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16. Abstract

The Texas Department of Transportation is moving to adopt the requirements and nomenclature of the asphalt binders developed for the Strategic Highway Research Program's (SHRP) Superpave design system for hot-mixed asphalt concrete. Under the present specifications, this would require the Department to maintain, test, and support two separate specifications for basically the same material, since the SHRP study did not include asphalt binders used for seal coats. This study successfully determined that the asphalts presently being used in Texas can meet the PG, or Superpave, grading system. The findings were based on official samples of material being used in the Department's program, though addition work must be undertaken to determine that these materials are being matched with the locations (environmentally as well as physically) to yield the most satisfactory product.

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PERFORMANCE-BASED SEAL COAT ASPHALT SPECIFICATIONS

by

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Research Report 1367-1

Research Project 0-1367

Performance-Based Seal Coat Asphalt Specifications

conducted for the

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the

U.S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
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IMPLEMENTATION STATEMENT

Performance-based specifications were developed by the Strategic Highway Research Program (SHRP) asphalt research program for hot-mixed asphalt concrete. The asphalt binder specification, an integral part of those specifications, includes the newly developed tests currently being adopted for measuring those properties identified as critical. The binders for use in seal coats were not included in the SHRP study. The results of this study determined that the binders currently being used in seal coats will meet the limitations established for asphalt binders by SHRP's Superpave grading system. The second phase of this project, to be completed by August 31, 1996, will establish a procedure to enable the selection of the most desirable asphalt binder capable of meeting the particular environmental and traffic conditions.

Prepared in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration

PREFACE

This is the first of a two-part report for Research Project 0-1367, "Performance-Based Seal Coat Asphalt Specifications." This study was established to provide the necessary information to the Texas Department of Transportation in its effort to use a single specification for asphalt binders for both hot-mixed asphalt concrete and asphalt seal coats, using the grading requirements established by the Strategic Highway Research Program's asphalt research program. This report presents the findings, conclusions, and recommendations based on the laboratory testing of asphalt binder products produced for use in seal coats in Texas.

The success of this project was made possible only through the cooperation and assistance of district personnel throughout the state, and with the guidance of Darren Hazlett of the Materials and Tests Division, who also represented the Department as the Project Director.

The authors also gratefully acknowledge the input and efforts of Eugene Betts, as well as the support of the Center for Transportation Research.

DISCLAIMERS

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the Federal Highway Administration or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation.

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SUMMARY

The Texas Department of Transportation is moving to adopt the requirements and nomenclature of the asphalt binders developed for the Strategic Highway Research Program's Superpave design system for hot-mixed asphalt concrete. Under present specifications, this would require the Department to maintain, test, and support two separate specifications for basically the same material, since the SHRP study did not include asphalt binders used for seal coats. This study determined that the asphalts presently being used in Texas can meet the PG, or Superpave, grading system. The findings were based on official samples of material being used in the Department's program, though additional work must be accomplished to determine that these materials are being matched with the locations, environmentally as well as physically, to yield the most satisfactory product.

CHAPTER 1. INTRODUCTION

1.1. BACKGROUND AND SIGNIFICANCE OF WORK

The performance-based specifications introduced by the Strategic Highway Research Program (SHRP) were developed for hot-mixed asphalt concrete. The federal and most state transportation departments, including the Texas Department of Transportation (TxDOT), are currently moving to adopt these specifications. Spray applications of modified and unmodified binders (e.g., seal coats) were not included in the development of the initial SHRP specifications. Binders for seal coats have previously been selected primarily in terms of a satisfactory history of performance, rather than of performance-based tests and criteria. These binders currently are specified using viscosity and penetration tests. To eliminate the need for maintaining two separate specifications and grading systems for asphalt binders, it is necessary to be able to specify seal coat binders in terms of the new Superpave grading system.

Current Asphalt Binder Specifications

There are three sets of specifications commonly used for grading asphalt binders: penetration-based specifications, viscosity specifications, and aged residue viscosity specifications (*1*). Other grading systems, such as performance-based asphalt, or "PBA," have evolved through modifications of the preceding ones, even though the primary tests and concepts have remained the same. In all cases, binders are graded based on their consistency at certain temperatures.

The penetration system is standardized in ASTM D946 and in AASHTO M20. It is based on the penetration test at 25° C, which is an empirical measurement of consistency. Although there is considerable experience with the penetration system, the penetration test is at best only marginally related to fundamental rheological behavior.

Viscosity-graded asphalts (referred to as "AC grades") are standardized in ASTM D3381 and AASHTO M226. In this system, the absolute viscosity of a binder at 60° C (140° F) is used to establish its grade. These viscosity measurements are considered reliable as long as linear viscous behavior is observed. Linear viscous behavior is often called "Newtonian," and means that the measured viscosity is independent of the rate at which the binder is sheared. Practically all neat asphalts exhibit Newtonian behavior. A significant short-coming of the system is that at 60° C, the viscosity of most aged and modified binders is shear-rate dependent, and the binder's behavior is non-Newtonian. The other deficiency of this system is that test results cannot be used to characterize the low-temperature behavior of the binder.

Aged residue-graded asphalts (referred to as "AR grades") are also standardized in ASTM D3381 and AASHTO M226. This system is almost identical to the viscosity grading system. The main exception is that the absolute viscosity at 60° C used for grading is determined on binder residue that has been aged in the rolling thin film oven (ASTM D2872 or AASHTO T240). This laboratory aging method is generally believed to simulate the aging that occurs during hot mixing and construction of asphalt concrete. The AR grading system suffers from the same deficiencies as does the AC grading system.

In summary, the asphalt binder tests used for these grading systems are only marginally related to field performance of asphalt concrete. At best, they are related to intermediate to high temperature performance through empirical parameters, which in many cases are not universally reliable indicators of the material performance in pavements. When used for seal coat construction, another current deficiency is that too wide a range is allowed for viscosity and penetration of the materials for selection and construction in a given location.

Superpave Asphalt Binder Specification

As part of the research activities of the SHRP Asphalt Research Program (1987 through 1993), a new set of asphalt binder specifications was developed (*2*). These binder specifications are an important part of the Superpave system, which is the final product of the SHRP asphalt research program. The major difference between Superpave binder specifications and those now in use is that the new test methods and related specification criteria were developed to be performance based. Using new tests methods, fundamental material properties are measured that were shown to be strongly indicative of actual pavement performance. Furthermore, the tests are run on binders that have been laboratory aged to simulate critical periods during a binder's service life. Perhaps one of the most significant improvements in the Superpave system is that binders are evaluated at temperatures that match anticipated project pavement temperatures. These temperatures range from 70° down to -40° C.

Superpave binder specifications and the mixture design and analysis system, which were designed to improve the performance of dense-graded asphalt concrete pavements, are currently being evaluated by the federal and state DOTs for possible implementation. A large number of public and private organizations are already using various facets of Superpave on an experimental basis. Most state DOTs have indicated they will adopt Superpave, in part or wholly, during the period between 1997 and 2000.

To eliminate the penetration and viscosity grading systems for asphalt binders, all agencies will be challenged to use the Superpave system for seal coat binders and other spray applications. Utilizing the same grading system for all asphalt binders, regardless of their use, is advantageous because it:

- increases overall efficiency by reducing user and producer confusion,
- would save asphalt producers (and ultimately taxpayers) from having to invest in extra storage capacity for a wider variety of binders, and
- increases user and producer laboratory efficiency by requiring only one set of binder test equipment.

The Superpave binder specification delivers materials with fundamental binder physical properties that are reliably related to asphalt concrete pavement performance. While SHRP researchers did not examine the use of Superpave binders for spray applications, it was recognized that it was possible that the underlying methodology is equally applicable to seal coat binders. Consequently, the Texas Department of Transportation (TxDOT) decided to initiate development of performance-based specifications for spray application binders to match the replacement of its current system with the Superpave binder specification.

1.2. OBJECTIVES OF THE STUDY

This study seeks to apply Superpave principles to improving the performance of seal coat[1] binders. It also seeks to utilize the Superpave binder specification for seal coat binders. This will reduce the magnitude of the binder types, simplify specifications, and remove method clauses, such as the necessity to control the polymer type and dosage level. Instead, TxDOT will have a specification that utilizes the Superpave binder test equipment to specify the seal coat binder and, ultimately, performance. Therefore, the following specific objectives were targeted:

1. produce a generic, performance-based specification for seal coat binders;
2. produce a specification that is applicable to asphalt cement, emulsion residue, and cutback residue, whether modified or unmodified;
3. document laboratory performance of seal coat asphalts typically used in Texas, and provide a database of properties for comparison with field performance of binders utilized in places with different traffic and climatic conditions; and
4. produce guidelines and specifications for seal coat binders that allow TxDOT to purchase cost-effective pavement treatments.

This study attempts to identify those Superpave binder grades that will provide satisfactory performance. A second phase to develop protocols and criteria for selecting the binder in terms of the conditions (i.e., climate and traffic) to which they will be exposed has been proposed as a natural and necessary extension of this research.

1.3. IMPLEMENTATION AND BENEFITS

We expect that there will be significant savings and benefits to TxDOT through implementing performance-based specifications for seal coat binders as a result of:

1. using a system that is expected to improve seal coat performance and delay the need for maintenance,
2. utilizing the same test equipment and grading both for asphalt concrete and seal coat binders, and

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[1] Various organizations have developed strict definitions for terms like *seal coat, surface treatment, chip seal,* etc. In this report, the term *seal coat* is used in a generic sense to indicate all spray application of asphalt followed by an application of cover aggregate.

3. simplifying specification criteria (as the properties of the final product are important) without the need to specify the type and quantities of the modifiers, or the need to establish criteria on the properties of the original materials.

1.4. RESEARCH APPROACH

To satisfy the objectives of this research program, we identified several key activities, following the approach described below as closely as possible:

1. identify the factors that influence performance of the surface treatments,
2. identify the types of distresses and the associated mechanisms that are critical in seal coats,
3. identify the material properties that are related to the critical distress mechanisms,
4. investigate applicability of Superpave test methods and procedures to provide the required properties for seal coats,
5. procure binders and emulsions used for seal coat projects throughout the state,
6. perform laboratory tests on the procured materials,
7. observe field performance of the materials, and
8. establish criteria based on the laboratory results and observed field performance.

1.5. SCOPE AND ORGANIZATION OF THE STUDY

Chapter 2 of this report discusses the factors influencing the performance of seal coats and the distress mechanisms in surface treatments. It also reports the results of the literature review on performance of seal coats and the contributions of other researchers in this area. Chapter 3 outlines the experimental procedures and activities followed throughout the program. Analysis and discussion of results are presented in Chapter 4. Finally, Chapter 5 presents conclusions and recommendations, along with a draft binder specification. A key research activity during this project was collecting information pertaining to seal coat performance and practice from TxDOT district personnel. A summary of this information is presented in Appendix A. Appendix B includes an abbreviated version of the Superpave binder specification as executed by AASHTO. Appendix C is a tabulation of the materials sampled, along with their tested properties.

CHAPTER 2. SEAL COAT PERFORMANCE AND INFLUENCING FACTORS

2.1. INFLUENCING FACTORS

Implicit in our development of performance-based specifications for seal coat binders was the notion that the service life of a seal coat will be increased through utilization of such specifications. Accordingly, the research project concentrated on the selection of appropriate materials for various climatic and traffic conditions. However, following our discussions with TxDOT district personnel, material suppliers, and other knowledgeable authorities, and following a literature review, it became apparent that numerous other factors often influence the performance of seal coats, and that asphalt binder materials characteristics, which is the focus of this research, represent only one of many influencing factors. Now, it is obvious that one should consider all of the other factors when evaluating the performance of a seal coat. If poor performance is not traced to the correct source, changes in specifications will be ineffectual. For example, if a seal coat placed in cool, wet weather performs poorly, the obvious cause (unfavorable environmental conditions) should be recognized and the observed performance of the project should not have undue influence on the binder specification. With very few exceptions, there is little evidence that binder properties can overcome poor construction conditions. The two major types of distress possible with seal coats are *bleeding* and *aggregate loss.* These are discussed in greater detail later in this chapter.

This chapter discusses factors identified as influential to seal coat performance. TxDOT engineers, other knowledgeable individuals, and the technical literature all indicated that the success of seal coats is influenced by the following factors:

- quality of design,
- quality and consistency of construction,
- quality and consistency of materials,
- environmental conditions, and
- traffic conditions.

Quality of Design

The product of a seal coat design is an optimized rate of application of asphalt material and aggregate. The asphalt application rate is designed in terms of liters of product per square meter. Aggregate application is designed and specified in two ways: on the basis of mass spread rate (kilograms per square meter) or on the basis of a volumetric spread ratio (square meters per cubic meter). TxDOT normally specifies aggregate application using the volumetric spread ratio method.

The most widely used design procedures are traceable to the one originally developed by Kearby (*3*), which has been modified and updated by various agencies and researchers. Hveem also published an early seal coat design method (*4*). Currently, the most widely distributed design guidelines in the U.S. are those developed by Lovering of the Asphalt Institute (*5, 6*); these guidelines are based primarily on work by Hanson (*7*), McLeod (*8, 9*) and Benson (*10*). Another execution of the Kearby method was reported by Monismith (*11*), though this method also appears to be heavily influenced by Lovering.

Epps (*12*) reported that the most common design procedure used by TxDOT prior to 1980 was the Kearby approach, which was then called the "board method." They also reported another method, a modified Kearby approach, developed by J. W. Livingston of the Atlanta District. In their comparison of the field performance resulting from the various design methodologies, Epps indicated that the modified Kearby approach developed by Livingston resulted in the best aggregate application rate. The Lovering and Livingston-modified Kearby method resulted in the best asphalt application rate.

Discussions with TxDOT and knowledgeable industry sources revealed that seal coats are seldom rigorously designed in Texas (or elsewhere for that matter). This discovery is not surprising and is by no means an indictment of TxDOT or industry practice. The bulk of the seal coat design research in the U.S. was performed from the mid-1940s through the early 1960s.[2] That research provided the necessary tools for TxDOT and other engineers to effectively establish the proper quantities of asphalt and aggregate materials, which generally do not change in a particular geographic area. Once effective quantities are established, specifiers tend to stick with application rates known to work. Nevertheless, the input parameters to the design procedures still form an important list of factors that must be considered when evaluating seal coat performance.

