal coat binder SPG specification. This program requires the participants to **grade** a hot-applied asphalt binder sample and an emulsion distributed by TxDOT, i.e. report the high and low temperature SPG grades of the samples using the current SPG specification (Table A-1). Each SPG grade requires a temperature at which the measured property Passes the specification threshold and a temperature at which the measured property Fails the threshold for both low and high temperatures.

Table A-1: Current SPG Specification for Statewide Implementation

Surface Performance Grade	SPG 64	SPG 67					SPG 70					SPG 73			
	-25	-13	-16	-19	-22	-25	-13	-16	-19	-22	-25	-16	-19	-22	-25
Average 7-day Max pavement surface design temperature, °C	<64	<67					<70					<73			
Min pavement surface design temperature, °C	>-25	>-13	>-16	>-19	>-22	>-25	>-13	>-16	>-19	>-22	>-25	>-16	>-19	>-22	>-25
Original Binder															
Flash point temp, T 48, Min, °C	230														
Viscosity, T 316: Max 0.15 Pa*s, test temp., °C	205														
Original Performance Properties															
Dynamic Shear, T 315: G*/sin δ, Min 0.65 kPa, Test temp @ 10 rad/s, °C	64	67					70					73			
Phase angle (δ), Max, @ temp. where G*/sin δ = 0.65 kPa	80	–	–	–	80	80	–	–	80	80	80	80	80	80	80
Pressure Aging Vessel Residue (R 28)															
PAV aging temperature, °C	100	100					100					100			
Creep stiffness, T 313: S, Max 500 MPa, Test temp. @ 8 sec., °C	-25	-13	-16	-19	-22	-25	-13	-16	-19	-22	-25	-16	-19	-22	-25

The SPG specification is applicable to both hot-applied asphalt binders and emulsion residues, with emulsion residues recovered by AASHTO PP 72-11 Procedure B prior to performing the tests included in Table A-1. For consistency, all participating laboratories are required to store the hot-applied asphalt binder and emulsion residue in approximately 20g batches and test them per the guidelines provided subsequently.

High Temperature grading

According to the SPG specification in Table A-1, the high temperature SPG grade of a hot-applied asphalt binder or emulsion residue is the highest temperature at which G*/sin $\delta > 0.65$ kPa as measured in the DSR by AASHTO T315 on the original unaged material. Therefore, to report the high temperature SPG grade, the participants must provide a temperature (T^0 C) at which G*/sin $\delta > 0.65$ kPa (Pass) and another temperature ($(T+3)^0$ C) at which G*/sin $\delta < 0.65$ kPa (Fail). With one Pass and one Fail temperature, the high temperature SPG grade is reported as T^0 C.

Figure A-1 gives the general procedure to be followed for high temperature SPG grading of a hot-applied asphalt binder or emulsion residue.

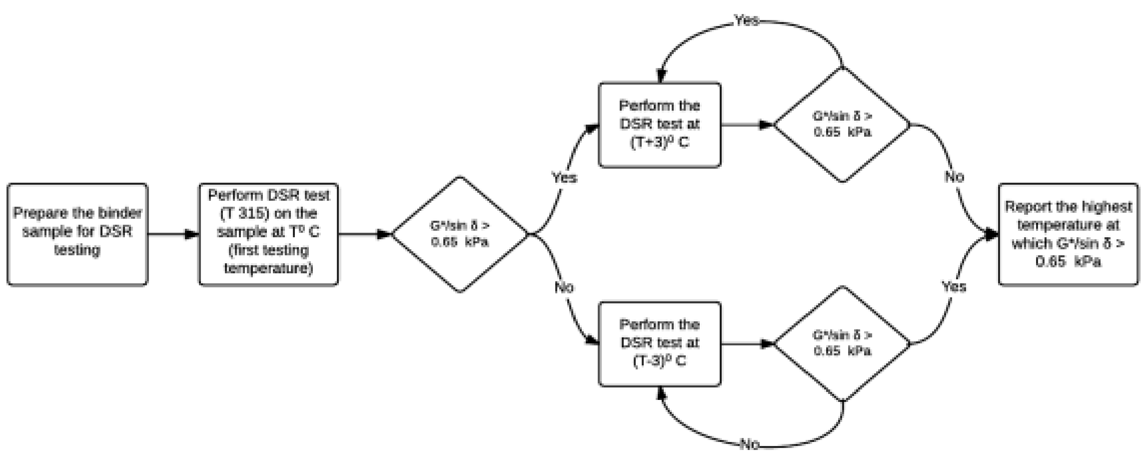


Figure A-1: SPG High Temperature Grading of Hot-Applied Asphalt Binders and Emulsion Residues

In addition, the continuous phase angle at the high temperature where G*/sin $\delta = 0.65$ kPa is interpolated and reported. For example, for the data given in Table 2, the interpolated phase angle at G*/sin $\delta = 0.65$ kPa is 74.67.

