# TOWARD STATEWIDE IMPLEMENTATION OF THE SURFACE PERFORMANCE GRADED SPECIFICATION FOR CHIP SEAL BINDERS

A Thesis

by

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# ABSTRACT

Over the past 15 years, a surface performance-graded (SPG) specification for chip seal binders was developed by the Texas Department of Transportation (TxDOT) using laboratory measurements and visual field performance (aggregate loss and bleeding) of 75 highway sections (HSs). The SPG was established in an effort to extend the service life of chip seals by providing a binder selection method that accounts for differences in climate. TxDOT recently commenced a statewide implementation effort of the SPG specification. The initial activities include (a) reviewing laboratory and field performance of HSs built in 2011 based on the latest version of the SPG specification, newly generated SPG requirement map, and revised surface condition index calculation; (b) characterizing binders from HSs built in 2013 and monitoring their field performance; (c) proposing additional parameters to complement the SPG specification; and (d) predicting bending beam rheometer (BBR) creep stiffness values from frequency sweep results. When comparing the expected performance of the binders (based on their SPG grade) against actual field performance after the first year in service, 80 percent of the HSs built in 2011 correlated well. Individual SPG properties were compared to corresponding field performance for 2013 chip seal binders in terms of aggregate loss or bleeding. Unexpected field performance from the Amarillo District largely contributed to poor correlation between the BBR creep stiffness properties and field performance in terms of aggregate loss for 2013 HSs. A phase angle parameter was introduced in the SPG specification to ensure modified binders contain sufficient polymers. The prediction of BBR creep stiffness values via a frequency sweep test was not reliable at colder temperatures, even when a 4-mm dynamic shear rheometer plate test was used.

# DEDICATION

*To My Father, Liang Chang,*

*To My Mother, Li Tang*

*for their kind support, love and patience.*

## ACKNOWLEDGMENTS

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This study was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). I wish to express my appreciation to TxDOT personnel for their support throughout this project. Special thanks are given to Dr. German Claros and the TxDOT Project Committee—Darren Hazlett (project director), Jerry Peterson, Gisel Carrasco, Kenneth Corse, Mike Craig, Carmen Iglehart, Robert Lee, and Stephen Smith—for providing technical guidance and assistance.

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# 1. INTRODUCTION

In the Texas Department of Transportation (TxDOT) specifications, Item 316, chip seals are defined as a spray application of asphalt emulsion or hot-applied asphalt cement covered with aggregate (TxDOT 2004). 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 on the contracted district-wide chip seal preventive maintenance program annually to treat approximately 8 percent of the state highway system. Over the past 15 years, a surface performance-graded (SPG) specification was developed and then validated by two TxDOT research projects (TxDOT Project 0-1710 and TxDOT Project 0-6616) for 75 highway sections (HSs) statewide (Vijaykumar, Martin, & Arambula, 2013; L. Walubita, Martin, Hazlett, & Barcena, 2004). The objective of the SPG specification is to extend the service life of chip seal treatments by improving their field performance. Currently, TxDOT is implementing the SPG specification to provide a better method for binder selection that accounts for differences in climate and relates to performance in terms of aggregate loss and bleeding over the critical first-year period.

## 1.1 BACKGROUND

TxDOT specifications (Item 316) define chip seals or seal coats as an application of asphaltic material covered with aggregate (DOT, 2004). The specification allows for single, double, or triple spray applications of hot-applied asphalt cements, asphalt emulsions, or cutback asphalts, each covered with aggregate. The application of chip seals is a simple, inexpensive, and effective preventive maintenance strategy to obtain a durable, weatherproof surface. The performance of chip seals depends on the careful construction as well as the properties of the asphalt binder and the aggregates used. It is recommended that chip seal binders should (a) be fluid enough to be sprayed yet viscous enough to be applied uniformly, (b) have sufficient consistency to wet and adhere to aggregate quickly, (c) be able to retain the aggregate upon curing, and (d) be resistant to excessive deformation under varying traffic loads as well as weather conditions (Epps, Gallaway, & Hughes, 1981).

Currently, the design and selection of chip seal binders in service are based on specifications that include tests of emulsion residues or hot-applied asphalt cements at standard temperatures that do not cover the entire range of in-service temperatures, measure properties that are not performance related, and do not consider representative aging conditions for the critical first year. Current specifications for the binding materials used in chip seals (Item 300) consider both the properties of the material during construction and in service, and a wide range of materials can be utilized to meet the current specified properties (DOT, 2004). An SPG specification for the selection of chip seal binders was developed as part of TxDOT Project 1710 and National Cooperative Highway Research Program (NCHRP) Project 14-17 (Shuler, 2011; L. F. Walubita & Martin, 2005). More recently, revision and further validation of the SPG specification with additional candidate tests was developed in TxDOT Project 0-6616 (Vijaykumar, Arambula, Freeman, & Martin, 2012). The SPG system relates the properties of chip seal asphalt binders to the conditions under which they are used; it accounts for the effects of the expected climatic conditions, pavement temperatures, and aging on the performance of the binder in service.

The SPG system is an extension of the concept behind the Strategic Highway Research Program (SHRP) performance grade (PG) classification system and utilizes the same laboratory testing equipment. This study focused on implementation of the SPG specification for chip seal binders (both emulsion residues and hot-applied asphalt cements) in service statewide through adoption of the SPG specification.

## 1.2 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 highway sections statewide. Based on field validation, given proper construction and design, the estimated SPG grades and the field performance of chip seal binders are well correlated (Vijaykumar et al., 2012; L. Walubita et al., 2004).

The SPG grade demand for each of the highway sections in TxDOT districts was determined by pavement surface temperature at 98 percent reliability based on air temperature from the closest weather station and LTPPBIND pavement temperature models in TxDOT Project 0-1710. For implementation, the SPG grade requirements should be considered for each county statewide based on climate and calculated surface pavement temperatures from a practical standpoint to minimize the number of SPG grades to 1–2 for each TxDOT district.

Although most of the laboratory testing recommended in the SPG specification is consistent with the PG binder grading system, the practicality of these tests for use by industry was not considered. Particularly, the shear strain sweep test used to evaluate the intermediate temperature property of chip seal binders was recently developed and may not be practical with existing equipment utilized currently by the industry. Further, the SPG specification recommends using 20 hr pressure aging vessel (PAV) aging in the laboratory to simulate 1 year of aging in the field (L. F. Walubita & Martin, 2005). This laboratory aging should be further validated by comparing laboratory aging binders after 20 hr in a PAV and field aging binders extracted from samples collected 1 year after construction.

## 1.3 RESEARCH OBJECTIVE

Similar to the Superpave asphalt binder specification, the SPG specification is intended to improve the field performance of chip seals (hot-applied asphalt binder or emulsions) by limiting aggregate loss or bleeding distress potential. This performance-related specification is meant to replace the current TxDOT Chip Seal Binder Material Selection Table (with the tiered system) and conventional chip seal binder specifications for materials in service provided in TxDOT Item 300. Subsequently, the objective of this study was to achieve a statewide implementation of the SPG specification for chip seal binders in Texas.

## 1.4 THESIS OUTLINE

This study focuses on the first-year (2013) implementation of the SPG specification and is organized into five chapters. Chapter 1 provides background and history information on the need for implementation the SPG specification, the research objectives, and the thesis contents. Chapter 2 is a literature review that introduces the previously developed SPG systems and the available test methods used to evaluate the chip seal binders. Chapter 3 describes the experimental design, including the methodology and materials used. The results of laboratory evaluation and field monitoring are presented and analyzed in Chapter 4. Lastly, Chapter 5 summarizes the conclusions and recommendations for further research.

# 2. LITERATURE REVIEW

This section describes a comprehensive review of information on the history and development of the SPG specification and exclusive use of the dynamic shear rheometer (DSR) for rheological testing of binders, including the linear amplitude sweep (LAS) test and 4-mm DSR frequency sweep test.

## 2.1 THE SPG SPECIFICATION HISTORY

The SPG specification for chip seal binders in service was developed and initially field validated under TxDOT Project 0-1710, *Superpave Binder Tests for Chip Seal Binders (Amy L. Epps, 2001; Barcena, Epps Martin, & Hazlett, 2002; L. Walubita et al., 2004; L. F. Walubita & Martin, 2005; L. F. Walubita, Martin, & Glover, 2005)*. Twenty-one commonly used TxDOT chip seal binders, including nine grades of hot-applied asphalt cements, were tested in the development of this specification. For each emulsion, researchers evaluated five emulsion residue recovery methods (hot oven, rotavap, hot plate, distillation, and stirred can). The tests used in the specification were conducted using standard PG testing equipment, and the analyses were performance based on and consistent with chip seal mix design, construction, behavior, in-service performance, and associated distresses. The researchers identified the most appropriate emulsion residue recovery process and performed standard and modified PG binder testing. This led to the development of the SPG specification, including the associated grade selection process.

The testing methodology used for developing the SPG specification was adapted from the standard PG binder testing process. Unlike the standard PG system, the high and low pavement temperatures were calculated at the surface to reflect the critical conditions for chip seal binder performance. Narrower temperature increments of 3°C were utilized. Binder

SPG properties were determined for unaged and PAV-aged material to account for the critical first year of chip seal binder performance. Rotational viscometer tests were conducted at several temperatures to determine the spraying temperatures for hot-applied asphalt cements. DSR testing was performed only on unaged binders to reflect the critical conditions for newly laid chip seals at high pavement temperatures. Finally, for low-temperature testing after PAV aging, the binder stiffness was measured at the short loading time of 8 sec using bending beam rheometer (BBR) equipment to simulate critical traffic loading conditions. The actual test temperature was used to determine the low-temperature SPG grade.

To develop the SPG specification, the measured binder properties were analyzed in conjunction with field performance ratings and the corresponding surface pavement temperatures were calculated using SHRP temperature models and the LTPPBIND database (LTPPBIND Version 3.0/3.1). Project information from 45 HSs from the 2001 and 2002 TxDOT district chip seals provided the basis for validation. Researchers collected data on factors that affected chip seal performance including binders (types and associated suppliers), aggregates (types, gradations, and coating), environmental conditions, and traffic. The surface condition index (SCI) criterion was used for the performance evaluation of the HSs for 1 year after their construction, and a minimum acceptable SCI threshold of 70 percent was selected for rating the HSs. The predominant chip seal distresses—aggregate loss and bleeding—associated with inappropriate material selection were monitored on each HS. Most of the materials used in these chip seals were sampled onsite for laboratory testing and SPG grading. The stirred can method was used for recovering emulsion residue, as it was found to yield better results than the hot oven, rotavap, hot plate, and distillation processes, in terms of quantity of residue, minimization of asphalt oxidation, maximization of water removal, and optimization of recovery process time. Based on Fourier transform infrared spectroscopy (FTIR) analysis, PAV aging was found to simulate 1 year of environmental exposure for chip seals (L. F. Walubita et al., 2005).

78 percent of the HSs had a good correlation between the SPG grade and observed performance. The discrepancies between laboratory and field performance results were attributed to the SPG limits and grading criteria; material variability; and design, construction, quality control, and traffic factors. Based on the initial field validation, the spraying viscosity-temperature limit was increased to 205°C from 180°C to include some additional modified binders. The G*/sin δ high-temperature threshold value was decreased to 0.65 kPa to include binders with values insignificantly below 0.75 kPa demonstrating adequate field performance. Last, an increased temperature grade increment of 6°C was adopted for the lower temperature limit to ensure a consistent change in reliability at both high and low design temperatures. Eight standardized binder SPG grades were established for Texas conditions at 98 percent reliability.

Table 1 shows the SPG specification proposed as part of TxDOT Project 0-1710. The researchers recommended that further validation, possibly with controlled test sections or pilot implementation projects, be performed to address some of the deficiencies and failures associated with the proposed SPG specification. The possibilities of directly incorporating traffic and loading conditions into the binder SPG grade selection process was also suggested. Last, the researchers recommended that performance monitoring be carried out for more than 1 year to capture the full effect of traffic, environmental conditions, and binder aging.

**Table 1. The Original Proposed SPG Specification.**

| Only three binder grades are shown, but the grades are unlimited and can be extended in both high- and low-temperature directions using 3° or 6°C increments, respectively | **Performance Grade** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **SPG 58** | | | | **SPG 61** | | | | **SPG 64** | | | |
| | **−10** | **−16** | **−22** | **−28** | **−10** | **−16** | **−22** | **−28** | **−10** | **−16** | **−22** | **−28** |
| Average 7-day Maximum Surface Pavement Design Temperature, °C | <58 | | | | <61 | | | | <64 | | | |
| Minimum Surface Pavement Design Temperature, °C | >−10 | >−16 | >−22 | >−28 | >−10 | >−16 | >−22 | >−28 | >−10 | >−16 | >−22 | >−28 |
| Original Binder | | | | | | | | | | | | |
| Viscosity ASTM D4402<br>Maximum: 0.15 Pa.s;<br>Minimum: 0.10 Pa.s<br>Test Temperature, °C | ≤205 | | | | ≤205 | | | | ≤205 | | | |
| Dynamic Shear, AASHTO T315 /ASTM D7175<br>*G*/Sin δ*, Minimum: 0.65 kPa<br>Test Temperature @ 10 rad/sec, °C | 58 | | | | 61 | | | | 64 | | | |
| Pressure Aging Vessel Residue (AASHTO PP1) | | | | | | | | | | | | |
| PAV Aging Temperature, °C | 90 | | | | 100 | | | | 100 | | | |
| Creep Stiffness, AASHTO T313 /ASTM D6648<br>S, Maximum: 500 MPa<br>m-value, Minimum: 0.240<br>Test Temperature @ 8 sec, °C | -10 | -16 | -22 | -28 | -10 | -16 | -22 | -28 | -10 | -16 | -22 | -28 |

The SPG specification developed in TxDOT Project 0-1710 was further developed and field validated as part of NCHRP Project 14-17, *Manual for Emulsion-Based Chip Seals for Pavement Preservation (Hoyt, Martin, & Shuler, 2010; Shuler, 2011)*. In addition, one new emulsion residue recovery method, namely the force draft oven method, was compared with the stirred can and hot oven methods to specify a standardized recovery method for use with the SPG specification. In this project, eight emulsions and five base binders were characterized using both the standard PG system and the original SPG system (Amy L. Epps, 2001; Barcena et al., 2002; L. F. Walubita & Martin, 2005; L. F. Walubita et al., 2005) and some additional DSR and chemical tests. Notably, strain sweep testing was investigated in this project as a possible addition to the SPG system for evaluating strain tolerance and resistance to aggregate loss of chip seals with emulsion residues during curing and at early ages. Strain sweeps and their correlation with the sweep test, ASTM D7000 (ASTM 2009), had been investigated elsewhere (Kucharek, 2007) for evaluating the potential of emulsions to resist aggregate loss during curing immediately after chip seal construction.

Based on these results, researchers developed a modified SPG emulsion residue specification (Hoyt et al., 2010). The strain sweep thresholds were selected to reflect the significantly different performance of two of the emulsions tested. Based on the recovery methods evaluated in their project, the researchers recommended the stirred can emulsion residue recovery method for use with this proposed specification. They also recommended that strain sweeps be performed with the DSR on curing and unaged emulsion residues to evaluate strain resistance and stiffness development. These tests can be used to predict when emulsion-based chip seals will develop enough stiffness to be opened to traffic. Strain sweeps could also be used to assess a material's resistance to aggregate loss, both in newly constructed chip seals and after the critical first seasons of weather and aging. However, the appropriate test parameters and the performance criteria should be refined further.

Researchers recommended that further field validation of the SPG specification thresholds, shown in Table 2, in regions other than Texas is needed before the specification for SPG can be approved and used at a national level. Moreover, evaluation of the available emulsion residue recovery methods was suggested to determine which of these most closely simulates emulsion residue in the field and to address possible destruction or change in any polymer networks in many commonly used modified emulsions during recovery. The possibility of replacing low-temperature testing using the BBR with an alternative test that measures G* at low temperatures directly was also a recommended improvement.

**Table 2. Modified SPG Specification.**

| Only three SPG grades are shown, but the grades are unlimited and can be extended in both directions of the temperature spectrum using 3° and 6°C increments for the high-temperature and low-temperature grades, respectively. | **Performance Grade** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **SPG 64** | | | | **SPG 67** | | | | **SPG 70** | | | |
| | **−12** | **−18** | **−24** | **−30** | **−12** | **−18** | **−24** | **−30** | **−12** | **−18** | **−24** | **−30** |
| Average 7-day Maximum Surface Pavement Design Temperature, °C | <64 | | | | <67 | | | | <70 | | | |
| Minimum Surface Pavement Design Temperature, °C | >−12 | >−18 | >−24 | >−30 | >−12 | >−18 | >−24 | >−30 | >−12 | >−18 | >−24 | >−30 |
| Original Binder | | | | | | | | | | | | |
| Dynamic Shear, AASHTO T315 /ASTM D7175 *G*/Sin δ*, Minimum: 0.65 kPa Test Temperature @ 10 rad/sec, °C | 64 | | | | 67 | | | | 70 | | | |
| Shear Strain Sweep % strain @ $0.8G_i^*$, Minimum: 25 Test Temperature @ 10 rad/sec linear loading from 1–50% strain, 1 sec delay time with measurement of 20–30 increments, °C | 25 | | | | 25 | | | | 25 | | | |
| Pressure Aging Vessel Residue (AASHTO PP1) | | | | | | | | | | | | |
| PAV Aging Temperature, °C | 100 | | | | 100 | | | | 100 | | | |
| Creep Stiffness, AASHTO T313 /ASTM D6648 S, Maximum: 500 MPa m-value, Minimum: 0.240 Test Temperature @ 8 sec, °C | -12 | -18 | -24 | -30 | -12 | -18 | -24 | -30 | -12 | -18 | -24 | -30 |
| Shear Strain Sweep $G_i^*$, Maximum: 2.5 MPa Test Temperature @ 10 rad/sec linear loading at 1% strain and 1 sec delay time, °C | 25 | | | | 25 | | | | 25 | | | |

The modified SPG specification developed in NCHRP 14-17 was revised and further validated by TxDOT Project 0-6616 with 30 randomly selected chip seal highway sections constructed in 2011 (Vijaykumar et al., 2012). Two residue recovery methods, AASHTO PP72-11 Procedure A, Force Draft Oven, and Procedure B, Texas Oven Method, were employed to obtain emulsion residues in this project. These two methods were evaluated in terms of water removal efficiency and oxidative aging using gel permeation chromatography (GPC) and FTIR, respectively. Based on the comparison of the carbonyl areas calculated from the FTIR spectra and DSR high-temperature results, the Texas oven method (AASHTO PP 72-11 Procedure B) is recommended for the SPG specification with similar performance to residue obtained in the field and faster.

The possibility of predicting the BBR test parameters—stiffness (S) and m-value—from parameters measured using the DSR frequency sweep test was explored in this project. The frequency sweep test in the DSR was performed on PAV-aged samples to obtain the complex modulus and phase angle values from which the BBR parameters were predicted using equations proposed in SHRP Report A-369 (Anderson et al., 1994). However, a poor correlation between the compared S and m-values was found because of the unreliability of the predictive equations at the very low BBR temperatures for loading times of less than 60 sec.