Each of these design methods is aimed at developing an asphalt and aggregate application rate. They variously consider the following factors:

- traffic level,
- the top size, gradation, bulk specific gravity, and loose unit weight of aggregate,
- the type of asphalt material (i.e., asphalt cement versus asphalt emulsion),
- the condition of the existing surface (dry, oxidized versus flushed),
- desired aggregate embedment depth, and
- in the case of multiple applications, the number of layers.

The following generalized equations are evident from the various design approaches:

Asphalt Application Rate = $f(1/T, E, S, A, 1/R)$

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[2] The only recent research of national scope in the area of seal coat design was performed in NCHRP Project 14-8A, *Chip Seals for High Volume Roads*. Presumably, much of that work has now been rendered inconsequential with the advent of sophisticated cold-mixed applications (such as microsurfacing), which are replacing seal coats on high volume roadways.

where

T = traffic factor,

E = aggregate embedment,

S = correction for condition of existing surface,

A = aggregate size, shape, gradation, durability, and porosity, and

R = residual asphalt content of binder (i.e., for asphalt cements R = 1.00).

Aggregate Application Rate = $f(G, U, W)$

where

G = average aggregate size,

U = aggregate loose unit weight, and

W = aggregate wastage factor.

Traffic levels influence asphalt application rate. In all of the methods, design traffic parameters decrease the application rate for higher volume pavements, and increase the application rate for lower volume pavements. Table 2.1 shows traffic factors established by the Asphalt Institute (*5*). Observing these values indicates that traffic levels must be considered to achieve superior seal coat performance.

Table 2.1 Typical Traffic Factors for Seal Coat Design (5)

Aggregate	Traffic Factor = Percentage (expressed as a decimal) of 20 percent void space in cover aggregate to be filled with asphalt				
	Traffic, vehicles per day				
	Under 100	100 to 500	500 to 1000	1000 to 2000	Over 2000
Recognized Good Type of Aggregate	0.85	0.75	0.70	0.65	0.60

Aggregate embedment is quantified in two ways, either in terms of a percentage of average seal coat thickness in the wheelpath, or, more simply, as the visual observation of percentage embedment of aggregate with respect to maximum size. In the latter case, Epps (*12*) reported values ranging from 7 to 100 percent for 60 projects analyzed. In that study, it was concluded, based on the consensus of the researchers from visual observations, that 80 percent embedment was reasonable from the standpoint of bleeding.

TxDOT personnel and the technical literature indicated that asphalt application rates must be adjusted for existing surface conditions to achieve superior seal coat performance. Table 2.2 shows surface correction factors attributed to Hanson (*7*). Considering that typical asphalt cement application rates range from about 0.9 to 1.4 liters per square meter, the adjustment values shown in Table 2.2 are quite significant. At a very high level of existing surface demand, it becomes impractical, from a construction standpoint, to increase the application rate to account for surface absorption. In those instances where high surface correction factors seem necessary, it may be more prudent to use a fog seal as a pretreatment to the seal coat to satisfy surface demand for asphalt.

Table 2.2 Asphalt Application Adjustment Rates to Account for Surface Condition (7)

Surface Condition	Adjustment Factor, l/m^2
Smooth, non-porous surface	0.00
Slightly porous, slightly oxidized surface	+0.14
Slightly pocked, porous, oxidized surface	+0.28
Badly pocked, porous, oxidized surface	+0.42
Flushed asphalt surface	-0.14
Note: + indicates add asphalt, - indicates subtract asphalt	

Most of the literature surveyed applied adjustments on the basis of bulk surface condition, with no accounting for localized differences in surface demand. An interesting variation on this approach was developed and reported by Shulz and Russell (*13*) in the Brownwood District, where lateral adjustments were made to application rates to account for typically lesser amounts of asphalt needed in the wheelpaths and greater amounts needed between the wheelpath. The lateral adjustment in application rate was facilitated by using asphalt distributor spray bar nozzles of various orifice sizes.

Epps (*12*) reported using a "putty method" to estimate the "surface hunger" of asphalt. Using this procedure, surface texture measurements were performed on 120 roadway sites. These measurements showed an average difference in surface texture of 0.254 cubic millimeters per square millimeter when comparing wheelpath with between-wheelpath texture. Epps suggested this would result in a difference of 0.28 liters per square meter.

Aggregate factors that need to be considered for superior seal coat performance include aggregate size, shape, gradation, durability, porosity, and cleanliness. Aggregate size is a design factor to the extent that it affects the amount of asphalt in terms of a desired embedment depth. Larger aggregates require more asphalt to achieve a prescribed embedment depth.

Aggregate shape is a critical factor because most design methods assume an aggregate shape that is largely cubical. The design method outlined by the Asphalt Institute (*5*) adjusts for aggregate shape by means of a parameter dubbed the "flakiness index." The flakiness index of an aggregate is determined from a test method that uses a special set of slotted sieves. It is used to estimate the average least dimension of the aggregate, which, in turn, is used to compute required asphalt application rate. A flaky aggregate (i.e., flat and/or elongated) results in a lower asphalt application rate, since its average least dimension is smaller. Consequently, less asphalt is needed for a desired embedment depth. Even if properly taken into account using an approach such as the Asphalt Institute method (5), flaky aggregates pose difficulties with seal coats because they do not orient themselves with respect to their least dimension during construction. TxDOT personnel reported that flaky aggregates tend to "roll over" under traffic, an action that decreases the effective mat thickness. The consequence of this is wheelpath bleeding and a failure to provide an adequate surface friction to the roadway surface. Flaky aggregate is also prone to degradation, which reduces the aggregate size. The net result of degradation is also bleeding. In recognition of these problems, some districts that have sources of flaky aggregate (e.g., Corpus Christi and Dallas) have placed a maximum limit on the flakiness index for seal coat aggregate. A typical maximum flakiness index is about 16. TxDOT (Tex-224-F) (22) has a test to measure this parameter. Specifying high quality aggregate in this manner is probably the best approach to dealing with the effect of aggregate shape.

Aggregate gradation influences seal coat design and performance in three ways: maximum size, well-graded versus uniformly graded, and dust content. Aggregates with larger average particle size require a higher application rate for a desired embedment depth. However, most agencies, including TxDOT, have abandoned the well-graded aggregate in favor of uniformly graded aggregate for seal coats. Table 2.3 shows the master gradation ranges of the most common seal coat aggregates used in Texas (*14*). The distribution of particle sizes clearly illustrates that TxDOT prefers uniformly graded aggregate.

Table 2.3 TxDOT Gradation Requirements for Seal Coat Aggregate (14)

Size, mm (in)	Grade 3	Grade 4	Grade 5
19	0	-	-
16	0 - 2	0	-
12.5	20 - 40	0 - 2	0
9.5	80 - 100	20 - 35	0 - 5
6.3	95 - 100	-	-
4.75	-	95 - 100	40 - 85
2.00	99 - 100	99 - 100	98 - 100
0.850	-	-	99 - 100
Note: Values are percent retained on sizes shown.			

In general, uniformly graded cover aggregates are advantageous because they tend to be cleaner, do not segregate in stockpiles or during handling, and result in a quieter ride (*5*) when compared with graded aggregates. Graded cover aggregates tend to require less asphalt and are less expensive than uniformly graded aggregate, which means that graded aggregate seal coats are less expensive in terms of first cost. Evidently, the performance and other advantages of uniformly graded aggregate outweigh the low first cost advantages of graded aggregate since TxDOT and other agencies have prohibited the use of graded aggregates.

The amount of dust (percent finer than 75 microns) contained by the aggregate affects seal coat performance. In the literature, there appears to be no consensus regarding the proper amount of dust in the cover aggregate. However, it was noted in at least two references (*5, 15*), and also in conversations with TxDOT personnel, that overly dusty aggregates were undesirable because the dust tends to disturb the bond between the asphalt and aggregate. While it is likely that a certain amount of stone dust material benefits seal coats by ensuring a proper void content, the excessive dust that tenaciously sticks to coarse aggregate is detrimental from the standpoint of adhesion. TxDOT specifications (*14*) require no more than 1.0 percent by weight of fine dust, clay-like particles and/or silt.

Aggregate toughness and durability play a role in seal coat performance because of their effect on aggregate size. If aggregates degrade when manipulated during construction or under traffic or are degraded due to chemical action, they are effectively reduced in size. If this happens, the amount of asphalt applied for the anticipated size becomes too great, resulting in bleeding.

The effect of aggregate porosity on seal coat performance is analogous to that resulting from existing surface conditions. Highly absorptive aggregates require an increase in application rate to satisfy their asphalt demand. Some TxDOT districts (e.g., Abilene, Lubbock, and Pharr) specify precoated seal coat aggregate, which, in effect, satisfies the demand of the aggregate for asphalt binder. Another benefit of precoated aggregate is that during the precoating operation, dust is removed or compensated. The Ft. Worth District sometimes fog seals the travel lanes of recently completed seal coats. This novel approach satisfies additional aggregate demand for asphalt but, more importantly, facilitates safety by providing contrasting delineation between shoulders and travel lanes.

Properly accounting for the residual asphalt content of the emulsion-sealing grade binders is necessary to achieve superior seal coat performance. The design methods examined generally accounted for residual asphalt content by dividing the application rate for asphalt cement by the asphalt residue in emulsions. For example, if a seal coat design resulted in an application rate of 1.15 liters per square meter for an asphalt cement, then the proper amount of emulsion to be used would be 1.15/0.65 or 1.77 liters per square meter. This calculation is based on the mass percentage of asphalt residue in sealing grade emulsions, which is typically 65 percent. Epps (*12*) suggests that the adjusted application rate to account for residual asphalt content be further adjusted by a factor of 0.80. In the previous example, the design application rate for an asphalt emulsion then would be 1.77×0.8 or 1.42 liters per square meter.

In summary, assuming that durable aggregates with proper size, gradation, and shape (preferably cubical) have been selected, and that project traffic and surface conditions have been carefully considered, the main purpose of designed application rates is to ensure optimum embedment of aggregates in the asphalt binder. Insufficient embedment results in aggregate loss, while an embedment that is too deep results in bleeding. Based on observed field performance (*12*), it is desirable to have no more than about 80 percent of the height of the aggregate covered with the binder.

Quality of Construction

As with other construction materials, quality of construction plays a very significant role in the performance of seal coats. There appears to be a consensus that selection of the best material and the best design approach cannot compensate for poor workmanship. As evidence, TxDOT personnel consistently indicated that construction — rather than material deficiencies — were the single biggest cause of poor performing seal coats. The following factors are some of the construction variables cited by TxDOT personnel and the technical literature that influence performance of seal coats:

- longitudinal and transverse variation in the rates of material application,
- length of time between application of binder and application of aggregate,
- variation in materials,
- type and time of compaction,
- environmental conditions during and immediately after construction,
- length of interval between end of construction and trafficking, and,
- improper embedment of the aggregate.

Variation in materials application causes a variety of problems. Obviously, if too much or too little asphalt is applied, bleeding and aggregate loss, respectively, can result. Low aggregate application, in effect, will cause bleeding because free asphalt remains on the surface. Too much aggregate applied may cause windshield damage if not thoroughly swept from the surface. Clearly, to achiever superior seal coat performance, variation in material application rates needs to be minimized.

TxDOT and most other agencies do not control seal coat construction in the same manner as they do higher type surfaces (such as asphalt concrete). Instead of measuring in-place seal coat compositional properties, application rates are monitored by carefully measuring quantities used over the length and width of application. The following equations (*6, 15*) are used to compute asphalt application rates:

$$R = \frac{T \times M}{W \times L}$$

where

R = rate of asphalt application, liters/square meter,

T = total volume applied in liters,

W = width of spread in meters,
L = length of spread in meters, and
M = multiplier to correct asphalt volume to basis of 15.6° C.

$$R = \frac{A}{W \times L}$$

where

R = rate of aggregate application in kilograms/square meter,
A = mass of aggregate used in kilograms,
W = width of spread in meters, and
L = length of spread in meters.

For aggregate spread ratio, the following equation is used:

$$SR = \frac{U}{R}$$

where

SR = spread ratio in square meters per cubic meter,
R = rate of aggregate application in kilograms/square meter, and
U = loose unit weight of aggregate in kilograms per cubic meter.

The volume of asphalt material used ("T" in the first equation above) is measured by "strapping" distributors before and after each application. A strapping rod is a calibrated dipstick that is inserted into a distributor tank to accurately measure the amount of material in the tank. Aggregate use ("A" in the above equation) is quantified by counting loads of aggregate hauled by trucks of known volume or mass. This approach is necessary and ideal for pay purposes. Diligence on the part of the inspector and contractor will minimize longitudinal variation. However, it does not tend to highlight transverse fluctuations in application.

Transverse variation in asphalt application rate causes a surface condition called streaking. This is manifested by longitudinal striations that, upon close examination, exhibit alternating patterns of lean and heavy strips of asphalt. The Asphalt Institute (*6*) cites the follow causes of streaking:

- improper spray bar height,
- spray bar rising as distributor tank empties,
- improper angle on one or more nozzles,
- plugged nozzles,
- wrong pump speed,
- asphalt material too viscous, and
- spray pressure too low due to worn or poorly maintained pump.

Figure 2.1 (*6*) illustrates a generalized view of spray bar geometry. It is clear from this figure that proper nozzle angle and height are critically important in achieving proper transverse application rates.