Table A-2: Example Data for Determination of Continuous Phase Angle at G*/sin δ = 0.65 kPa

G*/sin δ (kPa)	δ
0.853	74.0
0.64	74.7

The SPG specification (Table A-1) was developed for high temperature grading after reheating the binder to pour in the DSR mold. However, for the Round Robin test program, two procedures for sample preparation for DSR testing have been suggested for emulsion residues – with reheating and without reheating. Only the procedure with reheating is used for hot-applied asphalt binders. The guidelines for these procedures are described subsequently.

With reheating

1. Recover emulsion residue in accordance with AASHTO PP72 Method B.
2. Place 20g of residue in a 6oz metal tin[1] (approx. 3in diameter).
3. Place the sample tin in an oven heated at 160^{0} C (320^{0} F) for 10 minutes[2].
4. Stir the sample with a spatula after the tin has been in the oven for 5 minutes.
5. After 10 minutes, pour the sample to be tested in the 25mm DSR silicone mold.

[1]: http://www.globalgilson.com/tinned-sample-container-6oz

[2]: Some residues may require additional time and/or higher temperature to become fluid enough for pouring into the DSR mold. If additional time or higher temperature is needed, please record the conditions used for reheating.

Without reheating (only for emulsion residue)

1. Recover emulsion residue in accordance with AASHTO PP72 Method B.
2. Place the ball of residue on wax release paper and fold the release paper so that it encloses the residue.
3. Place the residue covered by the release paper into a sample container.
4. When taking samples for DSR testing, pull enough asphalt for the test or cut a sample large enough to test. Gloves can be used to place the sample in the 25mm DSR silicone mold.

Low Temperature Grading

According to the SPG specification in Table A-1, the low temperature SPG grade of a hot-applied asphalt binder or emulsion residue is the lowest temperature at which $S < 500$ MPa at 8 seconds as measured in the BBR by AASHTO T313 on the PAV aged material at the actual low temperature SPG grade (without a 10^{0} C shift). Therefore, to report the low temperature SPG grade, the participants must provide a temperature (T^{0} C) at which $S < 500$ MPa (Pass) and another temperature ($(T-3)^{0}$ C) at which $S > 500$ MPa (Fail). With one Pass and one Fail temperature, the low temperature SPG grade is reported as T^{0} C.

Figure A-2 gives the general procedure to be followed for low temperature SPG grading of a hot-applied asphalt binder or emulsion residue.

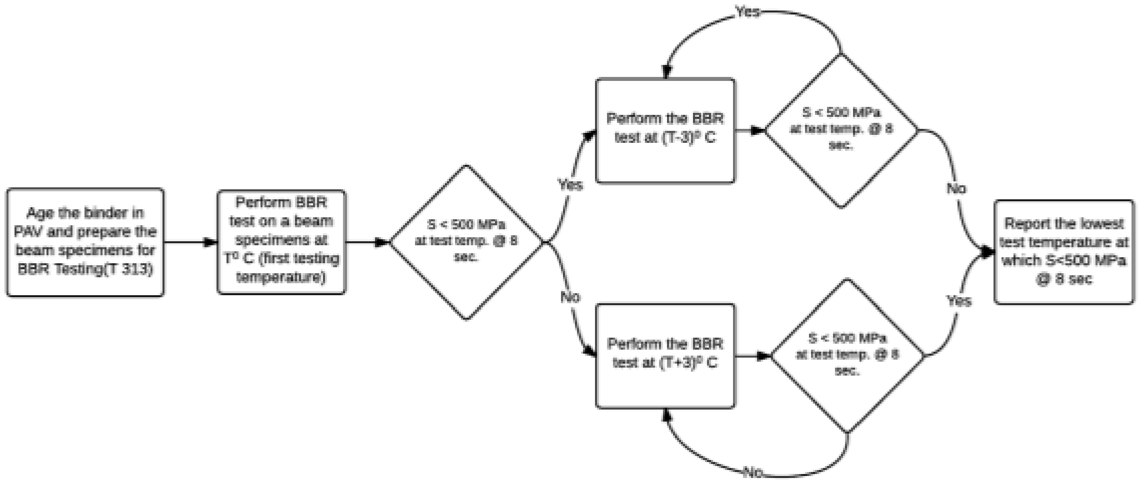


Figure A-2: SPG Low Temperature Grading of Hot-Applied Asphalt Binders and Emulsion Residues