For about 67 percent (20/30) of the 2011 HSs, the SPG binder grade predictions based on the laboratory results and temperature criteria proposed in the modified SPG specification (Table 2) were correlated with field performance. Additionally, many sections exhibited adequate field performance, although their corresponding binders did not meet the recommended strain sweep criteria that was developed using a limited dataset in the modified

SPG specification (Table 2). With the data available from more than 25 HSs in the study, the SPG strain sweep limit was revised to 17.5 percent to reflect the strain tolerance of chip seal binders in the field, shown in Table 3. Further, the m-value was removed from the revised and further-validated SPG specification due to the lack of correlation of laboratory failures for the m-value at low temperatures and field results, and the difficulties associated with accurately predicting this parameter from DSR frequency sweep testing.

**Table 3. Revised and Further-Validated SPG Specification.**

| Only three SPG grades are shown, but the grades are unlimited and can be extended in both directions of the temperature spectrum using 3°C increments for the high-temperature and low-temperature grades | Performance Grade | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SPG 64 | | | | SPG 67 | | | | SPG 70 | | | |
| | −13 | −16 | −19 | −22 | −13 | −16 | −19 | −22 | −13 | −16 | −19 | −22 |
| Average 7-day Maximum Surface Pavement Design Temperature, °C | <64 | | | | <67 | | | | <70 | | | |
| Minimum Surface Pavement Design Temperature, °C | >−13 | >−16 | >−19 | >−22 | >−13 | >−16 | >−19 | >−22 | >−13 | >−16 | >−19 | >−22 |
| Original Binder | | | | | | | | | | | | |
| Dynamic Shear<br>AASHTO T315/ASTM D7175<br>$G^*/\sin\delta$, Minimum: 0.65 kPa<br>Test Temperature @ 10 rad/sec, °C | 64 | | | | 67 | | | | 70 | | | |
| Dynamic Shear Strain Sweep<br>% strain @ $0.8G_i^*$, Minimum: 17.5<br>Test Temperature @ 10 rad/sec linear loading from 1–50% strain, 1 sec delay time with measurement of 20–30 increments, °C | 25 | | | | 25 | | | | 25 | | | |
| Pressure Aging Vessel Residue (AASHTO R30) | | | | | | | | | | | | |
| PAV Aging Temperature, °C | 100 | | | | 100 | | | | 100 | | | |
| Creep Stiffness<br>AASHTO T313/ASTM D6648<br>S, Maximum: 500 MPa<br>Test Temperature @ 8 sec, °C | −13 | −16 | −19 | −22 | −13 | −16 | −19 | −22 | −13 | −16 | −19 | −22 |
| Shear Strain Sweep<br>$G_i^*$, Maximum: 2.5 MPa<br>Test Temperature @ 10 rad/sec linear loading at 1% strain and 1 sec delay time, °C | 25 | | | | 25 | | | | 25 | | | |

## 2.2 ADDITIONAL PROPOSED TESTING

### 2.2.1 Linear Amplitude Sweep Test

The LAS test is an accelerated binder fatigue test that has been proposed to replace the current DSR intermediate temperature G*sin δ parameter in the PG grading system. The G*sin δ parameter is based on the assumption that asphalt binders in pavements function in the linear-viscoelastic range and are, therefore, insensitive to strain levels. These assumptions have long been challenged, especially as modified asphalts have been shown to exhibit increased fatigue resistance and nonlinear strain response. Recently, the LAS test has been approved by AASHTO as a provisional standard and is currently being considered for specification of asphalt binder fatigue resistance based on using viscoelastic continuum damage (VECD) mechanics to predict binder fatigue life as a function of strain in the pavement (Hintz, Velasquez, Johnson, & Bahia, 2011). The LAS test is a cyclic torsion test conducted in DSR that uses increasing loading amplitudes to accelerate damage and provides sufficient data for analysis in less than 30 min.

Recent ruggedness testing efforts have shown that the LAS test cannot be conducted by all DSRs. A simpler amplitude ramping procedure was evaluated to resolved the difficulties encountered with some rheometers (Hintz & Bahia, 2013). However, the results showed that there were challenges in achieving the abrupt stepped increases in strain required in the current LAS test procedure because of the limitations of most standard DSRs. Therefore, the loading sequence of the LAS test was recommended to be modified to include small increments in loading amplitude for every cycle. This resolves issues with compliance with DSR capabilities and eliminates crack tip conditioning, which occurs each time a load is incremented abruptly.

### 2.2.2 Predicting Low-Temperature Properties of Asphalt Binders

The AASHTO T313-02 protocol employing a BBR is the most common test method used to determine the low-temperature PG grade for asphalt binders. The AASHTO PP42 protocol, which employs a dual-instrument approach, BBR, and direct tension testing, is also used to determine a limiting low temperature, referred to as the critical cracking temperature. These two test methods, however, require large amounts of material for testing and relatively high temperatures (above 135°C) for preparing specimens. In addition, these methods are time consuming in terms of molding the test specimens.

A new technique using 4-mm parallel plates with a DSR combined with a machine compliance correction has been successfully developed at the Western Research Institute (WRI) with the support of the Turner–Fairbank Highway Research Center for measuring low-temperature properties of asphalt binders with small amounts of material (Sui, Farrar, Tuminello, & Turner, 2010).

The shear stress relaxation modulus, G(t), and its apparent relaxation rate, $m_r$, at 2 hr and at the true low PG temperature, collected from stress relaxation master curves, were correlated with the corresponding creep stiffness, S(t), and its apparent creep rate, $m_c$, at 60 sec and 10°C above the true low PG temperature from BBR measurements. A strong linear relationship was observed for stiffness, S(t), and relaxation modulus, G(t), as well as $m_c$ and $m_r$ based on data from six asphalt binders, as Figure 1 and Figure 2 illustrate (Sui et al., 2010). This new technique is a reliable, fast, and simple test method to obtain low-temperature rheology of asphalt binders.

The important features of this new technique are that it requires small-scale sampling and low-temperature sample preparation. The most direct method to determine low-temperature specification criteria using the 4-mm diameter plate DSR technique is to evaluate the correlation between BBR data and DSR data. This technique was found to have the potential to replace BBR for testing the low-temperature properties of all binders (Sui, Farrar, Harnsberger, Tuminello, & Turner, 2011).

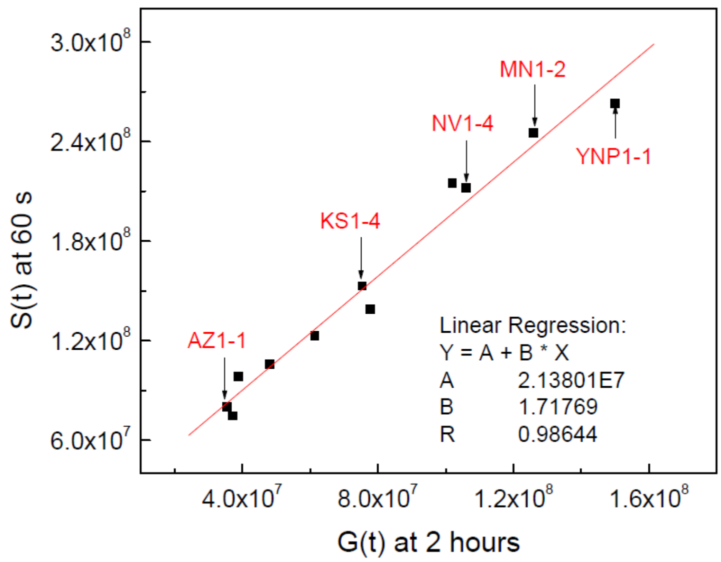



**Figure 1. S(t) at 60 sec from BBR vs. G(t) at 2 hr by 4-mm DSR.**

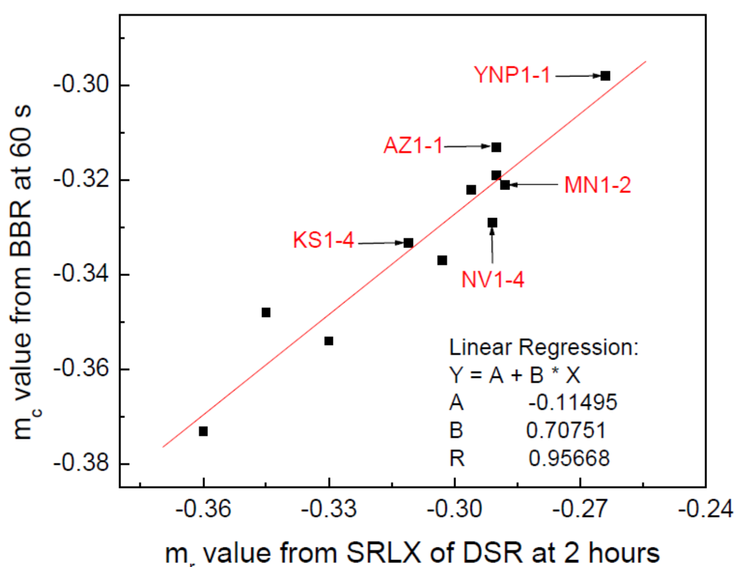



**Figure 2. $M_c$ Values at 60 sec from S(t) vs. $M_r$ Values at 2 hr from G(t) by 4-mm DSR.**

## 2.3 SUMMARY

This literature review described several methods for the evaluation and characterization of chip seal binders. Previous studies have identified aggregate loss and bleeding as the most commonly observed distresses in surface treatments (Amy L. Epps, 2001; L. Walubita et al., 2004). These distresses could be the result of improper construction, design, or materials. Based on the information from the literature review, the basic DSR and BBR tests, strain sweep test, and shear strain test were utilized to characterize the chip seal binders. Moreover, the PAV method, which is the laboratory method included in the PG specification for simulating long-term aging, was selected for use in the SPG specification.

The LAS test was recently developed as an accelerated binder fatigue test that has been proposed to replace the current DSR intermediate temperature G*sin δ parameter in the PG grading system. It also could be a potential test to replace the strain sweep test property in the SPG specification for determining the response of chip seal binders to increasing stress and therefore getting an indication of the material's susceptibility to linear application of loading instead of the step-by-step application commonly obtained with standard DSR devices at intermediate temperatures.

The 4-mm plate DSR frequency sweep test was identified as a potential method to evaluate the low-temperature properties of asphalt binders with less material and time. A strong linear relationship was observed for stiffness, S(t), and relaxation modulus, G(t), as well as $m_c$ and $m_r$, which indicated this 4-mm DSR method was evaluated as a replacement for the traditional BBR test for the characterization of the binder properties associated with brittleness and aggregate loss at low temperatures.

By using a combination of methods proposed in the literature to characterize the chip seal binders, this study was aimed at achieving statewide implementation of the SPG specification for the first year in the project.

# 3. EXPERIMENTAL DESIGN

The implementation of the SPG specification involves the following main tasks:

- SPG requirement grade determination.
- Chip seal binder collection.
- Highway section selection.
- Field performance monitoring.
- Laboratory testing and data synthesis.

The binders reported here were collected from 2013 statewide chip seals. The HS selection involved the identification of sections from those chip seals. Field performance monitoring involved the inspection of the selected HSs for visible surface distresses and pavement performance evaluation. The laboratory testing discussed in this chapter included laboratory aging to simulate 1 year of aging in the field, existing SPG tests, and exploring the exclusive use of the DSR for characterizing chip seal binders.

## 3.1 THE SPG GRADE REQUIREMENT MAP

Similar to the PG for hot mix asphalt guidance implemented nationwide, a SPG grade requirement map with 1–2 grades per TxDOT district was developed in this study to provide a tool for adequately selecting the type of hot-applied asphalt or emulsion to be used in chip seal projects in different climatic zones. This map was developed only for climate consideration, but the SPG grade requirement could increase high end or decrease low end based on traffic considerations, etc. The SPG grade requirement map was initially developed by using worst-case surface pavement temperatures within each county statewide starting from 95 percent confidence and rounding to the nearest 3°C increment, as shown in Figure 3.

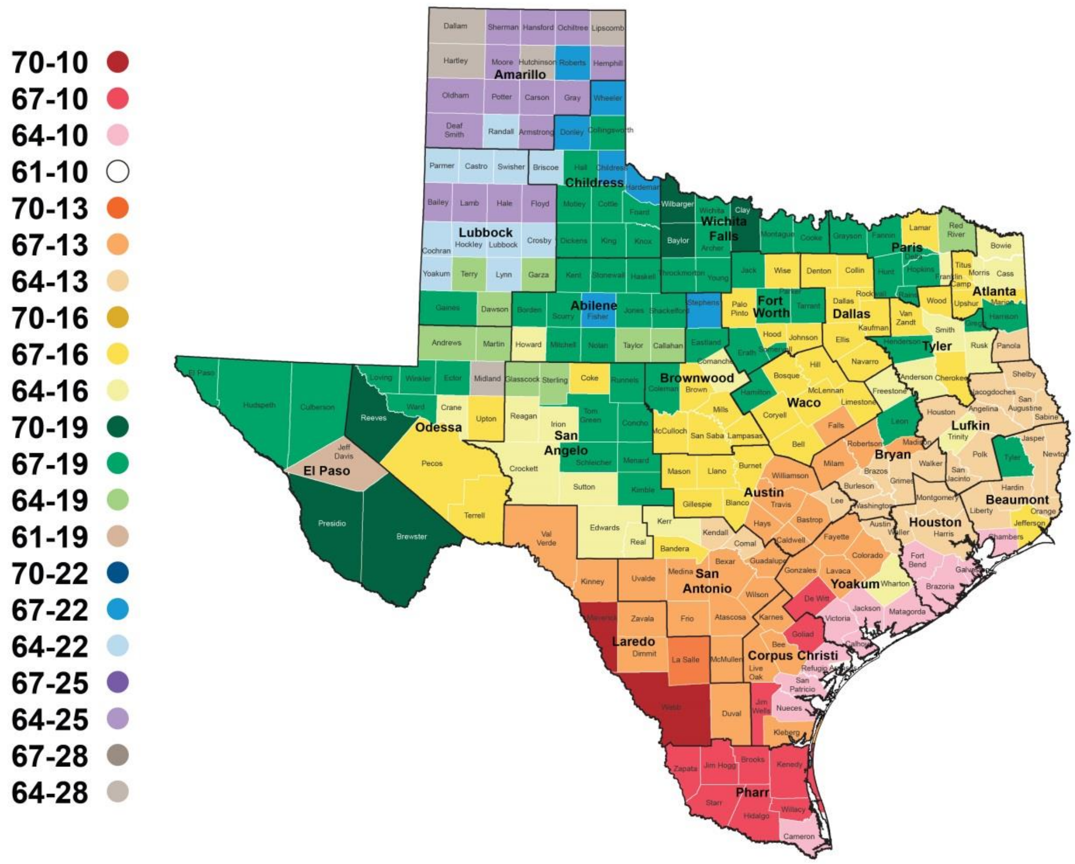



**Figure 3. The Draft SPG Grade Requirement Map.**

However, this draft map with more than 20 different SPG grades was considered impractical to be used for chip seal binder selection. According to Figure 3, most districts had one or two counties that had different SPG grades from the majority of others. For example, the SPG grades of Hamilton County (SPG 67-19) and Falls County (SPG 67-13) are different from the primary SPG grade (67-16) in the Waco District. This could result in more than three different grades for each district. Therefore, practical considerations were utilized to change to stricter grades (increased high temperature and/or decreased low temperature) and minimize the number of grades to 1–2 per district. Furthermore, SPG 67-10 in warm districts, such as Corpus Christi, Pharr, and Yoakum, was combined with SPG 67-13 because this low-temperature grade was not found in any previous chip seal binder characterization results in TxDOT Project 0-1710 and TxDOT Project 0-6616 or any 2013 chip seal binder characterization results (discussed in Chapter 4).

Figure 1 shows the finalized SPG requirement map subsequently developed. A majority of counties in south, central, and west Texas require 67°C for high SPG environmental demand, and colder districts like Amarillo and Lubbock require 64°C. The low SPG environmental requirement grade moves from southeast to northwest Texas statewide in three-degree increments from −13°C to −25°C.

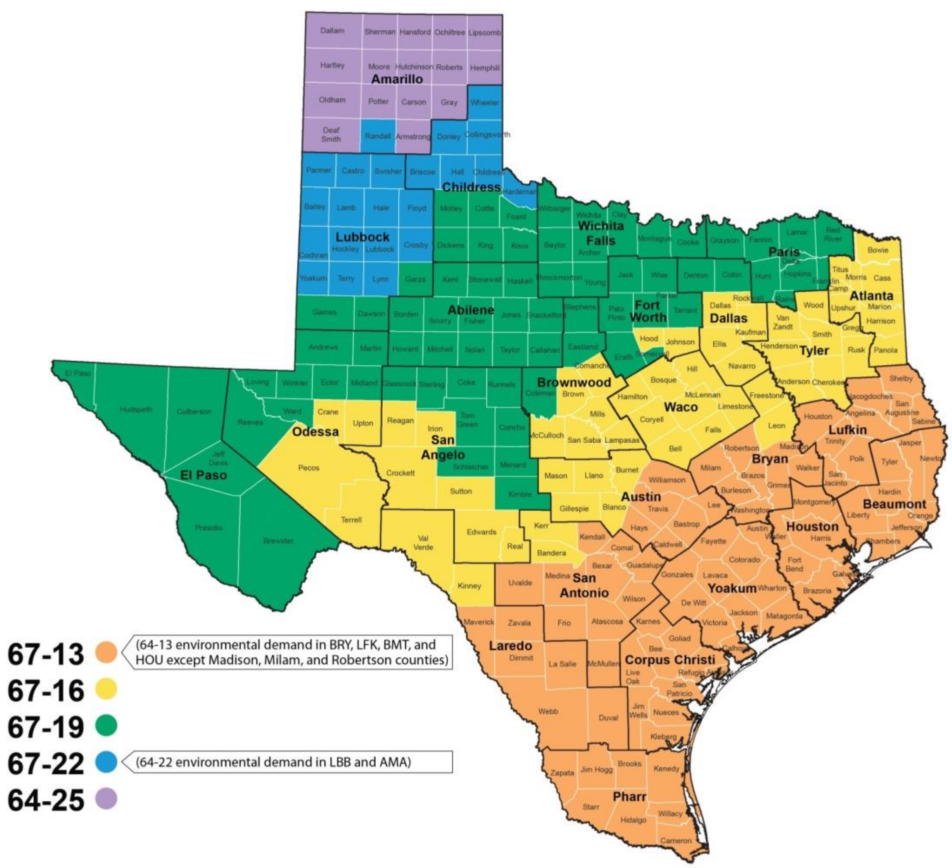



**Figure 4. The Finalized SPG Grade Requirement Map.**

## 3.2 ASPHALT BINDER COLLECTION

The chip seal binders in this study could not be collected by researchers during construction due to contract delay at the start of this study. This delay also resulted in the failure of collection of emulsions used for chip seals in this study because immediate recovery after construction was not possible. Consequently, hot-applied asphalt cements collected and characterized in this study were delivered from TxDOT district laboratories from their district-wide chip seal programs. The binder information was recorded, including binder type, supplier, sampled date, district, and highway section. In total, 29 chip seal binders encompassing six different binder types (AC10, AC10-2TR, AC15P, AC20-5TR, AC20XP, and A-R type II) from 15 TxDOT districts were collected, as shown in Table 4. Each binder was assigned an identifier with a three-letter abbreviation for the specific district plus a serial number (i.e., AMA-1).

All of the 29 collected chip seal binders used in district-wide programs in 2013 were characterized by the revised and further-validated SPG specification (Table 3). The detailed testing methods for the SPG specification are introduced in this chapter. The binder characterization results were used to produce a chip seal binder utilization map for Texas by TxDOT district. This utilization map was then compared to the SPG grade requirement map (Figure 4) to determine the ability of currently used binders to meet the SPG specification.