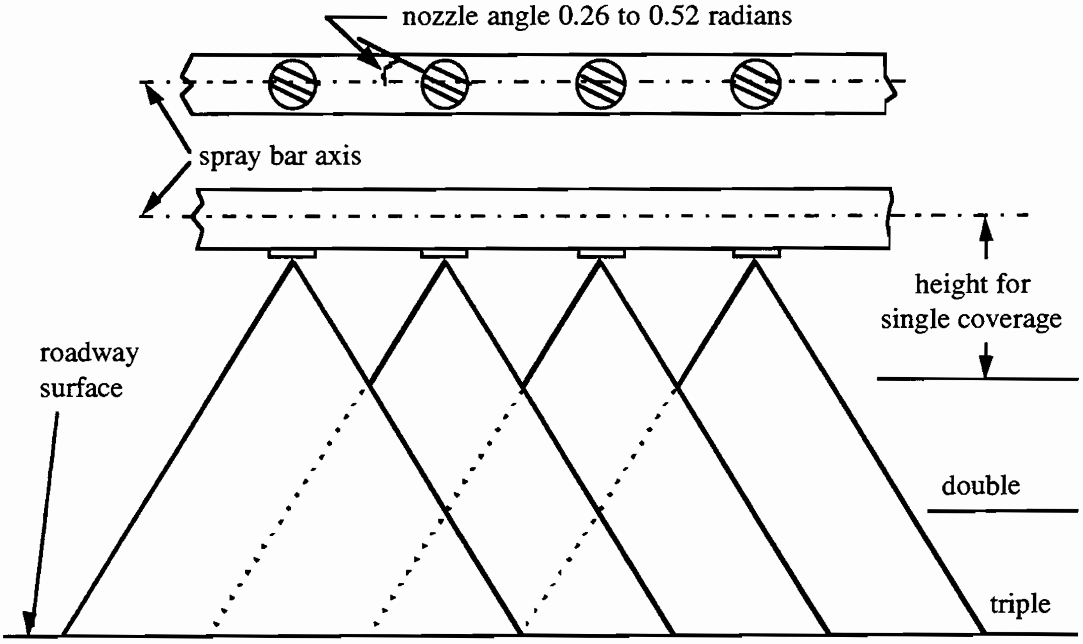

Figure 2.1 Spray Bar Geometry (6)

In the Brownwood District, Shulz and Russell (*13*) measured extraordinary variation in transverse application of asphalt. Of 35 spray nozzles they tested, only 9 where shown to be within 10 percent of the desired spray width. Their applied research resulted in a test to accurately measure spray width of nozzles. They also developed a "bucket test" to check the amount of asphalt delivered by each nozzle. Their test was subsequently standardized (Tex-922-K) *(22)* for general use in calibrating distributors on TxDOT projects. In addition to Shulz and Russell's method, ASTM provides a procedure for spot checking longitudinal as well as transverse application rates (*16*). The ASTM procedure, originally developed by Zube (*17*) of the California

Department of Transportation, utilizes absorbent cotton pads to measure variation in application rates.

The length of time between application of binder and application of aggregate affects the performance of seal coats. If aggregate is applied when the binder is too viscous, proper aggregate embedment and adhesion are not achieved. The result is aggregate loss. In the case of asphalt cement binders, viscosity is governed completely by temperature, assuming contamination is not an issue. Thus, aggregate must be applied immediately after application of the binder. In the case of asphalt emulsion binders, viscosity is governed primarily by the characteristics of the particular emulsion system and secondarily by temperature. If an emulsion is allowed to break (water evaporates from the system and asphalt droplets coalesce) the viscosity of the residual asphalt will be too high to facilitate proper embedment and adhesion. Evidently, regardless of binder type, it is imperative that aggregate be spread as soon as practically possible after application of the binder in order to prevent aggregate loss.

Quality and Consistency of Materials

Undue variation in project materials can cause a variety of problems. Variation in amount and type of dust can cause alternating fat and lean spots as well as aggregate loss. If aggregate size varies above and below the design value, the asphalt application rate is alternatively too little and too much. One of the advantages of TxDOT's approach of using single-sized seal coat aggregates is that the aggregates do not segregate during handling. This considerably reduces problems caused by variation in aggregate size.

To maintain a consistent sprayed binder film thickness, binder viscosity must be kept as constant as possible. Binders that are too viscous do not allow aggregate to be properly embedded or wetted, resulting in a loss of aggregate and free asphalt on the surface. Binders that are too "thin" flow excessively and form too thin a surface film to achieve proper embedment. This also results in aggregate loss and free asphalt on the surface. Figure 2.2 illustrates these extremes.

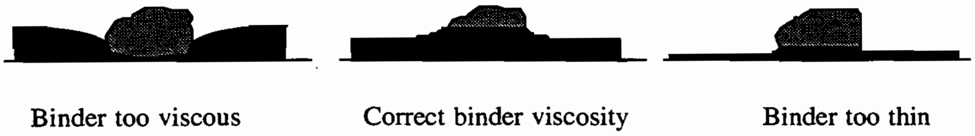

Figure 2.2 Effect of Binder Viscosity on Aggregate Embedment

For these reasons, TxDOT and other agencies carefully control application temperature. When asphalt cements are used for spray applications, a viscosity in the range from 0.020 to 0.120 Pa·s is recommended by the Asphalt Institute (*5*). A previous version of TxDOT specifications (*18*) required a more restrictive viscosity range of 0.10 to 0.12 Pa·s. Current specifications (*14*) place spray temperature requirements and further state that the actual spray temperature must not vary by more than 8° C from the specified temperature. Table 2.4 shows TxDOT's application temperature requirements for the most common sealing grade binders (*14*).

Table 2.4 Application Temperature Requirements (14)

Binder	Application Temperature, °C	
	Recommended	Maximum Allowable,
AC-5 or 10	135 - 180	190
AC-5 or 10 + 2% SBR	145 - 190	200
AC-10 + 3% SBR	150 - 180	180
RS-2, RS-2h, CRS-2, CRS-2h, CRS-2P, HFRS-2, HFRS-2P	45 - 70	80

Sealing grades of asphalt emulsions are necessarily precarious systems. Their formulation represents a compromise between two extremes. They must remain stable enough to survive transport, short-term storage, spraying, and aggregate embedment, and yet sufficiently unstable so that they will immediately begin to break and set after aggregate is applied and rolled. Emulsion systems that satisfy these requirements possess viscosity characteristics that are influenced by many factors in addition to temperature. Unlike asphalt cements, other factors that influence viscosity must be considered when using asphalt emulsions. In general, overheating, underheating, excessive handling and pumping, and improper storage are factors that will cause viscosity problems with asphalt emulsions. The Asphalt Institute (*6*) provides a comprehensive list of "dos" and "don'ts" with respect to proper storage and handling of asphalt emulsions. The effect of improper viscosity when using asphalt emulsions is the same as with asphalt cement — aggregate loss and free asphalt on the surface.

Rolling is one of the last important steps in proper seal coat construction. The purpose of rolling is twofold (*6*): (1) to completely force the aggregate into the binder film and (2) to orient the aggregate into a dense mass approaching the typical design air void content of 20 percent. There seems to be a general consensus that pneumatic-tired rollers are preferable because, unlike steel-wheeled rollers, they do not bridge surface irregularities and do not degrade the aggregate. Occasionally, pneumatic-tired rollers cause aggregate pick up problems; for that reason, some engineers specify the use of steel-wheel rollers. However, it is possible that when pick-up problems occur, it is an indication of a more fundamental problem related to binder or aggregate application rate, flaky aggregate, material variability, or to all of these. There is also a general consensus that rolling should begin as soon as practically possible after application of the aggregate. If too much time expires before rolling, the binder viscosity may be too high to facilitate thorough embedment.

Environmental Conditions

Environmental conditions were often cited by TxDOT and other personnel as having significant impact on seal coat performance. Evidently, to achieve superior seal coat performance, favorable conditions must occur in two critical periods: during construction and during the period right after construction upon early exposure to traffic. Precipitation, high winds, and low surface temperature are detrimental to proper adhesion and retention of the aggregate. Arrival of cool, wet weather during or right after construction often results in aggregate loss when the surface is first exposed to traffic.

To ensure reasonable environmental conditions, TxDOT specifications (*14*) require that seal coat construction not occur when the ambient air temperature is 15° C and falling. Construction may commence, however, when the temperature is 10° C and rising. Evidently, seal coat construction using latex-modified binders is more sensitive to environmental conditions because TxDOT's specifications raise these limitations to 25° C and 20° C, respectively. An additional TxDOT requirement when using latex-modified binders is that the surface temperature must be greater than 20° C.

The long-term performance of a seal coat can also be influenced by extraordinary weather events. An extended period of unusually hot weather can cause bleeding as well as accelerated aging. Extended cold weather can result in brittleness of the aged binder, and can lead to aggregate loss and cracking.

Traffic Conditions

The effect of traffic on seal coat performance is manifested in two ways. First, during and immediately after placement, there is a normal period when no traffic is allowed on the freshly placed mat. This period ranges from 30 minutes to several hours. The length of time with no traffic depends largely on the functional classification of the roadway being sealed. Relatively high traffic volume facilities necessitate shorter closure periods. Many engineers believe that sufficient time should be allowed for the bond to develop between the binder and the aggregate before normal speed traffic is allowed on the road. Otherwise, there is the potential for both aggregate loss and bleeding. According to one source (*6*), this period is 24 hours, with traffic speeds no greater than 30 kilometers per hour. While this may be impractical for certain facilities, there are remedial measures that may be employed to control traffic. Pilot vehicles have effectively been used to direct traffic on freshly placed, tender mats. Another effective technique utilizes active and visible law enforcement personnel to control the disposition of vehicles on fresh mats.

While the most consequential effects of traffic are short term in nature, there is also a long-term effect of traffic. As the asphalt ages and becomes brittle, minor aggregate movement under traffic may cause fracture of the asphalt and loss of the aggregate.

2.2. EFFECT OF ASPHALT BINDERS ON SEAL COAT PERFORMANCE

The first step in the development of performance-based specifications for seal coat binders is to identify the seal coat distresses that binders influence. Once that has been accomplished, it is possible to establish critical levels of binder properties that will result in favorable performance. There are two major types of distress associated with seal coats: bleeding and aggregate loss.

Bleeding

Bleeding, or flushing, refers to a condition of the seal coat where the binder has moved upward to the surface, creating a layer of asphalt at the top. Air void space, normally assumed to be approximately 20 percent by all the design methods, is greatly reduced. The result is a slick surface with low friction characteristics. This condition is hazardous, particularly during wet weather conditions. The previous section cited many of the causes of bleeding. Assuming that the seal coat design is correct and that aggregate materials and construction are of consistent quality, a binder may contribute significantly to bleeding distress if:

- it is too soft at the high temperatures to which it is exposed, and
- it is too soft to rigidly maintain aggregate orientation under the traffic to which it is exposed.

Aggregate Loss

Aggregate loss refers to a condition of the seal coat in which traffic dislodges aggregate particles. If sufficient aggregate is removed, free asphalt becomes the wearing surface and hazardous conditions exist. In addition, the loose stones cause vehicle damage. Undue aggregate loss can occur in the short term immediately after construction, or in the long term during the seal coat's service life. Again, assuming that the seal coat design is correct and that aggregate materials and construction are of consistent quality, a binder may contribute significantly to short-term aggregate loss if:

- it is incompatible with the aggregate,
- it is too soft to retain the aggregate under the mechanical abrasion of early traffic to which it is exposed, and
- it is too brittle under low temperature conditions during the first winter.

A binder may contribute to long-term aggregate loss if:

- it ages excessively and becomes brittle,
- it is too brittle under the low temperature conditions to which it is exposed, and
- a combination of numbers 1 and 2.

From the standpoint of bleeding and short-term aggregate loss, a very stiff, aging-prone binder is favorable. From the standpoint of long-term aggregate loss, a very compliant, non-aging binder is favorable. Thus, to ensure that a binder contributes an equitable share to overall seal coat performance, a compromise must be made. The binder must be stiff enough during its early life so that it does not bleed or suffer early aggregate loss, but not so stiff that long-term aggregate loss is excessive. The binder must also be compatible with the aggregate. Test methods and specification criteria must be established to address these desired performance characteristics.

CHAPTER 3. EXPERIMENTAL PROGRAM

The development of performance-based specifications for seal coat materials requires selecting appropriate laboratory tests, measuring properties that influence the performance, and establishing proper limits on the measured properties through the relationship between the properties and observed performance. Climate and traffic conditions also must be considered. Therefore, as a first step towards such specification development, the following activities were undertaken:

- identify critical factors and distresses in seal coats and survey TxDOT district personnel on seal coat performance,
- procure asphalt cements and emulsions of known performance characteristics when used for seal coats,
- characterize materials in laboratory using new Superpave test procedures,
- select the critical Superpave properties and establish their relevant criteria, and
- select field projects for evaluation and validation.

The primary objective is to be able to specify binders in terms of the new Superpave binder specification.

3.1. IDENTIFYING INFLUENCING FACTORS AND DISTRESSES

Most of the results of this fact finding exercise were detailed in Chapter 2.

3.2. PROCUREMENT OF MATERIALS WITH KNOWN PERFORMANCE CHARACTERISTICS

A significant finding of the TxDOT district personnel survey was that no one could definitely identify a binder that consistently resulted in poor seal coat performance. While this finding was unexpected, it was not surprising. Information presented in Chapter 2 illustrated that the performance of seal coats is influenced by many factors, only one of which is asphalt binder quality. It is also evident that, through a process of evolution over the years, unsuitable binders have been eliminated in many instances. Given this fact, TxDOT personnel were reluctant or unable to isolate the poor performance of a seal coat by positively identifying a binder that "did not perform as designed." Consequently, an alternative approach was taken for the purpose of this research. The discriminate analysis was performed using successful seal coat binders and binders that are not traditionally used for seal coats but clearly would be unsuccessful. Figure 3.1 illustrates the form of the discriminate analysis.

Through the cooperation of the TxDOT Materials and Tests Division, a large number of asphalt cements and emulsions used in seal coat projects were obtained for testing and evaluation. These materials were obtained from seal coat projects either from the tanker truck or from the manufacturer's storage tanks before being shipped to the site. The procured materials are listed in Table 3.1.

