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EVALUATION OF CRUMB RUBBER MODIFIED PAVING MIXTURES in the STATE OF NEVADA

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16. Abstract

CRM mixtures from three NDOT contracts were evaluated in terms of their temperature susceptibility, moisture sensitivity, permanent deformation resistance, and low temperature cracking resistance. The data from this experiment will be used to correlate between laboratory and field performance of CRM mixtures in the state of Nevada.

Based on the results of this research effort, the following recommendation can be made: The design of gap graded CRM mixtures can be conducted using a modified version of the Hveem mix design process. The most significant modification is in the area of compaction mixtures. It was discovered that the normal Hveem compaction procedure was inadequate for CRM mixtures. Therefore, a new method was recommended which calls for compacting the CRM samples in two lifts to avoid the separation of the sample. The impact of curing period on the stability of CRM mixtures was evaluated and proven to be insignificant. In the case of mixing, higher mixing temperature must be maintained when dealing with CRM mixtures.

The standard SHRP binder grading system, i.e. parallel plate, has some limitations in grading CRM binders. These limitations become very significant when dealing with CRM binders containing rubber particles larger than #200. Therefore, it is recommended to use the plate and cup system in conjunction with the BBR to grade CRM binders that contain any rubber particles larger than #200.

In summary, the FNF mixture represents the best CRM mixtures used in Nevada. However, the FNF mixture still suffers from poor moisture sensitivity and poor construction control. It is recommended that NDOT monitors the field performance of all project and use these performance in conjunction with the laboratory evaluations presented in this report to make decisions regarding the future use of CRM mixtures in Nevada.

17. Key Words
CRM, HMA, Crumb Rubber, Asphalt Mixtures

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1.0 INTRODUCTION

The use of crumb rubber modified binders to improve the performance characteristics of hot mixed asphalt (HMA) mixtures have shown mixed results throughout the U.S. Some studies showed improved performance properties such as added resistance to rutting, fatigue, and low temperature cracking while some field performances have shown problems with raveling bleeding and aging of the CRM HMA mixtures.

Before the Nevada Department of Transportation (NDOT) can assess the merit of using CRM HMA mixtures, it must have the following:

- A system to evaluate the CRM binders in order to assign the binder most suitable for the environmental and traffic loading conditions of a particular pavement segment;
- A procedure for mix design to select the most appropriate proportioning of binder and aggregate;
- A mixture analysis system to predict the long-term performance of CRM mixtures under the combined action of environment and traffic loadings.

It is necessary to develop a system that enables NDOT to predict the performance of CRM pavements before construction (as is done for traditional HMA mixes) and to select better pavement alternatives. In 1994, NDOT initiated a multi-year research project to develop a system for the evaluation of CRM binders and mixtures under Nevada's environmental and traffic conditions. The project started on January 1, 1994 and was completed on August 31, 1997.

1.1 Objective and Scope

The main objective of this study is to develop a system which NDOT can be used to design and evaluate CRM mixtures. The study consists of the following four tasks:

Task A: Review of Mix Design Procedures and Recommendations

Task B: Characterization of Binders

Task C: Laboratory Evaluation of Mixtures

In sum, the project develops a complete system by which NDOT can evaluate CRM binders and mixtures for potential use on field projects.

2.0 BACKGROUND

The use of crumb rubber modified (CRM) binders in the production of paving materials has increased significantly in recent years. Many paving contractors and engineering agencies have specialized in the placement of CRM mixtures for several years now. Technology however, has seen a more limited advancement due in part to limited research efforts. Until recently, typical design considerations such as asphalt type, rubber type, rubber gradation, mixing and compaction temperatures, as well as full scale mixture testing procedures were relatively undefined. Recently, the Strategic Highway Research Program (SHRP) has developed a set of standard testing guidelines and criteria for binders and mixtures. Since CRM binders and mixtures were part of the SHRP experiment, it is still necessary to evaluate the validity of these procedures for CRM binders and mixtures.

2.1 SHRP Binder Testing Procedures for CRM Binders

In order to evaluate the adequacy of the current SHRP binder grading procedures and criteria for CRM binders, it is first necessary to understand the basis of the testing program, as well as the effects that the addition of rubber will have on the binder properties. By understanding the procedures and the reasoning behind the SHRP performance grading program, along with the effects of the rubber on the measured properties, logical recommendations can be made as to the overall effectiveness of the standard SHRP procedures in determining the properties of the CRM binders.

2.1.1 SHRP Binder Classification Components

The performance grading of asphalt binders according to SHRP procedures involves the evaluation of the following properties [1,10]:

1. A measure of rotational viscosity near the mixing and compacting temperatures to evaluate the workability of the binder.
2. A measure of rheological properties, ($G^*/\sin\delta$), at high pavement temperatures to evaluate the binder's contribution to the resistance of rutting.
3. A measure of rheological properties, ($G^*\sin\delta$), at intermediate pavement temperatures to determine the binder's contribution to the resistance of fatigue cracking.
4. A measure of creep and failure properties, ($S(t)$ and $m(t)$), at low pavement temperatures to measure the contribution of the binder to the resistance to thermal cracking.

Several studies have been conducted to evaluate the current SHRP performance grading criteria and whether or not it is applicable to asphalt rubbers. Furthermore, in-depth studies by Bahia and Davies, and McGennis and Quinn, have developed certain behavioral trends based on CRM type, CRM content, asphalt type, and temperature.