**Table 4. 2013 Chip Seal Binder Inventory.**

| 2013 Chip Seal Binder Inventory | | | | | | | |
|---|---|---|---|---|---|---|---|
| **District** | **Code** | **County** | **Hwy** | **Binder Type** | **Binder Source** | **Month (sampled)** | **Month (stored)** |
| Amarilo | AMA-1 | Gray | IH 40 | AC20-5TR | - | - | 9/13 |
| | AMA-2 | Hartlee | FM 767 | AC10 | Valero | 8/13 | 9/13 |
| | AMA-3 | Hemphill | FM 2124 | AC10-2TR | Missouri Petroleum | 7/13 | 9/13 |
| | AMA-4 | Hemphill | FM 277 | AC20-5TR | NuStarWright Big Spring | 7/13 | 9/13 |
| Atlanta | ATL-1 | Bowie | FM 1000 | AC20-5TR | Lion | 6/13 | 9/13 |
| | ATL-2 | Cass | FM 1735 | AC20-5TR | Lion | 6/13 | 9/13 |
| Brownwood | BWD-1 | San Saba | FM 1480 | AC10-2TR | - | 6/13 | 9/13 |
| Bryan | BRY-1 | Freestone | SH 164 | AC20XP | - | 6/13 | 9/13 |
| Corpus Christi | CRP-1 | Bee | US 59 | AC 15P | Valero | 6/13 | 9/13 |
| | CRP-2 | Live Oak | FM 1203 | AC15P | Valero | 7/13 | 9/13 |
| El Paso | ELP-1 | Hudspeth | US 62 | A-R Type II | Cox | 6/13 | 9/13 |
| Lubbock | LBB-1 | Hale | FM 400 | AC20-5TR | - | 6/13 | 9/13 |
| | LBB-2 | Floyd | FM 1958 | AC10-2TR | Alon Big Spring | 6/13 | 9/13 |
| | LBB-3 | Yoakum | SH 214 | AC20-5TR | - | 7/13 | 9/13 |
| | LBB-4 | Yoakum | FM 769 | AC10-2TR | - | 7/13 | 9/13 |
| | LBB-5 | Lubbock | FM 1585 | AC20-5TR | - | 7/13 | 9/13 |
| Lufkin | LUF-1 | Polk | US 190 | AC20-5TR | Martin | 7/13 | 9/13 |
| | LUF-2 | Sabine | FM 1592 | AC15P | Martin | 6/13 | 9/13 |
| Odessa | ODA-1 | Ward | B120-D | AC10-2TR | - | 6/13 | 9/13 |
| Pharr | PHR-1 | - | - | AC15P | Valero Corpus Christi | - | 9/13 |
| San Angelo | SJT-1 | Concho | SH 208 | AC10-2TR | Alon | - | 9/13 |
| | SJT-2 | Concho | US 83 | AC20-5TR | Alon | - | 9/13 |
| | SJT-3 | Concho | US 83 | AC10 | Alon | - | 9/13 |
| San Antonio | SAT-1 | Gradalupe | - | AC15P | Valero Corpus Christi | 6/13 | 9/13 |
| | SAT-2 | Atascosa | IH 37 | AC20-5TR | Martin | 8/13 | 9/13 |
| Tyler | TYL-1 | Van Zandt | SH 110 | AC20-5TR | - | 7/13 | 9/13 |
| Waco | WAC-1 | Mclennan | FM 2311 | AC15P | - | - | 9/13 |
| | WAC-2 | Bell | FM 2410 | AC20-5TR | - | 7/13 | 9/13 |
| Wichita Falls | WFS-1 | - | US 380 | AC10-2TR | Wright Heartland | 6/13 | 9/13 |
| "-" Represents the lack of specific information | | | | | | | |

## 3.3 LABORATORY EXPERIMENT DESIGN

The aim of this study was to implement the SPG specification for chip seal binders in service statewide in Texas for both hot-applied asphalt cements and emulsion residues, as well as to explore the exclusive use of DSR for determining performance-related properties and to further field validate binder properties that control chip seal performance in service. Unfortunately, emulsion residues could not be tested due to a delayed project start date. A set of rheological tests and SPG grading were performed on samples of chip seal binders, collected during the application of chip seals for the selected HSs, to meet the research objectives. Table 5 shows the details of the laboratory evaluation carried out as part of this study.

**Table 5. Test Plan.**

| Test | | Conditions | Result Recorded |
|---|---|---|---|
| DSR | Dynamic Shear | High temp; 10 rad/sec | $G^*/\sin\delta$ |
| | Shear Strain Sweep | 25°C; 10 rad/sec linear loading from 1–50% strain, 1 sec delay time and 20–30 measurements | %strain @ 0.8 $G_i^*$ |
| | Linear Amplitude Sweep | 25°C; 10 Hz, loading increase linearly from 0–30% within 310 sec | %strain @ 0.8 $G_i^*$; %strain @ peak stress |
| PAV @ 100°C, 20 hr | | | |
| DSR | Shear Strain Sweep | 25°C; 10 rad/sec linear loading from 1–50% strain, 1 sec delay time and 20–30 measurements | $G_i^*$ |
| | Frequency Sweep | 6°C; frequency range of 0.15 to 23.9 Hz; 1% strain, 10 sec time delay | $G^*$, $\delta$ with loading time |
| | Frequency Sweep with 4-mm Plate | Low temp; frequency range of 0.1–50 rad/sec with linear strain | $G^*$, $\delta$ with loading time |
| BBR | Low-Temperature Creep Stiffness | Low temp; 8 sec loading time | Stiffness |

### 3.3.1 Aging

Rolling thin-film oven 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 were aged in the PAV for 20 hr at 100°C to simulate approximately 1 year of environmental exposure for chip seals in Texas. This 1-year time period is critical to ensure adequate performance for chip seal binders (Cindy Estakhri, 2003).

### 3.3.2 Existing SPG Tests

*Basic DSR Test and BBR Test*

The high- and low-temperature performances of each binder were evaluated by DSR and BBR tests, respectively, in this study. A Malvern/Bohlin DSR-II with 25-mm plates and 1-mm gap was used for high-temperature binder testing and SPG grading. In this test, the complex shear modulus, G*, and phase angle, δ, of unaged binders are measured at temperature grade increments of 3°C to obtain the highest temperature at which G*/sin δ is at least 0.65. These high-temperature properties are important to ensure aggregate retention and to prevent bleeding in chip seal binders at high temperatures. DSR testing provides the upper limit of the binder grade, which represents the average 7-day maximum pavement surface design temperature. Furthermore, the BBR test was performed at an 8-sec loading time to simulate traffic loading for PAV-aged binders at the low surface pavement temperature limit. The stiffness (S) was measured at temperature grade increments of 3°C to obtain the lowest temperature at which the maximum S is 500 MPa. The m-value, another parameter in the BBR test, was removed from the revised and further-validated SPG specification according to the lack of correlation of laboratory failures for the m-value at low temperatures and field results, and the difficulties associated with accurately predicting this parameter from DSR frequency sweep testing (Vijaykumar et al., 2012).

*DSR Strain Sweep Test*

The DSR strain sweep test at an intermediate temperature of 25°C was also performed to assess the strain susceptibility and resistance to aggregate loss of unaged chip seal binders. Strain sweep testing was conducted on the standard DSR with 8-mm plates and a 2-mm gap. A thermal equilibrium time of 10 min was allowed after mounting the sample and before the test began. The loading frequency used in the test was 10 rad/sec (1.59 Hz), as specified by the Superpave system. Twenty measurements were recorded at various strain levels ranging from 1 to 50 percent. This range was selected to capture the full range of strain levels that most binders tested in this study can resist. A delay time of 1 sec was applied after the application of each strain level, but before the measurement was recorded, to allow the sample to attain equilibrium at the strain level. In cases where the DSR was incapable of reaching a 50 percent strain level (due to insufficient torque when testing stiffer materials), all measurements after the maximum stress was reached were recorded at or very near that maximum stress point.

*DSR Shear Strain Test*

The shear strain test was performed on PAV-aged binders to assess the strain susceptibility and resistance to aggregate loss by using standard DSR with 8-mm plates and a 2-mm gap. The PAV aging is designed to simulate the 1-year aging for chip seal binders in service, which is considered the most critical time for adequate field performance. The PAV-aged binder was tested at 1 percent strain with 10 rad/sec frequency at an intermediate temperature of 25°C. Also, a 10-min thermal equilibrium time was applied after mounting the sample and before the test began.

### 3.3.3 Exclusive Use of DSR for Characterizing Chip Seal Binders

*DSR Frequency Sweep Test at 6°C*

In the revised and further-validated SPG specification, the BBR test is the only rheological test not performed using the DSR. As part of this study, the possibility of predicting the BBR creep stiffness from parameters measured using the DSR frequency sweep test was explored to possibly remove the BBR test from the SPG specification. Also, the frequency sweep test requires about one-fifth the amount of material required in the BBR test. The frequency sweep test in the DSR was performed to obtain the complex modulus and phase angle values from which the BBR stiffness was predicted. Subsequently, the predicted and measured values of stiffness were compared to ascertain the fit of the prediction model. Frequency sweeps were performed on PAV-aged binder samples with 8-mm plates and a 2-mm gap in the DSR at frequencies ranging from 1 to 150 rad/sec (0.15 to 23.9 Hz) and intermediate temperatures of 6°C, which was the lowest stable temperature that could be obtained in the DSR machine used in this study. The appropriate frequency for testing that enables the comparison of the DSR parameters with the BBR parameters was determined using Equation 1. Estimates of stiffness at 8-sec loading times, obtained from the complex modulus, G*, and phase angle, δ, using Equation 2, were compared to actual BBR measurements (Anderson et al., 1994).

$$T_d = [\frac{1}{273+T_s} - \frac{2.303 \times R \times \log(t_s \times \omega)}{250{,}000}]^{-1} - 273 \qquad \text{(Eq. 1)}$$

Where:
$T_d$ = test temperature for dynamic testing at frequency ω, °C.
$T_s$ = specified temperature for creep testing, °C.
R = ideal gas constant, 8.31 J/°K-mol.
$T_s$ = specified creep loading time, sec.
ω = dynamic testing frequency, rad/sec.

$$S(t) \approx \frac{3G^*(\omega)}{[1+0.2\sin(2\delta)]} ast \rightarrow \frac{1}{\omega} \quad \text{(Eq. 2)}$$

Where:
S (t) = creep stiffness at time, t, Pa.
$G^*(\omega)$ = complex modulus at frequency $\omega$, Pa.
$\delta$ = phase angle at frequency $\omega$, Pa.

*Linear Amplitude Sweep Test*

In general, the main objective from previous research carried out with the LAS test was to derive the fatigue law from viscoelastic materials; however, this objective was beyond the scope of this research. Instead, the use of the LAS test was explored as an alternative for determining the response to increasing strain of chip seal binders and therefore getting an indication on the material's susceptibility to linear application of loading instead of the step-by-step application commonly obtained with regular DSR devices at intermediate temperatures. In addition, the possibility of replacing the DSR shear strain sweep with the LAS test was explored.

The LAS test was performed using the research advanced DSR (Malven Kinexus pro), as shown in Figure 5, and the test used the same configuration and sample size as the DSR strain sweep test (8-mm plates with a 2-mm gap). The loading scheme consisted of a continuous oscillatory strain sweep with 10 Hz frequency, as shown in Figure 6. Strain was increased linearly from zero to 30 percent over the course of 3,100 cycles of loading for a total test time of 310 sec. Peak shear strain and peak shear stress were recorded every 10 load cycles (1 sec), along with phase angle ($\delta$, degrees) and complex shear modulus ($|G^*|$, Pa).


**Figure 5. The Research Advanced DSR.**

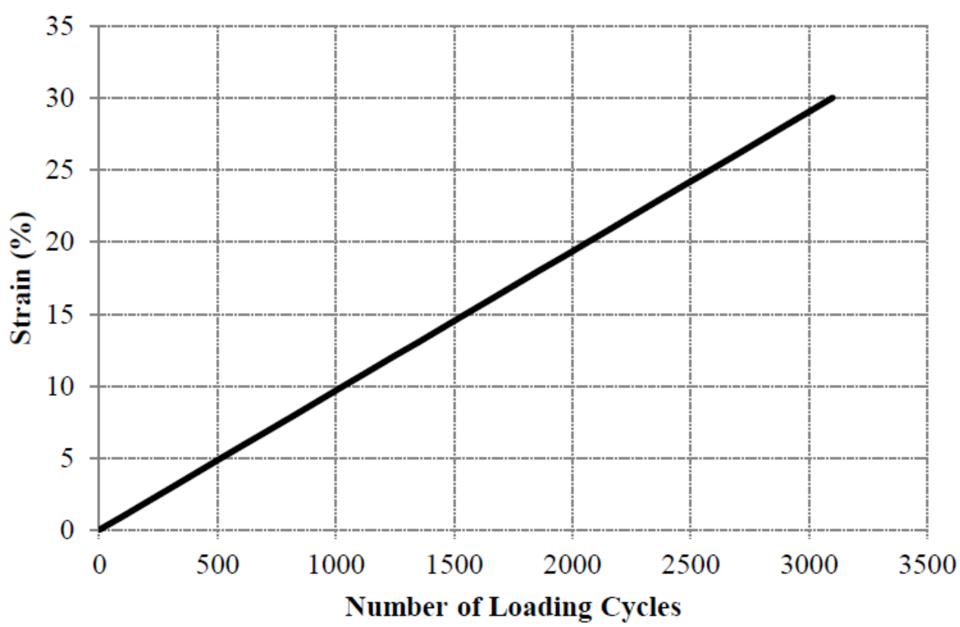



**Figure 6. Loading Scheme for Linear Amplitude Sweep Test.**

*4-mm DSR Frequency Sweep*

The possibility of using 4-mm plate DSR testing to determine low-temperature properties from frequency sweep results (−40ºC to 0ºC) was explored in this study. This test was aimed at determining the dynamic shear modulus and phase angle of asphalt binders when applying dynamic shear using parallel plate test geometry at low temperatures. This test was performed on the research advanced DSR (Figure 5) with testing sequence provided by WRI. Researchers utilized 4-mm diameter parallel metal plates with a 1.75-mm gap in this test. A frequency sweep was performed on PAV-aged binders in a frequency range of 0.1 to 50 rad/sec with 15 steps, as shown in Table 6.

**Table 6. Frequency Sweep Steps for 4-mm DSR.**

| Frequency rad/sec | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.10 | 0.15 | 0.25 | 0.39 | 0.63 | 1.00 | 1.58 | 2.51 | 3.98 | 6.31 | 10.00 | 15.85 | 25.12 | 39.81 | 50.00 |

The relaxation modulus, G(t), was then determined through interconversion of the storage modulus, G'(ω), by the approximate expression developed by (Christensen, 2012).

$$G(t) \approx G'(\omega)_{\omega=2/\pi t} \qquad \text{(Eq. 3)}$$

## 3.4 FIELD EXPERIMENT DESIGN

This section introduces the highway section selection procedure in this study. The selected HSs were located in six districts and covered a range of materials, environments, and traffic conditions so that the implementation of the SPG specification would be achieved for the entire array of Texas conditions.

### 3.4.1 Highway Section Selection

Nineteen chip seal HSs from six districts (Amarillo [AMA], Atlanta [ATL], Corpus Christi [CRP], San Angelo [SJT], San Antonio [SAT], and Tyler [TYL]) constructed in 2013 were selected for this study. The HSs were labeled with a three-letter TxDOT district abbreviation and a serial letter (i.e., AMA-a) and ordered alphabetically by districts, as shown in Table 7. The factors considered in selecting these sections were the binder or modifier type, traffic volume, aggregate type, and SPG environmental zones (Figure 4). Each selected section was evaluated in terms of the SCI developed in TxDOT Project 0-1710. For each HS, the researchers also collected information on the binder application rate, aggregate gradation and application rate, existing pavement surface, embedment depth, and truck percentage. Because of the project start delay, the binders used in each HS were not directly collected in the field by researchers. Therefore, the selection of corresponding binders used in the HSs was based on the matching district, binder type, and supplier, and collected from the same or nearest county.

## Table 7. Selected Sections.

| 2013 HS ID | Dist | County | Hwy | BRM | ERM | Len (mi) | Binder Type | Binder Rate | Agg Type | AADT 2013 | %Trk | Embedment Depth | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | Wheel Paths | Between Wheel Paths |
| AMA-a | Armarillo | Hartley | FM0767 | 236-0.002 | 272+0.599 | 36.6 | AC10 | 0.44 | PB GR 4 | 143 | 53 | 18 | 10 |
| AMA-b | Armarillo | Hutchinson | FM1551 | 318+1 | 320+1.254 | 3.2 | AC10-2TR | 0.37 | PB GR 4 | 3180 | 4.3 | 35 | 30 |
| AMA-c | Armarillo | Gray | IH0040R | 115+0.418 | 118+0.905 | 3.5 | AC20-5TR | 0.48 | PB GR 4S | 6182 | 45.9 | 25 | 10 |
| AMA-d | Armarillo | Hansford | SH0136 | 12-0.051 | 28+1.911 | 17.9 | AC10-2TR | 0.39 | PB GR 4 | 398 | 33.1 | 47 | 20 |
| AMA-e | Armarillo | Armstrong | SH0207 | 120+0.0 | 124+0.895 | 4.9 | AC10-2TR | 0.34 | PB GR 4 | 614 | 25.6 | 28 | 13 |
| AMA-f | Armarillo | Roberts | US0060 | 398+0.0 | 412+0.0 | 14.0 | AC10-2TR | 0.27 | PB GR 4 | 2474 | 32.2 | 28 | 20 |
| AMA-g | Armarillo | Moore | US0287R | 50+0.0 | 58+0.583 | 8.5 | AC20-5TR | 0.46 | PB GR 4S | 3236 | 42.4 | 75 | 60 |
| ATL-a | Atlanta | Harrison | US0080 | 810+1.180 | 818+1.155 | 7.4 | AC20-5TR | 0.32 | PB GR 4 | 4629 | 8.1 | 57 | 33 |
| ATL-b | Atlanta | Harrison | FM0134 | 262+2.587 | 274+0.113 | 8.0 | AC20-5TR | 0.29 | PB GR 4 | 674 | 22.6 | 20 | 13 |
| ATL-c | Atlanta | Marion | FM3001 | 718-0.052 | 726+0.012 | 6.5 | AC20-5TR | 0.3 | PB GR 4 | 463 | 28 | 13 | 10 |
| CRP-a | Corpus Christi | Jim Wells | FM0665 | 520+01.349 | 522+1.5 | 2.0 | AC15P | 0.293 | PC GR 3 | 10100 | 7.9 | 53 | 48 |
| CRP-c | Corpus Christi | San Patricio | FM2046 | 598+00.614 | 600+00.610 | 2.0 | AC15P | 0.306 | PC GR 3S | 335 | 11.6 | 10 | 10 |
| CRP-d | Corpus Christi | San Patricio | FM2512 | 558-00.048 | 558+01.964 | 2.0 | AC15P | 0.31 | PC GR 3 | 530 | 11.5 | 22 | 18 |
| SAT-a | San Antonio | Guadalupe | FM0621 | 528+0.00 | 532+0 | 9.9 | AC15P | 0.33 | PB GR 4 | 3912 | 28.1 | 55 | 38 |
| SAT-b | San Antonio | Kendall | SH0046 | 482+1.600 | 492+1.62 | 10.1 | AC15P | 0.31 | PB GR 4 | 8600 | 21.5 | 57 | 30 |
| SJT-a | San Angelo | Runnels | FM1692 | 360+1.013 | 364+0.936 | 3.0 | AC10-2TR | 0.42 | PB GR 3 | 470 | 5.8 | 58 | 32 |
| SJT-b | San Angelo | Sterling | SH0158 | 354+4.703 | 372+0.0 | 12.8 | AC10-2TR | 0.44 | PB GR 3 | 726 | 22 | 53 | 23 |
| SJT-c | San Angelo | Coke | US0087L | 436+0.0 | 442+0.0 | 4.6 | AC20-5TR | 0.43 | PB GR 3 | 2315 | 17.1 | 88 | 40 |
| TYL-a | Tyler | Rusk | US0259L | 300+0.0 | 304+0.0 | 4.9 | AC20-5TR | 0.33 | PD GR 4 | 6550 | 15.6 | 38 | 25 |

### 3.4.2 Binder Type

Binder type was the primary factor in both the development and initial validation process of the SPG specification. Six different types of hot-applied asphalt cements were collected in 2013 chip seal statewide programs. The field experimental design sampled four of the most commonly used hot-applied asphalt cements (Table 8) utilized by TxDOT.

