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CHARACTERIZATION of NEVADA'S 1993, 1994, and 1995 BINDERS USING SHRP TESTS

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16. Abstract

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Several of the binders are classified under the AC grading system as polymerized AC-20 (AC-20P). The rheological properties, however, indicate that some of these binders would be graded differently under the SHRP grading system. The report examines these differences and points out the discrepancies within the SHRP grading system.

The report also uses the environmental data as generated by the Superpave system and checks the recommended asphalt binder grades against the actual binders used on the project.

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Executive Summary

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The report also uses the environmental data as generated by the Superpave system and checks the recommended asphalt binder grades against the actual binders used on the project.

1.0 INTRODUCTION

In 1992, the Nevada Department of Transportation (NDOT) began a three-year research program to appraise the new binder specification system developed by the Strategic Highway Research Program (SHRP). The intention is to shift to the new system in the near future if it proves valid under Nevada conditions. NDOT has joined the Federal Highway Administration (FHWA) pool funds to purchase the laboratory equipment needed to implement SHRP's Superpave system. This report presents the results of a three years research project conducted by the Pavement/Materials Program of the University of Nevada to evaluate the binders.

NDOT manages a decade-old data base containing both the traditional properties of binders (viscosity, penetration, ductility, etc.) and the temperature and moisture sensitivity of all NDOT mixtures. The properties of mixtures which are measured include the resilient modulus, tensile strength and permanent deformation characteristics of both laboratory-prepared and field-produced mixtures. A smooth transition from this existing grading system to the SHRP Superpave system should be possible. There should be enough overlap, with no loss of the laboratory and field performance data which has been collected during the last decade.

1.1 Objectives

The specific objective of this research project is to evaluate NDOT's binders by means of SHRP's performance-based binder specification system.

A total of twenty-three binders were selected for evaluation. Twenty were in use on construction projects. The remaining three came from suppliers frequently used by NDOT. The combination of this testing data with eventual field performance data will provide an unusual opportunity to verify SHRP's binder specification system.

2.0 BACKGROUND

NDOT used 74,000, 117,000 and 118,000 tons of asphalt binders in 1993, 1994, and 1995, respectively on highway projects. Table 1 summarizes the distribution of asphalt cements among the various grades. Nationwide, the construction, rehabilitation, and maintenance of highways uses some 140 million barrels of asphalt a year [1].

Binder specifications have become essential to the quality of asphalt cement because of variations between different refineries producing asphalt binders. Asphalt binder is a residue from the distillation of crude oil, a by-product of gasoline, oil and petrochemical feed stock. Its qualities depend on a continuous and well-defined supply of crude oil, and they vary from source to source and refinery to refinery. Accordingly, state highway agencies have increasingly turned from empirical to performance-based specifications to obtain the right qualities.

2.1 Historical Development

AASHTO published specifications for penetration-graded asphalt binders in 1931 [2]. The penetration-grading system was the first specification to measure binder consistency at an average pavement service temperature of 25°C. The system is still used by some highway agencies because it is simple and gives fast results concerning the consistency of the binder.

The next development was a viscosity-based grading system, which sought to replace the empirical penetration test with a more fundamental viscosity test. The test measured the consistency of asphalt at 60°C, which approximates the average pavement temperature on a hot summer's day. Eventually, various viscosity tests were developed that suit different climates and applications of asphalt cement. The standard unit of measurement for viscosity became the poise.

By the early 1960's, the viscosity grading system had been adopted by the Federal Highway Administration (FHWA), the American Society of Testing and Materials (ASTM), AASHTO and many state highway departments [2]. It is usually referred to as the AC grading system. It is now the system most widely used in the United States, including Nevada. It was the first step toward implementing rheological testing in asphalt specification.

During the development of the AC grading system, the chemical and physical properties of the asphalt after the mixing process became a subject of concern. The California Department of Highways and other state agencies experienced changes in the asphalt's properties after plant mixing [1]. They recommended grading the asphalt after the lab aging so that all asphalt after mixing would behave about the same during construction.

Therefore, another grading system based on the viscosity of the aged residue was developed. This is referred to as the AR grading system [3]. Currently, the AR grading system is most widely used in the western United States. NDOT used the AR grading system until 1986.

All three grading or specification systems (Penetration, AC, and AR) for asphalt cement are used across the United States, but today's current high traffic loading and advanced technology make an additional specification for asphalt cement both possible and desirable. That specification should be related to pavement performance. The goal is to specify materials for construction on the basis of their potential performance.

2.2 Performance-Based Asphalt Specification System (PBA)

The Pacific Coast user/producer group started the development of a performance-based asphalt (PBA) specification system in 1989 [4]. Properly used, it will ensure that the long-term performance of pavement will depend on appropriate mix design and construction practices.

The premise during the development of PBA was that it address such pavement performance factors as rutting, fatigue cracking, thermal cracking and other distresses. It was also recognized that the environment and the aging process of the binder significantly influence the performance of pavement. Performance-based specifications must allow the engineer to define the required level of serviceability in each distress factor under prevailing environmental conditions. That is, the system must enable selection of a binder for use in a given climatic condition.

The PBA grading system lists five criteria for binder performance:

1. Asphalt binder temperature susceptibility, including thermal cracking, rutting, tenderness and mix production and placement.

2. Asphalt binder hardening, including both short-term hardening affecting mix setting and tenderness and long-term hardening affecting raveling, thermal cracking and block cracking.

3. Asphalt binder purity/consistency, including homogeneity, internal compatibility and uniformity.

4. Asphalt binder environmental/safety issues, including volatility, safe handling and health-related requirements.

5. Asphalt-aggregate mixture properties, including adhesion, permanent deformation and fatigue cracking [4].

Test methods were established to evaluate and classify the asphalt binder according to these performance criteria. Several possible test methods were rejected because of inadequate information correlating the test measurement and pavement performance. The chosen tests appear on the PBA grading chart in Figure 1.

As shown on the PBA grading chart, the selection of binder type depends on climatic guidelines. Graphical icons representing viscosity versus temperature appear on the grading chart. They visually provide the relative temperature susceptibility of each grade. For example, PBA-1 is more temperature susceptible than PBA-2 or PBA-3.

The goal of the Pacific Coast user/producer group was to adopt a performance-based asphalt binder specification that incorporated knowledge from all research activities relating binder properties to pavement performance. Some western states (Arizona, California, Nevada, and Oregon) have begun implementing the PBA grading system on selected projects. However, the Pacific Coast user/producer group is currently considering whether the optimal situation would be a blend between the PBA and the SHRP binder grading system.

3.0 SHRP'S PERFORMANCE-BASED BINDER GRADING SYSTEM

SHRP's asphalt research program aimed to develop a fundamental performance-based binder specification system. The intent is to assist highway agencies to build reliable, economical, and durable asphalt pavements. The SHRP grading system uses a distinct process to predict the performance characteristics of both virgin and modified asphalt binders. The process includes:

a) Safety,

b) Rheological properties,

c) Aging, and

d) Environmental factors.

Figure 2 is a summary of SHRP's binder specification system. The following sections describe each process and the various testing equipment used.

3.1 Safety

The Standard Test Method for Flash and Fire Point by Cleveland Open Cup (ASTM D 92) was adopted to determine the flash point of the binder. The flash point is the lowest temperature at which an open flame causes the vapor from the binder to ignite. The flash point temperature is obtained for safety regulations, and to determine if the binder has a high percentage of volatile and flammable materials.

3.2 Rheological Properties

Rheology is the science that studies the deformation and flow of material, whether in liquid, melt, or solid form, in terms of the materials' elastic and viscoelastic properties [5]. The science of rheology can be complex but rheology-testing itself need not be complicated. Some traditional methods used in determining the rheological characterization of asphalt binder include penetration measurement, determination of softening point temperature, and capillary viscosity measurements. Both the penetration and softening point tests are empirical. They therefore cannot be used to determine rheological behavior over a wide range of temperature. The capillary viscosity measurement, although a rational test, does not provide information on the time-dependency of the binder. To fully understand the behavior of asphalt binder, complete rheological information is preferred. It is therefore conclusive, since asphalt is a viscoelastic material, time and temperature effects are crucial in obtaining the rheological properties.

Both rational measurements and parameters are needed to obtain the rheological behavior of binder, which would serve as the basis of an effective performance-based binder specification. Basic rheological properties of asphalt binders include the following:

G': The storage modulus (elasticity) of the asphalt binder.

G'': The loss modulus (viscous loss) of the asphalt binder.

G^*: The complex modulus which is the amount of energy to deform the asphalt binder.

δ : The phase angle which is the difference between the phase of the sinusoidally varying input quantity and the phase of the output quantity which also varies sinusoidally at the same frequency. In the case of binder testing, the input quantity represents the applied strain and the output quantity represents the resulting stress [6].

Figure 3 is a graphical representation of the relationship among the above variables. These material properties are used in the SHRP's binder specification to evaluate the binder's resistance to tenderness, rutting, fatigue cracking, and thermal cracking.

In obtaining these rheological properties, sinusoidal shear strains γ are applied to the binder samples. At cold testing temperatures (below 34°C), the strains are kept constant at 1% and increased to 12% at higher test temperatures (above 52°C). Keeping the strain constant throughout a given test allows the sample to remain in the linear viscoelastic range. Although no material is perfectly linear under all conditions, linear viscoelastic characterization has been found in the past to best represent the rheological behavior of asphalt binders. These strain percentages

(1% and 12%) were determined by other researchers using strain sweeps at a constant temperature [5].

Since most rheological properties are time-dependent, it is essential to test the binder at a constant frequency, ω. The SHRP's binder specification recommends a frequency of 10 rad/sec and strains varying between 1% and 12% to evaluate the rheological properties (G^*, G'', G', δ). If the stress-strain behavior of the binder is completely elastic, the resulting stress will be in phase with the applied strain, as illustrated in Figure 4. Otherwise, when the response is completely viscous, the stress response will be 90° out of phase with the applied strain. In general, the phase angle (δ) can very from 0° to 90° which indicates the amount by which the resulting stress is out of phase with the applied strain.