Results to Report

In summary, after following the test plan discussed in this document, the following results are to be reported by the participants.

Original Unaged Binder – High Temperature Grading

Criteria: G*/sin δ < 0.65 kPa

Report:
Highest temperature at which G*/sin δ < 0.65 kPa
Phase angle at the temperature where G*/sin δ = 0.65 kPa

PAV Aged Binder – Low Temperature Grading

Criteria: S < 500 MPa at 8sec

Report: Lowest temperature at which S < 500 MPa at 8sec

A sample data sheet for reporting results is attached.

Seal Coat Binder SPG Specification Round Robin

Testing facility:

Date of testing:

Sample tested:

Sample ID:

Operator:

High Temperature Grading (please report one Pass temperature and one Fail temperature)

Temperature (^{0} C)	$\frac{G*}{\sin\delta}$ (kPa)	Phase angle, δ	Result
			PASS
			FAIL

δ interpolated at $\frac{G*}{sin\ \delta}$ = 0.65 kPa =

Low Temperature Grading (please report one Pass temperature and one Fail temperature)

Temperature (^{0} C)	S (MPa) at 8sec	Result
		PASS
		FAIL

SPG grade of the sample: ***SPG - ***

Phase angle criterion: <80 OR >80

Notes: (Report any deviations from suggested testing procedures)

1.
2.
3.
4.

ROUND ROBIN – II

Thank you for your participation in the second round-robin as part of the Texas Department of Transportation (TxDOT) implementation of the seal coat binder SPG specification. This program requires the participants to **grade** a hot-applied asphalt binder sample and an emulsion residue using the revised SPG specification for Round Robin II (Table A-3) that utilizes 6^0 C increments offset from those used in the PG specification.

The SPG specification is applicable to both hot-applied asphalt binders and emulsion residues, with emulsion residues recovered by AASHTO PP 72-11 Method B prior to performing the tests included in Table A-3. For consistency, all participating laboratories are required to store the hot-applied asphalt binder and emulsion residue in approximately 20g batches and test them per these guidelines.

Each SPG grade requires a temperature at which the measured property passes the specification threshold and a temperature at which the measured property fails the threshold for both low and high temperatures. The interpolated phase angle at the high temperature threshold ($G^*/\sin \delta = 0.65$ kPa) is also required.

Table A-3. Revised SPG Specification for Round Robin II.

Surface Performance Grade	SPG 61					SPG 67					SPG 73			
	-7	-13	-19	-25	-31	-7	-13	-19	-25	-31	-13	-19	-25	-31
Average 7-day Max pavement surface design temperature, °C	<61					<67					<73			
Min pavement surface design temperature, °C	>-7	>-13	>-19	>-25	>-31	>-7	>-13	>-19	>-25	>-31	>-13	>-19	>-25	>-31
Original Binder														
Flash point temp, T 48, Min, °C	230													
Viscosity, T 316: Max 0.15 Pa*s, test temp., °C	205													
Original Performance Properties														
Dynamic Shear, T 315: G*/sin δ, Min 0.65 kPa, Test temp @ 10 rad/s, °C	61					67					73			
Phase angle (δ), Max, @ temp. where G*/sin δ = 0.65 kPa	–	–	–	80	80	–	–	80	80	80	80	80	80	80
Pressure Aging Vessel Residue (R 28)														
PAV aging temperature, °C	100					100					100			
Creep stiffness, T 313: S, Max 500 MPa, Test temp. @ 8 sec., °C	-7	-13	-19	-25	-31	-7	-13	-19	-25	-31	-13	-19	-25	-31

In addition to the SPG tests required by specification in Table A-3, the participants are requested to perform the elastic recovery test by Tex-539-C and the multiple stress creep recovery test (MSCR) by AASHTO TP 70 on the original unaged material on both binder samples for information only to provide additional data toward selection of an appropriate parameter to ensure polymer modification. The m-value is also requested for each cold temperature for information only.