**Table 8. Binder Types.**

| # | Designation | Binder | Brief Description |
|---|---|---|---|
| 1 | B1 | AC10 | Asphalt cement with minimum 1000 poises viscosity at 60°C. |
| 2 | B2 | AC10-2TR | Asphalt cement with minimum 1000 poises viscosity at 60°C, modified with 2% tire rubber. |
| 3 | B3 | AC15P | Asphalt cement with minimum 1500 poises viscosity at 60°C, modified with a polymer. |
| 4 | B4 | AC20-5TR | Asphalt cement with minimum 2000 poises viscosity at 60°C, modified with 5% tire rubber. |

### 3.4.3 Traffic Volume

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 9.

**Table 9. Traffic Tiers.**

| Traffic Tier | Thresholds |
|---|---|
| T1 | AADT>5000 |
| T2 | 1000≤AADT≤5000 |
| T3 | AADT<1000 |

### 3.4.4 Aggregate Types

The aggregate types in this study were defined by TxDOT Item 302—Aggregates for Chip Seals—as shown in Table 10. The aggregate gradation was also recorded in this study based on aggregate gradation requirements provided by TxDOT Item 302, shown in Table 11.

**Table 10. 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 11. Aggregate Gradation Requirements (Cumulative Percent Retained[1]).**

| Sieve | Grade | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3S[2] | 3 Non-lightweight | 3 Lightweight | 4S[2] | 4 | 5S[2] | 5 |
| 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.

### 3.5 FIELD PERFORMANCE MONITORING

The 2013 field sections were surveyed using a visual survey technique from the long-term pavement performance distress identification manual (Miller & Bellinger, 2014) and analyzed to determine SCI score by the specific procedure developed in TxDOT Project 0-1710 (L. F. Walubita & Martin, 2005; L. F. Walubita et al., 2005). Examples of a field performance monitoring survey sheet (Figure 7) and a distress evaluation sheet (Figure 10) are provided subsequently in this section.

#### 3.5.1 Test Section Selection

Consistent with the previous TxDOT Project 0-1710 and TxDOT Project 0-6616, a test section was defined as a representative subsection of a field section with an area of approximately 5000 to 7000 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 also increases safety. The survey was conducted from the shoulder or edge of the pavement to make traffic control easier.
- Intersections, access road junctions, grades, and curves were avoided to minimize the effects of extremely slow and turning traffic, which could exaggerate distress, and 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 (TRMs) were also gathered and tabulated for each field section.

### 3.5.2 Distresses

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

*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 7. Low, moderate, and high severity levels were identified, consistent with the SHRP distress identification manual (FHWA 2003), as shown in Table 12.

**Table 12. 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 bituminous 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 13.

**Table 13. 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. |

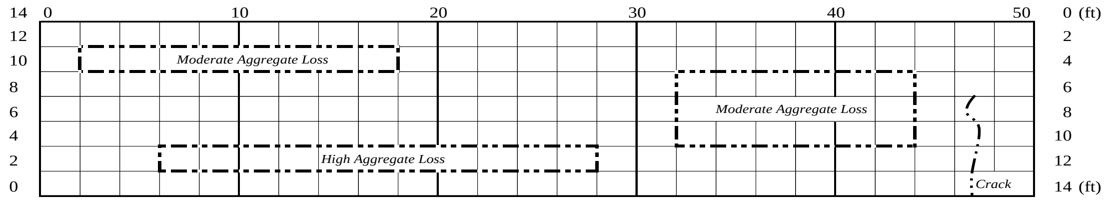
*Cracking—Transverse and Longitudinal*

Transverse (perpendicular to the pavement centerline) and longitudinal (parallel to the pavement centerline) cracks were not the primary focus in this study, but these distresses were recorded and reported in the analysis.

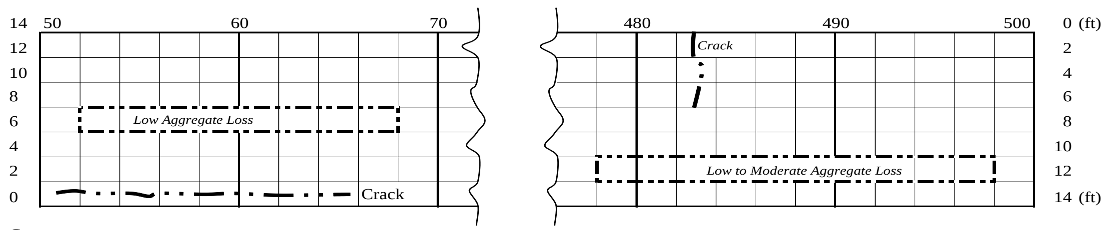
**COMPLETED FIELD PERFORMANCE MONITORING SURVEY**

**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 (DSD): | ***300%*** |

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

**Figure 7. Example Field Performance Monitoring Survey Sheet.**

### 3.5.3 Performance Evaluation and Rating Criteria

The SCI methodology and criterion was mostly consistent 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 4.

$$SCI_{Distress}=0.5(P_{DAC}+P_{DSD}) \quad \text{(Eq. 4)}$$

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 8 and Figure 9. However, the %Area and %Severity in those scales are determined by personal judgment, which results in subjective $P_{DAC}$ and $P_{DSD}$ scores. In order to avoid this issue, a quantitative approach to determine the %Area and %Severity for each distress based on the field evaluation data was developed in this study, as shown in Equation 5 and Equation 6. This approach enabled the evaluation of field performance to be more objective and consistent.

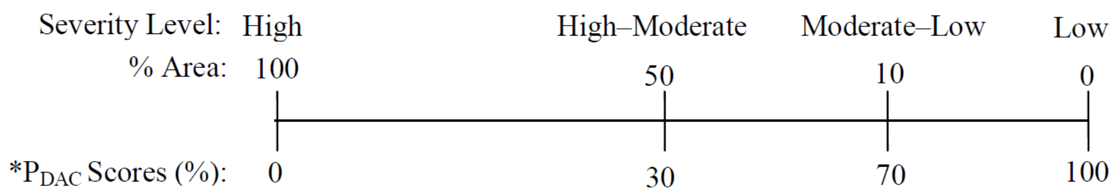



**Figure 8. SCI Distress Evaluation and Scores—Distress Area Coverage.**

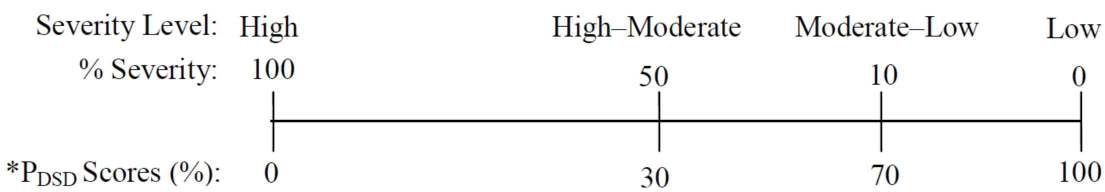



**Figure 9. SCI Distress Evaluation and Scores—Degree of Severity of Distress.**

$$\%Area = \frac{Area_{Low}+Area_{Medium}+Area_{High}}{Area_{Total}} \qquad \text{(Eq. 5)}$$

$$\%\text{Severity}=\frac{\text{Area}_{\text{Low}}}{\text{Area}_{\text{Dis}}}\times\left(\frac{\text{Area}_{\text{Low}}}{\text{Area}_{\text{Total}}}\times 10+0\right)+\frac{\text{Area}_{\text{Medium}}}{\text{Area}_{\text{Dis}}}\times\left(\frac{\text{Area}_{\text{Medium}}}{\text{Area}_{\text{Total}}}\times 40+10\right)+\frac{\text{Area}_{\text{High}}}{\text{Area}_{\text{Dis}}}\times\left(\frac{\text{Area}_{\text{High}}}{\text{Area}_{\text{Total}}}\times 50+50\right) \qquad \text{(Eq. 6)}$$

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.
$\text{Area}_{\text{Low}}$ = 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.
$\text{Area}_{\text{Dis}}$ = the total area for a given distress in evaluation section.
$\text{Area}_{\text{Total}}$ = the total area in evaluation section.

The $\text{SCI}_{\text{overall}}$ is a weighted average of the individual SCI scores for aggregate loss and bleeding, $\text{SCI}_{\text{AL}}$ and $\text{SCI}_{\text{BL}}$, respectively, with relative weights of 80 percent for aggregate loss and 20 percent for bleeding. Cracking and other distresses were not taken into account as principal distresses for chip seals in this study, as illustrated in Equation 7 and Equation 8. As shown in Table 14, field performance results were categorized on the basis of SCI scores with a threshold of 70 percent (SCI $\geq$ 70 percent for adequate overall performance

[$Pass_{Field}$] and SCI < 70 percent for inadequate overall performance [$Fail_{Field}$]). 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.

$$SCI = [\alpha_{AL} \times SCI_{AL}] + [\alpha_{BL} \times SCI_{BL}] + \cdots + [\alpha_{Distress} \times SCI_{Distress}] \quad \text{(Eq. 7)}$$

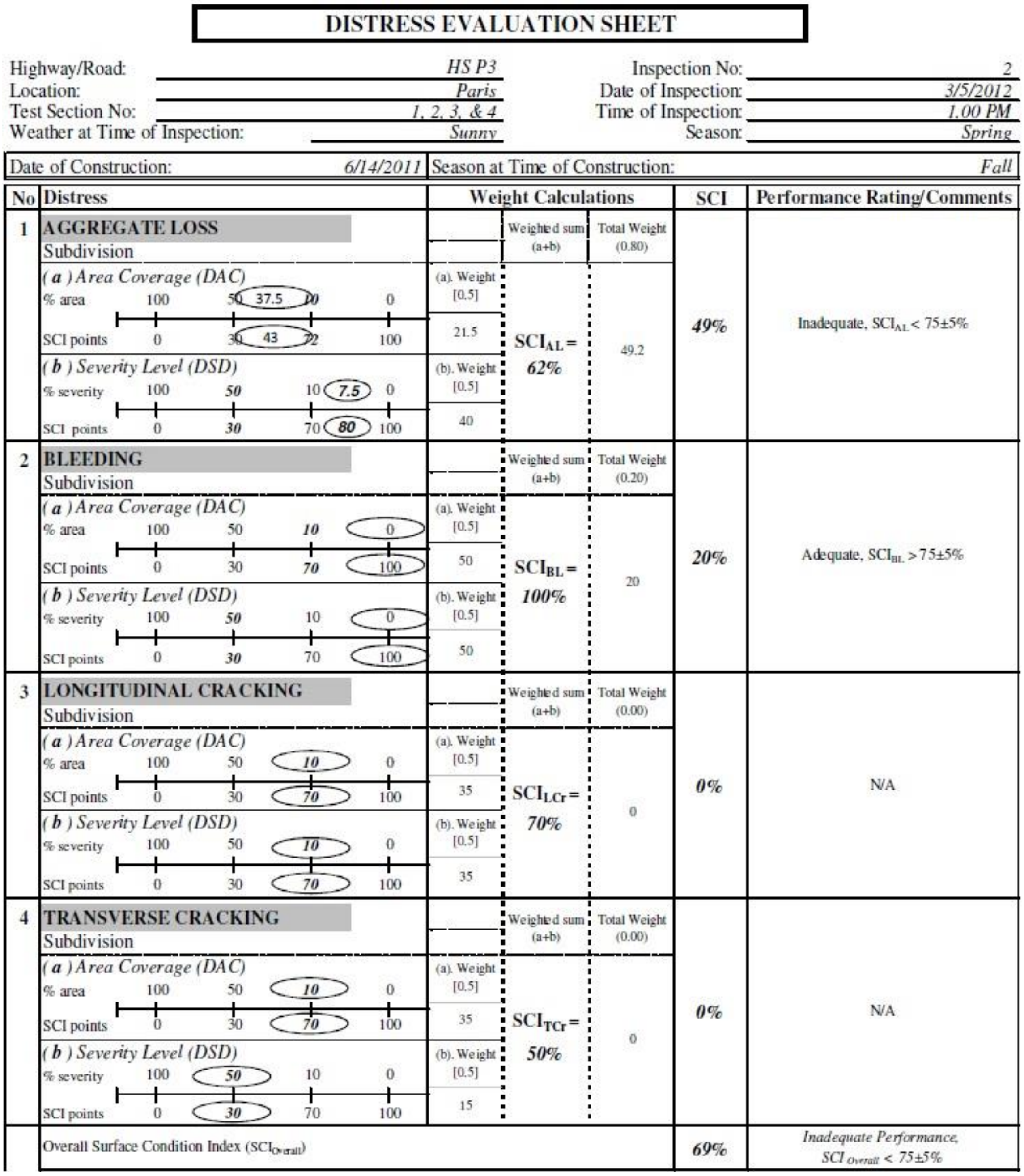
$$\alpha_{AL} + \alpha_{BL} + \cdots + \alpha_{Distress} = 1.00 \quad \text{(Eq. 8)}$$

Where:

SCI = overall field section SCI score as a percentage.
$SCI_{AL}$ = SCI score for aggregate loss as a percentage.
$SCI_{BL}$ = SCI score for bleeding as a percentage.
$SCI_{Distress}$ = SCI score for other distresses as a percentage.
$\alpha_{AL}$ = distress weighting factor for aggregate loss (~0.80).
αBL = distress weighting factor for bleeding (~0.20).
αDistress = distress weighting factors for other distresses (~0.00).

**Table 14. 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) |



**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 | | Weighted sum (a+b) | Total Weight (0.80) | 49% | Inadequate, $SCI_{AL} < 75 \pm 5\%$ |
| | *(a) Area Coverage (DAC)* % area: 100, 50, 37.5, 20, 0 / SCI points: 0, 30, 43, 72, 100 | (a). Weight [0.5] 21.5 | $SCI_{AL}$ = 62% | 49.2 | | |
| | *(b) Severity Level (DSD)* % severity: 100, 50, 10, 7.5, 0 / SCI points: 0, 30, 70, 80, 100 | (b). Weight [0.5] 40 | | | | |
| 2 | **BLEEDING** Subdivision | | Weighted sum (a+b) | Total Weight (0.20) | 20% | Adequate, $SCI_{BL} > 75 \pm 5\%$ |
| | *(a) Area Coverage (DAC)* % area: 100, 50, 10, 0 / SCI points: 0, 30, 70, 100 | (a). Weight [0.5] 50 | $SCI_{BL}$ = 100% | 20 | | |
| | *(b) Severity Level (DSD)* % severity: 100, 50, 10, 0 / SCI points: 0, 30, 70, 100 | (b). Weight [0.5] 50 | | | | |
| 3 | **LONGITUDINAL CRACKING** Subdivision | | Weighted sum (a+b) | Total Weight (0.00) | 0% | N/A |
| | *(a) Area Coverage (DAC)* % area: 100, 50, 10, 0 / SCI points: 0, 30, 70, 100 | (a). Weight [0.5] 35 | $SCI_{LCr}$ = 70% | 0 | | |
| | *(b) Severity Level (DSD)* % severity: 100, 50, 10, 0 / SCI points: 0, 30, 70, 100 | (b). Weight [0.5] 35 | | | | |
| 4 | **TRANSVERSE CRACKING** Subdivision | | Weighted sum (a+b) | Total Weight (0.00) | 0% | N/A |
| | *(a) Area Coverage (DAC)* % area: 100, 50, 10, 0 / SCI points: 0, 30, 70, 100 | (a). Weight [0.5] 35 | $SCI_{TCr}$ = 50% | 0 | | |
| | *(b) Severity Level (DSD)* % severity: 100, 50, 10, 0 / SCI points: 0, 30, 70, 100 | (b). Weight [0.5] 15 | | | | |
| | Overall Surface Condition Index ($SCI_{Overall}$) | | | | 69% | *Inadequate Performance, $SCI_{Overall} < 75 \pm 5\%$* |

**Figure 10. Example Distress Evaluation Sheet.**

## 3.6 SUMMARY

This chapter defined the methods and factors used to select the HSs and the procedure for calculating the SCI scores during field performance monitoring of these HSs. The wide variety of laboratory testing methods employed to evaluate and characterize the binders used in each HS were also described. The field performance monitoring and laboratory results obtained using these methods are detailed and analyzed in Chapter 4.

# 4. RESULTS AND ANALYSIS

The results of the laboratory testing and field performance monitoring activities conducted in this study are discussed in this chapter. The laboratory test results and SCI field performance results are summarized in this chapter, with additional detail provided in the Appendix. Digital images of the selected HSs and the distresses observed in the field illustrate the discussion.

## 4.1 RE-ANALYSIS OF 2011 HIGHWAY SECTIONS

Before implementing the revised SPG specification for 2013 chip seal binders, the 2011 chip seal binders were reviewed by (a) re-grading chip seal binders by the revised and further-validated SPG specification (Table 3); (b) updating environmental demands for specific HSs based on the SPG grade requirement map (Figure 4); and (c) revising SCI scores from field performance monitoring by the improved SCI calculation methodology. The results of this review of the 2011 HSs are shown as Table 15.

Based on the results in Table 15, for 80 percent (24 of 30) of the 2011 HSs, the laboratory characterization results were correlated with the field performance monitoring results, which is better than the previous correlation results (67 percent) reported in TxDOT Project 0-6616. For all of these 30 HSs, 25 sections showed adequate field performance, and the SPG grade of 23 sections met the demands from the SPG environmental requirement map (Figure 4). Those sections that did not meet the environmental demand were primarily unmodified binders (AC10) and emulsions (CRS-2 and CRS-2P). Twenty percent (6 of 30) of the 2011 HSs lacked correlation between the laboratory and field performances, which may have been caused by (a) limited BBR testing data from the previous study, with some low-temperature properties (S) extrapolated from the actual laboratory data; (b) high and low traffic volumes affecting field performance; and (c) construction issues such as improper material application rates and poor construction practices that were avoided as much as possible but could have affected field performance.