It is expected that each of the rheological properties is directly influenced by the addition of rubber particles. However, the effects of the rubber on the CRM binder are not always the same for the individual properties. The effects depend on the combination of asphalt type, CRM type, CRM content, and temperature. Each of the rheological properties may be influenced by different combinations of these factors.

2.1.2 Effects of CRMs on Viscosity at High Temperatures

In studies conducted by Bahia and Davies [1,2], it was determined that the addition of rubber had a significant effect on the viscosity of the binder at high temperatures. It was concluded that temperature, although a major contributor to viscous behavior of a material, was less important than CRM content. The viscosity of the binder increases exponentially with elevated CRM contents, and is further augmented by coarser rubber particle gradations. A study by McGennis and Quinn [3] on fine mesh crumb rubber asphalts showed that CRM binders have significantly higher viscosities than their base asphalts at typical working temperatures (135°C). In fact several of the samples tested in both studies did exceed the Association of American State Highway and Transportation Officials (AASHTO) specifications which limit the viscosity at 135°C to 3 Pa.s. Chehovits concluded that the viscosity range at placement temperatures for CRM binders is mainly affected by the rubber type, content, and degree of rubber swelling, and can vary from 100 to 20,000 centipoise for various applications [10]. These violations of the specifications are frequent with CRM binders, and it is commonly accepted that the viscosity criteria may be exceeded as long as the binder can be mixed at a safe temperature [3].

2.1.3 Effects of CRMs at High Pavement Temperatures

CRMs have been observed to contribute significantly to the binder's ability to resist rutting at high pavement temperatures (45°-75°C). In studies by Bahia and Davies [1,2], and McGennis and

Quinn [3], it has been observed that the addition of rubber may increase the upper limit of the SHRP performance grade anywhere from one to three grades, based on the type and amount of CRM added. Unlike the viscosity however, temperature is the most influential factor, followed by rubber content and asphalt source [1]. The main constituent in the increase in $G^*/\sin\delta$ is the increase in the complex modulus G^*, but a decrease in δ also contributes. Bahia and Davies [1] have shown that this increase in $G^*/\sin\delta$ is not directly dependent on the rubber type, but is influenced quite significantly by the CRM content. Average rates of increase in $G^*/\sin\delta$ of approximately 14.5 percent for every one percent increase of CRM have been measured [1].

2.1.4 Effects of CRMs at Intermediate Pavement Temperatures

The effect of CRMs on the loss modulus, $G^*\sin\delta$ (G"), is not easy to consistently predict. It has been observed that G" may either increase or decrease with the use of CRMs, based mostly on the asphalt source and test temperature. At low temperatures several CRM binders exhibited a slight reduction in G", when compared to their base asphalts. This trend was not true for all binders though, some did show noticeable increases in G". This was true in the case where G" of the rubber exceeds that of the base asphalt (temperatures above 25°F) [2]. McGennis and Quinn found that in every case, the addition of rubber created a decrease in $G^*\sin\delta$ [3]. These results were obtained from research conducted on fine mesh rubber asphalts tested at intermediate temperatures of

10° to 20°C.

2.1.5 Effects of CRMs at Low Pavement Temperatures

The effects of CRMs at low pavement temperatures are highly dependent on the asphalt source and type, along with rubber content. Several studies have shown that the stiffness, S(t), will decrease due to the lower stiffness of the rubber at very low temperatures (0° to -20°C). McGennis and Quinn also concluded that binders with high concentrations of rubber may experience less aging in the Rolling Thin Film Oven Test (RTFOT), or that the rubber may release constituents that soften the base asphalt [3]. Regardless of the precise reason, a decrease in the low temperature stiffness have been documented by Bahia and Davies as well [1,2]. The effect of CRMs on the creep rate, m(t), are not quite as certain. While Bahia and Davies noted only minor changes in m(t), most of which were undesirable reductions, McGennis and Quinn documented increases in creep rate for all fine mesh CRM binder that they evaluated.

2.1.6 Effects of CRMs on SHRP Performance Grade

Based on the aforementioned alterations in the binder properties with the addition of rubber particles, the performance grades of the CRM binder will be significantly different from those of the base asphalt. With an increase in $G^*/\sin\delta$ at high pavement temperatures one may expect an elevation in the upper performance grade of one to three temperatures. Additionally, decreases in the stiffness, S(t), at low temperatures may improve the low temperatures limit, which may result in performance grades that are one to two temperatures lower than the base asphalt. The overall result would be to classify the binder as having a wide temperature range.

2.2 Evaluation of Current Mixture Design Procedures

2.2.1 CRM Binder Evaluation

Currently the wet process is the most commonly used method to produce CRM mixtures. The process consists of adding the rubber to the hot binder, mixed, and partially reacted before the binder system is introduced into the aggregate system [5]. The reaction that occurs between the asphalt and the rubber is really a partial absorption of some of the asphalt constituents by the rubber, which cause the rubber to swell significantly, thereby increasing the stiffness of the binder [6]. This reaction will cause a drastic increase in the viscosity of the binder. The binder viscosity is not the only property that is influenced by the addition of rubber, several research studies have concluded that the high in-service temperature stiffness will increase, elastic characteristics will increase, low temperature properties will be improved, and aging resistance will be enhanced [6]. CRM binders can be used in dense-graded, open-graded, and gap-graded HMA. However, for each of these applications the binder characteristics must be determined and incorporated into the design process. One problem with using CRM binders is that a limit on the particle size must be imposed.