When an asphalt binder is subjected to low temperatures or high loading frequencies, the binder approaches pure elastic behavior. At this region, the binder becomes brittle and the viscous flow modulus (G'') will peak then start to diminish, indicating slight viscous flow. At the peak of G'' the binder moves into a glass transition stage. Therefore, in shifting a binder's G'' peak to a lower temperature, its resistance to low temperatures will be improved and in return reduce thermal induced cracking.

When dealing with high temperatures, the behavior of binder is dependent on its elastic properties. In measuring the elastic properties, the loss tangent (G''/G') has been found to be a good indicator. If the loss tangent is low at a given high temperature this indicates the presence of an elastic nature. This, in return, would help prevent deformation due to a low viscous flow.

Another important rheological property of a binder is its stiffness and the development of the master curve. Some of the current methods used to determine the stiffness modulus (S(t)) are the sliding-plate rheometer and the Van Der Poel nomograph. The Van Der Poel stiffness was determined by uniaxial tension-compression whereas the sliding plate applies a constant shear. When determining the stiffness, it should be clearly stated whether the value reported is for shear or extensional loading. With the stiffness data collected over a range of temperatures, the combined data can then be used to determine the master curve as illustrated in Figure 5. The master curve is obtained at a single reference temperature. Thus, for each stiffness curve determined at a particular test temperature, a horizonal shift factor is produced. The shift factor, one for each temperature, is an equivalency between time and temperature which is known as the time-temperature superposition. The resulting master curve provides a complete characterization of the linear stress-strain-time-temperature response of a typical binder. The time-dependency is reflected in the master curve, whereas the temperature is reflected by the shift factor.

Dynamic Shear Rheometer (DSR)

The DSR is one of four rheological testing-equipment items used in the SHRP's performance-based grading. The system used in this research was developed by Rheometrics and is referred to as the Rheometrics Asphalt Analyzer (RAA). The instrument can apply a precise oscillatory, steady, or step shearing strain to the test sample and precisely measure the sample's stress response. The responses obtained from the RAA for performance grading are G*, G', G" and δ.

One of the most important aspects of obtaining repeatable rheological data while conducting binder testing with the RAA is the sample and equipment preparation. The parallel plate configuration with the temperature sensor inside the upper plate was used in the test as shown in Figure 6. The size of the plates (i.e. 8 mm or 25 mm diameter) varies depending on the test temperature. For more details of sample and RAA preparation, refer to SHRP's performance-based specifications [6].

The Bending Beam Rheometer (BBR)

The BBR is another device used in the performance-based specification. It is a "creep" test device operated by applying a constant load at the center of a simply supported asphalt binder beam for a selected period of time (Figure 7). During the loading time the deflection at the center of the beam is continuously measured. The asphalt beam is 127 mm long, 12.7 mm wide and 6.3 mm thick, supported at both ends on metal supports that are 100 mm apart. The Cannon BBR was used in this research. The data generated from the test include the time history of load and deflection. The analysis of the data provides the stiffness (S(t)) values and the log slope (m) of the creep curve at selected loading times.

Direct Tension Device

The direct tension device measures the tensile failure properties of asphalt binders at low temperatures. The specimen is placed in an environmental chamber and subjected to a uniaxial tensile load. The specimen is 40mm x 6mm x 6mm (18mm gauge length) and is connected with plexiglass inserts on either end (Fig. 8).

During testing, the specimen is pulled and the deformation of the binder is measured by monitoring the elongation of the asphalt portion. At the same time the load is constantly monitored to keep the deformation rate constant. The maximum load and elongation are then used to calculate the stress and strain-to-failure of the material. The strain at failure is used to characterize the binder's resistance to fatigue cracking and thus to control initiation of cracking in pavements.

In the performance-based specifications, the direct tension is not used if the creep stiffness measured by the BBR is below 300,000 KPa. If the creep stiffness is between 300,000 and 600,000 KPA, the direct tension failure strain requirements can be used in lieu of the creep stiffness requirement, but the log slope of the creep curve must remain less than 0.30 (see SHRP specification's footnote).

Brookfield Viscometer

The rotational viscometer is used to determine the viscosity of the asphalt binder at high temperatures, for either blending, mixing, or field compaction operations. The viscometer is the Brookfield Digital Rheometer Model DV-III, the only ASTM-approved test in the four tests used to determine the binders' rheological properties in SHRP's performance-based grading system.

The viscometer consists of a rotating spindle that can be used to measure the viscosity of asphalt binders in the range of 0.01 Pa*s (0.1 poise) to 200 Pa*s (2000 poise). These viscosities are measured in the typical temperature range of 100 to 260^{0}C (100 to 500^{0}F). The viscometer is operated by submerging the spindle in 10.5 ml of binder that is placed into a temperature-controlled thermosel. During the test the calibrated spindle is rotated by a motor with a specified rotational speed (20 rpm). Given the torque, the rotational speed of the spindle, and the geometry of the spindle and cup, the viscosity of the sample can be determined.

3.3 The Aging Process

To achieve a true performance-based specification, the binder tested in the laboratory must be treated like one used in the field. To accomplish similitude between laboratory and field binders, two types of aging process are performed. For short-term aging, the rolling thin film oven test (RTFOT) is used to represent aging or hardening of the binder that occurs during the mixing and lay-down process. To simulate long-term exposure in the field, the PAV was adopted into the SHRP specification. The value of G^* tested for several original, laboratory-aged, and field-aged binders validated the hypothesis that the PAV is closely related to field aging [5].

After short-term aging through the RTFOT, the asphalt binder is aged using the PAV for 20 hours under a constant pressure of 2.07 Mpa and temperature between 90 and 110°C. The temperature of the test varies depending on the climate in which the asphalt will be used. The vessel can hold 10 thin trays with 50g ± 0.5g of binder per tray. The dimensions and levelness of the trays have to be maintained during the test to ensure the binder maintains a uniform film thickness while being aged.

Once the binder is aged through the PAV, its rheological properties are evaluated again with the RAA and the BBR. The temperature and pressure during a test is very critical and therefore must be constantly monitored and maintained with a tight tolerance (temperature ± 0.2°C and pressure ± 20 Kpa).

3.4 Environmental Factors

To successfully acquire a performance-based binder specification, the SHRP research team categorized pavement temperatures into three binder performance groups: a) High, b) intermediate, and c) Low temperature [5]. The high is based on the average seven days high temperature in the summer months. The intermediate is calculated empirically with respect to fatigue cracking, and the low pavement temperature is the expected low for the life of the pavement. To achieve specific environmental data for a given site, it is necessary to collect information from a local weather station. The atmospheric temperature is then converted to an expected pavement temperature. The conversion can be made using the Superpave temperature model or any other model that the agency may select.

Based on the expected high and low pavement temperatures, SHRP has selected the following ranges:

High Pavement Temperature (seven categories)

$<46^oC$ ($<115^oF$)

$<52^0C$ ($<126^0F$)

$<58^0C$ ($<136^0F$)

$<64^0C$ ($<147^0F$)

$<70^0C$ ($<158^0F$)

$<76^0C$ ($<169^0F$)

$<82^{0}$C ($<180^{0}$F)

Low Pavement Temperature (seven categories)

$>-10^{0}$C ($>14^{0}$F)

$>-16^{0}$C ($>3^{0}$F)

$>-22^{0}$C ($>-8^{0}$F)

$>-28^{0}$C ($>-18^{0}$F)

$>-34^{0}$C ($>-29^{0}$F)

$>-40^{0}$C ($>-40^{0}$F)

$>-46^{0}$C ($>-51^{0}$F)

It is anticipated that these temperature ranges would encompass all the temperature regimes which exist in U.S. and Canada.

4.0 SHRP's CONSIDERATION OF PAVEMENT FAILURE FOR BINDER CLASSIFICATION

SHRP's primary objective in developing a performance-based specification for asphalt binder was to relate certain pavement failures with the binders' rheology at different temperatures and degree of aging (short- and long-term). Some of the most significant failures in pavements consist of tenderness (early rutting), rutting, fatigue cracking and thermal cracking. Therefore, SHRP considered these most common failures and developed test procedures for the binder grading specification. The following represents a discussion of the various failure modes as perceived by SHRP's binder specification system.

4.1 Rutting

Pavement rutting is total plastic deformation at the surface. All layers in the system may contribute to total surface rutting. The discussion of rutting in this report will concentrate on the asphalt concrete layer. Although rutting in the asphalt concrete layer is primarily influenced by the aggregate interlock and mixture properties, the binder also influences rutting. In some cases polymerized binders show great resistance to rutting, and they are becoming more popular across the U.S. The occurrence of rutting is greatly influenced by high pavement temperatures. Based on the average seven day high pavement temperature in one year, SHRP selected seven testing temperatures (46^0, 52^0C, 58^0C, 64^0C, 70^0C, 76^0C, and 82^0C) for which the binders' rheological properties are to be determined.

While testing at these temperatures, a measurement of the non-recoverable deformation from the binder at a loading rate similar to traffic is established with respect to rutting resistance. To simulate the loading of a passing truck traveling at 80 km/h (50 mph), a sinusoidal loading is used at 10 rad/sec (1.6 Hz). The resulting $G^*/\sin\delta$ value is the specification criterion for rutting. The minimum acceptable value for the rutting criterion is 1.0 Kpa.

During the laydown process, a tender mix can also occur. In an attempt to prevent this, SHRP's specification adopted a test to be performed on the RTFO residue with a minimum value of 2.2 Kpa from $G^*/\sin\delta$.

4.2 Fatigue Cracking

The most difficult challenge in the SHRP's binder specification is to assure satisfactory resistance to fatigue cracking. Since fatigue cracking generally occurs in the later life of the pavement, the PAV is used to simulate the long term aging of the binder. Based on evaluation of field data, SHRP adopted a specification criteria for fatigue cracking based on the dissipated energy, which is related to $G^{*}\sin\delta$.