**Table 15. Reviewed Laboratory versus Field Results for 2011 HSs.**

| 2011 ID | Binder Type | Traffic (AADT) | SPG Environmental Requirement Grade | SPG Grade Measured | Phase Angle @ Continuous SPG Grade (°) | %Strain@ 0.8Gi* | G* @ 25°C (MPa) | Performance 1 Year after Construction | | | Correlation between field and lab (Yes-Y/No-N) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | $SCI_{AL}$ | $SCI_{BL}$ | SCI | |
| a-1 | AC20-5TR | 410 | 67-16 | 70-19* | 76.54 | 31 | 0.6 | 67 | 94 | 73 | Y |
| a-2 | AC20-5TR | 440 | 67-16 | 67-22* | 76.51 | 26 | 0.6 | 99 | 51 | 90 | Y |
| a-3 | AC20-5TR | 2867 | 67-16 | 73-19* | 77.08 | 30 | 0.6 | 77 | 88 | 79 | Y |
| a-4 | AC20-5TR | 2000 | 67-16 | 76-22* | 74.79 | 27 | 0.3 | 92 | 83 | 91 | Y |
| a-5 | AC20-5TR | 7550 | 67-16 | 70-22* | 77.32 | 29 | 0.7 | 97 | 40 | 85 | Y |
| a-6 | AC20-5TR | 7440 | 67-16 | 67-16* | 77.36 | 25 | 1.2 | 78 | 93 | 81 | Y |
| b-1 | CRS-2 | 270 | 67-19 | 61-10* | 86.49 | 14 | 1.6 | 63 | 76 | 65 | Y |
| b-2 | CRS-2 | 327 | 67-16 | 67-16* | 86.84 | Invalid | 1.5 | 51 | 100 | 61 | N |
| b-3 | CRS-2P | 2014 | 67-16 | 70-13* | 78.71 | 16 | 0.8 | 68 | 93 | 73 | N |
| b-4 | AC20-5TR | 2850 | 67-16 | 76-16 | 50.45 | 36 | 1.5 | 76 | 99 | 81 | Y |
| b-5 | AC20-5TR | 5700 | 67-16 | 76-16 | 49.86 | 32 | 1.3 | 76 | 81 | 77 | Y |
| b-6 | AC20-5TR | 5663 | 67-16 | 76-19* | 73.65 | Invalid | 1.1 | 76 | 88 | 78 | Y |
| c-1 | AC10 | 715 | 67-22 | 64-19* | 87.70 | 15 | 1.2 | 69 | 100 | 75 | N |
| c-2 | AC10 | 160 | 67-19 | 64-19* | 87.51 | 12 | 1.6 | 58 | 60 | 58 | Y |
| c-3 | AC10 | 70 | 67-22 | 64-13* | 87.42 | 15 | 1.3 | 61 | 99 | 69 | Y |
| l-1 | CRS-2P | 600 | 64-13 | 76-16 | 70.51 | 13 | 1.2 | 72 | 99 | 78 | Y |
| l-3 | AC20-5TR | 2582 | 64-13 | 73-19* | 77.93 | Invalid | 0.7 | 68 | 98 | 74 | Y |
| l-4 | AC20-5TR | 4400 | 64-13 | 73-19* | 77.99 | 25 | 1 | 100 | 64 | 93 | Y |
| l-6 | AC20-5TR | 5475 | 64-13 | 70-19* | 80.71 | 33 | 0.7 | 92 | 89 | 92 | Y |
| p-1 | CRS-2P | 250 | 67-19 | 73-16 | 77.35 | 13 | 0.6 | 77 | 89 | 80 | N |
| p-2 | CRS-2P | 310 | 67-19 | 70-16 | 75.71 | 15 | 0.9 | 93 | 99 | 94 | N |
| p-3 | AC20-5TR | 3900 | 67-19 | 76-19* | 77.42 | 26 | 0.8 | 66 | 99 | 72 | Y |
| p-4 | AC20-5TR | 2260 | 67-19 | 70-31* | 71.05 | 19 | 0.8 | 99 | 85 | 96 | Y |
| p-5 | AC20-5TR | 7100 | 67-19 | 67-22* | 76.18 | 17 | 0.8 | 75 | 83 | 76 | Y |
| p-6 | AC20-5TR | 5881 | 67-19 | 70-22* | 78.90 | 21 | 1 | 62 | 100 | 69 | N |
| s-2 | AC15P | 597 | 67-13 | 73-22* | 75.11 | 19 | 0.6 | 90 | 84 | 88 | Y |
| s-3 | AC15P | 2514 | 67-13 | 70-36* | 73.17 | 16 | 0.4 | 69 | 73 | 70 | Y |
| s-4 | AC15P | 2993 | 67-13 | 70-33* | 70.07 | 27 | 0.4 | 72 | 74 | 72 | Y |
| s-5 | AC15P | 5571 | 67-13 | 70-36* | 70.99 | 25 | 0.6 | 79 | 46 | 72 | Y |
| s-6 | AC15P | 7183 | 67-13 | 73-22* | 76.27 | 19 | 0.5 | 89 | 69 | 85 | Y |

*Low temp property (S) was extrapolated from the actual laboratory data

**NOTE:** Values in shaded cells correspond to failure in the laboratory test and inadequate performance in the field (noncompliance with the standard thresholds).

## 4.2 LABORATORY TEST RESULTS

Four types of laboratory tests (the basic DSR, strain sweep, frequency sweep, and BBR tests) were performed on the hot-applied binders collected from the 2013 statewide chip seal program HSs in this study. Of these, three tests (the basic DSR, strain sweep, and BBR tests) were used to grade the binders tested according to the revised and further-validated SPG specification (Table 3). The LAS test and 4-mm DSR test were only performed on selected typical chip seal binder samples. The detailed results of all laboratory tests performed in this study are presented in this section.

### 4.2.1 Binder SPG Grading Results

In the revised and further-validated SPG specification (Table 3), the G*/sin $\delta$ threshold value at the higher temperature limit was set at 0.65 kPa based on validation of experimental results in previous studies. The threshold value for maximum creep stiffness, S, measured in the BBR test was set at 500 MPa. The SPG grade of each binder tested was determined on the basis of these criteria.

As shown in Table 16, 69 percent (20 of 29) of the 2013 chip seal binders met the SPG environmental grade requirement based on the laboratory characterization results ($Pass_{Lab}$), which means their SPG grade satisfied the SPG environmental grade demand (Figure 4), whereas 31 percent (9 of 29) did not ($Fail_{Lab}$). Two binders that were unable to satisfy the high-temperature grade were the unmodified binders (AC10), and these two binders were not able to meet the low-temperature grade either. In contrast, modified binders (mostly AC10-2TR, AC15P, and AC20-5TR) generally met the environmental demand, sometimes sufficiently exceeding the required property, defined as Pass+ in Figure 11 and

Figure 12. Thus, modified binders were able to exhibit better performance than unmodified ones in the laboratory, in agreement with previous research (Walubita et al. 2004; Aishwarya et al. 2012). Binders that meet the environmental demand are supposed to exhibit adequate performance in the field to avoid aggregate loss and bleeding, while those that fail in the laboratory are expected to demonstrate inadequate performance in the field. Further, binders classified as the same type based on the current specification could exhibit different SPG grades because of differences in production, base binders, additives, and modifiers used (Aishwarya et al. 2012), which was also demonstrated in this study.

## Table 16. Laboratory Characterization Results for 2013 Chip Seal Binder.

| 2013 ID | Binder Type | SPG Environmental Requirement Grade | SPG Grade Measured | Phase Angle @ Continuous SPG Grade (°) | %Strain@ 0.8Gi* | G* @ 25°C (MPa) |
|---|---|---|---|---|---|---|
| AMA-1 | AC20-5TR | 64-25 | 73-19 | 77.52 | 38.38% | 1.54 |
| AMA-2 | AC10 | 64-25 | 61-19 | 88.84 | 26.71% | 1.56 |
| AMA-3 | AC10-2TR | 64-25 | 67-22 | 80.98 | 43.76% | 1.67 |
| AMA-4 | AC20-5TR | 64-25 | 73-19 | 75.76 | 36.71% | 1.31 |
| ATL-1 | AC20-5TR | 67-16 | 70-22 | 73.49 | 24.72% | 1.14 |
| ATL-2 | AC20-5TR | 67-16 | 70-25 | 74.53 | 21.44% | 1.06 |
| BWD-1 | AC10-2TR | 67-16 | 67-22 | 82.04 | 34.78% | 1.78 |
| BRY-1 | AC20XP | 67-16 | 73-19 | 75.68 | 41.61% | 1.62 |
| CRP-1 | AC15P | 67-13 | 70-28 | 75.78 | 21.34% | 0.909 |
| CRP-2 | AC15P | 67-13 | 76-28 | 71.39 | 23.46% | 0.76 |
| ELP-1 | A-R Type II | 67-19 | 79-25 | 55.05 | 13.91% | 0.85 |
| LBB-1 | AC20-5TR | 64-22 | 73-22 | 70.60 | 33.25% | 1.78 |
| LBB-2 | AC10-2TR | 64-22 | 64-16 | 85.30 | 34.89% | 1.91 |
| LBB-3 | AC20-5TR | 64-22 | 76-19 | 61.11 | 32.16% | 1.54 |
| LBB-4 | AC10-2TR | 64-22 | 67-16 | 81.26 | 35.51% | 2.08 |
| LBB-5 | AC20-5TR | 64-22 | 73-22 | 69.84 | 36.78% | 1.14 |
| LUF-1 | AC20-5TR | 64-13 | 70-22 | 74.22 | 31.32% | 1.08 |
| LUF-2 | AC15P | 64-13 | 67-25 | 69.39 | 22.87% | 0.79 |
| ODA-1 | AC10-2TR | 67-19 | 67-16 | 82.82 | 39.43% | 1.81 |
| PHR-1 | AC15P | 67-10 | 70-31 | 74.94 | 25.98% | 0.828 |
| SJT-1 | AC10-2TR | 67-19 | 67-19 | 83.11 | 29.88% | 2.6 |
| SJT-2 | AC20-5TR | 67-19 | 76-19 | 63.25 | 27.57% | 1.65 |
| SJT-3 | AC10 | 67-19 | 61-13 | 89.50 | 16.12% | 3.45 |
| SAT-1 | AC15P | 67-13 | 70-28 | 75.82 | 21.92% | 0.746 |
| SAT-2 | AC20-5TR | 67-13 | 73-25 | 81.30 | 23.67% | 1.52 |
| TYL-1 | AC20-5TR | 67-16 | 70-22 | 75.05 | 18.58% | 1.08 |
| WAC-1 | AC15P | 67-16 | 67-22 | 77.86 | 26.63% | 1.16 |
| WAC-2 | AC20-5TR | 67-16 | 73-22 | 73.12 | 17.72% | 1.48 |
| WFS-1 | AC10-2TR | 67-19 | 67-22 | 81.40 | 33.31% | 1.76 |

**NOTE:** Values in shaded cells correspond to failure in the laboratory test and inadequate performance in the field (noncompliance with the standard thresholds).

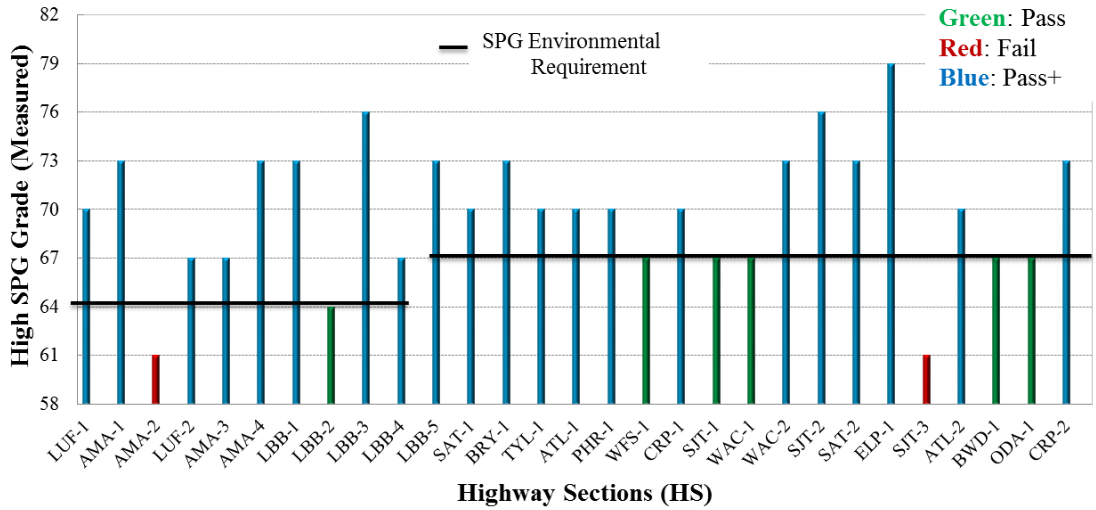



**Figure 11. High SPG Grades Measured vs. SPG Environmental Requirement.**

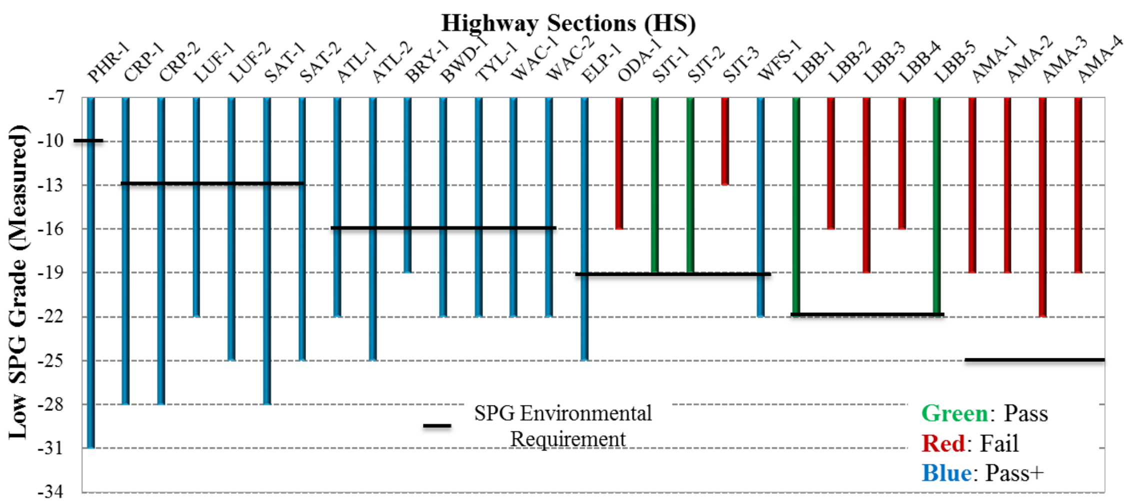



**Figure 12. Low SPG Grades Measured vs. SPG Environmental Requirement.**

*Effects of Binder Type on SPG Grading*

Generally, AC20-5TR materials, followed by AC15P and AC10-2TR, exhibited superior high SPG grades. The highest SPG grade temperature characterized for AC20-5TR binders was 76°C. On the other hand, AC15P materials exhibited better low SPG grades than AC20-TR and other binders. The lowest SPG grade temperature measured for AC15P was

−28°C. Unmodified AC10 binders exhibited inadequate performance at both high and low temperatures.

As shown in Table 17, binders classified as the same type based on current SPG specifications exhibited different grades and expected performance according to the SPG specification. For example, seven different SPG grades were measured for all the AC20-5TR chip seal binders collected in 2013 statewide chip seal programs. For these binders, the high SPG grade was in the range of 70°C to 76°C, while the low SPG grade ranged from −19°C to −25°C. This finding can be attributed to differences in base asphalt cement, additives, and modifiers used in production.

**Table 17. Difference in SPG Grade for Each Binder Type.**

| Asphalt Type | SPG Grade Measured |
|---|---|
| AC10 | 61-13, 61-19 |
| AC10-2TR | 64-16, 67-16, 67-19, 67-22 |
| AC15P | 67-22, 67-25, 70-28, 70-28, 76-28 |
| AC20-5TR | 70-19, 70-22, 70-25, 73-19, 73-22, 73-25, 76-19 |

*Introducing a Phase Angle Threshold for the SPG Specification*

A threshold for the phase angle at the interpolated continuous SPG grade, intended to ensure modified binders contain sufficient polymer, was suggested in this study. As Figure 13 shows, the phase angles at the interpolated continuous SPG grade of all the unmodified binders were larger than 85°C, whereas those for modified binders were less than 85°C. Further, the values decreased with an increased percentage of modifier or polymer. In order to ensure sufficient polymer in modified binders, researchers recommend adding a phase angle threshold of 80 to the SPG specification when the useful SPG temperature interval of the binder is greater than or equal to 89 (for example, SPG 67-22). This threshold requires the use of binders with a higher polymer content to obtain adequate field performance, especially in extreme hot or cold environmental zones.

Four binders from the 2013 chip seals were unable to satisfy this threshold, as shown in Table 16. One of these was AC20-5TR materials (SAT-2), and the other three were AC10-2TR materials (AMA-3, BWD-1, and WFS-1). All of these four binders were expected to exhibit inadequate performance in terms of aggregate loss or bleeding in the field.

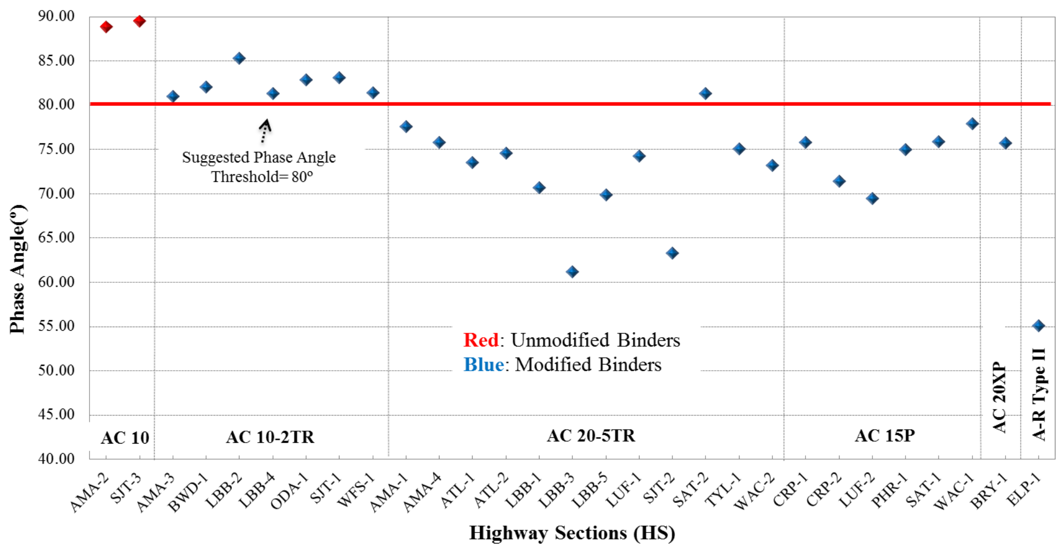



**Figure 13. Recommended Phase Angle Threshold for the SPG Specification.**

### 4.2.2 Strain Sweep Test Results

The strain sweep test was designed to evaluate whether the binder develops adequate strain tolerance and stiffness to prevent the bond between the aggregate and the binder from failing at intermediate temperatures. As shown in Figure 14, 27 of 29 collected binders from the 2013 HSs met the minimum SPG strain criteria (% $\gamma$ at $0.8G_i^*$ = 17.5 percent). Only two binders, ELP-1 (A-R type II) and SJT-3 (AC10), failed the strain sweep test at 13.91 percent and 16.12 percent, respectively, and thus these binders were not expected to exhibit adequate field performance in terms of aggregate loss.