Any particles that are greater in size than the void spaces in the aggregate matrix will reduce aggregate to aggregate interlock. There are two methods in which the CRM binder can be used in HMA design. First, rubber can be added to the binder in quantities that will not significantly modify the binder or mixture properties. These CRM binders typically contain 5% or less rubber. Furthermore, these binders should include only fine mesh rubber particles, unless they are open-graded where coarser particles can be permitted. The viscosity of these binders should be limited to 500 centipoise [6]. Secondly, CRM binders that have vital modifications in their properties because of the addition of rubber, can be used to help enhance the properties of the mixture. Typically these binders include higher percentages of rubber, 10 to 25% by weight of asphalt, and an asphalt binder that is one AC or penetration grade softer than normal for that climate. Again particle size is determined by the gradation of the aggregate. Viscosities are limited to 4000 centipoise for dense-graded mixtures, in order to insure proper coating, but may be tolerated as high as 6000 centipoise for gap-graded mixtures [6].

2.2.2 Modifications to Trial Binder Contents

The rubber in the CRM binder is responsible for replacing certain portions of the asphalt. Since this absorption of some asphalt binder by the rubber is inevitable, binder contents need to be increased to insure adequate aggregate coating and adhesion. Typical trial ranges are generally shifted upwards on the order of

8% to 15% based on the gradation of the mixture. The exact increase in the trial binder content range is determined from both the final application (i.e. dense, open, or gap-graded HMA), and CRM content of the binder [6].

2.2.3 Modifications to Mixing Procedures

Any form of mixing, whether it be mechanical or hand, is applicable to CRM mixtures, with a few simple modifications. Mixing times between 30 seconds and 2 minutes are recommended to insure sufficient coating without extensive mixture temperature loss. Since the viscosity of CRM binders will be increased, the temperatures at mixing and compaction must be elevated, except for mixtures using binders with low CRM contents, whose properties remain relatively unchanged. Typical mixing temperatures for CRM mixtures as reported in the literature are 275°-300°F from Chehovits [7], 325°-350°F from Vallerga [8], and 375°F from Schuler [9].

2.2.4 Modifications to Specimen Compaction

It has been an accepted fact that CRM mixtures are far more temperature dependent during compaction than are unmodified mixtures. Chehovits et al. concluded that a change in the mix design compaction temperatures from 275°F to 300°F can generate an optimum asphalt content variation of up to 0.5%. For this reason, a constant compaction temperature must be maintained throughout the mixture design [6]. Furthermore, due to the increased high temperature viscosity of the CRM binder, elevated temperatures are necessary to insure proper compaction in most cases. Crafco, Inc. has reported using typical Hveem compaction temperatures of 230°F to compact CRM mixtures with success. However, no other documents support that this temperature is adequate in providing proper compaction. In fact, most literature suggests compaction temperatures upwards of 300°F. A study conducted by Stroup-Gardiner et al. supported this theory, since compaction under typical 230°F conditions could not be achieved for any of the CRM samples tested. Their results indicated that inadequate compaction resulted at this temperature, and elevated temperatures, 300°F, were imperative to obtain compaction. This study also involved a Marshall mixture design, in which a temperature of 275°F was used [11].

2.2.5 Modifications to Specimen Testing

Marshall and Hveem specimen testing programs are conducted in accordance with the standards set forth by the Asphalt Institute's Manual Series No. 2 and the American Society for Testing Materials Annual Book of ASTM Standards. Specifications for CRM mixtures may require slight adjustments, however. CRM dense-graded mixtures have exhibited less compaction under traffic than unmodified mixtures, so design air voids may be reduced. These mixtures also display higher flow values due to higher binder contents that are required. CRM mixtures also yield lower stability values, both Marshall (though not usually out of specifications) and Hveem (as low as 10 to 15).

With regards to gap-graded CRM mixtures, it has been suggested that the same modified compaction and testing procedures be used, with the knowledge that stability values will be far lower than the dense-graded mixtures. The flow and VMA values will increase due to higher binder contents used in the gap-graded mixtures [6].

One concern prior to specimen testing is the rebound of the material after compaction. However, several researchers have found the rebound to be negligible. Still, many publications recommend that the samples be allowed to cool overnight in the mold after compaction before extrusion for testing.

Results of a study conducted by Stroup-Gardiner et al. in which CRM dense-graded mixtures were used in both Marshall and Hveem mixture design programs showed very good agreement with the guidelines for compaction and testing discussed in this section, as well as anticipated trends of the test results [11].

2.3 Mixture Property Testing for CRM Mixtures

The performance of a HMA mixture is evaluated in many different ways, depending on the specific properties that are used by the individual agency. Testing programs generally follow the mix design process, in order to evaluate the performance, or more realistically the expected performance, of the mixture before it is placed in the field. However, some testing is performed on core samples or samples from the field, in which case the product has already been used and the test results are to check design properties. In either case, typical testing programs are developed in order to establish the performance of the pavement in several capacities. Routine properties that are examined are temperature susceptibility resistance to moisture damage, resistance to rutting, resistance to fatigue, and resistance to thermal cracking. These standard tests are used for both dense-graded and gap-graded CRM mixtures.

2.3.1 Moisture Susceptibility Testing

One of the principal properties of an asphalt concrete mixture is its ability to resist the actions of freeze-thaw cycles. Many studies have been performed in order to evaluate how certain mixture gradations, binders, and modifiers may help resist the effects of moisture. For CRM mixtures the same concerns are present. It is now commonly accepted that moisture sensitivity testing is performed on most mixtures following the mixture design in order to establish a certain behavioral criteria that is to be expected during the life of the in-service pavement.