In determining the fatigue behavior of asphalt binder, a loading time of 10 rad/sec (1.6 Hz) is applied to the PAV residue where $G^{*}\sin\delta$ is determined. For specification purposes, a minimum $G^{*}\sin\delta$ value of 5.0 MPa is acceptable.

4.3 Thermal Cracking

Thermal cracking is another serious failure in roadways and can result from a single thermal cycle where the temperature reaches a critical low. At low temperatures, the asphalt binder becomes brittle and loses the ability to absorb energy through viscous flow. As a result, the asphalt binder strain becomes intolerable and cracking occurs in the pavement. The temperature at which the pavement cracks is referred to as the limiting stiffness temperature. Since thermal cracking generally occurs in the later life of the pavement, the PAV is used to simulate the long term aging of the binder. At the limiting stiffness temperature the stiffness is obtained at a loading period of 60 seconds. In an effort to prevent thermal cracking, SHRP relates the limiting stiffness temperature at which a max stiffness of 300 MPa is obtained.

Another important factor in determining low temperature cracking is the time of loading that influences the magnitude of thermal shrinkage stresses. It was recognized from earlier SHRP contracts (A-002A and A-005) that thermal shrinkage is dependent on the time of loading. Because the time-dependency varies for different types of asphalt binder, especially polymerized, the shape of the master curve is a reliable means of determining the thermal shrinkage stress that develops during the cooling process. Therefore, SHRP adopted the slope (m) of the master curve to be implemented in the binder specification. The minimum criterion for the slope of the master curve is 0.30.

5.0 LABORATORY TESTING PROGRAM

As mentioned earlier, twenty-three binders were evaluated and fully discussed in this report. Twenty out of the twenty-three binders were used on actual construction projects. The location of these projects and their descriptions are presented in Table 2.

Prior to the start of the laboratory testing program, the SHRP binder specification system was thoroughly examined to identify the test parameters and the materials properties needed for the grading process. The following represents a summary of the identified properties.

* Rutting: original material with a minimum $G^*/\sin(\delta)$ value of 1.0 Kpa measured at the maximum pavement temperature.

* Tenderness: RTFO residue with a minimum $G^*/\sin(\delta)$ value of 2.2 Kpa measured at the maximum pavement temperature.

* Fatigue cracking: PAV residue with a maximum $G^*(\sin(\delta))$ value of 5,000 Kpa measured at the intermediate temperature.

* Thermal cracking: PAV residue with a maximum stiffness value of 300,000 Kpa at a minimum m-value of 0.30 measured at the minimum pavement temperature.

* Thermal cracking: PAV residue with a minimum failure strain of 1.0% at 1.0 mm/min at minimum pavement temperature.

It should be noted that the failure strain criterion is not used if the creep stiffness measured by the BBR is below 300,000 Kpa. If the creep stiffness is between 300,000 and 600,000 Kpa the direct tension failure strain requirement can be used in lieu of the creep stiffness requirement, but the log slope of the creep curve must remain less than 0.30.

5.1 The Grading Process

The process used in this research to test the asphalt binders under the SHRP grading system is summarized in Figure 9 and as fully described in the interim AASHTO test method [8]. It should be noted that this process may differ from one laboratory to another since the SHRP grading procedure has not been finalized yet.

As is the case with every grading system, the SHRP system can be used in two different ways: a) to check if a binder meets the requirements of a given grade, and b) to identify the appropriate grade for a given binder. Since the objective of this research was to identify the grades of the various Nevada binders, process b had to be followed.

Following process b requires more testing and more elaborate data analysis than process a. The initial objective of process b is to identify all the possible environments that a binder can fit. The final grade of the binder is then based on the widest environmental range. For example, if an AC-20P meets the requirements for PG52-10, PG52-16, and PG52-22, the final grade given to this binder would be PG52-22, since it represents the worst environmental conditions that this binder can withstand.

5.2 Data Analysis

The first step in grading a given binder consists of checking its flash point and viscosity against the specification limits. The SHRP's specification limits call for a minimum flash point of 230°C and a maximum viscosity of 3 Pa*s at 135°C. Checking the binders' data (Table 3) against these limits indicate that all binders satisfy the requirements of flash point and viscosity.

The second step in the evaluation process deals with the rheological properties of the original binder as it comes from the tank. The RAA dynamic shear rheometer (DSR) was used to evaluate the complex modulus and phase lag of all binders at 10 rad/sec frequency. At this stage, the class of the binder is unknown, therefore a temperature sweep must be conducted in order to identify the highest temperature at which the binder would reach the minimum specified value of $G^*/\sin(\delta)$.

Knowing that the $G^*/\sin(\delta)$ of an asphalt is inversely related to temperature, the testing proceeded at the lowest temperature (46°C) in the specification toward the highest temperature (82°C) (Figure 2). The relationships between $G^*/\sin(\delta)$ and temperature for all twenty-three binders were measured. Using these relationships, the temperatures at which the binders reach the minimum value of $G^*/\sin(\delta)$ of 1.00 Kpa were identified as follow:

Contract	Binder	Temperature (°C) at $G^*/\sin(d) = 1.0$ Kpa
N/A	AC-20	66.0
N/A	AC-20	66.3
2480	AC-20P	64.5
2491	AC-20P	61.5
2501	AC-30	68.7
2501	AC-20P	63.8
2530	AC-20P	63.4
2544	AC-20P	63.6
2545	AC-20P	67.5
2552	AC-20P	64.5
2558-93	AC-20P	62.1
2558-94	AC-20P	62.8
2591	AC-20P	66.5
2594	AC-20P	63.6
2603	AC-20+TLA	74.4
2604	AC-40	70.0
2604	AC-30	70.1
2611	AC-20	66.5
2611	AC-20P	65.4
2615	AC-20P	64.7
2617	AC-20P	62.4
2622	AC-30P(1)	75.3
2622	AC-30P(2)	77.6

The third step in the grading process consists of evaluating the binders' properties after aging through the RTFO. As mentioned earlier, the RTFO is used to simulate the aging during the mixing and paving operations. The percentage of weight loss through RTFO aging should not exceed 1 percent. The percentage weight losses for all binders are summarized in Table 3. The data indicate that all binders would pass.

The rheological testing of the RTFO residues followed the same procedure as the one used for the virgin binders. The relationships between $G^*/\sin(\delta)$ and temperature for all binders after RTFO aging were measured. Using these relationships, the temperatures at which the binders reach the minimum value of $G^*/\sin(\delta)$ of 2.2 Kpa were identified. At this point the high temperature grades of the binders can also be identified according to the specification in Figure 2. The following is a summary of the high temperature grades:

Contract	Binder	Temperature (°C) at $G^*/\sin(d) = 2.2$ Kpa	High Temp Grade
N/A	AC-20	67.5	PG64
N/A	AC-20	68.3	PG64
2480	AC-20P	63.0	PG58
2491	AC-20P	57.8	PG52
2501	AC-30	69.8	PG64
2501	AC-20P	63.2	PG58
2530	AC-20P	63.6	PG58
2544	AC-20P	63.0	PG58
2545	AC-20P	58.4	PG58
2552	AC-20P	63.0	PG58
2558-93	AC-20P	58.7	PG58
2558-94	AC-20P	56.5	PG52
2591	AC-20P	62.6	PG58
2594	AC-20P	63.3	PG58
2603	AC-20+TLA	72.6	PG70
2604	AC-40	68.6	PG64
2604	AC-30P	70.0	PG70
2611	AC-20	66.7	PG64
2611	AC-20P	65.2	PG64
2615	AC-20P	62.5	PG58
2617	AC-20P	57.9	Pg52
2622	AC-30P(1)	76.7	PG70
2622	AC-30P(2)	73.1	PG70

The fourth step in the grading process is the evaluation of the rheological properties of the binders after aging through the PAV. The PAV temperature is based on the high temperature grade of each binder. The specification requires the temperature at which $G^*\sin(\delta)$ reaches a maximum value of 5 Mpa. Therefore, for each binder there will be a minimum temperature selected above which the maximum value of $G^*\sin(\delta)$ is not exceeded. After the PAV aging, all binders were tested at four temperatures. The relationships between temperature and $G^*\sin(\delta)$ were measured. The minimum temperatures for the various binders are listed below:

Contract	Binder	Temperature (°C) at $G^*\sin(d) = 5.0$ Mpa
N/A	AC-20	17.7
N/A	AC-20	21.2
2480	AC-20P	17.2
2491	AC-20P	19.0
2501	AC-30	22.7
2501	AC-20P	16.9
2530	AC-20P	15.9
2544	AC-20P	13.2
2545	AC-20P	19.5
2552	AC-20P	17.2
2558-93	AC-20P	20.4
2558-94	AC-20P	20.2
2591	AC-20P	22.4
2594	AC-20P	16.8
2603	AC-20+TLA	30.5
2604	AC-40	30.1
2604	AC-30	23.0
2611	AC-20	25.8
2611	AC-20P	15.9
2615	AC-20P	18.8
2617	AC-20P	18.5
2622	AC-30P(1)	23.4
2622	AC-30P(2)	23.3

The bending beam tests were then conducted on the PAV residues under two temperatures, namely -20 and -10°C. The two BBR points were used to draw the relationships between the stiffness (S(t)) and the slope (m) as a function of temperature.

Using the bending beam results, the low temperature grades of the binders are identified based on the maximum stiffness value of 300 Mpa and a minimum slope value of 0.30. It should be noted that none of the binders required the direct tension test. The final grading of all twenty-three binders are as follows:

Contract	Binder	SHRP Grade
N/A	AC-20	PG64-16
N/A	AC-20	PG64-22
2480	AC-20P	PG58-28
2491	AC-20P	PG52-16
2501	AC-30	PG64-16
2501	AC-20P	PG58-28
2530	AC-20P	PG58-28
2544	AC-20P	PG58-28
2545	AC-20P	PG58-22
2552	AC-20P	PG58-28
2558-93	AC-20P	PG58-22
2558-94	AC-20P	PG52-16
2591	AC-20P	PG58-16
2594	AC-20P	PG58-28
2603	AC-20+TLA	PG70-16
2604	AC-40	PG64-10
2604	AC-30	PG70-22
2611	AC-20	PG64-16
2611	AC-20P	PG64-28
2615	AC-20P	PG58-28
2617	AC-20P	PG52-22
2622	AC-30P(1)	PG70-22
2622	AC-30P(2)	PG70-16

The SHRP grading system showed that the AC-30P, AC-30 and AC-20+TLA binders would withstand the highest temperature. An AC-40 binder was graded at the high temepratture similar to the AC-20. In the case of the low temperature, the grades of AC-30P and AC-30 binders ranged between -16 and -22^{0}C while the AC-40 would only withstand temperatures as low as -10°C. The AC-40 binder provided for this experiment did not show any advantage over an AC-30 or even an AC-20 binder.