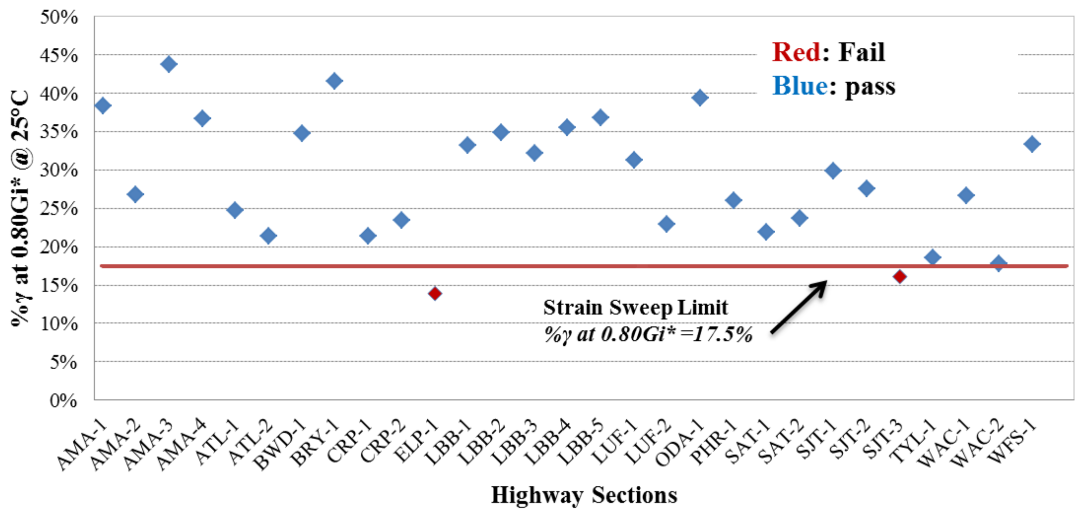



**Figure 14. Strain Sweep Test Results for Unaged Binders.**

Furthermore, Figure 15 illustrates that modified binders were found to have better strain tolerance, as indicated by higher strain at failure (20 percent reduction in G*), than unmodified binders. As can be seen in Figure 15, the modulus remains constant as the strain increases, until at some critical strain level, it drops significantly. This drop in G* value was more significant in less-modified binders (AC10-2TR) and unmodified binders (AC10).

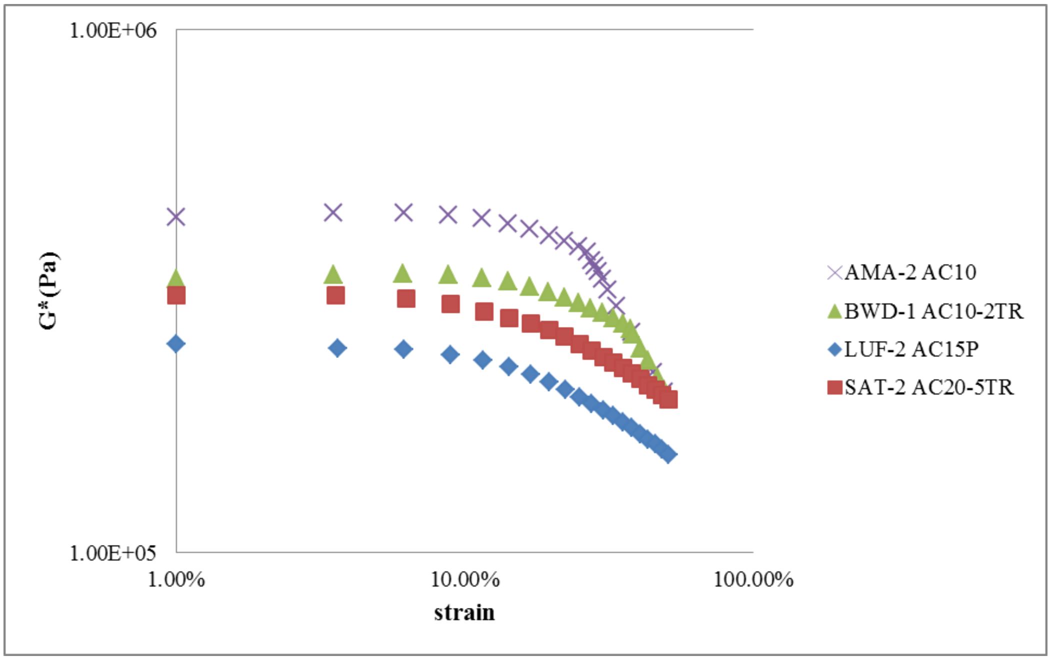



**Figure 15. Strain Sweep Test for Different Types of Binders.**

### 4.2.3 Shear Strain Test Results

The shear strain test was performed on PAV-aged chip seal binders to assess the resistance to aggregate loss for aged materials, as shown in Figure 16. Of the 29 PAV-aged binders tested, only two binders, SJT-1 (AC10-2TR) and SJT-3(AC10), failed the maximum G* criteria ($G_i$* = 2.5 MPa) and thus may have inadequate field performance in terms of aggregate loss after 1 year of aging in service.

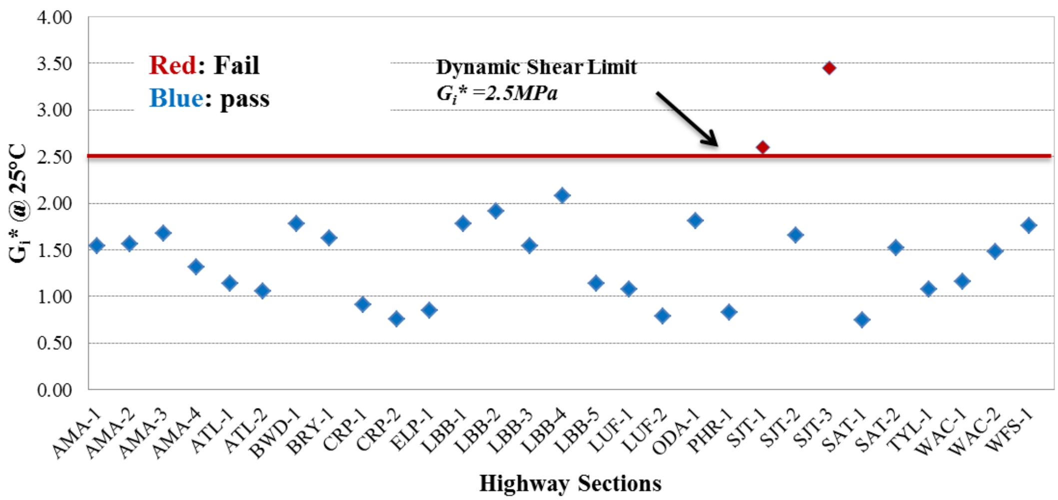



**Figure 16. Strain Sweep Test Results for PAV-Aged Binders.**

### 4.2.4 Frequency Sweep Test Results

Frequency sweep tests are specified in AASHTO T315 and were performed on PAV-aged binder samples using DSR testing to predict the BBR test parameter (creep stiffness). Correlation between the predicted S from the frequency sweep and measured S from the BBR test is shown in Figure 17. The overall correlation of the 29 binders tested in this study ended up being 0.3081, which was considered very poor for predicted versus measured S values.

Normally, these predictive equations are applied on PG binders and used to predict the stiffness and m-value for 60-sec loading times, not 8-sec loading times as used in this study. Furthermore, the BBR test temperatures for PG binders are normally limited in the range −6°C to −18°C, which corresponds to −16 to −28 low-temperature PG grade due to the 10°C shift for time-temperature superposition. However, this 10°C shift rule was not applied in the SPG specification to the BBR test temperatures because it is not applicable for chip seal binders with aggregate loss due to traffic at low temperatures.

Moreover, as depicted in Figure 18, Figure 19, and Figure 20, the reliability of the prediction became poorer along with the reduction in the test temperature. This finding could also be a result of the lack of applicability of the predictive equations developed in SHRP Report A-369 at the very low BBR temperatures utilized in this study.

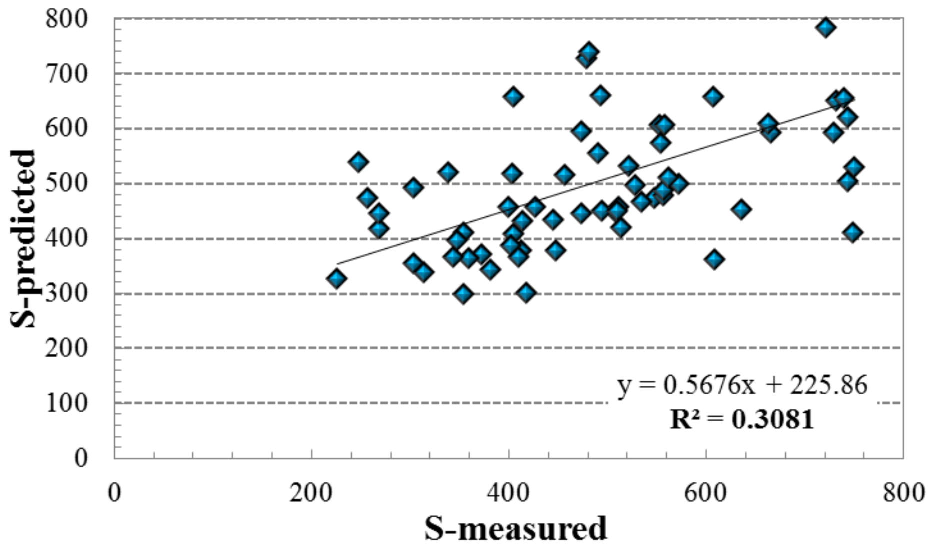



**Figure 17. Comparison of S-Measured and S-Predicted for Overall Correlation.**

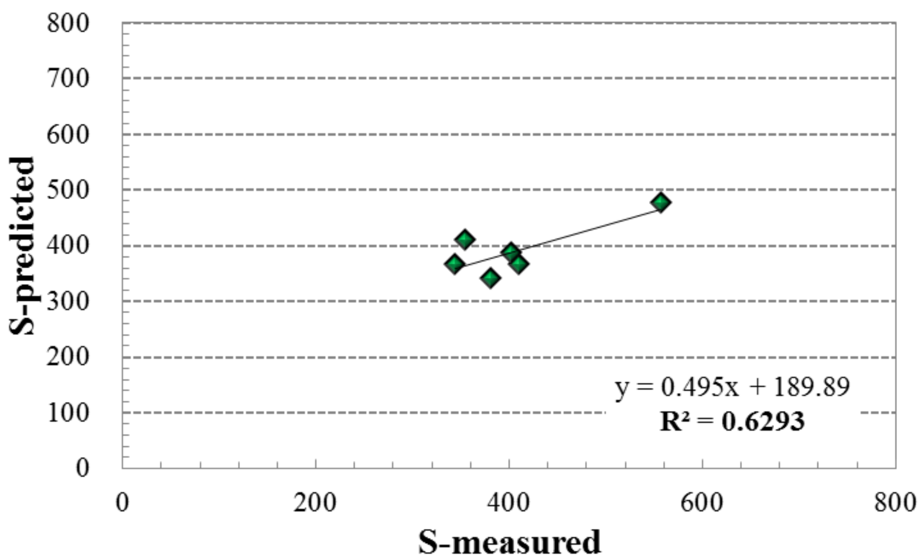



**Figure 18. Comparison of S-Measured and S-Predicted at −13ºC and −16ºC.**

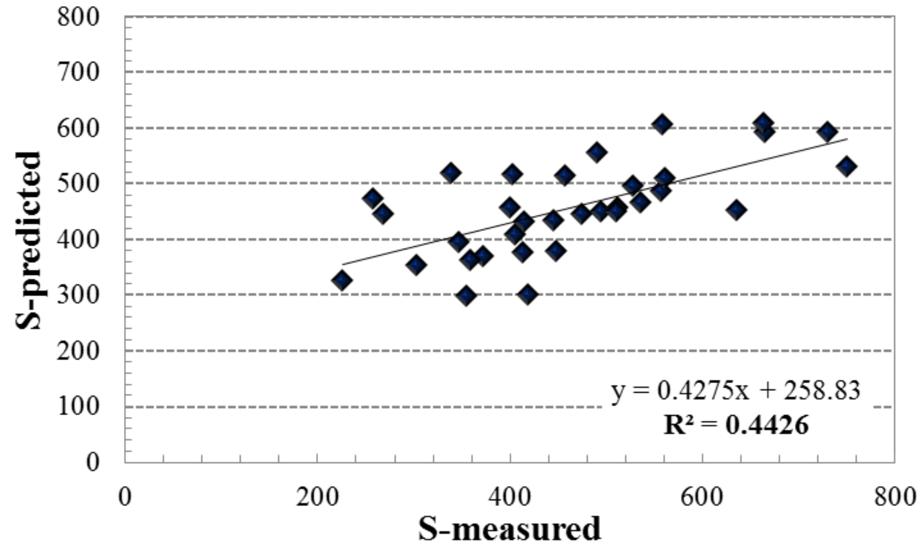



**Figure 19. Comparison of S-Measured and S-Predicted at −19ºC and −22ºC.**

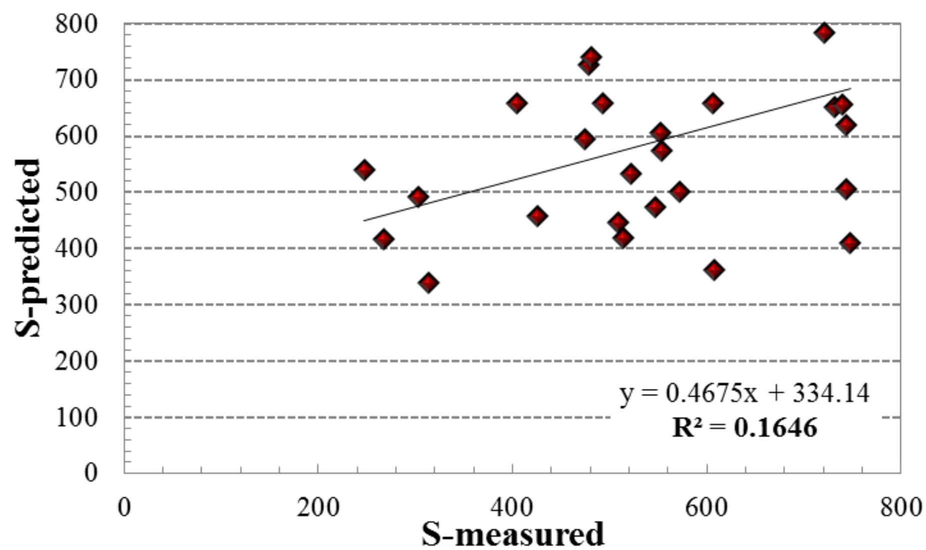



**Figure 20. Comparison of S-Measured and S-Predicted at −25ºC and −28ºC.**

### 4.2.5 Linear Amplitude Sweep Test Results

Researchers selected two AC 20-5TR binders (WAC-2 and TYL-1) as common materials in chip seals to explore the use of the LAS test. Figure 21 and Figure 22 present the main results. As depicted, TYL-1 had a slightly higher percent (i.e., 2.5 percent) strain at peak stress as compared to WAC-2. In this same regard, the percent strain at 0.8 G* was 3 percent higher for the same binder, which suggests a correlation between the two different properties. Further, as shown in Table 18, the results measured in the LAS test, both percentage strain at peak stress and percentage strain at 0.8 G*, were comparable to shear strain sweep test results. Therefore, it is possible to add an LAS test threshold—minimum 15 percent strain @ peak stress or minimum 5 percent strain @ 80 percent of initial complex modulus—to replace the shear strain sweep test threshold as part of the SPG specification to evaluate intermediate temperature properties of chip seal binders.

Nevertheless, due to the high cost of the advanced DSR equipment used for this test and the lack of access to this equipment, further research is still required for examining a more practical use of this test with conventional DSR equipment in order to replace or complement the shear strain sweep for reduced testing time and faster results.

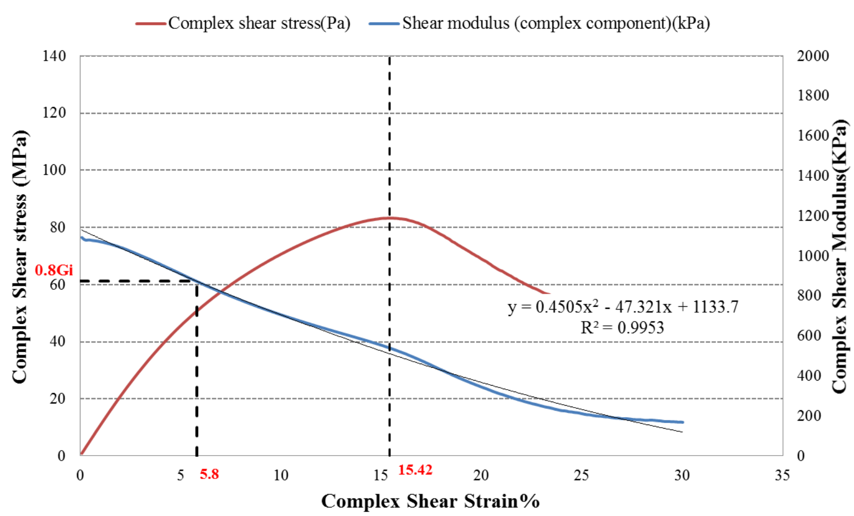



**Figure 21. Linear Amplitude Sweep Results for Binder TYL-1.**

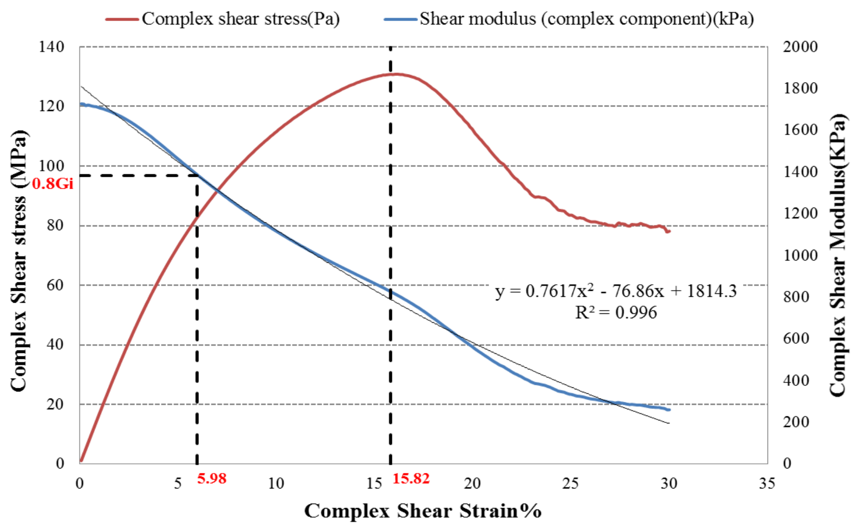



**Figure 22. Linear Amplitude Sweep Results for Binder WAC-2.**

**Table 18. Linear Amplitude Sweep versus Amplitude Sweep.**

| **2013 Binder ID** | **Amplitude Sweep** | **Linear Amplitude Sweep** | |
|---|---|---|---|
| | %strain @ 0.8 $G_i$ | %strain @ peak stress | %strain @ 0.8 $G_i$ |
| WAC-2 | 18.44 | 15.82 | 5.98 |
| TYL-1 | 18.58 | 15.42 | 5.8 |

### 4.2.6 4-mm DSR Test Results

Because of the unreliability of BBR S predictions using the equations from SHRP Report A-369, the possibility of using a 4-mm plate DSR to determine low-temperature properties from frequency sweep results (−40°C to 0°C) was explored. The correlation between measured and predicted stiffness found at −19°C and −21°C by means of 4-mm plate geometry were quite good, as shown in Figure 23. The predicted stiffness was estimated through an interconversion method from storage modulus (shear) to creep stiffness (bending) based on viscoelastic transformation. However, the prediction was not reliable at different testing temperatures. Nonetheless, more detailed studies are still required to validate this finding and propose additional equations suitable or predicting low-temperature stiffness.