The purpose of moisture susceptibility testing is to determine the stripping potential of the HMA. Hugo and Nachenius indicate that CRM mixtures have, in the past, exhibited more severe and premature stripping than unmodified mixtures, because of the degree of reaction that occurs between the rubber and asphalt during blending. Shorter reaction times and lower reaction temperatures tended to produce binders that were susceptible to stripping [13]. Others believe that it is due to the continual reaction between the rubber and the binder which enhances the rate of binder stiffening in the field. Stripping in CRM gap-graded mixtures also tends to be more significant due to the higher air voids which allow for more severe moisture penetration. Some typical tests to determine moisture susceptibility are Vacuum saturation and immersion, Immersion-compression test, Lottman, Modified Lottman, and Root-Tunnecliff tests [12].

2.3.2 Permanent Deformation Testing

CRM mixtures have become increasingly popular where increased resistance to rutting is required, because of the ability of the rubber to deform and then rebound, experiencing less permanent strain. CRM mixtures are also desirable because of their improved binder and mixture properties at high temperatures, which is when most severe rutting occurs.

Both types of permanent deformation testing, static load and repeated load, have been used to evaluate CRM mixtures. A study conducted by Krutz and Stroup-Gardiner [14] evaluated both types of testing on asphalt CRM mixtures and their corresponding unmodified mixtures in order to estimate the effectiveness of each test method in identifying the rut resistance of each mixture. Their testing concluded that the repeated load test could distinguish between the CRM mixture and the neat mixture, whereas the static load test could not. Furthermore, they showed that at 104°F, the static load testing could only indicate the presence of the rubber, although the repeated load testing could indicate the differences in the binders. Krutz and Stroup-Gardiner suggested that only repeated load testing be performed, as well as testing at temperatures at or above 104°F, where most severe rutting is likely to occur [14].

3.0 TASK A: REVIEW OF MIX DESIGN PROCEDURES AND RECOMMENDATIONS

The objective of this task is to review the various mix design procedures that have been used with CRM mixtures and recommend a procedure that can be implemented by NDOT. While the various procedures were reviewed, it was kept in mind that NDOT uses the Hveem mix design method, therefore, any recommended procedure must be based on the Hveem mix design method. The majority of the earlier work that was conducted on CRM mixtures was based on the Marshall mix design. As mentioned in the background section, special modifications must be made in the mixing, compaction, and testing of CRM mixtures.

As a result of this review two mix design methods are recommended: mix design method for gap graded CRM mixtures and mix design method for dense graded CRM mixtures. The recommended mix design method for gap graded CRM mixtures was evaluated through a field project (NDOT Contract # 2513) and some modifications were deemed necessary. The current version of the recommended mix design method for gap graded CRM mixtures is summarized below.

3.1 Mix Design Method for Gap Graded CRM Mixtures

The following mix design method is recommended for gap graded CRM mixtures and is based on the Hveem mix design method with some modifications. The method was originally developed and then modified based on laboratory experience with CRM gap graded mixtures from NDOT contract #2513.

Trial binder content:	7.0 - 11.0 % by dry weight of aggregate.
Binder mixing temperature:	340 - 360°F
Aggregate mixing temperature:	340 - 360°F
Compaction Temperature:	275 - 300°F

Design Criteria:

Hveem Stability:	15 minimum
Air Voids:	4 %

Compaction: The normal Hveem compaction procedure showed a problem where a nonuniform sample was obtained. The samples were separating around mid-height immediately after extrusion. Based on these observation and after several trials, the following compaction procedure seemed to be the most appropriate:

Compact the sample in two lifts:

1. First lift: 50 blows at 200 psi
2. Second lift: 50 blows at 200 psi
3. Final compaction: 50-75 blows at 350 psi followed by 50-75 blows at 500 psi.

Level Loading: After compaction, cool down at 140°F for 1.5 hours and then apply a level loading using the double plunger method, at 0.25 in/min up to 1,000 psi and release immediately.

Extrusion: After level loading, Keep at 140°F for 4 hours and then extrude into the stabilometer for testing.

Cooling Period: Initially there were some concerns about the tendency of the CRM mixtures to rebound while cooling down which would provide different stabilities at various cooling periods. This issue was investigated by measuring the stabilities of independent CRM samples which were cooled down for 4, 16, and 24 hours. The 4 hours samples were tested immediately after extrusion while the 16 and 24 hours samples were set in a 140°F oven after they have been extruded from the molds and then tested. The data (Table 1) showed that there is not any significant difference among the various periods of cooling. Therefore, it is recommended that a 4 hours cooling period be used prior to the stability measurement.

Using the above mix design method, a complete mix design was conducted for NDOT contract #2513. Figure 1 shows the aggregate gradation used on this project. Table 2 summarizes the mix design data for this mixture. Based on the data summarized in Table 2, the recommended mix design is as follows:

AC_{opt} = 10.1 % Stability = 15 Air voids = 5.5 %

The above mix design is exactly the same as the one recommended by the Marshall Mix design conducted by Western Technologies Inc. (WTI).

3.2 Mix Design Method for Dense Graded CRM Mixtures

The following mix design method is applicable for dense graded CRM mixtures and is based on the Hveem mix design method with some modifications. It is anticipated that some additional modifications will be necessary once this method is applied for actual dense graded CRM mixtures.