In the case of the AC-20P grading, the SHRP grading system showed three distinct grades for the polymerized AC-20's. It indicated that three AC-20P's can only withstand up to -16°C, three AC-20P's can be used up to -22°C, and eight AC-20P's can be used up to -28°C. On the other hand, the high temperature grades were more consistent; eleven out of the forteen AC-20P's were appropriate for use under 58°C temperature. One AC-20P binder was graded as 64-28 which represents the widest temperature range ever encountered on AC-20P's used in Nevada.

Seven AC-20P binders were all given the same grade of PG58-28. The temperatures at which all these binders reached a maximum value of $G^*/\sin(\delta)$ of 2.2 Kpa were: 63.0, 63.2, 63.6, 63.0, 63.0, 63.3, and 62.5^{0}C. While the low temperatures at which both the S(t) and m limits were satisfied were: -18, -18.2, -19.2, -19.1, -19.9, -18.4, and -19.0^{0}C. It can be seen that the high temperatures for all seven binders are grouped closer together than their low temperatures. This shows that the impact of the polymer is more significant at the lower temperatures.

5.3 Project Locations and Recommended Grades

The locations of the projects throughout the state of Nevada are shown in Figure 10. In order to check the grading of the binders against the locations of the projects, the environmental conditions of the projects are needed. The Superpave model was used to identify the asphalt binder grades appropriate for the location of the projects. The Superpave data base contains environmental data for a total of 72 stations within the state of Nevada.

The pavement temperatures data, as generated by the Superpave model, are summarized in Table 4. The predicted high pavement temperatures seem to be higher than anticipated for these locations. Based on the predicted high and low pavement temperatures, the Superpave model recommends asphalt binder grades as shown in Table 5. The Superpave 98 percent reliability recommendations are based on the average pavement temperatures plus two standard deviations while the 50 percent reliability uses the average values.

The grading data (Table 5) indicate that if the Superpave recommendations are used, four of the AC-20P's (2544, 2545, 2558, and 2611), two AC-30's (2501 and 2604), AC-20+TLA (2603), AC-40 (2604), and both AC-30P (2622) binders would meet the requirements under the 50 percent reliability. If the Superpave 98 percent reliability recommendation is used, the AC-20+TLA (2603), one AC-30

(2604), and both AC-30P's (2622) would meet the requirements of the projects. The majority of the binders (16 out of 23) met the low temperature requirements of the projects at the 50 percent reliability level. This further supports the initial observation that the high pavement temperature predicted by the Superpave model may be too conservative (i.e. too high).

6.0 SUMMARY AND CONCLUSIONS

The newly developed SHRP binder specification system was successfully used to grade twenty-three Nevada binders. All the rheological tests were conducted without any problems following the procedures recommended by SHRP.

The SHRP grading system clearly identified the AC-30, AC-20+TLA, and the AC-30P binders as having different rheological properties from the other binders. They were identified to be applicable under warmer temperatures than the AC-20P's, while their low temperature characteristics were less desirable than the AC-20P's.

There were some discrepancies among the gradings of the various AC-20P binders. The SHRP grading system indicated that some AC-20P binders would be appropriate over a wider temperature range than others. One of the AC-20P binders was identified as being applicable under a very narrow range of temperatures (2491). One disturbing observation is that the SHRP system graded an AC-20 as PG64-16 and another AC-20 as PG64-22 which indicates that both of these unmodified binders would perform better than the polymerized AC-20p's. The system also graded an AC-40 (2604) as PG64-10 which is below the AC-30 and the AC-30P binders.

At this stage it is not known whether this discrepancy is coming from the SHRP grading system itself or if the AC-20P binders are actually different. The temperature susceptibility characteristics of the various binders indicate that the latter may be true.

The rheological data showed consistent behavior from all the binders that were classified under the same group. This indicates that the field performance of these binders should be very similar.

The environmental data needed for the recommendation of the specific binders were obtained from the Superpave model. In the majority of the cases, the Superpave recommendations did not coincide with the determined grades of the binders. The Superpave recommendations were too conservative on the high temperature grade.

It is highly recommended that the field performance of these projects should be monitored and field samples should be obtained to validate the applicability of the SHRP grading system for Nevada's conditions.

FHWA recommends that every state highway agency validate the SHRP binder and mixture testing and evaluation systems for its own conditions prior to the implementation process. The results of this research project and the follow-up study recommended in phase II would provide NDOT with the necessary data for the validation and implementation of SHRP systems.

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[7] Strategic Highway Research Program, Research Project A-006, Performance Based Specifications for Asphalt-Aggregate Mixtures, Washington, DC, 1993.

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Table 1 : NDOT 1993 and 1994 asphalt binder quantities.

Asphalt Type	Quantity (Tons) 1993	1994	1995
AC-10	3,958	9,381	5,245
AC-10R	NA	5,707	NA
AC-20	17,957	27,167	16,950
AC-20+TLA	NA	913	NA
AC-20P	51,424	70,093	71,416
AC-30	668	2,548	24,195
CRM	NA	1,392	203
Total	**74,007**	**117,201**	**118,009**

Table 2: Description of field projects.

NDOT Contract Number	Binder Type	AC-layer Thickness	Location
N/A	AC-20	N/A	N/A
N/A	AC-20	N/A	N/A
2480	AC-20P	3/4" Open 3" Dense	US-95-CL MP120.99 to MP132.14
2491	AC-20P	3/4" Open 5" Dense	I-80-LA LA-MP15.89 to EU-MP02.88
2501	AC-30	4" Dense	I-15-CL MP00.00 to MP16.35
2501	AC-20P	3/4" Open 2" Dense	I-15-CL MP00.00 to MP16.35
2530	AC-20P	3/4" Open 4" Dense	I-15-CL MP95.53 to MP118.5
2544	AC-20P	3/4" Open 5.0" Dense	I-80-EL MP06.50 to MP26.61
2545	AC-20P	3/4" Open 4" Dense	I-80-CH MP02.21 to MP 12.83
2552	AC-20P	3/4" Open 4" Dense	I-15-CL MP70.00 to MP77.00
2558-93	AC-20P	3/4" Open 5" Dense	I-80-WA MP00.00 to MP12.47
2558-94	AC-20P	"	"
2591	AC-20P	3/4" Open 7" Dense	I-80-HU/LA MP01.80 to MP03.20
2594	AC-20P	3/4" Open 2" AC-20P 3" AC-30	SR-163-CL MP16.4 to MP 19.13
2603	AC-20 +TLA	3/4" Open 3" Dense	SR-159-CL Charleston to Boulder
2604	AC-40	Not Used	Not Used

2604	AC-30	4" Dense	I-15-CL MP26.28 to MP34.91
2611	AC-20	2" Dense	US-93-EL MP83.22 to MP141.88
2611	AC-20P	3/4" Open 2" Dense	US-93-EL MP83.22 to MP141.88
2615	AC-20P	3/4" Open 4" Dense	I-80-EL MP43.5 to MP52.79
2617	AC-20P	3/4" Open 4" Dense	US-95-MI MP69.81 to MP83.08
2622	AC-30P (1)	3/4" Open 3.5" Dense	US-95-CL MP07.70 to MP01.20
2622	AC-30P (2)	"	"

Table 3 : Summary of flash point, viscosity, and RTFO weight loss for all binders.

Cont. Number	AC Type	Flash Pt. (^0C)	Brookfield Vis. @ 135^{0}C (cP)	RTFO Wt. Loss (%)
N/A	AC-20	293	.375	.14
N/A	AC-20	271	.400	.15
2480	AC-20P	257	.763	.33
2491	AC-20P	259	.363	.28
2501	AC-30	274	.463	.15
2501	AC-20P	266	.638	.13
2530	AC-20P	277	.650	.26
2544	AC-20P	319	.658	.05
2545	AC-20P	271	.319	.15
2552	AC-20P	279	.596	.26
2558-93	AC-20P	266	.313	.15
2558-94	AC-20P	266	.279	.21
2591	AC-20P	280	.500	.10
2594	AC-20P	288	.725	.06
2603	AC-20 +TLA	299	.566	.11
2604	AC-40	263	.371	.19
2604	AC-30	NA	.567	.28
2611	AC-20	NA	.350	.32
2611	AC-20P	NA	.750	.10
2615	AC-20P	307	.617	.20
2617	AC-20P	NA	.367	.21
2622	AC-30P(1)	284	1.454	.08
2622	AC-30P(2)	299	2.567	.08

Table 4: Maximum and minimum pavement temperatures based on superpave data base.

Contract	Superpave (°C)			
	50 % Reliability		98 % Reliability	
	Min	Max	Min	Max
2480	-12	62	-17	68
2491	-24	57	-35	59
2501	-7	64	-12	66
2501	-7	64	-12	66
2530	-7	64	-11	68
2544	-27	56	-37	58
2545	-19	57	-27	61
2552	-11	65	-17	68
2558	-18	56	-27	59
2591	-24	57	-35	59
2594	-7	60	-12	62
2603	-7	64	-12	66
2604	-7	64	-12	66
2611	-26	54	-34	56
2615	-30	53	-39	57
2617	-15	59	-23	62
2622	-7	64	-12	66

Table 5: Recommended binder grades based on superpave data base.