High Temperature Grading

To prepare the sample prior to DSR testing:

1. Place 20g of sample in a 6oz metal tin[1] (approx. 3 in. diameter).
2. Place the sample tin in an oven heated at 160^0 C (320^0 F) for 10 minutes[2].
3. Stir the sample with a spatula after the tin has been in the oven for 5 minutes.
4. After 10 minutes, pour the sample to be tested in the 25mm DSR silicone mold.

[1]: http://www.globalgilson.com/tinned-sample-container-6oz

[2]: Some residues may require additional time and/or higher temperature to become fluid enough for pouring into the DSR mold. If additional time or higher temperature is needed, please record the conditions used for reheating.

According to the SPG specification (Table A-3), the high temperature SPG grade of a hot-applied asphalt binder or emulsion residue is the warmest test temperature at which $G^*/\sin\delta > 0.65$ kPa as measured in the DSR by AASHTO T315 on the original unaged material. Therefore, to report the high temperature SPG grade, the participants must provide a test temperature (T^0 C) at which $G^*/\sin\delta > 0.65$ kPa (Pass) and another test temperature ($(T+6)^0$ C) at which $G^*/\sin\delta < 0.65$ kPa (Fail). With one pass and one fail test temperature, the high temperature SPG grade is reported as T^0 C. Figure A-3 provides the procedure to be followed for high temperature SPG grading of a hot-applied asphalt binder or emulsion residue. For each test temperature, please conduct **two** measurements on the same sample without additional conditioning time before changing the test temperature for subsequent measurements.

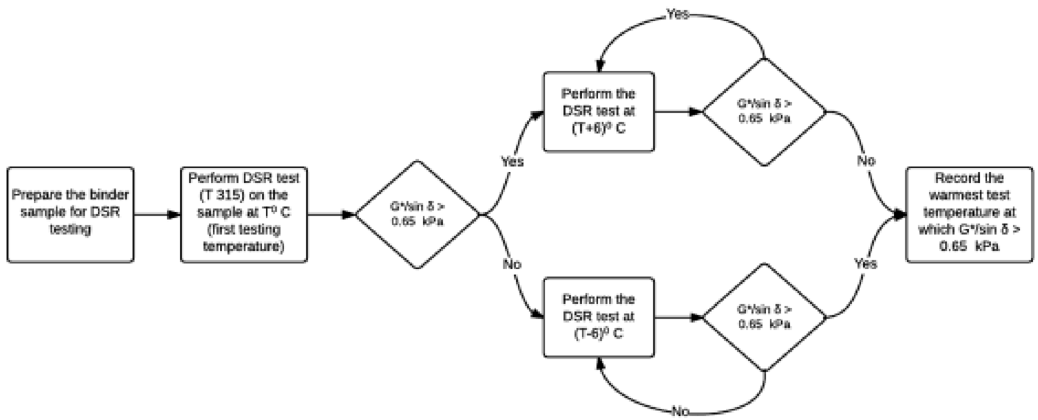


Figure A-3. SPG High Temperature Grading of Hot-Applied Asphalt Binders and Emulsion Residues.

Low Temperature Grading

According to the SPG specification in Table A-3, the low temperature SPG grade of a hot-applied asphalt binder or emulsion residue is the coldest test temperature at which S < 500 MPa at 8 seconds as measured in the BBR by AASHTO T313 on the PAV aged material at the actual low temperature SPG grade (without a 10^0 C shift). Therefore, to report the low temperature SPG grade, the participants must provide a test temperature (T^0 C) at which S < 500 MPa (Pass) and another test temperature ($(T-6)^0$ C) at which S > 500 MPa (Fail). With one pass and one fail test temperature, the low temperature SPG grade is reported as T^0 C. Figure A-4 provides the procedure to be followed for low temperature SPG grading of a hot-applied asphalt binder or emulsion residue.