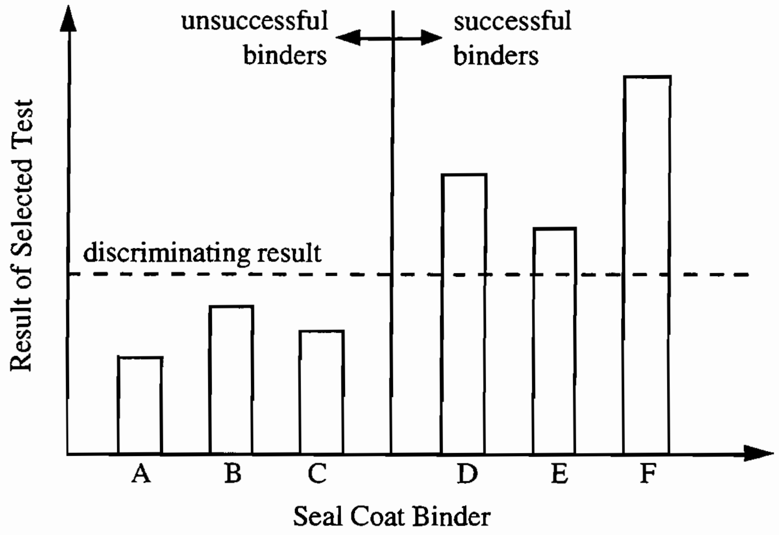

Figure 3.1 Discriminate Analysis Used to Establish Tests and Criteria for Seal Coat Binders

Table 3.1 Seal Coat Binders Sampled and Evaluated

Successful Binders	Unsuccessful Binders
AC-5 AC-5 (2 % latex) AC-10 (2 % latex) AC-15P AC-15-5TR CRS-2 CRS-2P HFRS-2 HFRS-2P	AC-1.5 AC-3

Designation "P" in the asphalt cement or emulsion grade indicates "Polymer." The latex contents shown are percent by mass of solids determined by infrared spectrophotometer analysis. AC-15P implies an asphalt binder that has a minimum viscosity of 150 Pa·s at 60° C and a minimum of 3 percent styrene-butadiene-styrene block copolymer. Designation "TR" indicates tire rubber. AC-15-5TR is an asphalt binder that has 5 percent tire rubber. The tire crumb rubber must have 100 percent finer than 0.850 millimeter and 8 percent finer than 0.425 millimeter.

For this grade, the base asphalt cement must also have a minimum viscosity 150 Pa·s at 60° C. A thorough description of these and other binders is provided in Item 300 of TxDOT standard specifications (*15*).

3.3 MATERIALS CHARACTERIZATION

The primary test procedures used to evaluate the procured binders were the absolute viscosity and penetration tests as executed by TxDOT (Tex-502-C and Tex-528-C) *(22)*, dynamic mechanical analyses using a dynamic shear rheometer (DSR), and low temperature compliance and relaxation analyses using a bending beam rheometer (BBR). Viscosity and penetration tests were measured only to frame the Superpave test results and were not anticipated to be a part of the performance-based specification. DSR and BBR tests were performed according to AASHTO provisional standards TP5 and TP1. In the case of asphalt emulsions, all tests were performed on residue from distillation (Tex-521-C)*(22)*. DSR test results were measured on the original binders, on residue from the rolling thin film oven (RTFO, AASHTO T240), and on residue from the pressure aging vessel (PAV, AASHTO provisional standard PP1). A brief description of the DSR and BBR tests follows.

Dynamic Shear Rheometer

The output of the DSR test for binders are values for complex shear modulus (G*) and phase angle (δ). G* is a measure of binder stiffness in shear, and δ is an indicator of the degree of elasticity of the binder, both reported for a given test temperature. At high pavement temperatures such as 60° C, δ approaches 90° for most asphalt binders, which indicates the binder mechanically behaves almost completely as a viscous fluid. Aged binders and/or binders tested at intermediate pavement temperatures such as 25° C exhibit much lower δ values, typically in the range from 35° to 45°. These δ values indicate that the mechanical response of the binder to load is partly elastic and partly viscous.

In the DSR test, a small sample of binder is placed between, and adheres to, two parallel plates (Figure 3.2). One plate is then oscillated at 10 radians per second.

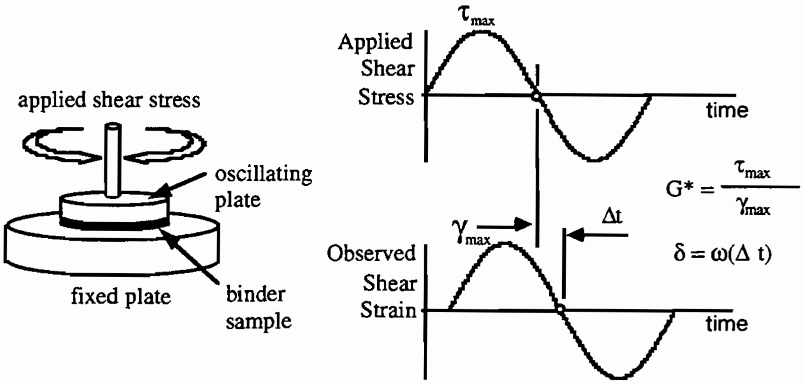

Figure 3.2 Principle of DSR Test (19)

Asphalt binders exhibit both viscous and elastic mechanical behavior at normal testing temperatures and, consequently, there is a time lag between applied shear stress and measured shear strain. Because the testing mode is oscillatory, the time lag is reported in angular terms of either radians or degrees. Thus, the time lag between applied shear stress and observed shear strain is used to compute δ by simply multiplying by the angular frequency (ω). Maximum applied shear stress (τ_{max}) divided by maximum shear strain (γ_{max}) is G*.

Superpave uses these test results in the form of two parameters:

- G*/sin δ for unaged and RTFO residue tested at high pavement temperatures, and
- G*sin δ for PAV residue at intermediate temperatures.

Theoretical derivation and validation of these two parameters has been presented elsewhere *(20)*. The term "sin δ" can be considered an elasticity bonus applied to G*. During high pavement temperatures when a stiff binder would be desirable from the standpoint of rutting, sin δ would increase the term G*/sin δ as δ gets smaller. In other words, a binder that exhibits elastic behavior (lower δ) at high pavement temperatures is favorable with respect to rutting. Superpave places minimum limits of 1.00 kilopascal on unaged binder and 2.20 kilopascals on RTFO aged binder. At intermediate temperatures where fatigue cracking is of concern, a soft elastic binder would be more favorable. Superpave places a maximum restriction of 5000 kilopascals on G*sin δ. In this case, a binder owing more of its mechanical properties to elastic behavior would possess a lower sin δ and the term G*sin δ is reduced. Whether a binder is at high temperatures or intermediate temperatures, Superpave places a bonus on binders that exhibit relatively high amounts of elastic response to load.

Bending Beam Rheometer

The output of the BBR test is a creep stiffness (S) and logarithmic creep rate (m). The test is performed on binders at low pavement temperatures in the range from 0° to about -40° C. It is the test that Superpave uses to ensure that binders contribute an equitable share of resistance to low temperature cracking.

In the BBR test (Figure 3.3), a small asphalt binder beam specimen is subjected to a creep load. The beam responds to the creep load by deflecting with a corresponding reduction in stiffness. The strain response of the beam to creep loading is used with known beam geometry to compute S. From the standpoint of low temperature cracking, a low S is favorable because this means that the binder is not too stiff. The m-value is computed as the slope of the logarithmic relationship between creep stiffness and creep loading time. A high m-value is favorable from the standpoint of low temperature cracking. Binders that quickly change stiffness (i.e., steep slope or higher m-value) are better able to relax stresses that build up when a pavement is subjected to falling temperatures. Both S and m are measured at 60 seconds of creep loading at a temperature 10° C warmer than the design low pavement temperature. SHRP researchers found *(20)* that this shift in loading time and test temperature from actual pavement conditions closely approximated the critical stiffness at 2 hours loading time that produced low temperature cracking. This clever use of time-temperature superposition shortened the test from 2 hours to 4 minutes.

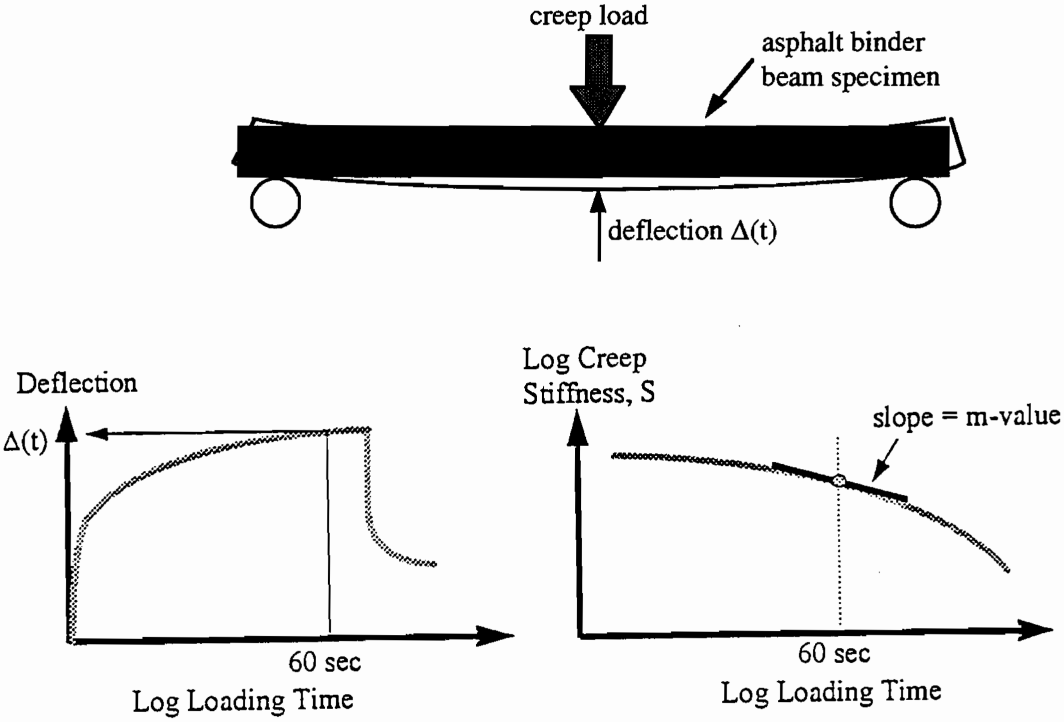

Figure 3.3 Principle of the BBR Test (19)

Laboratory Aging

In Superpave, laboratory aging of binders is used to simulate their condition at critical stages in their service life. The RTFO is used to simulate the condition of an asphalt binder immediately after construction when pervasive rutting has been observed. The PAV is used to simulate the condition of a binder after about 8 to 10 years of service, when fatigue and low temperature cracking typically become problems.

The RTFO (AASHTO T240) uses a forced draft oven to age binders at 163° C. During the 90-minute aging period, binders are contained in special bottles that are fixed in a rotating circular carriage (Figure 3.4). When a bottle passes the 6 o'clock position, a blast of air is directed into the bottle containing the binder sample. The RTFO was a device already in use by some agencies prior to SHRP. SHRP researchers (2) selected it for use over the more commonly used thin film oven (TFO) because it tended to be a more repeatable aging protocol, it is a shorter duration test, and its rolling action tends to better maintain some modified asphalt in a homogeneous condition.

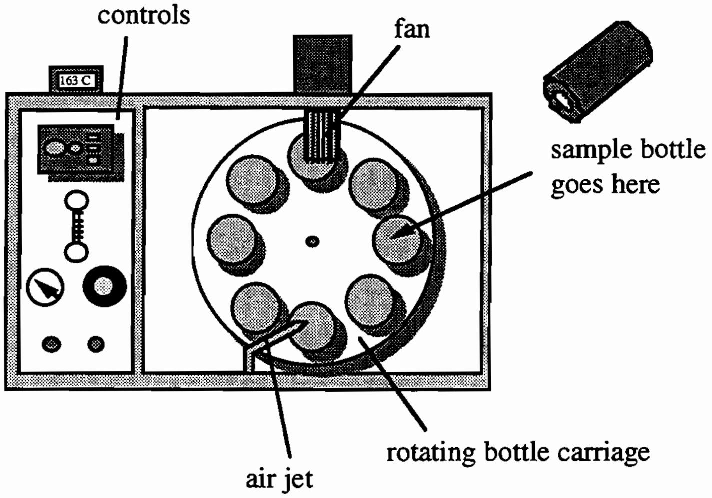

Figure 3.4 Rolling Thin Film Oven Apparatus (18)

The PAV uses heat and compressed air to age binders. Several PAV test configurations exist. However, the unit generically (Figure 3.5) consists of a pressure vessel that is contained in a temperature chamber (usually a forced draft oven), along with instrumentation to monitor aging temperature and pressure. The aging is performed for 20 hours, normally at a temperature of 100° C and at a pressure of 2070 kilopascals. When binders are intended for use in harsh aging climates like deserts, the aging temperature is increased to 110° C. Likewise, very mild, cool climates require the binder to be aged at 90° C.

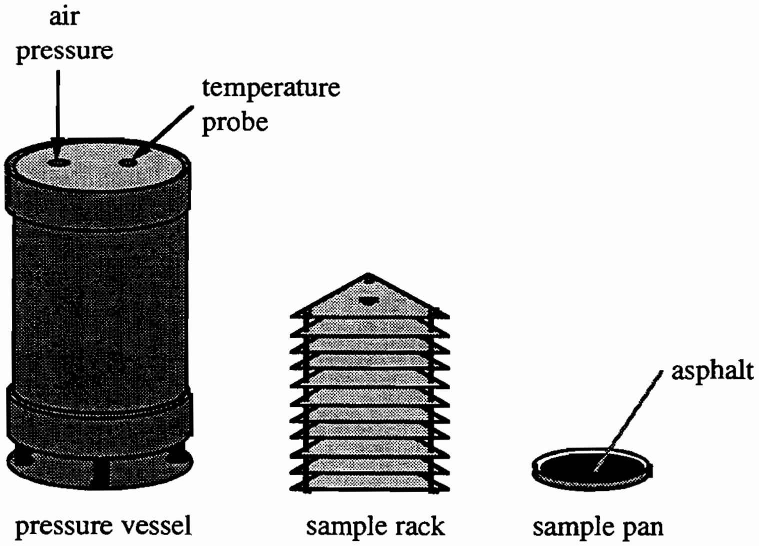

Figure 3.5 Pressure Aging Vessel Apparatus (18)

Superpave Performance Based Binders

The abbreviated version of the Superpave binder specification presented in Appendix B has been provisionally adopted by AASHTO (Designation MP1). The format of the performance grades is PG XX-YY. XX is normally referred to as the high temperature grade, and represents the high pavement design temperature for which the pavement is being protected. Likewise, -YY is referred to as the low temperature grade. So a binder that has been classified as a PG 64-22 indicates that it meets the specification criteria up to at least 64° C and down to at least -22° C. As the environmental temperature extremes for which the binder is being selected becomes greater, the difference between high and low temperature grade becomes higher (e.g., 86° for a PG 64-22).