Contract Number	AC Grade	SHRP Grade	Superpave 50% Reliability	Superpave 98% Reliability
2480	AC-20P	PG58-28	PG64-16	PG70-22
2491	AC-20P	PG52-16	PG58-28	PG64-40
2501	AC-30	PG64-16	PG64-10	PG70-16
2501	AC-20P	PG58-28	PG64-10	PG70-16
2530	AC-20P	PG58-28	PG64-10	PG70-16
2544	AC-20P	PG58-28	PG58-28	pg64-40
2545	AC-20P	PG58-22	PG58-22	PG64-28
2552	AC-20P	PG58-28	PG70-16	PG70-22
2558-93	AC-20P	PG58-22	PG58-22	PG64-28
2558-94	AC-20P	PG58-16	PG58-22	PG64-28
2591	AC-20P	PG58-16	PG58-28	PG64-40
2594	AC-20P	PG58-28	PG64-10	PG64-16
2603	AC-20+TLA	PG70-16	PG64-10	PG70-16
2604-1	AC-40	PG64-10	PG64-10	PG70-16
2604-2	AC-30	PG70-22	PG64-10	PG70-16
2611-1	AC-20	PG64-16	PG58-28	PG58-40
2611-2	AC-20P	PG64-28	PG58-28	PG58-40
2615	AC-20P	PG58-28	PG58-34	PG58-40
2617	AC-20P	PG52-22	PG64-16	PG64-28
2622-1	AC-30P	PG70-22	PG64-10	PG70-16
2622-2	AC-30P	PG70-16	PG64-10	PG70-16

Pacific Coast Conference on Asphalt Specifications
1992 CONFERENCE DRAFT
May 26, 1992

TENTATIVE PERFORMANCE BASED ASPHALT BINDER GRADES (Note 1)

Asphalt Binder Performance Issue	Asphalt Binder Test Method Correlated with the Performance Issue	AASHTO Test Method	PBA-1	PBA-1a	PBA-2	PBA-3	PBA-4	PBA-5	PBA-6	PBA-7
			Moderate Climate		Moderate/Cold Climate	Moderate/Very Cold Climate	Hot Climate	Hot/Cold Climate	Hot/Very Cold Climate	Very Hot Climate
	Environmental Guidelines for Selecting the PBA Grade: Lowest recorded temperature / Highest mean monthly temperature		above -10F below 90F		above -20F below 90F	below -20F below 90F	above -10F above 90F	above -20F above 90F	below -20F above 90F	above -10F above 100F
Low temperature thermal cracking.	Penetration (4C [39.2F], 200g, 60s), dmm RTFO Aged Residue (Note 2.)	T-49	Report (Note 3.)	Report	15+	30+	Report	15+	30+	Report
Low temperature thermal cracking.	Penetration (25C [77F], 100g, 5s), dmm RTFO Aged Residue	T-49	25+	25+	Report	---	20+	---	---	---
Low temperature thermal cracking.	Ductility (7.2C [45F], 1 cm/min), cm RTFO Aged Residue (Note 4.)	T-51	---	---	10+	---	---	Report	---	---
High ambient temperature mix stability (tenderness, rutting).	Absolute Viscosity (60C [140F]), P.(Note 5.) Original Binder RTFO Aged Residue	T-202 T-202	800+ 2500-5000	1600+ 8000-	1100+ 2500-6000	1100+ 3000+	2800+ 14000-	2000+ 4000+	2000+ 5000+	1100+ 3000+
Consistency during construction: - Pumpability, handling - Mix tenderness.	Kinematic Viscosity (135C [275F]), cSt Original Binder RTFO Aged Residue	T-201 T-201	--- 275+	--- 275+	--- 275+	2000- 275+	--- 350+	2000- 400+	2000- 275+	2000- 275+
Hardening during the hot mix paving process.	Absolute Viscosity Ratio (60C [140F]) RTFO Viscosity/Original Viscosity		4.0-	4.0-	4.0-	4.0-	4.0-	4.0-	4.0-	4.0-
Severe climate aging.	Penetration (25C [77F], 100g, 5s), dmm Tilt Oven Residue (Note 6.)	T-49	---	---	---	Report	---	---	Report	30+
Severe climate aging.	Ductility (25C [77F], 5 cm/min), cm Tilt Oven Residue	T-51	---	---	---	Report	---	---	Report	40+
Severe climate aging.	Absolute Viscosity (60C [140F]), Poise Tilt Oven Residue	T-202	---	---	---	Report	---	---	Report	50000-
Safe Handling.	Flash Point, Cleveland Open Cup, C [F] Original Binder	T-48	232+ (450+)		232+ (450+)	232+ (450+)	232+ (450+)	232+ (450+)	232+ (450+)	232+ (450+)
Environmental Impact.	Mass Loss after RTFO Test, %	T-240	Report	Report	Report	Report	Report	Report	Report	Report
Asphalt Binder Purity.	Solubility in Trichloroethylene, % Original Binder	T-44	99.0+	99.0+	99.0+	Report	99.0+	Report	Report	Report
Asphalt Cement Internal Compatibility.	Ductility (25C [77F], 5 cm/min), cm RTFO Aged Residue	T-51	75+	75+	75+	75+	50+	50+	60+	75+

Figure 1: Pacific Coast User/Producer PBA Grading Chart

PERFORMANCE GRADE	PG 46-			PG 52-							PG 58-					PG 64-					
	34	40	46	10	16	22	28	34	40	46	16	22	28	34	40	10	16	22	28	34	40
Average 7-day Maximum Pavement Design Temperature, °C[a]	<46			<52							<58					<64					
Minimum Pavement Design Temperature, °C[a]	>-34	>-40	>-46	>-10	>-16	>-22	>-28	>-34	>-40	>-46	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-40
ORIGINAL BINDER																					
Flash Point Temp, T48: Minimum °C	230																				
Viscosity, ASTM D4402:[b] Maximum, 3 Pa•s, Test Temp, °C	135																				
Dynamic Shear, TP5:[c] G*/sinδ, Minimum, 1.00 kPa Test Temp @ 10 rad/s, °C	46			52							58					64					
ROLLING THIN FILM OVEN (T240) OR THIN FILM OVEN RESIDUE (T179)																					
Mass Loss, Maximum, percent	1.00																				
Dynamic Shear, TP5: G*/sinδ, Minimum, 2.20 kPa Test Temp @ 10 rad/s, °C	46			52							58					64					
PRESSURE AGING VESSEL RESIDUE (PP1)																					
PAV Aging Temperature, °C[d]	90			90							100					100					
Dynamic Shear, TP5: G*sinδ, Maximum, 5000 kPa Test Temp @ 10 rad/s, °C	10	7	4	25	22	19	16	13	10	7	25	22	19	16	13	31	28	25	22	19	16
Physical Hardening[e]	Report																				
Creep Stiffness, TP1: S, Maximum, 300 MPa, m - value, Minimum, 0.300 Test Temp @ 60s, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30
Direct Tension, TP3:[f] Failure Strain, Minimum, 1.0% Test Temp @ 1.0 mm/min, °C	-24	-30	-36	0	-6	-12	-18	-24	-30	-36	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	-30

[a] Pavement temperatures are estimated from air temperatures using an algorithm contained in the SUPERPAVE software program, 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 measurements of G*/sinδ 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 T201 or T202).

[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 64- and above, except in desert climates, where it is 110°C.

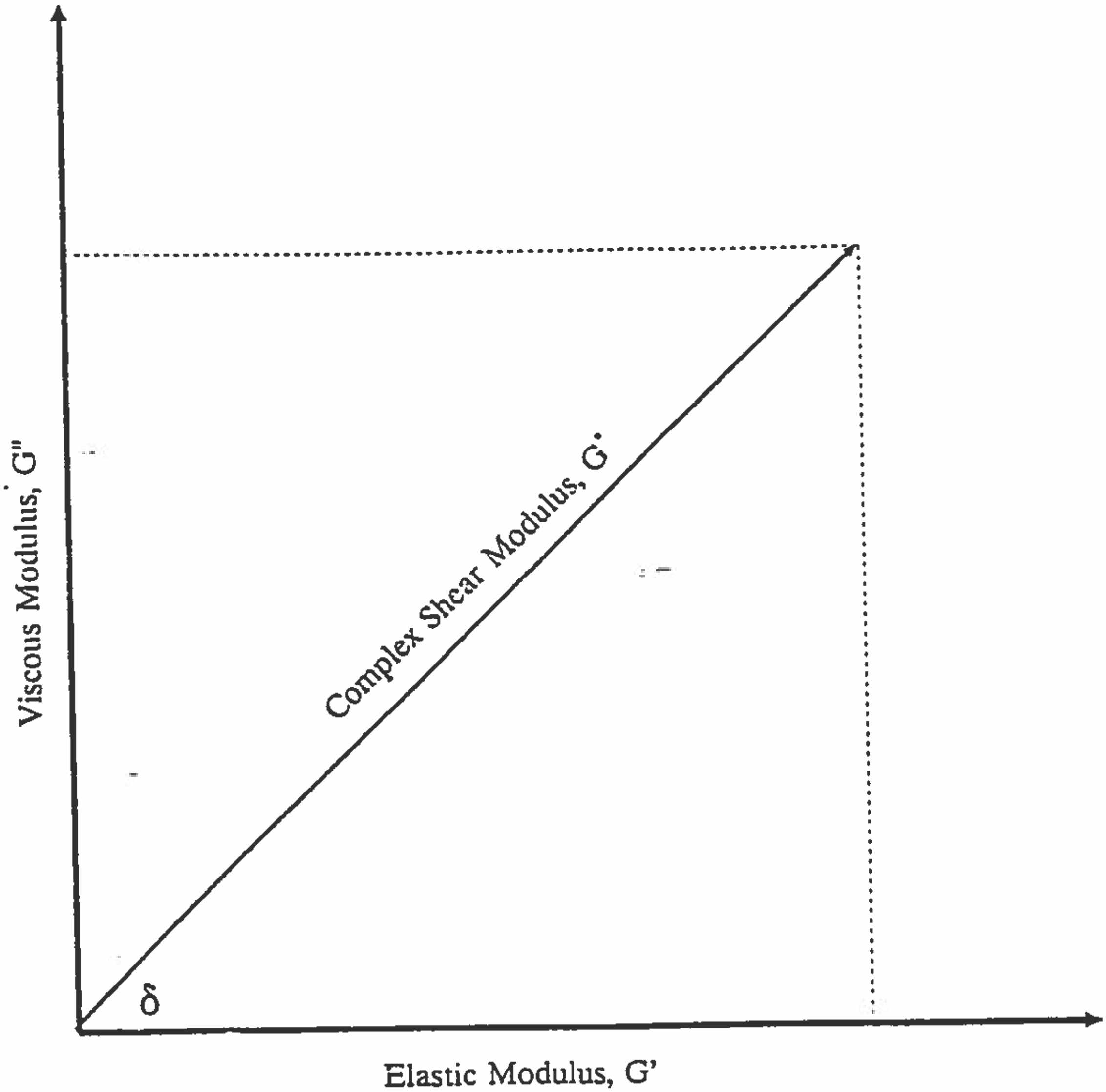
[e] Physical Hardening — TP1 is performed on a set of asphalt beams according to Section 13.1, except the conditioning time is extended to 24 hrs ± 10 minutes at 10°C above the minimum performance temperature. The 24-hour stiffness and m-value are reported for information purposes only.