Trial binder content:	4.5 - 8.0 % by dry weight of aggregate.
Binder mixing temperature:	340 - 360°F
Aggregate mixing temperature:	340 - 360°F
Compaction Temperature:	275 - 300°F
Design Criteria:	
Hveem Stability:	20 minimum
Air Voids:	4 %

4.0 TASK B: CHARACTERIZATION OF CRM BINDERS

As discussed in the background section, the Superpave performance based binder grading system will be implemented in the characterization of CRM binders. Unfortunately, the evaluation of rheological properties of CRM binders was not conducted as part of SHRP's asphalt research. Based on evaluating only neat asphalts, the SHRP system recommended the use of the parallel plate configuration for evaluating the rheological properties of the binder as shown in Figure 2a. It also recommends a sample size of 2 and 1 mm for the virgin and aged binders, respectively. In the case of CRM binders, these sample sizes are too small to evaluate the interaction between the asphalt and rubber particles.

To date however, little research has been directed towards the evaluation of other test configurations for determining the rheological properties of CRM binders; namely the plate and cup configuration as shown in Figure 2b. The following presents a clear description of each testing system.

4.1 Description of the Parallel Plate Test System

The SHRP grading system recommends the use of the parallel plate configuration. The size of the plate and the thickness of the sample depend on the temperature of the test. For high temperature testing (greater than 35° C), the plate diameter is 25mm and the sample thickness is 1mm. For intermediate temperatures testing (between 10° C an 35° C), the plate diameter is 8mm and the sample thickness is 2mm. Refer to Figure 2a for an illustration of the test configuration. Furthermore, the strain level changes for different test temperatures. The recommended strain is 12% for high temperatures and 1% for intermediate temperatures. The test procedure requires the application of sinusoidal shear strain over a given range of frequencies. At the final frequency, 10 rad/sec, the rheological properties are measured and analyzed.

For the rheological properties at low temperatures, the SHRP grading system recommends the use of the Bending Beam Rheometer (BBR). This procedure generates the low temperature creep characteristics, such as creep stiffness S(t) and slope of the creep curve m, by applying a static load at the center of a simply supported beam while measuring the deflection with time.

4.2 Plate and Cup Test System

The plate and cup configuration was recommended by Goodrich to provide the same rheological data with less operator obligation. As in the case of the parallel plate, the 25 and 8 mm plates are used. The plate diameter is selected based on the test temperature. The size of the binder sample is 42 mm in diameter and 7.5 mm in depth as shown in Figure 2b. This sample size is significantly larger than the one used in the parallel plate system. Therefore, the large size of the rubber particles should not create any problems.

The entire testing sequence is controlled by the testing software. The diameter of the plate and the depth into the cup that the plate penetrates are selected based on the temperature of the test and the stiffness of the material that is being tested. As shown in Figure 2b, the actual plate consists of a 25mm upper part and an 8mm lower part. Under high temperature testing the plate is lowered until the 25mm face is in contact with the binder while under intermediate and low temperatures only the 8mm face is in contact with the binder surface. The plate and cup configuration can also be used to generate the low temperature characteristics which are normally obtained from the BBR test.

4.3 Selection of Testing Systems and Materials

In this task, an evaluation of three different testing systems was accomplished. The first and second systems are based on the parallel plate/BBR and plate and cup systems , respectively, while the third system is a combination of the two.

System 1: Use the parallel plate test configuration as recommended by SHRP (Figure 2a).

System 2: Use the plate and cup test configuration as recommended by Goodrich (Figure 2b) at both high and low temperatures.

System 3: Use the plate and cup test configuration at high and intermediate temperatures and use the BBR at low temperatures.

It should be noted that although different methods will be used to grade the binders, or more precisely to get the limiting temperatures, the SHRP specification, which is currently AASHTO Performance Graded Binder Specification (MP1), will be used to convert the limiting temperatures into a performance grade for all methods.

The above three systems were evaluated on five different CRM binders which cover a wide range of percent rubber and particle sizes. They also included a good range of base asphalts, which provided several different asphalt-rubber combinations, and furthermore, two of the binders contained polymer additive. The following binders were used for the evaluation:

CRM system 1:	10% crumb rubber, 100 % passing #200, blended with AC-5.
CRM system 2:	10% crumb rubber, 100 % passing #200, blended with AC-10.
CRM system 3:	10% crumb rubber, 100 % passing #200, blended with AC-5 and 3% SBS polymer.
CRM system 4:	20% crumb rubber, 100 % passing #8, blended with AC-20.
CRM system 5:	10% crumb rubber, 100 % passing #20, blended with AC-5, extender oil, and KRATON polymer.

4.4 Sample Preparation and Preliminary Testing

In order to prepare samples for testing and subsequent aging, it was first necessary to heat the binders and mix them thoroughly to ensure homogeneity. Usually this required that the binders be heated in excess of 325°F, and in some cases it was found necessary to approach 400°F. The performance grading procedures include testing of the original binder, the Rolling Thin Film Oven Test (RTFOT) residue, and the Pressure Aging Vessel (PAV) residue using the Dynamic Shear Rheometer (DSR) and the Bending Beam Rheometer (BBR).