When compared with current binder specifications, one of the innovations of the Superpave specification is that the physical property criteria do not change according to grade. The criteria remain the same regardless of grade, but the testing temperature at which the physical property criteria must be met changes. Physical property requirements are shown in the first column of the specification. For unaged and RTFO aged asphalt, the parameter $G^*/\sin\delta$ must be greater than 1.00 and 2.20 kilopascals at high pavement temperatures. At intermediate pavement temperatures, $G^*\sin\delta$ must be less than 5000 kilopascals. At low pavement temperatures, S and m must be less than 300 megapascals and greater than 0.300, respectively. Again, the testing temperatures are shifted by +10° C to simulate actual project conditions at a more reasonable testing time. So a binder that is designed for low pavement temperatures of -22° C is tested at -12° C.

CHAPTER 4. ANALYSIS OF RESULTS

The approach used to establish performance-graded seal coat binders involved two main steps. The first step required laboratory experimentation (described in Chapter 3) to evaluate seal coat binders currently used in Texas. A discriminate analysis (Figure 3.1) of these data, described in this chapter, is used to develop binder physical property specification criteria. The second step, which is the goal of a project continuation yet to be accomplished, will be to validate those criteria through either field performance or experience.

Asphalt binders used on seal coat projects throughout Texas were supplied by the TxDOT Materials and Tests Division for analysis (Table 4.1). As mentioned earlier, no binders were procured that were positively identified as unsuccessful binders when used for seal coat projects. To facilitate the analysis, samples of relatively soft and hard binders judged to be unsuitable for seal coat use were tested. Successful binders included neat and modified asphalt cements and asphalt emulsions (also modified and unmodified). With respect to asphalt emulsions, we felt that the method of recovery of emulsion residue could affect test results on the recovered binder. Consequently, we conducted a small experiment to ascertain the preferred method of emulsion residue recovery.

Table 4.1 Grades and Sources of Binders Used in Study

Grade	Source
Unsuitable Binders	
AC-1.5	Kerr-McGee, Gulf States Asphalt
AC-3	Total Petroleum, Exxon Co., Lion Oil, Kerr-McGee, Fina
Successful Binders	
AC-5	Diamond Shamrock, Fina, Chevron, Exxon, Texas Fuel & Asphalt, Neste/Wright, Coastal Refining, Total, Kerr-McGee
AC-5 (2% latex)	Fina, Coastal Refining, Texas Fuel & Asphalt, Trumbull
AC-10 (2% latex)	Coastal, Texas Fuel & Asphalt
AC-15P	Texas Fuel & Asphalt, Neste/Wright, Koch Materials
AC-15-5TR	Neste/Wright
HFRS-2	Koch Materials[1]
HFRS-2P	Koch Materials[1]
CRS-2	Koch Materials[1]
CRS-2P	Koch Materials[1]

[1] Source of base asphalt not identified.

4.1. METHOD OF RECOVERY OF EMULSION RESIDUE

Two methods are available for recovering emulsion residue: the evaporation method and distillation method. For current specification purposes, TxDOT uses the distillation method (Tex-521-C) (21), which is essentially the same as the procedure prescribed in ASTM D244 (*20*). The evaporation method is also standardized in ASTM D244. To compare the physical properties of emulsion residues recovered using the two methods, the DSR was employed according to the test matrix in Table 4.2.

Table 4.2 Testing Matrix to Evaluate Effect of Emulsion Residue Recovery Method

Binder	Recovery Method	Test Temperature, °C					
		52		58		64	
		G*	δ	G*	δ	G*	δ
CRS-2	evaporation	√	√	√	√	√	√
	distillation	√	√	√	√	√	√
	base	√	√	√	√	√	√
HFRS-2	evaporation	√	√	√	√	√	√
	distillation	√	√	√	√	√	√
	base	√	√	√	√	√	√
HFRS-2P	evaporation	√	√	√	√	√	√
	distillation	√	√	√	√	√	√
	base	√	√	√	√	√	√

√ - indicates one determination per cell

The results of this analysis are shown in Figures 4.1, 4.2, and 4.3. The efficacy of a recovery technique was judged by comparing the physical properties of the recovered residue with the physical properties of the base asphalt. A residue less disturbed by the recovery method would have properties more similar to those of the base asphalt. For the CRS-2 and HFRS-2, the distillation recovery procedure produced a binder having properties essentially the same as those of the base asphalt (Figs 4.1 and 4.2). For the modified emulsion HFRS-2P, neither method appeared to produce a residue whose properties were similar to those of the base asphalt (Fig 4.3). In this instance, both methods produced stiffness values much less than those of the base asphalt. The residues obtained from the evaporation method tended to be heated more, which resulted in a consistently higher stiffness than the distillation method. Given this information, we decided to use the distillation method for the primary test program.

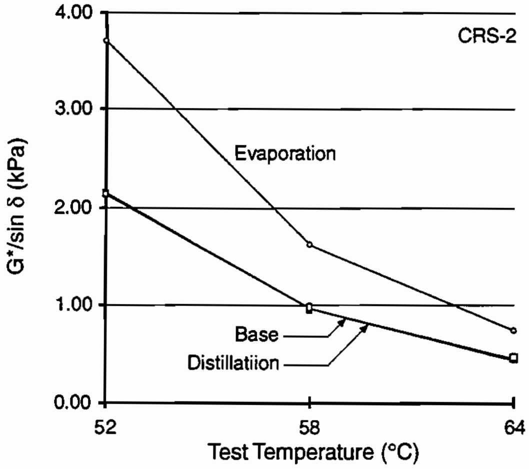

Figure 4.1 Effect of Recovery Method on Physical Properties of CRS-2 Residue

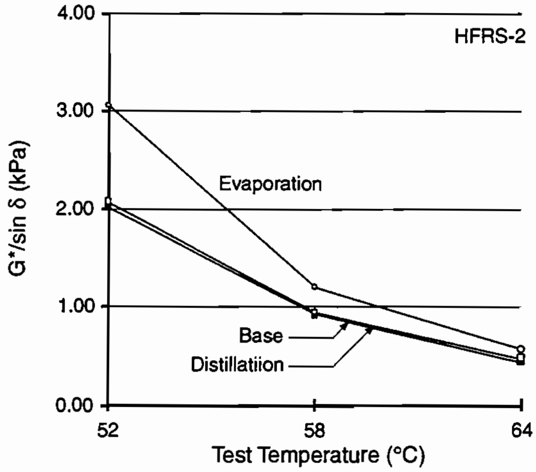

Figure 4.2 Effect of Recovery Method on Physical Properties of HFRS-2 Residue

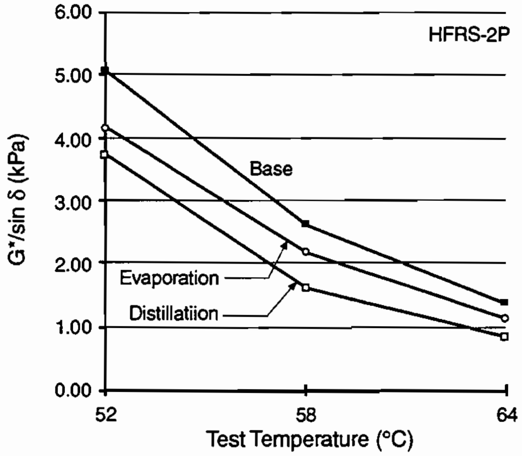

Figure 4.3 Effect of Recovery Method on Physical Properties of HFRS-2P Residue

4.2 HIGH PAVEMENT TEMPERATURE ANALYSES

Properties of seal coat binders at high temperatures enhance resistance to bleeding and short-term aggregate loss. A very stiff binder at high pavement temperatures would not tend to bleed because it would be too stiff to flow. A very stiff binder at high pavement temperatures would more rigidly maintain aggregate orientation under traffic, which would also help eliminate bleeding distress because the aggregate could not densify below 20 percent air voids. Likewise, a very stiff asphalt would more tenaciously retain aggregate under the mechanical abrasion of traffic, which would minimize short-term aggregate loss. In terms of the Superpave binder specification, all three high temperature distress mechanisms would be ameliorated by maximizing the stiffness parameter G*/sin δ for both unaged and RTFO aged binder. Consequently, a discriminating value of G*/sin δ was sought in the analysis.

To find this value, DSR tests were performed at 52°C, 58°C, and 64°C for unaged asphalt and RTFO aged asphalt. A detailed listing of these test results is presented in Appendix C. A graphical representation is shown in Figures 4.4 through 4.6.

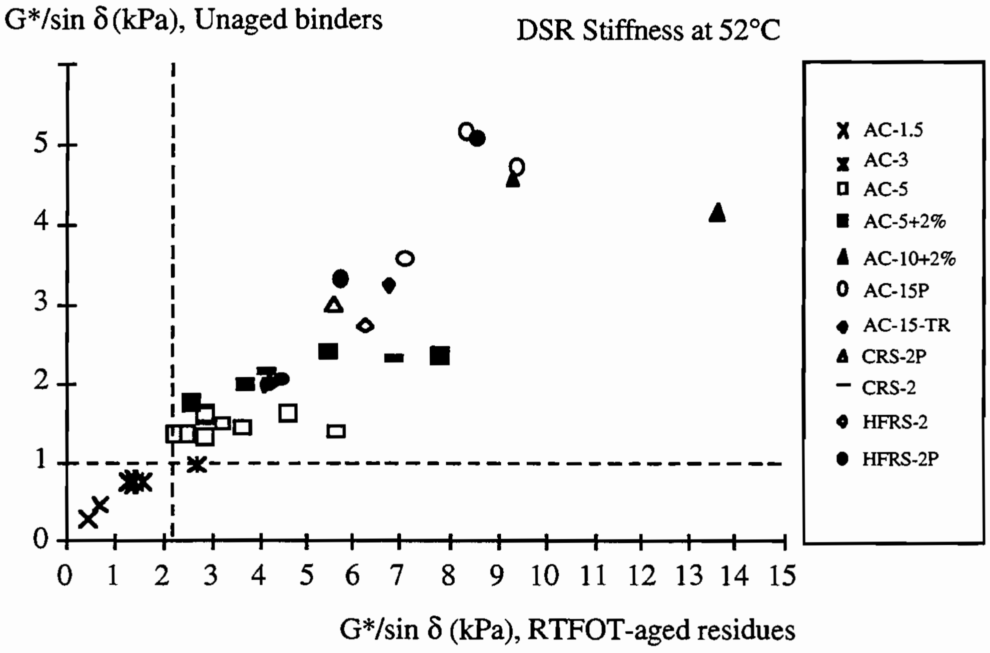

Figure 4.4 DSR Stiffness (G/sin δ) of Unaged and RTFOT aged Binders at 52°C*

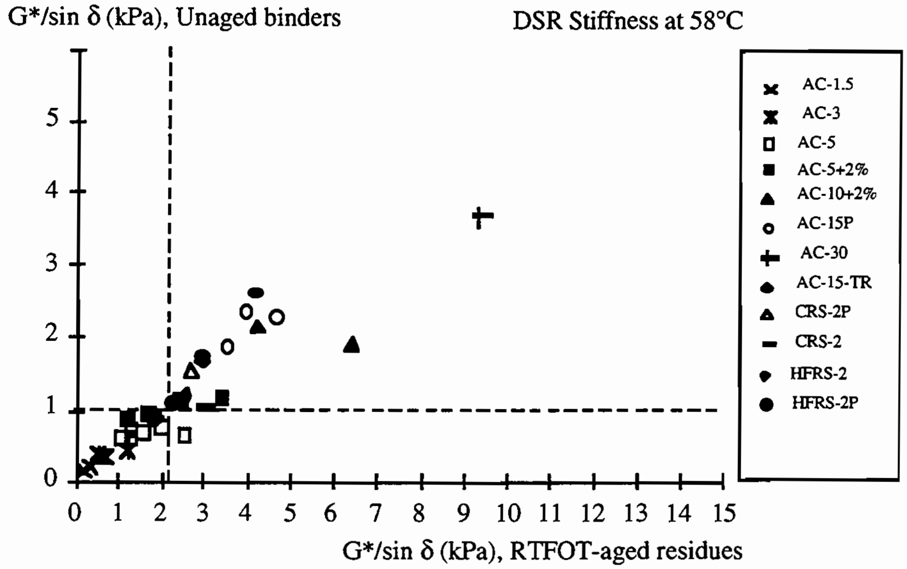

Figure 4.5 DSR Stiffness (G/sin δ) of Unaged and RTFOT aged Binders at 58°C*

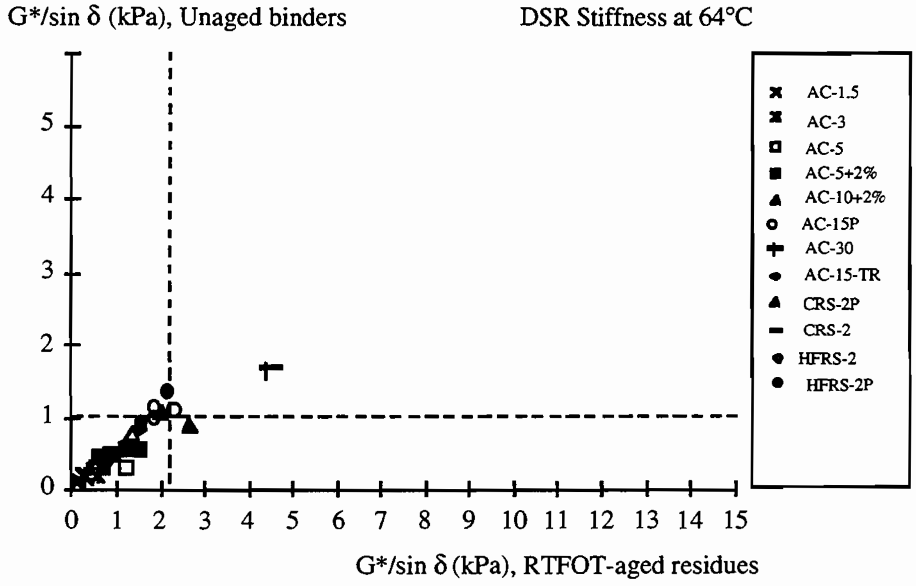

Figure 4.6 DSR Stiffness (G/sin δ) of Unaged and RTFOT aged Binders at 64°C*

Clearly, the RTFO is not intended to simulate aging in seal coat binders. The RTFO stiffness data are shown only for reference purposes to properly frame the binders in terms of the PG system. Development of a specification criterion used only the properties of unaged seal coat binders. The data for unaged binder plotted in Figures 4.4 through 4.6 indicate that a G*/sin δ value of about 1.00 kPa discriminates between suitable and unsuitable seal coat binders when tested at 52° C. The lowest G*/sin δ value observed for these binders at 52° C was 1.25 kPa. When testing temperature is increased to 58° C, the discriminating value for G*/sin δ was about 0.50 kPa. At 64° C, the value was approximately 0.25 kPa.