[f] If the creep stiffness is below 300 MPa, the direct tension test is not required. If the creep stiffness is 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.

Figure 2. SHRP's binder specification chart.

PERFORMANCE GRADE	PG 70-						PG 76-					PG 82-				
	10	16	22	28	34	40	10	16	22	28	34	10	16	22	28	34
Average 7-day Maximum Pavement Design Temp, °C[b]	<70						<76					<82				
Minimum Pavement Design Temperature, °C[b]	>-10	>-16	>-22	>-28	>-34	>-40	>-10	>-16	>-22	>-28	>-34	>-10	>-16	>-22	>-28	>-3
ORIGINAL BINDER																
Flash Point Temp, T48: Minimum °C	230															
Viscosity, ASTM D4402:[c] Maximum, 3 Pa·s, Test Temp, °C	135															
Dynamic Shear, TP5:[d] G*/sinδ, Minimum, 1.00 kPa Test Temp @ 10 rad/s, °C	70						76					82				
ROLLING THIN FILM OVEN (T240) OR THIN FILM OVEN (T179) RESIDUE																
Mass Loss, Maximum, percent	1.00															
Dynamic Shear, TP5: G*/sinδ, Minimum, 2.20 kPa Test Temp @ 10 rad/s, °C	70						76					82				
PRESSURE AGING VESSEL RESIDUE (PP1)																
PAV Aging Temperature, °C[e]	100(110)						100(110)					100(110)				
Dynamic Shear, TP5: G*sinδ, Maximum, 5000 kPa Test Temp @ 10 rad/s, °C	34	31	28	25	22	19	37	34	31	28	25	40	37	34	31	28
Physical Hardening[f]	Report															
Creep Stiffness, TP1:[d] S, Maximum, 300.0 MPa, m - value, Minimum, 0.300 Test Temp @ 60s, °C	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24
Direct Tension, TP3:[d] Failure Strain, Minimum, 1.0% Test Temp @ 1.0 mm/min, °C	0	-6	-12	-18	-24	-30	0	-6	-12	-18	-24	0	-6	-12	-18	-24

Figure 2. SHRP's binder specification chart (continued).



Storage (Elastic) Modulus

$G' = (G^*)\cos(\delta)$

Loss (Viscous) Modulus

$G'' = (G^*)\sin(\delta)$

Loss Tangent

$\tan(\delta) = G''/G'$

Figure 3: Relationship Among the Various Rheological Properties of Asphalt Binders