Prior to rheological testing, the mass loss, the flash point, and the viscosity of the CRM binders had to be measured. The mass loss percent is recorded as a percentage of the original weight that is lost during one RTFOT cycle. The criteria is that the maximum mass loss be limited to 1.0%. The Brookfield viscosity is measured in Pa*s and the Superpave specification allows for asphalt binders with a maximum viscosity of 3 Pa*s at 135°C. However, as one might expect, CRM binders are much more viscous than unmodified binders, and some higher percentages of rubber, such as 20% by weight of binder, are far too viscous to fall under the SHRP specifications. In the case of CRM Binder 4, it was impossible to measure its viscosity using the Brookfield viscometer. Since the scope of this project was to determine the adequacy of current methods for use in performance grading CRM binders, it was decided to allow the Brookfield viscosity specification to be overlooked. The Flash Point temperature is simply found from the Cleveland open cup method and recorded in degrees Celcius, and it is checked to insure safety up to a minimum of 230° C. Table 3 summarizes the data from the preliminary testing of the binders. This preliminary testing is conducted on all binders prior to the beginning of the rheological testing and is uniform for all the three grading systems that are being evaluated. The data in Table 3 indicate that all CRM binders except CRM binder 1 failed the brookfield viscosity limit of 3 Pa*s. Therefore, the Superpave limit on the Brookfield viscosity is not applicable for CRM binders. The flash point and RTFO mass loss criteria were met by all five CRM binders.

4.5 Evaluation of the Testing Systems

This section of the data analysis covers all of the rheological data collected by the three systems. As mentioned earlier system 3 will use a combination of the first and second systems.

The testing at the high and intermediate temperatures give three limiting temperatures for each CRM binder system. The first temperature is Tmax for the original binder, which is the temperature at which $G^*/\sin(\delta) = 1.0$ KPa. The second temperature is Tmax for the RTFOT residue, which is the temperature at which $G^*/\sin(\delta) = 2.20$ KPa. The third temperature is Tint for the PAV residue, which is the temperature at which $G^*(\sin((\delta)) = 5.0$ MPa. In testing system 1, these temperatures are produced by using the parallel plate configuration (Figure 2a). In testing system 2 and 3, these temperatures are produced using the plate and cup configuration (Figure 2b).

In the case of low temperature, the binders properties that must be measured include the slope of the creep curve (m) and the creep stiffness (S) of the PAV aged binders. The Superpave grading system requires the evaluation of the temperature at which S = 300 MPa and m = 0.300 at 60 sec loading time. Testing systems 1 and 3 use the BBR to evaluate these properties while testing system 2 uses the plate and cup configuration.

The following criteria were used to evaluate the merit of the three systems:

1. The system should be reliable. In other words, the measured temperatures should be realistic.
2. It is assumed that the results from the plate and cup at the high and intermediate temperatures are the standard since this configuration eliminate the particle size problem. Therefore, the data generated by the parallel plate configuration will be judged against the plate and cup data.
3. It is assumed that the results from the BBR at the low temperatures are the standard. Therefore, the data generated by the plate and cup will be judged against the BBR data.

Table 4 summarizes the four temperatures that are used in the Superpave grading process. These temperatures are defined as follows:

Tmax(Virgin): This is the temperature at which the virgin binder reaches a $G^*/\sin(\delta)$ = 1.0 KPa.

Tmax(RTFO): This is the temperature at which the RTFO aged binder reaches a $G^*/\sin(\delta)$ = 2.2 KPa.

Tint(PAV): This is the temperature at which the RTFO/PAV aged residue binder reaches a $G^{*}(\sin(\delta)) = 5$ MPa.

Tmin(PAV): This is the temperature at which the RTFO/PAV aged binder reaches a $S = 300$ MPa and $m = 0.300$.

Using this data, the three grading systems were evaluated based on the three criteria that were defined earlier. In the case of the reliability criteria, the parallel plate system (system 1) had difficulties grading the coarser CRM binders (CRM binders 4 and 5). These difficulties were more pronounced in the case of CRM binder 4 which represents the coarser one of the two (100 passing #8). Table 5 summarizes the results of the trial tests that were conducted in order to achieve a reliable measurement of the $G^{*}/\sin(\delta)$ for the CRM binder 4. The large variability of the trial measurements indicates that there is a serious problem in testing this type of CRM binder using the parallel plate system. In the case of the CRM binder 5 the problem was not as severe. Occasionally some replicates had to be conducted in order to obtain reliable data. It can be concluded that the parallel plate system (system 1) is not applicable to CRM binders that contain particles as large as #8. In the case of CRM binders containing particles as large as #20, the parallel plate system may be used with extreme caution.

In the case of the accuracy of the measured temperatures, the parallel plate system showed different temperatures than the plate and cup system on several occasions. However, the magnitude of these differences were not significant enough to make a difference in the final high temperature of the CRM binder except in the case of CRM binder 5. In this case the measured high temperatures on the RTFO residue were 78.2 and 74.2 as measured by the parallel plate and plate and cup systems, respectively. The reason that the four degrees difference made a change in the final grade, is that it spans over the 76 grade. It should also be noted that the high temperatures reported in Table 4 for CRM binder 4 under system 1 represent the most reasonable measurement based on multiple trials. Therefore, based on these facts, it is recommended that the parallel plate system be only used on CRM binders containing particles passing #200.

In the case of the low temperature criterion, the data in Table 4 showed that the plate and cup system has failed to reproduce the BBR measurement in all cases. Therefore, it is recommended that the BBR should be used to evaluate the low temperature properties of CRM binders regardless of their gradations. It should be noted that the fabrication of the beam samples for the BBR test requires extra care due to the presence of the rubber particles which tends to introduce air bubbles inside the sample.