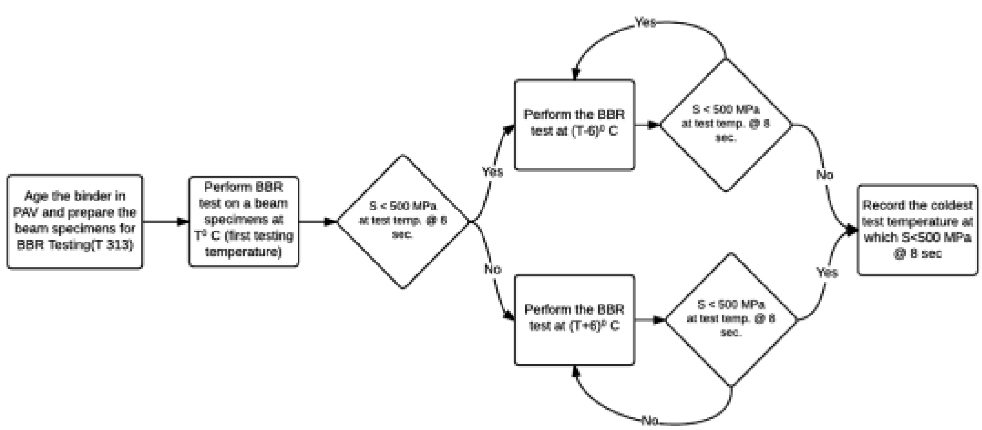


Figure A-4. SPG Low Temperature Grading of Hot-Applied Asphalt Binders and Emulsion Residues.

Additional Testing

To further explore parameters other than phase angle at the high temperature threshold to ensure polymer modification, participants are requested to perform the elastic recovery test at 50° F (10° C) by Tex-539-C to report ER (%) and the MSCR test with original unaged binder at 61° C and 55° C by AASHTO TP 70 to report J_{nr} (kPa^{-1}) and minimum recovery (MR, %) values for information only. The m-value is also requested for each cold temperature for information only to further explore the use of this parameter or the corresponding T_c (determined from the difference in the temperatures where the m-value and S thresholds are met) to ensure adequate stress relaxation or flexibility.

Results to Report

A sample data sheet for reporting the following results for each binder sample is attached.

Original Unaged Binder – High Temperature Grading

Criteria: $G^*/\sin\delta > 0.65$ kPa

Report:

- Warmest test temperature at which $G^*/\sin\delta > 0.65$ kPa and phase angle for replicates 1 and 2
- Coldest test temperature at which $G^*/\sin\delta < 0.65$ kPa and phase angle for replicates 1 and 2
- Interpolated phase angle at the temperature where $G^*/\sin\delta = 0.65$ kPa

PAV Aged Binder – Low Temperature Grading

Criteria: S < 500 MPa at 8sec

Report:

- Coldest test temperature at which S < 500 MPa at 8 sec (and m-value at 8 sec for information only)
- Warmest test temperature at which S > 500 MPa at 8 sec (and m-value at 8 sec for information only)

Additional Results for information only

- ER (%) at 50° F (10° C) on residue recovered by AASHTO PP 72-11 Method B
- J_{nr} (kPa^{-1}) and MR (%) values @ 0.1 and 3.2 kPa for original unaged binder at 61° C and 55° C

Seal Coat Binder SPG Specification Round Robin II

Testing facility:

Date of testing:

Sample tested:

Sample ID:

Operator:

High Temperature Grading (please report one Pass temperature and one Fail temperature)

Temperature (^{0}C)	$\frac{G*}{\sin\delta}$ (kPa)		Phase angle, δ		Result
	Replicate 1	Replicate 2	Replicate 1	Replicate 2	
					PASS
					FAIL

Interpolated δ for Replicate 1 =___ ☐ < 80 or ☐ > 80

Interpolated δ for Replicate 2 = ___ ☐ < 80 or ☐ > 80

Low Temperature Grading (please report one Pass temperature and one Fail temperature)

Temperature (^{0}C)	S (MPa) at 8sec	m – value at 8 sec for information only	Result
			PASS
			FAIL

SPG grade:

Additional Results for information only

% ER @ 55 F (10 C)	Jnr (1/kPa) @						MR (%) @					
	55 C			61 C			55 C			61 C		
	0.1 kPa	3.2 kPa	Jnr Diff (%)	0.1 kPa	3.2 kPa	Jnr Diff (%)	0.1 kPa	3.2 kPa	MR Diff (%)	0.1 kPa	3.2 kPa	MR Diff (%)

Notes: (Report any deviations from suggested testing procedures)

1.
2.
3.
4.