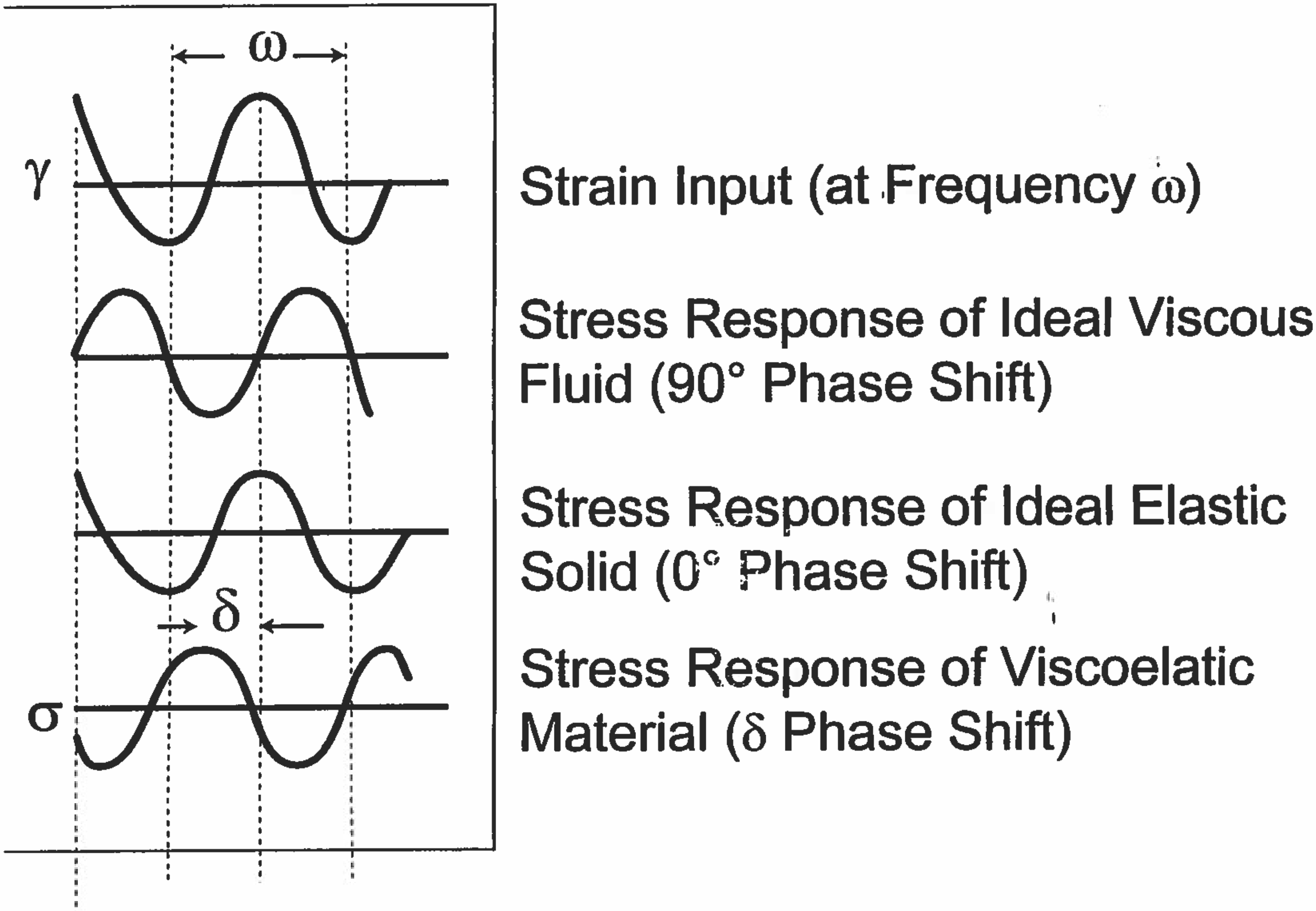


Figure 4: Relationship Among Stress-Strain-Phase Lag

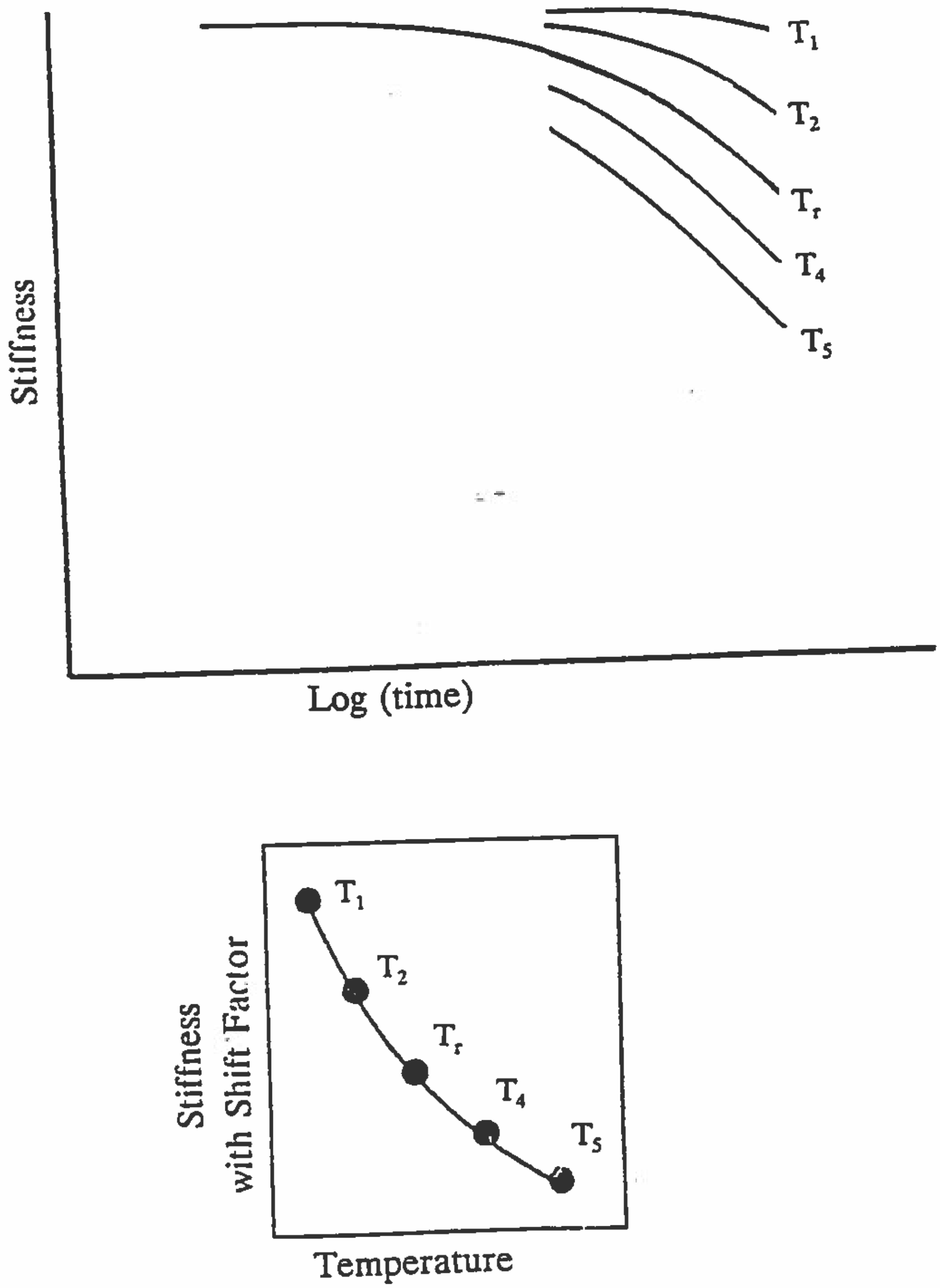


Figure 5: Master Curve for Asphalt Binders

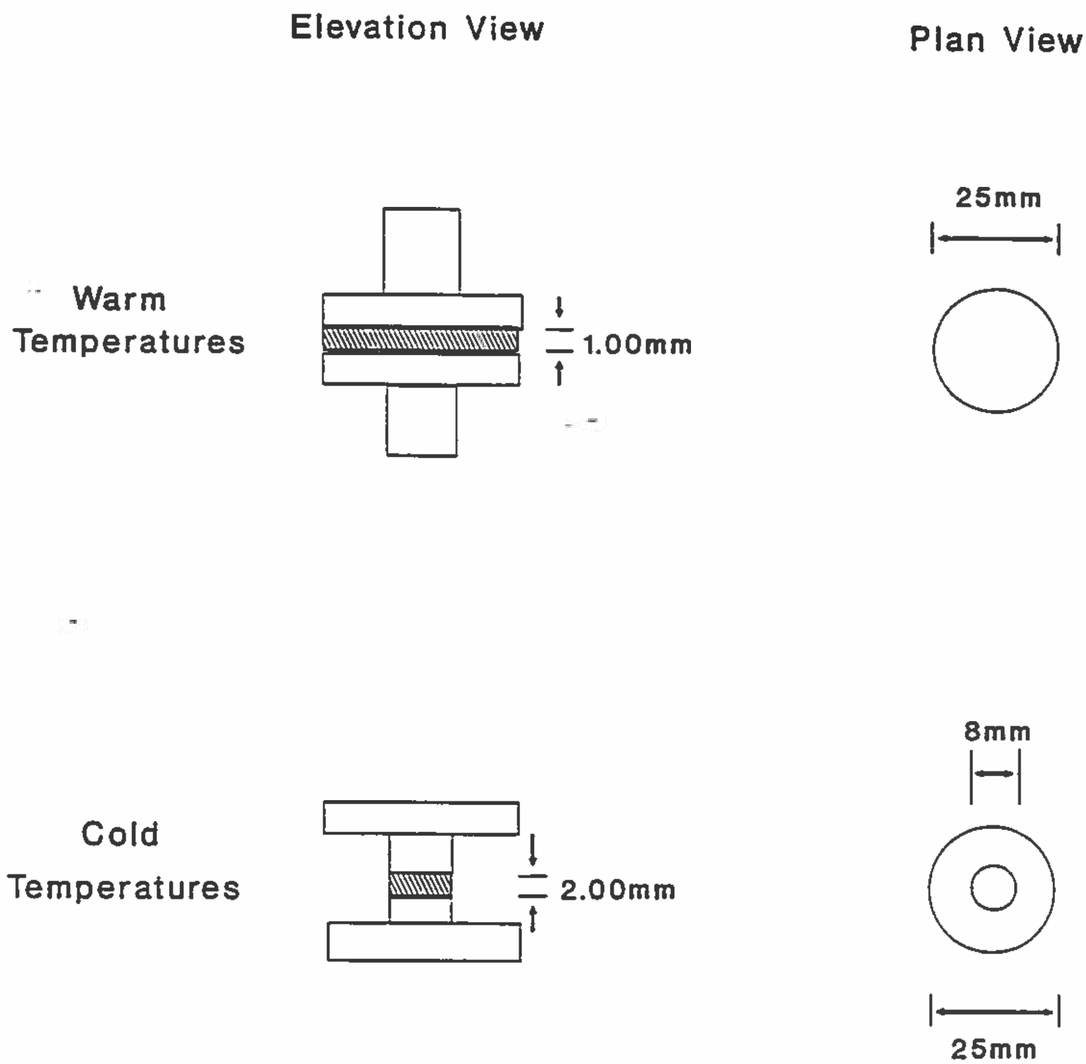


Figure 6: Parallel Plate Test Configurations

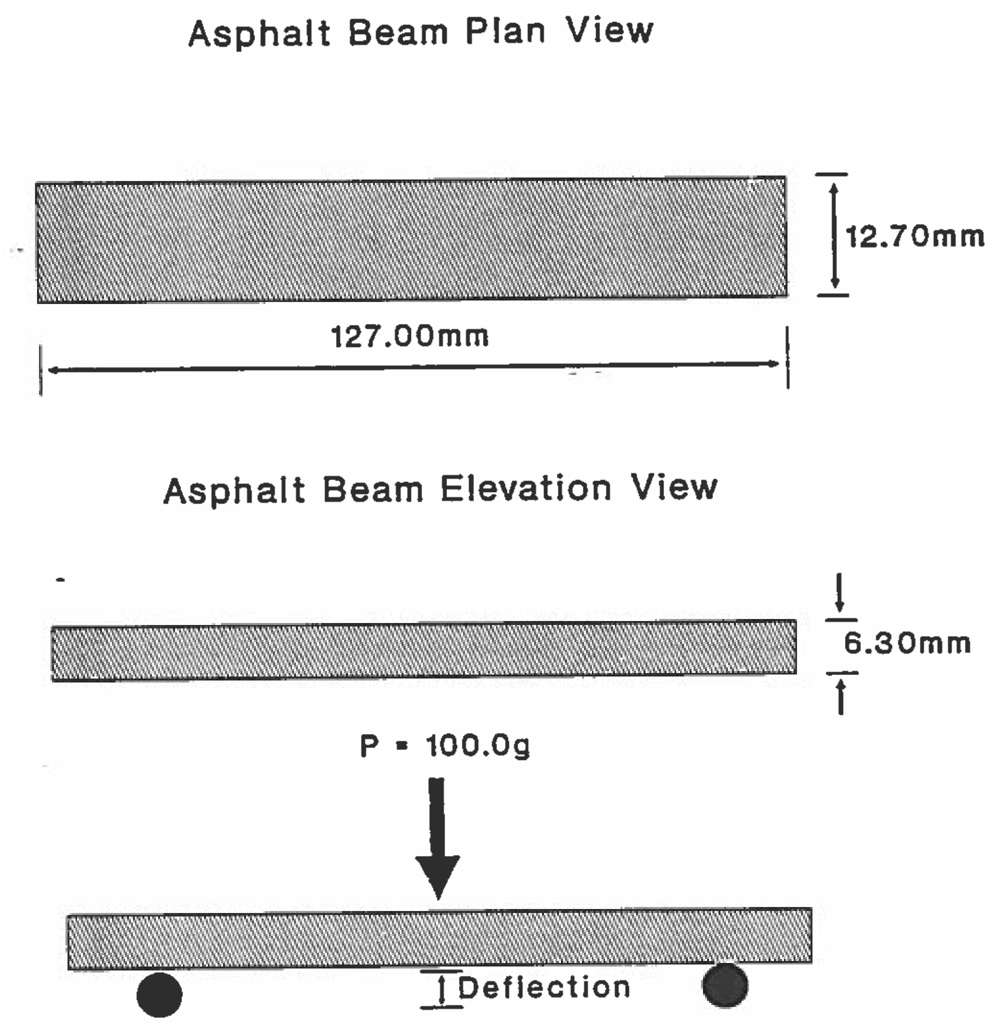


Figure 7: Bending Beam Test Configuration