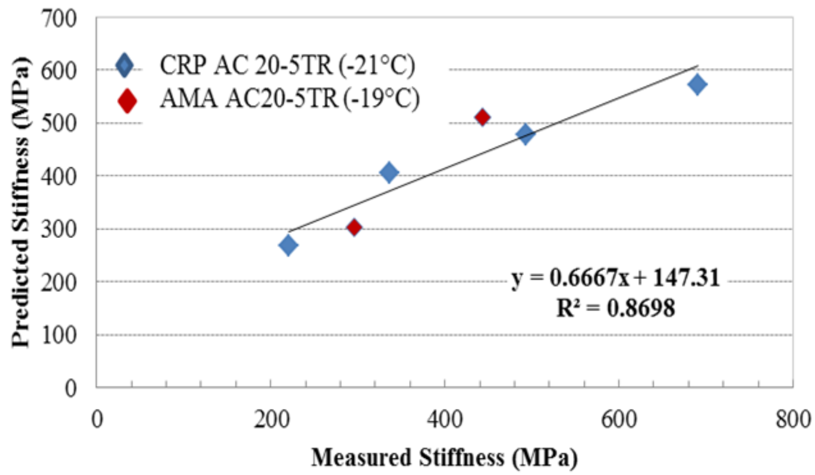



**Figure 23. Predicted Stiffness at $T_{low}$ Using 4-mm DSR Frequency Sweep Test.**

## 4.3 FIELD PERFORMANCE MONITORING RESULTS

Visual condition surveys were performed on the 19 selected HSs 1 year after construction. As depicted in Table 19, 84 percent (16 of 19) of the HSs exhibited adequate performance at 1 year after construction, whereas 16 percent (3 of 19) did not. Further, four HSs had inadequate resistance to aggregate loss, while only one HS exhibited inadequate resistance to bleeding. Comparing the performance between different kinds of aggregates used in chip seals was beyond the scope of this study, but most of the aggregates were precoated to prevent aggregate loss.

**Table 19. Laboratory versus Field Results for 2013 Chip Seal Binders.**

| 2013 HS | Traffic (AADT) | Binder Type | SPG Environmental Requirement Grade | SPG Grade Measured | G*/sin δ @ $T_{High}$ (kPa) | S @ $T_{low}$ (MPa) | Phase Angle @ Continuous SPG Grade (°) | %Strain @ 0.8Gi* | G* @ 25°C (MPa) | Performance 1 Year after Construction | | | Correlation between field and lab (Yes-Y/No-N) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | $SCI_{AL}$ | $SCI_{BL}$ | SCI | |
| AMA-a | 1280 | AC10 | 64-25 | 61-19 | 0.61 | 1055 | 88.84 | 27 | 1.56 | 72 | 89 | 75 | N |
| SJT-a | 3460 | AC10-2TR | 67-19 | 67-19 | 0.70 | 403 | 83.11 | 30 | 2.6 | 57 | 96 | 65 | N |
| SJT-b | 820 | AC10-2TR | 67-19 | 67-19 | 0.70 | 403 | 83.11 | 30 | 2.6 | 99 | 94 | 98 | Y |
| AMA-b | 2500 | AC10-2TR | 64-25 | 67-22 | 1.14 | 607 | 80.98 | 44 | 1.67 | 95 | 99 | 95 | N |
| AMA-d | 590 | AC10-2TR | 64-25 | 67-22 | 1.14 | 607 | 80.98 | 44 | 1.67 | 90 | 92 | 91 | N |
| AMA-e | 575 | AC10-2TR | 64-25 | 67-22 | 1.14 | 607 | 80.98 | 44 | 1.67 | 77 | 100 | 81 | N |
| AMA-f | 2350 | AC10-2TR | 64-25 | 67-22 | 1.14 | 607 | 80.98 | 44 | 1.67 | 71 | 100 | 77 | N |
| CRP-a | 5700 | AC15P | 67-10 | 76-28 | 1.24 | 155 | 71.39 | 23 | 0.76 | 72 | 86 | 75 | Y |
| CRP-c | 230 | AC15P | 67-10 | 76-28 | 1.24 | 155 | 71.39 | 23 | 0.76 | 34 | 100 | 47 | N |
| CRP-d | 470 | AC15P | 67-10 | 76-28 | 1.24 | 155 | 71.39 | 23 | 0.76 | 54 | 100 | 63 | N |
| SAT-a | 2075 | AC15P | 67-13 | 70-28 | 1.06 | 222 | 75.82 | 22 | 0.746 | 88 | 91 | 89 | Y |
| SAT-b | 6500 | AC15P | 67-13 | 70-28 | 1.06 | 222 | 75.82 | 22 | 0.746 | 86 | 75 | 84 | Y |
| ATL-a | 4700 | AC20-5TR | 67-16 | 70-25 | 0.83 | 308 | 74.53 | 21 | 1.06 | 93 | 96 | 94 | Y |
| ATL-b | 725 | AC20-5TR | 67-16 | 70-25 | 0.83 | 308 | 74.53 | 21 | 1.06 | 70 | 92 | 74 | Y |
| ATL-c | 500 | AC20-5TR | 67-16 | 70-25 | 0.83 | 308 | 74.53 | 21 | 1.06 | 68 | 100 | 75 | Y |
| TYL-a | 6025 | AC20-5TR | 67-16 | 70-22 | 0.80 | 44 | 75.05 | 19 | 1.08 | 91 | 100 | 92 | Y |
| SJT-c | 2450 | AC20-5TR | 67-19 | 76-19 | 0.98 | 474 | 63.25 | 28 | 1.65 | 100 | 60 | 92 | Y |
| AMA-c | 6065 | AC20-5TR | 64-25 | 73-19 | 1.30 | 719 | 77.52 | 38 | 1.54 | 88 | 100 | 90 | N |
| AMA-g | 2950 | AC20-5TR | 64-25 | 73-19 | 1.43 | 755 | 75.76 | 37 | 1.31 | 80 | 94 | 83 | N |

**NOTE:** Values in shaded cells correspond to failure in the laboratory test and inadequate performance in the field (noncompliance with the standard thresholds).

### 4.3.1 Example of Adequate Performance, SCI ≥ 70 Percent

An example of adequate field performance is shown in Figure 24 for HS SJT-b 1 year after construction. This section is located on SH 0158, Sterling County, San Angelo District. The SPG requirement grade in that county is 67-19 based on the SPG map (Figure 4). The AADT is approximately 820 veh/day on this section. Consistent with digital pictures, as shown in Figure 24, this section exhibited adequate performance in aggregate loss, bleeding, and overall combined distress. The $SCI_{AL}$, $SCI_{BL}$, and SCI values were 99, 94, and 98, respectively.

**Figure 24. Example of Adequate Performance—HS SJT-b 1 Year after Construction.**

### 4.3.2 Example of Inadequate Performance, SCI < 70 Percent

Figure 25 shows an example of inadequate performance for HS CRP-c 1 year after construction. This section is located on FM 2046, Kendall County, Corpus Christi District. The inadequate performance for aggregate loss ($SCI_{AL}$ = 34) and overall (SCI = 47) is reflected in the digital pictures (Figure 25). This section received a chip seal with AC15P binder. The AADT on this section was recorded at approximately 230 veh/day. The SPG grade requirement is SPG 67-10.

**Figure 25. Example of Inadequate Performance—HS CRP-c 1 Year after Construction.**

## 4.4 THE SPG CHARACTERIZATION RESULTS VS. FIELD PERFORMANCE

The SPG laboratory characterization results and binder properties ($G^*/\sin\delta$, % $\gamma$ at 0.8 $G_i^*$ from the DSR, and S from the BBR) were correlated with the overall field performance (overall SCI score) in the previous study (Vijaykumar et al., 2012). However, this correlation was considered inappropriate in this study because these properties are designed to correlate to specific distresses for chip seals (aggregate loss or bleeding). Therefore, in this study, each binder property was compared to the SCI for individual distresses. The threshold G*/sin δ from the DSR at high temperatures was correlated with the $SCI_{BL}$ 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 and % γ at 0.8 $G_i$* from the DSR at intermediate temperatures were correlated with the $SCI_{AL}$ to evaluate the strain susceptibility and resistance to aggregate loss.

Figure 26 and Figure 27 show the key performance-related binder properties (G*/sin δ from the DSR and S from the BBR) used in the SPG specification for the chip seal binders from each HS and the corresponding individual SCI score. In Figure 26 and Figure 27, SCI scores are shown above the symbol to indicate overall performance, and AADT for 2013 is provided above the symbol. In addition, the strain sweep results (% γ at 0.8 $G_i$* from the DSR) were similarly compared with the field performance results, as shown in Figure 28, to develop an improved limiting value for the percent strain parameter based on the larger dataset available in this study.

Specifically, only two of 19 sections failed to correlate at high temperatures with G*/sin δ at $T_{high}$ and $SCI_{BL.}$ The AMA-a (AC10) failed in the laboratory but demonstrated adequate resistance to bleeding, while SJT-c (AC20-5TR) was the opposite. Conversely, the reliability of the correlation between BBR S and $SCI_{AL}$ was not as good as that of the high-temperature performance. Four of the sections satisfied the requirement in the revised SPG specification but still exhibited inadequate resistance to aggregate loss. In contrast, all seven sections from the Amarillo District performed well with respect to aggregate loss but failed the BBR S criteria.

These comparisons are summarized in Table 20 and discussed subsequently along with comparisons of other laboratory tests and field results.

### 4.4.1 G*/sin δ Correlated with $SCI_{BL}$

As shown in Figure 26, most of the binders tested in this study had G*/sin δ values greater than 0.65 kPa along with traffic volume. Those binders beyond the DSR high temperature limit were expected to exhibit adequate performance in the field in terms of bleeding ($Pass_{Field}$). Consideration was given to moving the threshold to 0.6 kPa, but this change would only improve the correlation by one HS. This good correlation indicated that the existing threshold for this parameter was valid and maintained a tie to field performance for the majority of the 19 HSs in this study. A similar good correlation was found for 75 HSs in TxDOT Project 0-1710 and TxDOT Project 0-6616.

**Table 20. Correlation between Laboratory and Field Performance Results.**

<table>
<tr><th>Parameter</th><th>Existing SPG Limit</th><th colspan="2">Laboratory vs. Field Results</th><th>Comments</th></tr>
<tr><td rowspan="2">DSR<br>G*/sin δ<br>$T_{HIGH}$</td><td rowspan="2">Min<br>0.65 kPa</td><td>Correlated<br>$Pass_{LAB}$–$Pass_{FIELD}$: 17<br>$Fail_{LAB}$–$Fail_{FIELD}$: 0</td><td>89%</td><td rowspan="2">Threshold in this parameter mainly correlated with field performance.<br>Hs with $Pass_{Lab}$ and $Fail_{Field}$ had high embedment depth; HS with $Fail_{Lab}$ and $Pass_{Field}$ had relatively low traffic.</td></tr>
<tr><td>Uncorrelated<br>$Pass_{LAB}$–$Fail_{FIELD}$: 1<br>$Fail_{LAB}$–$Pass_{FIELD}$: 1</td><td>11%</td></tr>
<tr><td rowspan="2">BBR<br>S @ 8 sec,<br>$T_{LOW}$</td><td rowspan="2">Max<br>500 MPa</td><td>Correlated<br>$Pass_{LAB}$–$Pass_{FIELD}$: 9<br>$Fail_{LAB}$–$Fail_{FIELD}$: 0</td><td>42%</td><td rowspan="2">Uncorrelation ($Fail_{LAB}$–$Pass_{FIELD}$) was found in all AMA HSs, but those are expected to fail after a few years in service. The threshold in this parameter still has a good correlation in other districts, except four HSs had a low embedment depth or high traffic volume.</td></tr>
<tr><td>Uncorrelated<br>$Pass_{LAB}$–$Fail_{FIELD}$: 3<br>$Fail_{LAB}$–$Pass_{FIELD}$: 7</td><td>58%</td></tr>
<tr><td rowspan="2">Strain<br>Sweep<br>% γ @ 0.8<br>Gi* 25°C</td><td rowspan="2">Min<br>17.5%</td><td>Correlated<br>$Pass_{LAB}$–$Pass_{FIELD}$: 16<br>$Fail_{LAB}$–$Fail_{FIELD}$: 0</td><td>79%</td><td rowspan="2">Threshold in this parameter mainly correlated with field performance. The uncorrelated HSs may be caused by low embedment depth or high traffic volume.</td></tr>
<tr><td>Uncorrelated<br>$Pass_{LAB}$–$Fail_{FIELD}$: 3<br>$Fail_{LAB}$–$Pass_{FIELD}$: 0</td><td>21%</td></tr>
</table>

One of these HSs (SJT-c) exhibited inadequate performance to resist bleeding in the field 1 year after construction ($SCI_{BL}$ < 70). However, this HS had 88 percent embedment depth in wheel paths, which may be considered inappropriate practice during construction. Another HS (AMA-a) with $Fail_{Lab}$ and $Pass_{Field}$ had relatively low traffic and may fail in the near future with the cumulative effects of traffic and environmental loads.

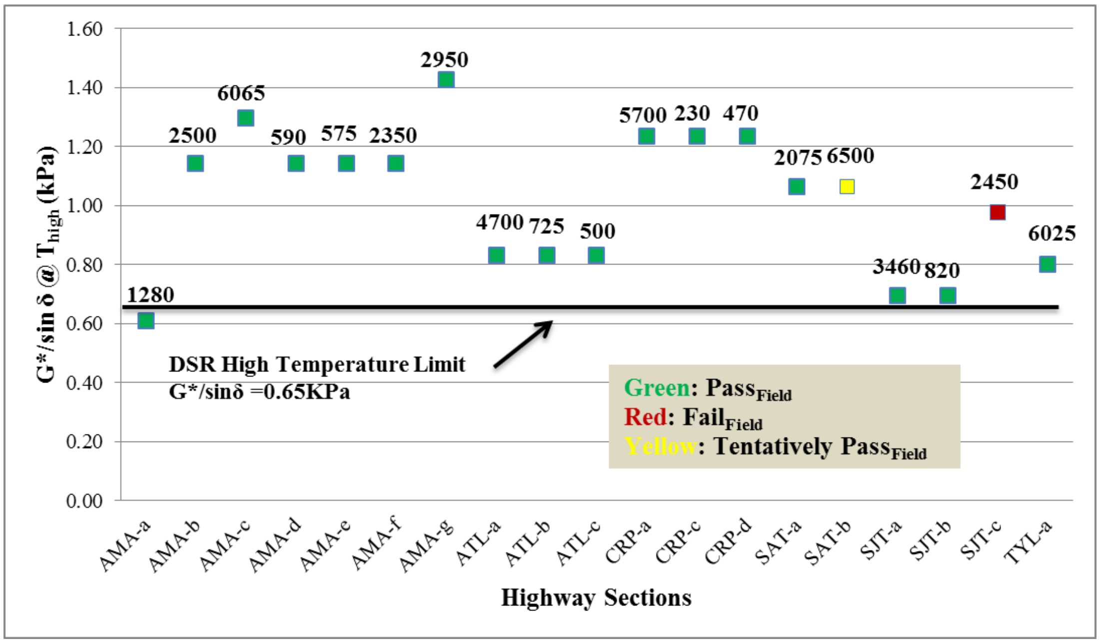



**Figure 26. G*/sin δ for 2013 HSs with $SCI_{BL}$ and Traffic Volume.**

### 4.4.2 Flexural Creep Stiffness Correlated with $SCI_{AL}$

Figure 27 shows plots of creep stiffness (S), along with traffic volume, for all of the HSs in this study. As shown in Figure 27, a poor correlation was observed between the creep stiffness threshold (S = 500 MPa) and field performance for aggregate loss ($SCI_{AL}$) in all HSs from the Amarillo (AMA) District. All of these HSs failed the BBR flexural creep test at low temperatures ($Fail_{Lab}$) but exhibited adequate performance in the field to resist aggregate loss

($Pass_{Field}$) with a variety of traffic volumes. These HSs from AMA could also fail in the near future with cumulative effects of traffic and environmental loads.

Otherwise, the majority of the other binders (8/12) in this study had S values less than 500 MPa, and the majority also exhibited adequate performance in the field. Four HSs, ATL-c, CRP-c, CRP-d and SJT-a, still had inadequate performance in terms of aggregate loss with less than 500 MPa S value. However, three of these HSs, ATL-c, CRP-c, and CRP-d, had less than 20 percent embedment depth, both in wheel paths and between wheel paths. In addition, HS SJT-a had a relatively high traffic volume. Thus, the BBR threshold at low temperatures was valid in most statewide districts. The BBR creep stiffness threshold will be based on further field evaluation of sections in colder climates.

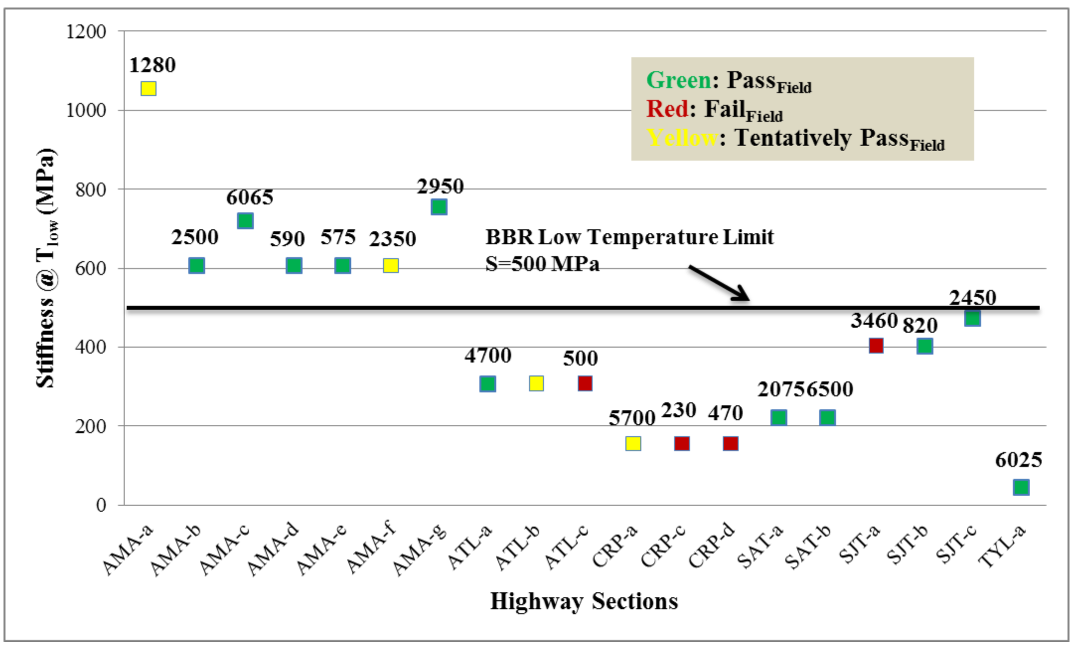



**Figure 27. Creep Stiffness for 2013 HSs with $SCI_{AL}$ and Traffic Volume.**

### 4.4.3 Percent Strain at 0.8 $G_i$* Correlated with $SCI_{AL}$

After revising the percent strain limit from 25 percent to 17.5 percent for the strain sweep test threshold at intermediate temperatures to the revised and further-validated SPG specification (Aishwarya et al. 2012), this threshold better related to the field performance in terms of aggregate loss. As shown in Figure 28, all of the binders from the selected HSs had a percent strain value greater than 17.5. A majority of these HSs (15/19) exhibited adequate performance to resist aggregate loss in the field. Four HSs, consistent with the creep stiffness threshold analysis, exhibited inadequate field performance, with a percent strain value larger than 17.5, for the same reasons.