For high temperature properties, a PG 52 with the normal Superpave criterion for unaged asphalt binder and a G*/sin δ of 2.20 kPa for short-term aged asphalt would encompass currently used seal coat binders judged to be acceptable. The PG grades of 58-YY and 64-YY do not discriminate between unsuitable and satisfactory binders without changing the criteria for grading.

Figure 4.5 shows that stiffer binders like AC-10 (2% latex), AC-15P, AC-15TR, HFRS-2P and CRS-2P met the requirements to be specified as PG 58 in the Superpave PG system. The lowest G*/sin δ value of these seal coat binders at 58°C is 1.53 kPa. Therefore, it would be possible for districts that successfully used these seal coat binders to specify PG 58. The test results at 64°C in Figure 4.6 show no discerning pattern. Only three of the binders tested marginally met the Superpave criterion of 1.00 kPa at that temperature. Therefore, it does not appear feasible, based on the binders tested, to specify seal coat binders as PG 64, since many well-performing binders would be eliminated.

It should be noted that none of the Superpave binder test procedures address the very real problem of short-term aggregate loss resulting from incompatibility between the asphalt binder and aggregate. While it is possible that another SHRP product (e.g., the net adsorption, desorption test) could be used to address this issue, no testing was accomplished under this project to test this hypothesis.

4.3 LOW PAVEMENT TEMPERATURE ANALYSES

Properties of asphalt binders at low temperatures directly contribute to the resistance of seal coats to both short- and long-term aggregate loss. A very compliant binder at low temperatures is not as susceptible to aggregate loss. In terms of the Superpave binder specification, this distress mechanism would be ameliorated by minimizing S and maximizing m-value, both measured on PAV aged materials. Consequently, discriminating values of S and m were sought in the analysis.

A detailed listing of these test results is presented in Appendix D. A graphical representation is shown in Figures 4.7, 4.8, and 4.9 for S and m at -12°, -18° and -24° C.

Figure 4.7 indicates that the binders tested far exceed the Superpave S and m criteria of 300 MPa and 0.300 at -12° C, and could easily be classified as PG XX-22 grades. Figure 4.8 shows that the binders mostly meet Superpave requirements at -18° C. At this temperature, one HFRS-2 binder exceeded the stiffness limitations. A CRS-2 and AC-10 (2%) were marginal on m-value at -18°C. Moreover, a tested impractical use asphalt binder for seal coat material like AC-30 was plotted in the same graph for comparison purposes. Continuing to examine the performance of the asphalts at decreasing temperatures, five asphalt types and grades representative of those previously selected for examination were tested at - 24° C. All of the materials tested, modified or unmodified, failed to meet the Superpave criteria as shown in Figure 4.9. This agreed with the apparent trend noted in the testing of the asphalts at the previous low temperatures where the values were approaching the limits recommended in the Superpave criteria as the temperatures were reduced.

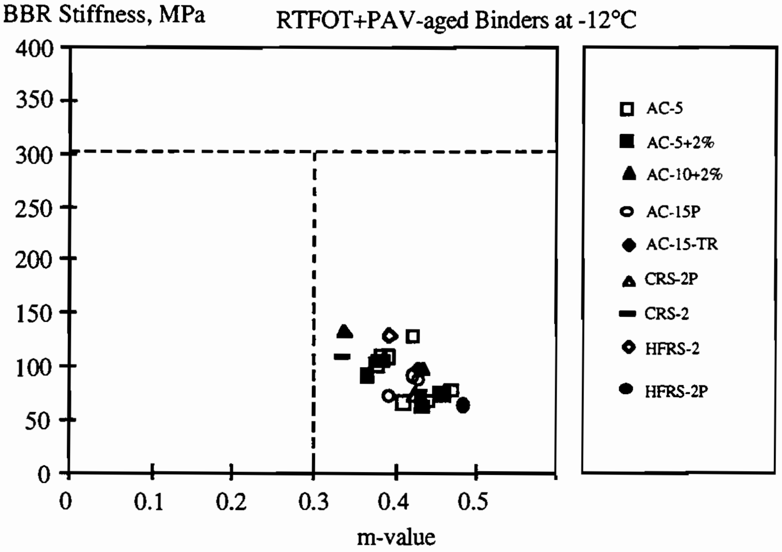

Figure 4.7 Creep Stiffness (S) and Logarithmic Creep Rate (m) of RTFOT+PAV aged Binders at -12°C

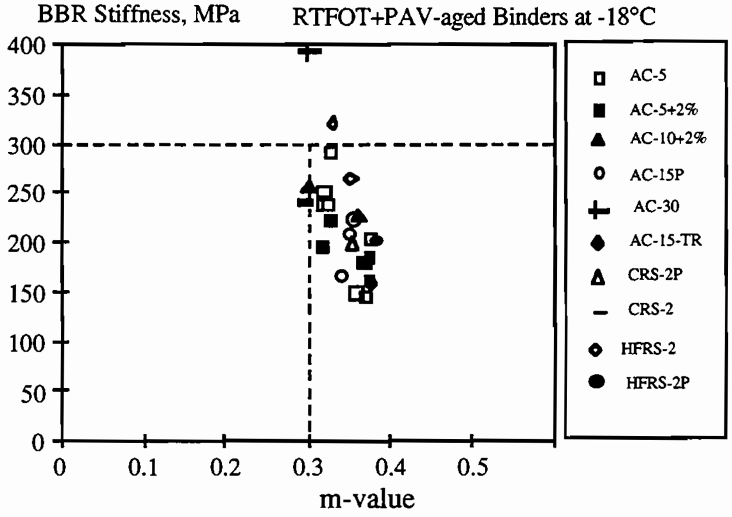

Figure 4.8 Creep Stiffness (S) and Logarithmic Creep Rate (m) of RTFOT+PAV aged Binders at -18°C

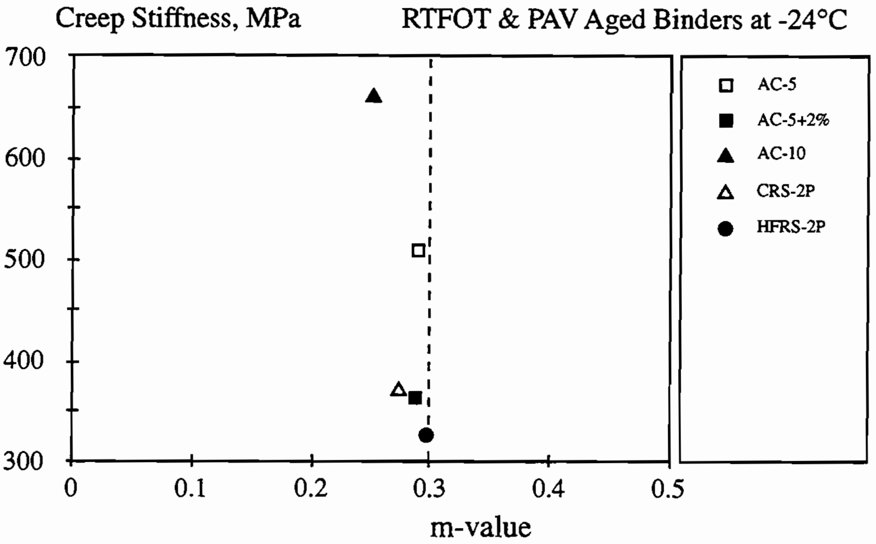

Figure 4.9 Creep Stiffness (S) and Logarithmic Creep Rate (m) of RTFOT+PAV aged Binders at -24°C

Figure 4.10 shows the stiffness values of unaged asphalt at -18° C. It is possible that these binders simulate the condition of seal coat binders at a very early age, for example, during their first winter when short-term aggregate loss might occur. At this temperature, all binders exhibit stiffness values in the range from about 75 to 175 MPa.

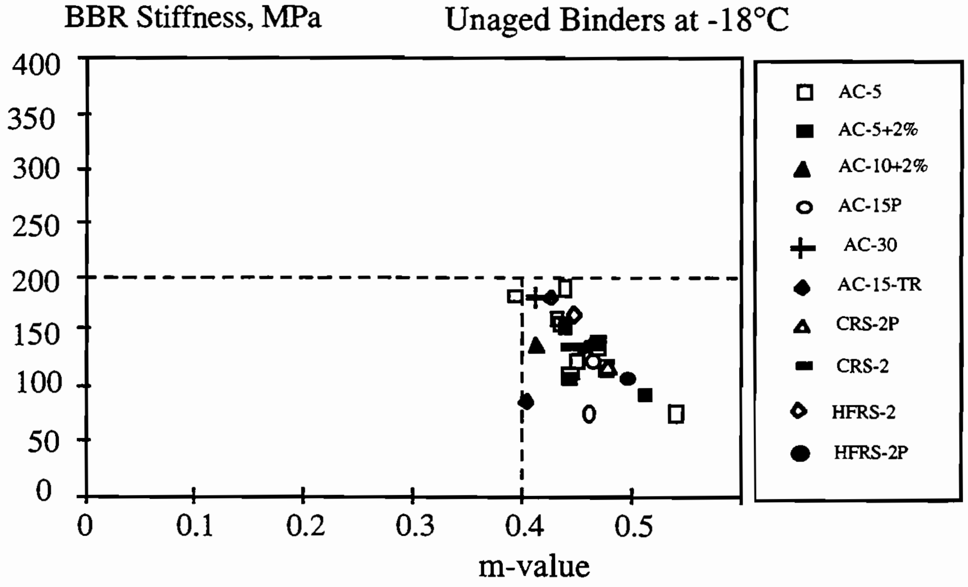

Figure 4.10 Creep Stiffness (S) and Logarithmic Creep Rate (m) of Unaged Binders at -18°C

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

In developing performance-based asphalt specifications for seal coats, we undertook the following:

1. Determine the existing asphalts currently in use by TxDOT for seal coats; obtain field input for those materials and the user evaluation of their service;
2. Laboratory testing, based on the SHRP Recommended Protocol, of those asphalts and emulsions sampled by TxDOT to represent materials actually used; and,
3. Evaluate those test results in accordance with the American Association of State Highway and Transportation Officials (AASHTO) Recommended Guide developed by the SHRP Asphalt Research Program.

CONCLUSIONS

Currently there is no definite trend in Texas as to the type of asphalt binder selected for use on seal coats; the only consistent trend identified was that asphalt cements softer than AC-5 are not used. At best, binders with higher stiffness values at high temperatures are used on roadways with high traffic volumes. Binders are selected based on a history of satisfactory performance. Asphalt binders with an established history of acceptable performance for seal coats classify as PG 52-28 in the Superpave binder specification.

RECOMMENDATIONS

To satisfy statewide purchase, a PG 52-28 could be specified. While the data clearly showed that specifying a PG 52-28 would embrace all successful binders in Texas, this is not an implementable finding. If TxDOT simply specified PG 52-28, it is highly likely that contractors would furnish an AC-5 binder. Based on the district survey results, AC-5 provides adequate service on many facilities. However, widespread use of more sophisticated binder systems (e.g., CRS-2P, AC-10 with 2 percent latex, etc.) indicates that there are situations when a neat AC-5 would not provide satisfactory service. As outlined in Chapter 2, many interrelated factors contribute to seal coat performance. It is likely that some engineers specify more robust systems to overcome potential deficiencies in construction practice, aggregate materials, adverse climate, dust, or high traffic. In those cases, the best approach is to locally classify seal coat binders using the performance-based tests and specify grades accordingly. A more detailed analysis should be conducted on a district-by-district basis.

Ultimately, selection criteria based on climate and traffic should be developed and incorporated as part of a performance-based specification.

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APPENDIX A
SUMMARY OF TxDOT DISTRICT PERSONNEL INTERVIEWS ON SEAL COAT PERFORMANCE AND PRACTICE

APPENDIX A
SUMMARY OF TxDOT DISTRICT PERSONNEL INTERVIEWS ON SEAL COAT PERFORMANCE AND PRACTICE

In the fall of 1993, all districts of the Texas Department of Transportation were contacted for information on the asphalts normally used in their annual seal coat programs. Over two-thirds of the districts responded at that time; those responding represented a cross-section of both asphalt suppliers and environmental conditions encountered in Texas.

The following information was obtained from a follow-up telephone survey (initially those responding districts and, later, the remaining districts) on their experience with their 1994 summer seal coat program. Specifically, they were asked which asphalts were used and what problems did they encounter that could conceivably have resulted from the asphalts used (either emulsion or AC). In addition, they were asked to note any problems with the specifications as written (i.e., Was there any problems with the performance of an asphalt that might be the related to the specification itself?). The following identifies the individuals contacted and the responses obtained:

ABILENE: Thomas Bohuslav, (915)673-3761

No emulsions were used and based on previous observation, they didn't seem to need latex additives and, therefore, couldn't justify the added cost. With the exception of a small quantity of low volume roads, all rock was precoated.