4.6 Determination of PG Grades

The process by which a PG grade is determined is based on converting the limiting temperatures into a performance grade (PG) following the Superpave grading form shown in Figure 3. Table 6 summarizes the PG grades for all the five CRM binders based on all three grading systems. As recommended above, grading system 1 should only be used for fine crumb rubber (100% passing #200) while grading system 3 is recommended for coarse crumb rubber with some percent retained on #200. This recommendation may be too conservative, however, since this study did not include any CRM binders containing particles between the #20 and #200 sieves, more refined recommendations can not be made at this point.

4.7 Grading the 2513 CRM Binder

The CRM binder used on NDOT contract #2513 was graded using grading systems 1 and 3 as defined earlier. This binder was supplied by Baker of Mesa Arizona and consists of 20% crumb rubber (100 % passing #10) mixed with AC-10.

Initial attempts to use grading system 1 failed to produce any reliable results. This was followed by modifying grading system 1 to use a 2mm gap at the high temperature testing instead of the 1 mm gap as recommended by SHRP. Increasing the gap to 2mm has helped some but it did not resolve the entire problem. Still more than one trial was needed to achieve realistic measurements using grading system 1. Figures 4 and 5 summarize the grading data generated by systems 1 and 3, respectively. It can be seen from this data that eventhough the final PG grades produced by the two systems are the same (PG76-28), there are still some significant discrepancies between the high temperatures measured by the two systems. For instance the maximum temperature on the original CRM binder was 90.2 using system 1 and 76.9 when using system 3. As the binder is aged through the RTFO the difference between the two temperatures became smaller. However, it should be noted here that the reported temperatures in the case of system 1 represent the best measurements out of several trials.

The initial tests on this binder also showed that it is impossible to measure its Brookfield viscosity while its flash point and the percent mass loss in the RTFOT met the SHRP specifications (figures 4 and 5). As mentioned earlier, it was decided to overlook the Brookfield viscosity specification for CRM binders. Therefore, the 2513 CRM binder can be graded as: **PG76-28.** This binder has provided an additional CRM binder system which falls between binders 4 and 5 (that were tested under the first part of this task) in terms of the maximum size of rubber particles. The findings from this binder supported the earlier recommendations which indicated that the use of grading system 1 should be limited to CRM binders which contains fine crumb rubber particles (100% passing #200).

4.8 Grading the 2680 CRM Binder

NDOT contract #2680 was constructed during the Summer of 1995 on US95 south of Las Vegas. The project included two CRM test sections and a control section. One of the sections was constructed using the ISI CRM system and the other one was constructed using the FNF CRM system. The ISI section included a gap graded (GG) layer and an open graded (OG) friction course while the FNF section included only a gap graded layer. Figure 6 shows the gradation curves for the ISI and FNF sections. The CRM binders consist of the following:

	ISI	FNF
Base Binder:	AC-20	AC-10
CRM max size:	#10	#16
CRM percent (%):	17	18
Optimum Binder Content By Total Weight of Mix (%):	9.0 (OG) 8.0 (GG)	7.2

The binder testing program for this project had two objectives: a) to evaluate the PG grade of the binder, b) to evaluate the impact of blending time on the PG grade. Therefore, the CRM binders were sampled at various time intervals during the production of the CRM HMAC mixtures. The PG grading process used the parallel plate system with 1 and 2 mm gap sizes and the plate and cup system.

PG Grading Process: Table 7 summarizes the measured limiting temperatures using all the parallel plates with 1 mm gap (system 1), parallel plates with 2 mm gap (system 2) and the cup and plate system (system 3). Based on the results of the first five CRM binders, it was recommended to use the BBR to evaluate the minimum limiting temperature for all CRM binders. Therefore, the limiting minimum temperatures for all binders in Table 7 are the same for all three systems. Table 8 summarizes the PG grades for all the binders using the three testing systems.

The data in Table 7 show that there are significant differences among the measured limiting temperatures of the CRM binders using the three systems. In addition, the data in Table 8 show that the differences in the limiting temperatures translate into significant changes in the PG grades for the CRM binders. For the base binders, on the other hand, all three systems provided the same PG grade. The data from the 2680 binders support the earlier conclusions concerning the use of the parallel plate system to measure the rheological properties of CRM binders. The plate and cup system along with the BBR should always be used to grade CRM binders. The ISI OG and GG CRM binders received different PG grades eventhough they contain the same CRM types and percentages. This may be contributed to the variability in manufacturing CRM binders.

The control section on contract #2680 had an AC-30 and AC-20P in the wearing course and open graded friction, respectively. The AC-30 binder graded as PG 64-22 and the AC-20P graded as PG 64-22. The same PG grades for the AC-30 and AC-20P was a little bit of a surprise. However, earlier data showed that there is not a direct relation between the AC and PG grading systems.

Impact of Blending Time: As mentioned earlier, samples were obtained at various time intervals during the production of the CRM HMA mixtures. The Plate and Cup system was used to evaluate the impact of blending time on the rheological properties of the CRM binders. Table 9 summarizes the final PG grades for the samples that were obtained at various time intervals. The data in Table 9 indicate that the ISI CRM binder was not affected by the blending time while the FNF CRM binder changes as a function of blending time. FNF CRM binders sampled between 7 and 10 p.m. showed the highest variation on the high temperature grade. This data indicate that the PG 76-22 grade is more representative for both the ISI OG and GG CRM binders. Two of the hourly samples of the FNF CRM binders graded similar to the original binder as PG 88-22 while two other samples had higher high temperature grade and one sample had a lower high temperature grade. For all cases, the blending time did not affect the low temperature grade of the CRM binder.