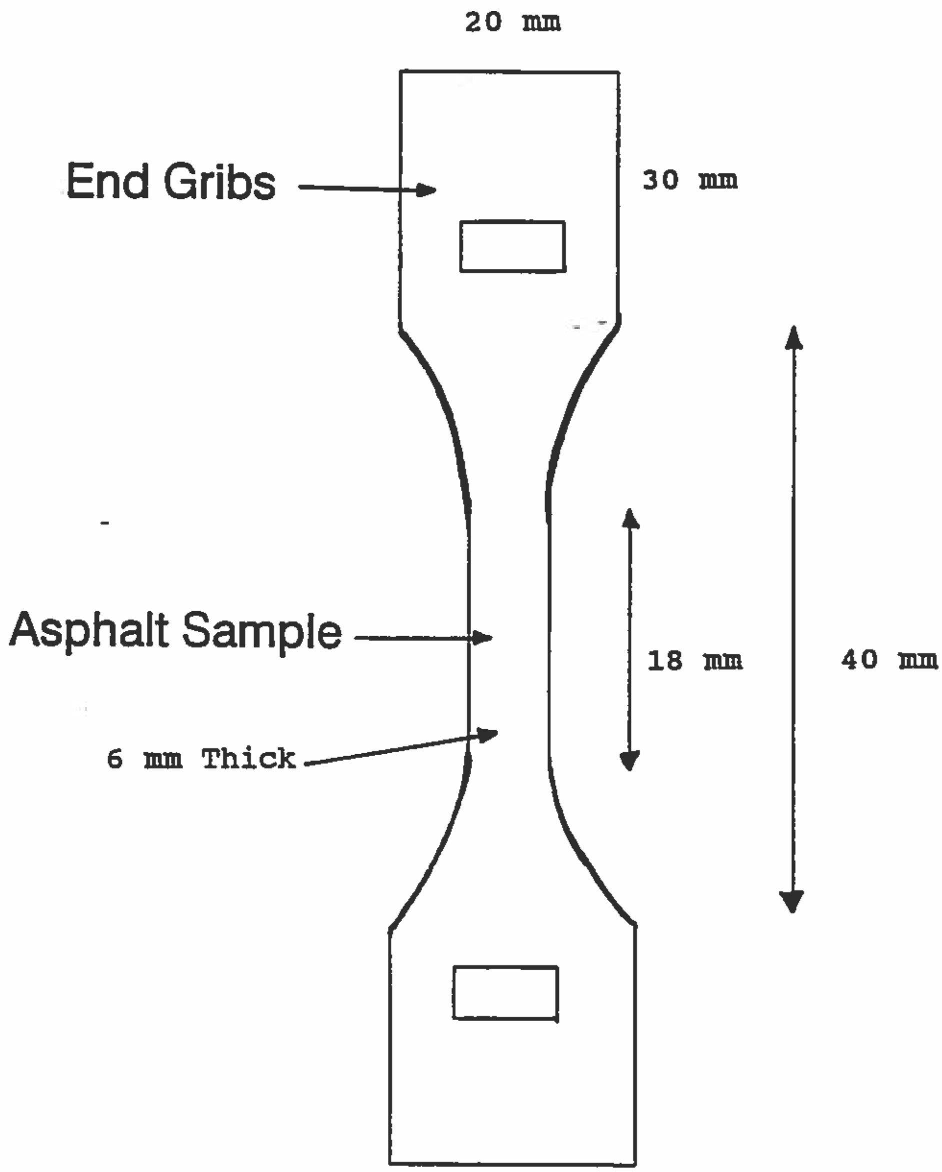


Figure 8. Schematic of the Direct Tension Test

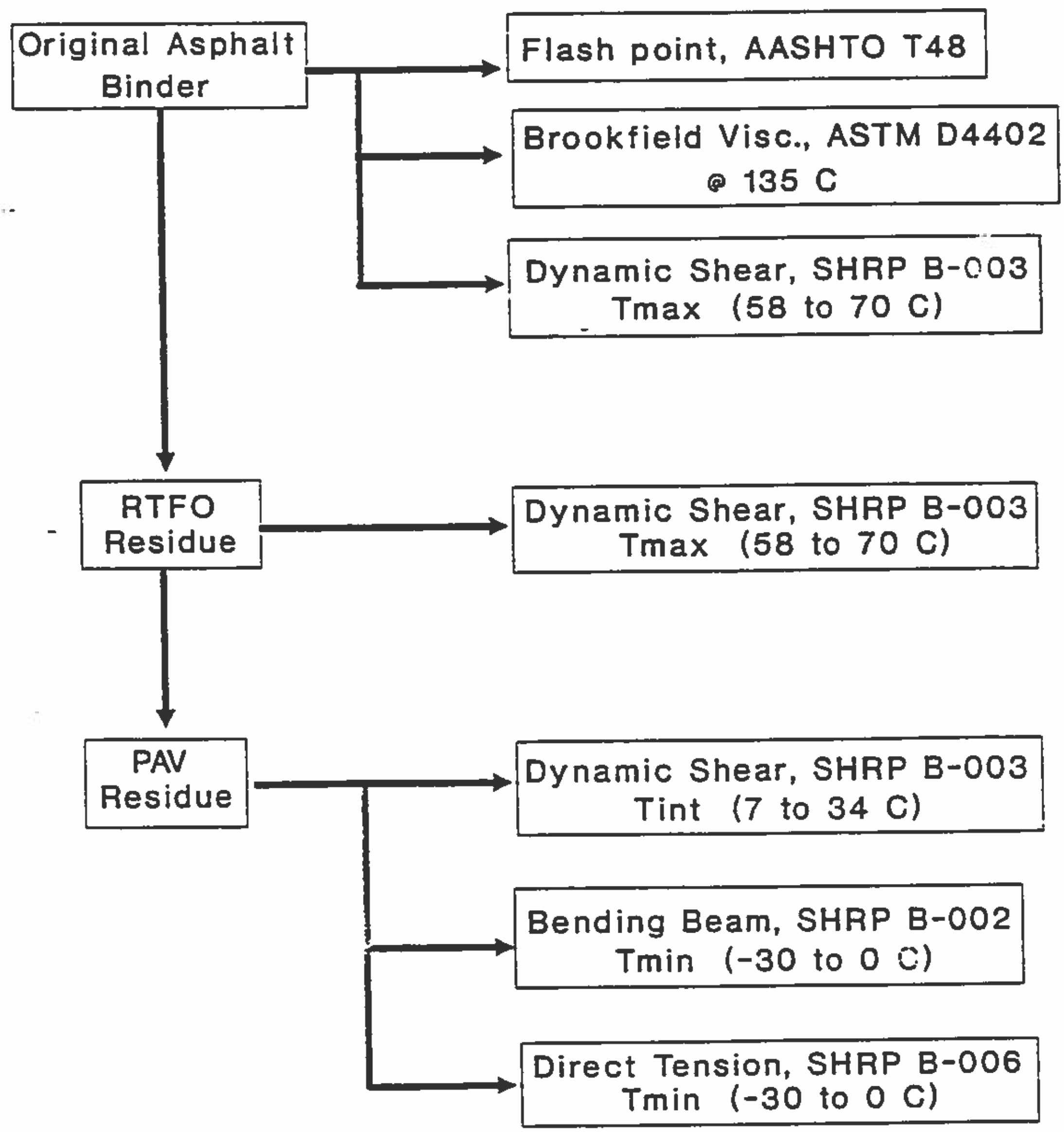


Figure 9: Flow Chart of the Laboratory Testing Program to Grade the Asphalt Binder

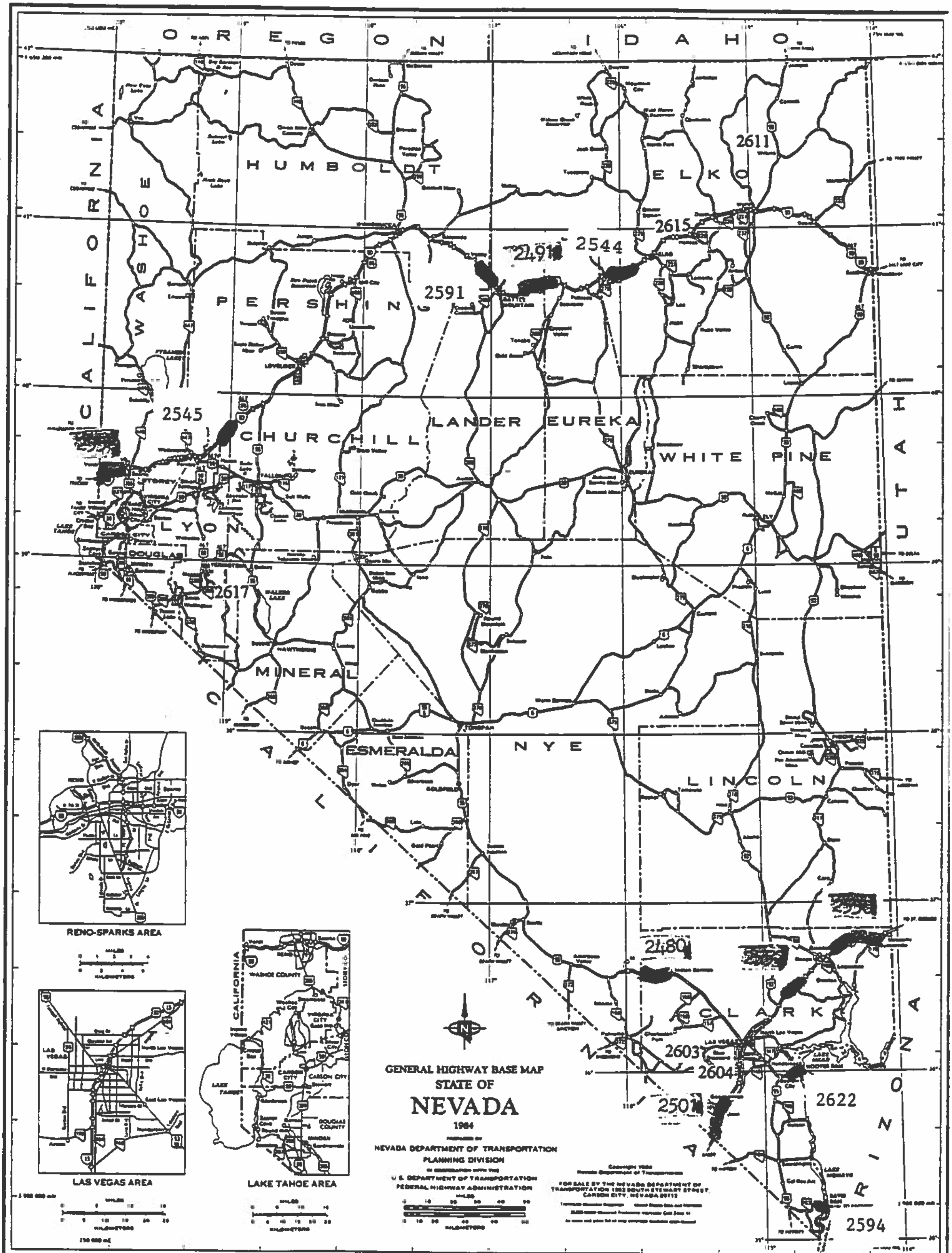


Figure 10: Locations of the Projects Throughout the State of Nevada