AC-5&10 from Fina and Kerr-McGee were used in their program. Problems were encountered with Fina having more volatiles and flushed on them while they had no problems with Kerr-McGee.

They did one small project using Neste/Wright AC-15TR and had good success. They are concerned about the cost involved since they apparently have a successful program without it.

AMARILLO: Billy Parks, (806)356-3201 & Bruce Epp, (806)356-3270

Previous experience two to three seasons ago was with AC-5P and CRS-2,2P & 2H. Next year was only AC-5P and in the 1994 season only AC-5 was used. The temperature at application was 350 F. Aggregate was either precoated limestone or precoated siliceous.

Cost was the major factor in the type of asphalt selected for the program.

The major problem observed was raveling due to excessive brittleness in the winter.

ATLANTA: John Baker, (903)799-1240

One-half of their program was done with Koch CRS-2P and the other half was with Neste/Wright AC-15TR. Precoated aggregate was used with the AC-15TR and uncoated lightweight aggregate with the emulsion. No problems were encountered with the emulsion. The use of the tire rubber was new to them which made them a little cautious at first but they were successful with it. Next year's program will be the same half and half.

AUSTIN: Lenny Bobrowski, (512)832-7000

Their program consisted of using HFRS-2 & 2P with mostly crushed limestone aggregate. No problems related to the asphalt were noted.

BEAUMONT: Clinton Bond, (409) 898-5744

Basic asphalt material used was CRS-2P from Koch. No problems were encountered with the emulsion. A test section was placed using Exxon AC-5 on one lane and an AC-15TR on the other. The AC-5 was a complete failure but the 15TR performed well.

Next year's program will include about 50 miles of AC-15TR.

BROWNWOOD: Richard Walder, (915) 646-2591

About 90% of their program used Koch CRS-2. They switched to HFRS-2 when temperatures were very hot. MC3200 and CRS-1P were used in winter operations.

They found that the polymer added grade was slower to break, splatters outside the lane and detouring traffic rolls it up. In their opinion, the use of polymer also did not justify the added cost. This district preferred CRS-2 because rain didn't affect it like the HFRS-2.

BRYAN: Elias Rneili, (409) 778-9797

HFRS-1P and AC-15P were used in their program. Although they followed the chart on season use, they had a number of problems with the High Float material. Mostly satisfied with the AC-15P during the summer but marginal in cooler weather.

CHILDRESS: Terry Keener, (817) 937-2571, ext. 147

This program used several emulsions, mostly locally supplied, and did a small amount with the AC-15TR. There were a number of problems that they attribute to the aggregate being used. This was a granite from Meridian, Oklahoma. They found that Oklahoma had the same problem with the material and no longer allowed it to be used on their projects.

This district expressed concern about the wide spread in the specification limits for penetration with the emulsions.

CORPUS CHRISTI: Mario Garza, (512) 808-2223 & Ralph Condra, (210)780-3993

AC-15P worked well according to Condra but Garza reported that an attempt to use in late season in December was a major disaster. The seal was shot on Tuesday and all aggregate was gone by Wednesday with thousands of vehicles damaged. Condra reported that one transport of AC15-5TR didn't shoot hot enough so there was some streaking but it still held the rock well.

Plans are to use AC15-5TR exclusively next year on their program.

DALLAS: James E. Hunt,(214) 320-6116

Based upon information furnished, the district used AC-5 with latex as the primary asphalt and precoated aggregate. They reported having placed microseals, plant mixed seals and seals using the crumb rubber. No other details were given except to report that they considered this past season to have yielded the highest quality the district had ever experienced.

A previous response from this district indicated that they had used AC-5 with latex from Exxon, Baytown; Coastal, Corpus Christi; Gulf States, Beaumont; Texas Fuel & Asphalt, Corpus Christi and Fina, Big Springs.

EL PASO: David Head, (915) 774-4300, ext. 200

No emulsions were used. AC-5 & 10 from Fina and Chevron were the asphalts used, the source depending upon which contractor was doing the job. Both performed about the same. There did not appear to be any problems during with the unusually hot weather this last summer, all projects had bleeding problems, even HMAC surfaces. This problem was especially prominent on high trafficked areas. The district is considering not using seal coats on high traffic city streets this next year.

Another problem was the use of rhyolite aggregate which breaks down easily and promoted stripping. Consideration is being given to changing to a dolomite for next year's program.

FT. WORTH: Richard Williammee, Jr., (817) 370-6675

Only used Koch CRS-2 and CRS-2H emulsions in their program. There were some problems initially with setting the rate of shooting which had to be adjusted during the work. A local natural limestone aggregate, grade 4, was used. There are a few bleeding spots but the total program appears to be in good shape. Within two weeks after the seal coat was completed, a fog seal was applied to the surface. Anticipating the research needs, some test sections were prepared by placing aluminum foil on the roadway surface prior to the seal coat application.

HOUSTON: LARRY HECKATHORN, (409) 849-5521

Asphalt used was either AC-5 or AC-10 with precoated aggregate. No estimate at this time if their were any problems because all seal coats were overlayed with HMAC as part of the same project.

LUBBOCK: Clarence Rogers, (806) 748-4447

Emulsions with natural aggregate and AC-5P with precoated aggregate made up their program for 1994. No problems except some slight ones caused by the aggregates. They have had application problems with MC 1200, 2400 & 3600.

LUFKIN: Cheryl Flood, (409) 633-4331

This district has an annual budget of $2 million, mostly seal coats. No emulsions are used. For low traffic roads, AC-5 (mostly Texaco) and grades 4 & 5 lightweight aggregate are used. On high traffic roads (> 580 ADT), AC-5 + 2% latex and grade 3 limestone aggregate are specified. Aggregates are precoated. Although there has been some minor bleeding, in general, they have had success with their seal coats and are pleased with the performance.

ODESSA: Steve Smith

No problems encountered. They no longer allow polymers since their experience shows no advantage versus the added cost. Only AC-5 used from Fina and Coastal and AC-20 for precoat on aggregates.

The first year, after one year, they experienced some bleeding but felt this was caused primarily by inexperience and that they need more design input.

Only one project was placed with tire rubber and this was overlayed. Plans are to let several tire rubber underseals this next season.

PARIS: Mark Magson, (903) 737-9300

Only report was on their use of AC-15-5TR where they encountered stripping problems. He is canvasing the district area engineers to see if there any additional problems to report.

PHARR: Richard Buchen, (210) 787-2771

Emulsions were used only towards the end of the season, or when the temperatures turned cooler. AC-10 & 15, AC with latex and AC15-5TR used and no major problems were encountered. Most of the problems were associated with cold weather or when the asphalt was delivered too cool from the supplier. Gravel aggregate was used with no problem, precoated aggregate used only for high traffic roads.

SAN ANGELO: Dennis Wilde, (915) 944-1501

Asphalt used was AC-5P and a small amount of AC15-5P. They had problems in high traffic and turn out areas with the AC-5P in urban areas. It was believed that this was the result of high temperatures and traffic having to be let back on to the newly sealed roadway too soon. They were very pleased with the AC15-5P and are anxious to see how it performs under winter conditions.

SAN ANTONIO: Frank Jaster, (210) 615-6042

The materials used in their seal coat program consisted of a variety of aggregates, mostly grades 3 & 4 and their modifications, some precoated. Limestones from Redland Stone, Vulcan, Gifford-Hill and Colorado Materials; Flintrock from Capitol Sand & Gravel; Sandstone from Delta Materials; and Traprock and Limestone Rock Asphalt from Vulcan were the aggregates and sources.

Both asphalt binders and emulsions were used. The sources and grades were: HFRS-2P, CRS-2P, MC-2400 w/latex, AC-5 w/latex, AC-10 w/latex, AC-15P, and CRS-1P from Texas Fuel and Asphalt, Koch Materials, Coastal Refining Co. and Gulf States.
No problems were noted.

TYLER: Wayne Leake, (903) 510-9249

Some emulsions were used with micro-surfacing and some retention problems were encountered. The aggregate was precoated. AC15-5TR was used on most of the program with good results. Next year's program is planned to be the same as this one.

WACO: Duane Schwarz, (817) 772-2890 & Andy Tetter

Primary program used AC-15P with either natural or lightweight grade 4 aggregate. Two transports of AC-15-5TR were placed as a trial. No problems were encountered in general except weather when they ran into a late season or after an afternoon shower. They have a $4 million program planned for this coming season.

WICHITA FALLS: Ralph Self,(817) 720-7790

Previously AC-5 and AC-10 asphalts were used in their seal coat program but this was changed this past season to CRS-2 and CRS-2H from Koch. The reasons for the change were based on environmental needs as well as more safety in handling a material at lower temperatures. Plans are that this next season the district will use mostly AC-15-5TR and some CRS-2 and -2H.

The aggregates are crushed limestone and lightweight. Granite aggregate was used with CRS-2 but was a disastrous failure. The aggregate lost under traffic, apparently sticking to the tires. The application rate was 0.42 gal/sq yd for the CRS-2 with a grade 4 aggregate.

The district had bad experiences when the combination of precoated aggregates and CRS-2 emulsions were used. The district theory was that with precoated aggregate there were little to no voids left in the rock to be filled with the emulsion and probably, water surrounded the aggregate particle before the asphalt could adhere to the surface of the stone.

This district is interested in knowing of any problems from other districts in the use of AC-15-5TR, specifically, is it better to use plain or precoated aggregate when using this product. They apparently have heard of some having had problems when using AC-15P with uncoated aggregate.

YOAKUM: E. J. Blaschke, (512) 293-4378

The asphalt used was AC-5 with 2% polymer from TFA, Corpus Christi. There was also 3 sections placed using AC15-5TR for trial.

There was loss of aggregate, probably because of wet and cold conditions. Overnight traffic assisted in the loss of the grade 3 aggregate which was precoated. Some of the aggregate was limestone rock asphalt from Vulcan.

SUMMARY:

There was a reluctance on the part of all of the individuals interviewed to place the blame for the problems encountered on the asphalt used in their programs. This is understandable, once the number of things that can go wrong with a seal coat operation are considered. An overnight drop in temperature, a light coating of dust on the aggregate, an unexpected shower, or an emulsion not breaking as designed are only a few of the possible causes for a failed operation.

It is worth noting, however, that many of these causes — in addition to a district's reluctance to use an emulsion (or emulsions in general), or relying on emulsions only — may point to its inability to preselect the product or grade of asphalt for the conditions existing at the project site. In addition, there are significant comments pointing to the inability of a particular emulsion to react properly or for a particular AC to fail to hold the aggregate. This may well reflect the need to update the seal coat specifications.

APPENDIX B
SUPERPAVE BINDER SPECIFICATION (AASHTO MP1)

AASHTO Performance Graded Binder Specification (MP1)

Performance Grade	PG 52							PG 58					PG 64					PG 70			
	-10	-16	-22	-28	-34	-40	-46	-16	-22	-28	-34	-40	-16	-22	-28	-34	-40	-10	-16	-22	-28
Average 7-day Maximum Pavement Design Temperature, °C [a]	<52							<58					<64					<70			
Minimum Pavement Design Temperature, °C [a]	>-10	>-16	>-22	>-28	>-34	>-40	>-46	>-16	>-22	>-28	>-34	>-40	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28
Original Binder																					
Flash Point Temp, T48: Minimum °C	230																				
Viscosity, ASTM D 4402: [b] Maximum, 3 Pa·s (3000 cP), Test Temp, °C	135																				
Dynamic Shear, TP5: [c] G*/sin δ, Minimum, 1.00 kPa Test Temperature @ 10 rad/s, °C	52							58					64					70			
Rolling Thin Film Oven (T240) or Thin Film Oven (T179) Residue																					
Mass Loss, Maximum, %	1.00																				
Dynamic Shear, TP5: G*/sin δ, Minimum, 2.20 kPa Test Temp @ 10 rad/sec, °C	52							58					64					70			
Pressure Aging Vessel Residue (PP1)																					
PAV Aging Temperature, °C [d]	90							100					100					100(110)			
Dynamic Shear, TP5: G*sin δ, Maximum, 5000 kPa Test Temp @ 10 rad/sec, °C	25	22	19	16	13	10	7	25	22	19	16	13	28	25	22	19	16	34	31	28	25
Physical Hardening [e]	Report																				
Creep Stiffness, TP1: [f] S, Maximum, 300 MPa m-value, Minimum, 0.300 Test Temp, @ 60 sec, °C	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	-6	-12	-18	-24	-30	0	-6	-12	-18
Direct Tension, TP3: [f] Failure Strain, Minimum, 1.0% Test Temp @ 1.0 mm/min, °C	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	-6	-12	-18	-24	-30	0	-6	-12	-18

Notes:

a. Pavement temperatures can be estimated from air temperatures using an algorithm contained in the SUPERPAVE software program or may be provided by the specifying agency, or by following the procedures as outlined in PPX.

b. This requirement may be waived at the discretion of the specifying agency if the supplier warrants that the asphalt binder can be adequately pumped and mixed at temperatures that meet all applicable safety standards.

c. For quality control of unmodified asphalt cement production, measurement of the viscosity of the original asphalt cement may be substituted for dynamic shear measurmeents of G*/sin δ at test temperatures where the asphalt is a Newtonian fluid. Any suitable standard means of viscosity measurement may be used, including capillary or rotational viscometry (AASHTO T 201 or T 202).

d. The PAV aging temperature is based on simulated climatic conditions and is one of three temperatures 90° C, 100° C or 110° C. The PAV aging temperature is 100° C for PG 58- and above, except in desert climates, where it is 110° C.

e. Physical Hardening - TP 1 is performed on a set of asphalt beams according to Section 13.1, except the conditioning time is extended to 24 hrs ± 10 minutes at 10° C above the minimum performance temperature. The 24-hour stiffness and m-value are reported for information purposes only.

f. If the creep stiffness is below 300 MPa, the direct tension test is not required. If the creep stiffness between 300 and 600 MPa the direct tension failure strain requirement can be used in lieu of the creep stiffness requirement. The m-value requirement must be satisfied in both cases.