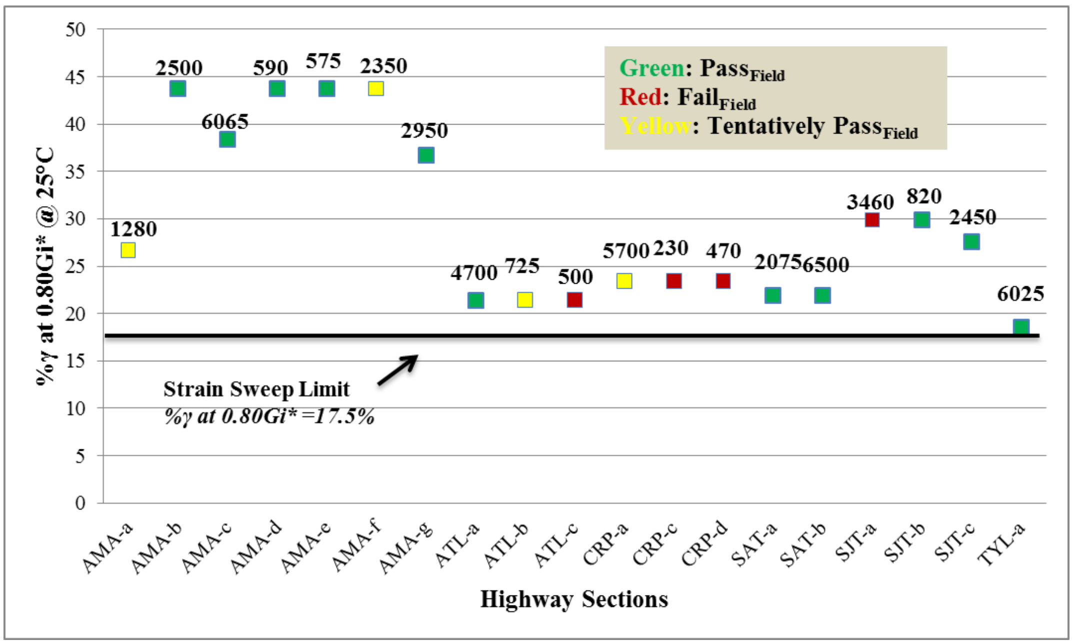



**Figure 28. Strain Sweep for 2013 HSs with $SCI_{AL}$ and Traffic Volume.**

## 4.5 DISCUSSION

Some difficulties were encountered when selecting the corresponding binder for a specific HS because the binders used in this study were not directly collected during construction but instead collected on a different district-wide chip seal HS. The selection of corresponding binders used in the HS was based on the districts, binder suppliers, and nearest county, which could cause the mismatching of the binder and the HS. Furthermore, the unexpected results from the Amarillo District largely contributed to the lack of correlation between field performance and laboratory characterization results in terms of the BBR creep stiffness property at low temperatures. The SPG specification has never been verified in a cold district by previous studies (TxDOT Projects 0-1710 and 0-6616). However, the field performance of all HSs in this district will be monitored in the following years and are expected to fail in the near future.

Given the random selection of the pavement sections based on construction schedules and the lack of control over construction practices and design modifications, these results are valid and can be used to implement the SPG specification. While some section-specific causes of these discrepancies have been discussed in the previous section, reasons for inconsistent field performance results are presented subsequently.

### 4.5.1 Material Variability and Testing Procedures

In addition to the properties of the binders and the aggregates used in the chip seals, variability, sampling, transportation, and storage of the materials as well as the test method employed could have created differences between observed performance in the laboratory and the field.

*Variability*

A wide variation was observed in the laboratory SPG characterization of all kinds of binders (Table 17), even some from the same supplier in the same district. For example, AC20-5TR binder LBB-1 from the Lubbock District was graded as SPG 73-22 in the laboratory characterization, while the SPG grade of another AC20-5TR binder, LBB-3, was SPG 76-19. Both of these binders were provided by the same supplier.

*Time, Transportation, and Storage Effects*

Some of the binders were unable to be tested right after sampling due to the contract delay in this study. This delay could have caused aging of the binder, which could have contributed to inaccurate results. Also, the materials could have been adversely affected by transportation.

*Characterization of Aged Binder Properties*

In order to characterize the low-temperature properties of the hot-applied binders tested in this study, the binders were aged in the PAV for 20 hr at 100°C. This laboratory aging protocol was unable to be validated in terms of simulating 1 year of aging in the field because the aggregates used in most of these chip seals were precoated. The comparison between laboratory aging and field aging would not be valid because the FTIR chemical analysis of binders extracted from field samples would have inaccurate results due to the presence of the precoated aggregates. This relationship could be further validated using the SPG specification implementation process in the future by selecting HSs that do not use precoated aggregates.

### 4.5.2 Field Performance Evaluation

Two to four test sections were monitored for each HS to obtain a more complete and accurate picture of the field performance. Although the performance evaluation was improved by a quantitative approach to eliminate personal judgments, the visual survey-based performance evaluation system used in this study is subjective. Consistent with 30 HSs in TxDOT Project 0-6616, HSs with an SCI score between 70 and 75 were tentatively or marginally classified as $Pass_{Field}$ in the field and correlated with a $Pass_{Lab}$ in the laboratory characterization.

Further, instead of capturing three critical times in the life of chip seal—at construction, one summer and one winter after construction, and 1 year after construction—the performance monitoring session was only performed 1 year after construction in this study due to the project delay. The lack of history and initial condition could have produced inaccurate results in terms of field performance evaluation of the HSs.

### 4.5.3 Design and Construction Practices

The SPG specification assumed that the material application rates and construction practices met TxDOT's design procedures and standard practices. Construction issues such as improper material application rates and poor construction practices were avoided as much as possible but could have affected field performance.

# 5. CONCLUSIONS AND RECOMMENDATIONS

This study focuses on the first year of the SPG specification implementation project based on the laboratory results of the 2013 chip seal binders and selected 2013 HS field performance. The SPG specification was developed to improve performance and extend the life of chip seals by providing an improved method for chip seal binder selection that accounts for differences in climate and directly relates to performance in terms of aggregate loss and bleeding over the critical first-year period. The SPG grade requirement map was developed based on the worst-case scenario for Texas statewide. In addition, the SCI score calculation method was revised using a quantitative methodology to eliminate subjectivity when evaluating the field performance of chip seals.

Table 15 shows the results of reviewing the 2011 HSs based on the revised and further-validated SPG specification, the SPG grade requirement map, and the revised SCI calculation method. For about 80 percent (24 of 30) of the 2011 HSs, the laboratory characterization results were correlated with the field performance monitoring results.

The laboratory characterization results for the 2013 binders are shown in Table 16, which indicates that 69 percent (20 of 29) of the 2013 chip seal binders met the SPG environmental grade requirement and demonstrates that the modified binders were superior to unmodified binders for meeting the environmental demand in the SPG specification. The method of comparison between laboratory characterization results and field performance for 2013 chip seal binders was changed to individual SPG property and distress evaluations. The high-temperature property ($G^*/\sin \delta$ at $T_{high}$) and the intermediate-temperature property (percent strain at 0.8 $G_i^*$) correlated well with the $SCI_{BL}$ and $SCI_{AL}$, respectively. The unexpected field performance from the Amarillo District largely contributed to the poor correlation between the BBR creep stiffness properties and field performance in terms of aggregate loss for 2013 HSs. The SPG specification will be further validated in extremely cold districts by monitoring the field performance in the future.

Table 21 shows the current SPG specification for implementation of chip seal binders statewide based on the results of this study. A new parameter and threshold, a phase angle at an interpolated continuous SPG temperature of at most 80°C, is suggested to ensure sufficient polymers in chip seal binders because superior performance of modified binders was observed in this study. Further, the prediction of BBR stiffness by DSR frequency sweep may not be applicable to use in the SPG specification because of the different loading time and colder testing temperature, compared to the PG grade specification.

On the basis of the limited samples and results, the exclusive use of the DSR, including the LAS test and the 4-mm DSR frequency sweep test, is suggested for further research and validation before incorporation in the SPG specification. Additional research should also be conducted to validate the findings from this study and complement the experimental design by including more types of binders (including emulsions) and more climates, especially extremely cold districts.

**Table 21. 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 | | | |
| Shear Strain Sweep, T 315: % strain @ 0.8 $G_i$*, Min: 17.5 Test temp. @ 10 rad/s linear loading from 1–50% strain, 1 sec. delay time with 20-30 measurements, °C | 25 | 25 | | | | | 25 | | | | | 25 | | | |
| 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 |
| Dynamic Shear, T 315 G*, Max: 2.5 MPa Test temp. @ 10 rad/s, °C | 25 | 25 | | | | | 25 | | | | | 25 | | | |

## 5.1 RECOMMENDED FUTURE RESEARCH

For further implementation of the SPG specification, researchers recommend the following for subsequent studies:

- Further implementation of the SPG specification is suggested, with additional validation for sections in cold areas from Texas, covering a wider variety of materials, especially emulsions.

- The possibility of replacing the measured BBR stiffness (S) with values predicted from the DSR frequency sweep results should be further explored. The equations used for the conversion of the DSR parameters into the BBR parameters should be modified to enable predictions at lower BBR test temperatures and loading times.
- The laboratory aging for chip seal binders to simulate 1 year of aging in the field should be further validated by selecting HSs that do not use precoated aggregates.
- The simplification of the LAS test is recommended for further research as an alternative test for determining the chip seal binders' response to increasing strain.

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## APPENDIX

### TABLE A1. DSR AND BBR TEST RESULTS.

| 2013 Binder ID | DSR on original binder @ high temperature | | | | Creep stiffness on PAV binder @ low temperature | | |
|---|---|---|---|---|---|---|---|
| | Test Temp. (°C) | Pass (P) /Fail (F) | Phase Angle @Continuous SPG Grade | G*/sin δ (kPa) | Test Temp. (°C) | Pass (P) /Fail (F) | Stiffness (MPa) |
| AMA-1 | 73 | Pass | 77.52 | 0.723 | −19 | Pass | 303 |
| | 76 | Fail | | 0.532 | −22 | Fail | 511 |
| AMA-2 | 61 | Pass | 88.84 | 0.831 | −19 | Pass | 445 |
| | 64 | Fail | | 0.609 | −22 | Fail | 750 |
| AMA-3 | 67 | Pass | 80.98 | 0.891 | −22 | Pass | 338 |
| | 70 | Fail | | 0.64 | −25 | Fail | 607 |
| AMA-4 | 73 | Pass | 75.76 | 0.79 | −19 | Pass | 359 |
| | 76 | Fail | | 0.578 | −22 | Fail | 557 |
| ATL-1 | 70 | Pass | 73.49 | 0.731 | −22 | Pass | 413 |
| | 73 | Fail | | 0.571 | −25 | Fail | 522 |
| ATL-2 | 70 | Pass | 74.53 | 0.67 | −25 | Pass | 481 |
| | 73 | Fail | | 0.509 | −28 | Fail | 701 |
| BWD-1 | 67 | Pass | 82.04 | 0.747 | −22 | Pass | 372 |
| | 70 | Fail | | 0.558 | −25 | Fail | 514 |
| BRY-1 | 73 | Pass | 75.68 | 0.787 | −19 | Pass | 400 |
| | 76 | Fail | | 0.598 | −22 | Fail | 665 |
| CRP-1 | 70 | Pass | 75.78 | 0.841 | −28 | Pass | 426 |
| | 73 | Fail | | 0.619 | −31 | Fail | 560 |
| CRP-2 | 73 | Pass | 71.39 | 0.805 | −28 | Pass | 435 |
| | 76 | Fail | | 0.59 | −31 | Fail | 574 |
| ELP-1 | 79 | Pass | 55.05 | 0.755 | −25 | Pass | 471 |
| | 82 | Fail | | 0.645 | −28 | Fail | 692 |
| LBB-1 | 73 | Pass | 70.60 | 0.814 | −22 | Pass | 457 |
| | 76 | Fail | | 0.6 | −25 | Fail | 554 |
| LBB-2 | 64 | Pass | 85.30 | 0.888 | −16 | Pass | 410 |
| | 67 | Fail | | 0.649 | −19 | Fail | 510 |

## TABLE A1. DSR AND BBR TEST RESULTS (CONTINUED).

| 2013 Binder ID | DSR on original binder @ high temperature | | | | Creep stiffness on PAV binder @ low temperature | | |
|---|---|---|---|---|---|---|---|
| | Test Temp. (°C) | Pass (P) /Fail (F) | Phase Angle @Continuous SPG Grade | G*/sin δ (kPa) | Test Temp. (°C) | Pass (P) /Fail (F) | Stiffness (MPa) |
| LBB-3 | 76 | Pass | 61.11 | 0.724 | −19 | Pass | 448 |
| | 79 | Fail | | 0.623 | −22 | Fail | 635 |
| LBB-4 | 67 | Pass | 81.26 | 0.675 | −16 | Pass | 381 |
| | 70 | Fail | | 0.493 | −19 | Fail | 535 |
| LBB-5 | 73 | Pass | 69.84 | 0.77 | −22 | Pass | 490 |
| | 76 | Fail | | 0.603 | −25 | Fail | 740 |
| LUF-1 | 70 | Pass | 74.22 | 0.696 | −22 | Pass | 494 |
| | 73 | Fail | | 0.523 | −25 | Fail | 552 |
| LUF-2 | 67 | Pass | 69.39 | 0.756 | −25 | Pass | 493 |
| | 70 | Fail | | 0.59 | −28 | Fail | 731 |
| ODA-1 | 67 | Pass | 82.82 | 0.687 | −16 | Pass | 344 |
| | 70 | Fail | | 0.48 | −19 | Fail | 528 |
| PHR-1 | 70 | Pass | 74.94 | 0.808 | −31 | Pass | 478 |
| | 73 | Fail | | 0.595 | −34 | Fail | 573 |
| SJT-1 | 67 | Pass | 83.11 | 0.695 | −19 | Pass | 403 |
| | 70 | Fail | | 0.536 | −22 | Fail | 663 |
| SJT-2 | 76 | Pass | 63.25 | 0.662 | −19 | Pass | 474 |
| | 79 | Fail | | 0.557 | −22 | Fail | 558 |
| SJT-3 | 61 | Pass | 89.50 | 0.921 | −13 | Pass | 402 |
| | 64 | Fail | | 0.646 | −16 | Fail | 557 |
| SAT-1 | 70 | Pass | 75.82 | 0.854 | −28 | Pass | 478 |
| | 73 | Fail | | 0.644 | −31 | Fail | 780 |
| SAT-2 | 73 | Pass | 81.30 | 0.782 | −25 | Pass | 474 |
| | 76 | Fail | | 0.565 | −28 | Fail | 721 |
| TYL-1 | 70 | Pass | 75.05 | 0.657 | −22 | Pass | 354 |
| | 73 | Fail | | 0.512 | −25 | Fail | 509 |
| WAC-1 | 67 | Pass | 77.86 | 0.83 | −22 | Pass | 405 |
| | 70 | Fail | | 0.582 | −25 | Fail | 572 |
| WAC-2 | 73 | Pass | 73.12 | 0.804 | −22 | Pass | 347 |
| | 76 | Fail | | 0.623 | −25 | Fail | 547 |
| WFS-1 | 67 | Pass | 81.40 | 0.773 | −22 | Pass | 418 |
| | 70 | Fail | | 0.549 | −25 | Fail | 608 |

**TABLE A2. PREDICTED AND MEASURED BBR RESULTS.**

| 2013 Binder ID | BBR Temperature (°C) | S-measured (MPa) | S-predicted (MPa) |
|---|---|---|---|
| AMA-1 | −19 | 303 | 355 |
| | −22 | 511 | 457 |
| AMA-2 | −19 | 445 | 434 |
| | −22 | 750 | 530 |
| AMA-3 | −22 | 338 | 520 |
| | −25 | 607 | 658 |
| AMA-4 | −19 | 359 | 364 |
| | −22 | 557 | 487 |
| | −25 | 743 | 620 |
| ATL-1 | −22 | 413 | 378 |
| | −25 | 522 | 533 |
| ATL-2 | −22 | 257 | 473 |
| | −25 | 481 | 740 |
| | −28 | 701 | 1145 |
| BWD-1 | −22 | 372 | 370 |
| | −25 | 514 | 419 |
| BRY-1 | −19 | 400 | 458 |
| | −22 | 665 | 593 |
| CRP-1 | −25 | 314 | 339 |
| | −28 | 426 | 457 |
| CRP-2 | −25 | 247 | 540 |
| | −28 | 435 | 540 |
| LBB-1 | −22 | 457 | 516 |
| | −25 | 554 | 575 |
| LBB-2 | −16 | 410 | 366 |
| | −19 | 510 | 450 |
| | −22 | 561 | 510 |
| LBB-3 | −19 | 448 | 378 |
| | −22 | 635 | 453 |
| | −25 | 743 | 505 |
| LBB-4 | −16 | 381 | 342 |
| | −19 | 535 | 467 |
| | −22 | 729 | 592 |
| LBB-5 | −22 | 490 | 556 |
| | −25 | 740 | 655 |

**TABLE A2. PREDICTED AND MEASURED BBR RESULTS (CONTINUED).**

| 2013 Binder ID | BBR Temperature (°C) | S-measured (MPa) | S-predicted (MPa) |
|---|---|---|---|
| LUF-1 | −22 | 494 | 449 |
| | −25 | 552 | 606 |
| LUF-2 | −22 | 268 | 446 |
| | −25 | 493 | 659 |
| | −28 | 731 | 945 |
| ODA-1 | −16 | 344 | 366 |
| | −19 | 528 | 497 |
| PHR-1 | −25 | 268 | 417 |
| | −28 | 405 | 659 |
| SAT-1 | −22 | 226 | 327 |
| | −25 | 303 | 491 |
| | −28 | 478 | 727 |
| SAT-2 | −22 | 414 | 432 |
| | −25 | 474 | 594 |
| | −28 | 721 | 783 |
| SJT-1 | −16 | 354 | 411 |
| | −19 | 403 | 518 |
| | −22 | 663 | 608 |
| SJT-2 | −19 | 474 | 446 |
| | −22 | 558 | 606 |
| SJT-3 | −13 | 402 | 387 |
| | −16 | 557 | 478 |
| TYL-1 | −22 | 354 | 300 |
| | −25 | 509 | 447 |
| | −28 | 732 | 652 |
| WAC-1 | −22 | 405 | 408 |
| | −25 | 572 | 500 |
| WAC-2 | −22 | 347 | 396 |
| | −25 | 547 | 474 |
| WFS-1 | −22 | 418 | 302 |
| | −25 | 608 | 362 |
| | −28 | 748 | 410 |