APPENDIX C
TEST DATA ON SEAL COAT BINDERS

Table C1. Binder Properties at 52° C

Grade	Source	G* Tank kPa	G* RTFO kPa	δ Tank Deg	δ RTFO Deg	G*/sin δ Tank kPa	G*/sin δ RTFO kPa
AC-1.5	Kerr McGee	0.44	0.69	88.60	88.10	0.44	0.69
AC-1.5	Gulf States	0.28	0.46	89.43	89.83	0.28	0.46
AC-3	Total	0.77	1.36	88.60	87.50	0.77	1.36
AC-3	Exxon	0.71	1.35	89.93	89.64	0.71	1.35
AC-3	Lion-Oil	0.97	2.68	88.87	86.62	0.97	2.68
AC-3	Kerr McGee	0.76	1.26	88.63	87.33	0.76	1.26
AC-3	Fina	0.75	1.59	89.05	87.37	0.75	1.59
AC-5	Diamond Shamrock	1.32	2.25	87.80	85.98	1.32	2.26
AC-5	Fina	1.44	3.63	88.80	86.53	1.44	3.64
AC-5	Chevron	1.61	2.89	86.80	84.95	1.61	2.90
AC-5	Exxon	1.30	2.50	89.30	87.90	1.30	2.50
AC-5	TFA	1.45	3.22	86.91	83.21	1.45	3.24
AC-5	Neste/Wright	1.58	2.91	88.63	87.42	1.58	2.91
AC-5	Coastal	1.62	4.59	86.01	80.88	1.62	4.65
AC-5	Total	1.28	2.90	89.07	86.65	1.28	2.91
AC-5	Kerr McGee	1.38	5.63	88.06	86.24	1.38	5.64
AC-5(2%)	Fina	1.94	3.69	79.60	79.60	1.97	3.75
AC-5(2%)	Coastal	2.31	7.55	82.42	75.31	2.33	7.81
AC-5(2%)	TFA	2.38	5.42	83.80	80.50	2.39	5.50
AC-5(2%)	Trumbull	1.71	2.60	84.71	84.32	1.72	2.61
AC-10(2%)	Coastal	4.11	13.00	80.60	72.94	4.17	13.60
AC-10(2%)	TFA	4.53	9.08	79.84	76.99	4.60	9.32
AC-15P	TFA	4.98	8.06	74.69	73.90	5.16	8.39
AC-15P	Neste/Wright	4.53	8.75	73.09	68.09	4.74	9.43
AC-15P	Koch	3.43	6.73	73.86	71.53	3.57	7.10
AC-15-5TR	Neste/Wright	3.13	6.35	74.99	70.93	3.24	6.72
CRS-2P	Koch	2.93	5.38	76.41	75.82	3.01	5.55
CRS-2	Koch/Base	2.14	4.11	87.63	85.40	2.14	4.12
CRS-2	Koch/Residue/d	2.30	6.71	86.57	80.41	2.30	6.81
HFRS-2	Koch/Base	2.00	4.22	88.06	85.96	2.00	4.23
HFRS-2	Koch/Residue/d	1.98	4.12	87.44	85.06	1.98	4.14
HFRS-2	Koch, Truck	2.75	6.17	85.56	82.67	2.76	6.22
HFRS-2P	Koch/Base	4.88	8.15	73.94	71.72	5.08	8.58
HFRS-2P	Koch/Residue/d	3.19	5.46	74.12	72.22	3.32	5.73
HFRS-2P	Koch/Extract	1.95	4.37	75.20	76.29	2.02	4.50

Table C2. Binder Properties at 58° C

Grade	Source	G* Tank kPa	G* RTFO kPa	δ Tank Deg	δ RTFO Deg	G*/sin δ Tank kPa	G*/sin δ RTFO kPa
AC-1.5	Kerr McGee	0.21	0.33	89.80	89.30	0.21	0.33
AC-1.5	Gulf States	0.14	0.22	88.43	89.11	0.14	0.22
AC-3	Total	0.36	0.64	89.80	88.70	0.36	0.64
AC-3	Exxon	0.34	0.62	89.39	89.67	0.34	0.62
AC-3	Lion Oil	0.42	1.18	89.79	88.08	0.42	1.18
AC-3	Kerr McGee	0.38	0.54	89.65	88.86	0.38	0.54
AC-3	Fina	0.33	0.69	89.86	88.75	0.33	0.69
AC-5	Diamond Shamrock	0.60	1.08	88.90	87.30	0.60	1.08
AC-5	Fina	0.65	1.57	89.60	87.90	0.65	1.57
AC-5	Chevron	0.73	1.29	88.00	86.66	0.73	1.29
AC-5	Exxon	0.59	1.08	89.90	89.00	0.59	1.08
AC-5	TFA	0.67	1.56	88.20	84.98	0.67	1.57
AC-5	Neste/Wright	0.69	1.31	89.28	88.52	0.69	1.31
AC-5	Coastal	0.76	2.01	87.40	83.43	0.76	2.02
AC-5	Total	0.59	1.30	89.78	87.79	0.59	1.30
AC-5	Kerr McGee	0.63	2.53	89.05	87.59	0.63	2.53
AC-5(2%)	Fina	0.92	1.71	80.20	80.60	0.93	1.73
AC-5(2%)	Coastal	1.11	3.33	84.20	78.20	1.12	3.40
AC-5(2%)	TFA	1.11	2.43	85.59	82.43	1.11	2.45
AC-5(2%)	Trumbull	0.84	1.22	85.45	85.82	0.84	1.22
AC-10(2%)	Coastal	1.88	6.20	82.70	75.98	1.90	6.39
AC-10(2%)	TFA	2.12	4.10	81.66	79.50	2.14	4.17
AC-15P	TFA	2.29	3.89	78.16	77.00	2.34	3.99
AC-15P	Neste/Wright	2.22	4.46	77.81	72.80	2.27	4.67
AC-15P	Koch	1.78	3.38	75.34	72.37	1.84	3.55
AC-15-5TR	Neste/Wrigth	1.62	2.81	77.50	74.21	1.66	2.92
CRS-2P	Koch	1.50	2.62	78.06	77.92	1.53	2.68
CRS-2	Koch/Base	0.96	1.81	88.73	86.97	0.96	1.81
CRS-2	Koch/Residue	1.01	2.96	87.57	83.28	1.01	2.98
HFRS-2	Koch/Base	0.91	1.85	88.97	87.60	0.91	1.85
HFRS-2	Koch/Residue	0.88	1.78	88.20	86.55	0.88	1.78
HFRS-2	Koch, Truck	1.19	2.54	87.06	84.70	1.19	2.55
HFRS-2P	Koch/Base	2.50	4.00	74.81	72.57	2.59	4.19
HFRS-2P	Koch/Residue	1.65	2.79	73.35	71.48	1.72	2.94
HFRS-2P	Koch/Extract	1.04	2.26	77.06	78.12	1.07	2.31

Table C3. Binder Properties at 64° C

Grade	Source	G* Tank kPa	G* RTFO kPa	δ Tank Deg	δ RTFO Deg	G*/sin δ Tank kPa	G*/sin δ RTFO kPa
AC-1.5	Kerr McGee	0.11	0.17	88.50	89.40	0.11	0.17
AC-1.5	Gulf States	0.08	0.11	87.08	88.18	0.08	0.11
AC-3	Total	0.18	0.31	89.10	89.80	0.18	0.31
AC-3	Exxon	0.17	0.30	88.49	89.54	0.17	0.30
AC-3	Lion Oil	0.19	0.54	89.06	89.39	0.19	0.54
AC-3	Kerr McGee	0.18	0.27	89.46	89.79	0.18	0.27
AC-3	Fina	0.16	0.31	88.82	89.84	0.16	0.31
AC-5	Diamond Shamrock	0.30	0.53	89.91	88.50	0.30	0.53
AC-5	Fina	0.30	0.71	89.60	89.00	0.30	0.71
AC-5	Chevron	0.35	0.59	89.30	88.10	0.35	0.59
AC-5	Exxon	0.28	0.49	89.30	89.80	0.28	0.49
AC-5	TFA	0.38	0.69	88.98	87.09	0.38	0.69
AC-5	Neste/Wright	0.31	0.58	89.94	89.37	0.31	0.58
AC-5	Coastal	0.35	0.68	88.78	86.25	0.35	0.68
AC-5	Total	0.28	0.55	89.31	89.06	0.28	0.55
AC-5	Kerr McGee	0.31	1.19	89.75	88.66	0.31	1.19
AC-5(2%)	Fina	0.47	0.84	81.20	82.00	0.48	0.85
AC-5(2%)	Coastal	0.54	1.51	85.90	80.80	0.54	1.53
AC-5(2%)	TFA	0.55	1.17	86.97	84.54	0.55	1.18
AC-5(2%)	Trumbull	0.44	0.60	85.98	86.78	0.44	0.60
AC-10(2%)	Coastal	0.89	2.59	84.60	79.00	0.89	2.64
AC-10(2%)	TFA	1.05	1.99	83.29	81.30	1.06	2.01
AC-15P	TFA	1.11	1.82	80.07	80.20	1.13	1.85
AC-15P	Neste/Wright	1.07	2.24	81.33	77.71	1.08	2.29
AC-15P	Koch	0.96	1.79	77.80	74.45	0.98	1.86
AC-15-5TR	Neste/Wright	0.84	1.45	79.64	76.51	0.85	1.49
CRS-2P	Koch	0.77	1.31	80.26	80.10	0.78	1.33
CRS-2	Koch/Base	0.44	0.84	89.76	88.46	0.44	0.84
CRS-2	Koch/Residue	0.48	1.33	88.83	85.16	0.48	1.33
HFRS-2	Koch/Base	0.42	0.82	89.89	88.56	0.42	0.82
HFRS-2	Koch/Residue	0.42	0.80	88.91	88.01	0.42	0.80
HFRS-2	Koch, Truck	0.55	1.14	88.19	86.38	0.55	1.14
HFRS-2P	Koch/Base	1.32	2.11	77.40	74.38	1.35	2.19
HFRS-2P	Koch/Residue	0.88	1.48	78.52	75.79	0.90	1.53
HFRS-2P	Koch/Extract	0.57	1.16	81.02	80.60	0.58	1.18

Table C.4 Binder Properties at -12° and -18° C

Grade	Source	PAV Aged Residue Tested at				Unaged Tested at		Stiffness Ratio at -18°C
		-12°C		-18°C		-18°C		
		S	m	S	m	S	m	
AC-5	Diamond Shamrock	104	0.381	235	0.323	181	0.396	1.30
AC-5	Fina	109	0.392	236	0.328	160	0.434	1.48
AC-5	Chevron	66	0.413	146	0.363	108	0.445	1.35
AC-5	Exxon	77	0.471	201	0.381	132	0.471	1.52
AC-5	TFA	67	0.444	160	0.377	73	0.542	2.19
AC-5	Neste/Wright	126	0.423	290	0.331	189	0.439	1.53
AC-5	Coastal	101	0.377	219	0.33	120	0.451	1.83
AC-5	Total	108	0.386	250	0.323	155	0.436	1.61
AC-5	Kerr McGee	62	0.437	142	0.374	114	0.477	1.25
AC-5+2%	Fina	105	0.388	219	0.332	152	0.44	1.44
AC-5+2%	Coastal	91	0.367	194	0.32	104	0.444	1.87
AC-5+2%	TFA	71	0.434	179	0.371	90	0.513	1.99
AC-5+2%	Trumbull	74	0.46	182	0.379	136	0.471	1.34
AC-10+2%	Coastal	132	0.338	256	0.301	136	0.414	1.88
AC-10+2%	TFA	98	0.433	227	0.362	135	0.458	1.68
AC-15P	TFA	92	0.425	222	0.358	120	0.466	1.85
AC-15P	Neste/Wright	72	0.397	165	0.343	74	0.462	2.23
AC-15P	Koch	87	0.43	207	0.353	136	0.467	1.52
AC-15-TR	Neste/Wright	63	0.435	158	0.377	86	0.503	1.84
CRS-2P	Koch	74	0.425	199	0.356	116	0.477	1.72
CRS-2	Koch/Base							
CRS-2	Koch/Resid/d	109	0.336	237	0.299	135	0.445	1.76
HFRS-2	Koch/Base							
HFRS-2	Koch/Resid/d	98	0.428	264	0.352	164	0.448	1.61
HFRS-2	Koch, Truck	129	0.394	320	0.331	181	0.425	1.77
HFRS-2P	Koch/Base							
HFRS-2P	Koch/Resid/d	64	0.486	200	0.386	105	0.498	1.90
HFRS-2P	Koch/Extract							

Table C.5 Conventional Properties of Seal Coat Binders

Grade	Source	Penetration at 25 C, 0.1 mm	Viscosity at 60 C, Pa-s
AC-1.5	Kerr McGee	370	18.4
AC-1.5	Gulf States	300	12.5
AC-3	Total	254	31.5
AC-3	Exxon	299	30.1
AC-3	Lion Oil	263	32.9
AC-3	Kerr McGee	360	27.3
AC-3	Fina	278	27
AC-5	Diamond Shamrock	176	46.6
AC-5	Fina	149	53.8
AC-5	Chevron	155	56.7
AC-5	Exxon	184	56
AC-5	TFA	180	55.7
AC-5	Neste/Wright	156	54
AC-5	Coastal	165	53.6
AC-5	Total	165	49.5
AC-5	Kerr McGee	196	49.2
AC-5(2%)	Fina	147	78.8
AC-5(2%)	Coastal	136	83.8
AC-5(2%)	TFA	144	94.6
AC-5(2%)	Trumbull	176	77.1
AC-10(2%)	Coastal	100	150
AC-10(2%)	TFA	1.01	141.8
AC-15P	TFA	102	291.3
AC-15P	Neste/Wright	116	196.5
AC-15P	Koch	122	216.1
AC-15-5TR	Neste/Wright	125	194.3
CRS-2P	Koch	105	266.7
CRS-2	Koch/Base	131	82
CRS-2	Koch/Residue/d	78	155
HFRS-2	Koch/Base	146	77.9
HFRS-2	Koch/Residue/d	112	107.2
HFRS-2	Koch, Truck	97	124.4
HFRS-2P	Koch/Base	100	294
HFRS-2P	Koch/Residue/d	104	298.4
HFRS-2P	Koch/Extract		