5.0 TASK C: LABORATORY EVALUATION OF MIXTURES

The objective of this task is to evaluate the strength properties of the CRM mixtures used on NDOT projects. Two types of samples were evaluated: a) samples manufactured in the laboratory based on the recommended mix design, referred to as the lab mixed-lab compacted (LMLC) samples, and b) Samples collected at the construction site, referred to as the field mixed-lab compacted (FMLC) samples. Mixture samples were collected from a total of three NDOT CRM projects; contracts #2513, #2680, and #2623. Both Contracts #2513 and 2680 have been previously described in this report.

Contract #2623 was constructed during the summer of 1994 on SR 225 north of Elko, Nevada. Only FMLC mixtures were available from the #2623 project. The CRM binder for contract #2623 is an AC-10 plus 17% BAS CRM (100% passing #10) and 3.2% extender oil. The optimum binder content was 9.6% by dry weight of aggregate. Figure 7 shows the gradation curve for the #2623 CRM mixtures.

The objective of testing the LMLC samples is to determine how well the laboratory process can simulate field production while the objective of testing the FMLC samples is to predict the field performance of the mixtures. This laboratory evaluation program includes the following steps:

a. Evaluate the resilient modulus of the mixtures at three different temperatures (34, 77, and 104 degrees F);

b. Evaluate the indirect tensile strength of the mixtures at

77 degrees F;

c. Evaluate the moisture sensitivity of the mixtures using the modified Lottman moisture-conditioning procedure;

d. Evaluate the permanent deformation characteristics of the mixtures using triaxial permanent deformation testing; and

e. Evaluate the low-temperature characteristics of the mixtures using the thermal restrained strength test.

5.1 Temperature Susceptibility of CRM Mixtures

The resilient modulus of the mixtures were evaluated at three different temperatures (34, 77, and 104°F) in order to evaluate their temperature susceptibility. Table 10 summarizes the resilient modulus data for both the FMLC and LMLC mixtures. The data also show the standard deviation (STD) and the coefficient of variation (COV) which represent the degree of variability in the measured values. The COV is defined as the ratio of the standard deviation over the average of the three replicate measurements. Typically, COV values below 15 percent are considered low variability while COV values above 25 percent are considered high variability. The COV values reported in Table 10 indicate that the variability of this data is at an acceptable level.

The data summarized in Table 10 present the following conclusions concerning the two objectives of testing LMLC and FMLC mixtures.

Can LMLC mixtures simulate field production?

- The mixtures from contract #2513 indicate that the laboratory prepared (LMLC) mixtures possess higher strength properties than the field produced mixtures (FMLC).
- The ISI OG mixtures from contract #2680 indicate that the laboratory produced (LMLC) mixtures possess similar properties to the field produced (FMLC) mixtures.
- The FNF mixtures from contract #2680 indicate that the laboratory produced (LMLC) mixtures possess strength properties that are very low compared to the field produced (FMLC) mixtures.

In summary, three mixtures gave three different conclusions concerning the ability of the laboratory process to simulate the field produced CRM mixtures. The most significant contradiction between the LMLC and FMLC mixtures occurred with the FNF CRM mixtures which also showed the most significant impact of blending time on the rheological properties of the CRM binder. It can be concluded that it is more difficult to simulate the behavior of CRM mixtures in the laboratory than it is to simulate conventional HMA mixtures.

Predict mixtures performance based on FMLC properties.

The data in Table 10 indicate that the actual M_r values of the FNF FMLC mixtures are comparable to dense graded HMA mixtures while they are marginal for the ISI OG FMLC mixtures and significantly low for the #2513 FMLC mixtures. The #2623 mixtures showed mixed results where the M_r at 77°F are marginal while the M_r at 104°F are extremely low. Figure 8 shows the temperature susceptibility curves for the FMLC mixtures. The FNF mixtures showed the best temperature susceptibility characteristics, these mixtures show lower modulus at the low temperature and high modulus values at the high temperatures. The ISI, #2513, and #2623 mixtures show poor temperature susceptibilities with the ISI mixtures having relatively higher absolute values than the #2513 and #2623 mixtures. Based on the temperature susceptibility data , it could be expected that the #2513, ISI, and #2623 mixture may experience premature rutting problems.

5.2 Moisture Susceptibility of CRM Mixtures

The moisture susceptibility of CRM mixtures was evaluated through the Lottman moisture conditioning process. This process consists of measuring the resilient modulus and tensile strength of the mixtures before and after being subjected to one cycle of freezing and thawing. In this research, the resilient modulus (Mr) and the tensile strength (TS) at 77°F were measured at the unconditioned and conditioned stages. Table 11 summarizes the moisture sensitivity data for all mixtures. During the summer of 1994, NDOT has implemented the following specifications for asphalt concrete mixtures:

Minimum value for dry TS (77°F)
for binders different than AC-10 = 65 psi

Minimum value for dry TS (77°F) for mixtures with AC-10 = 50 psi

Minimum value for TS ratio = 70%

Again the data in Table 11 will be evaluated in light of the two objectives that were mentioned earlier.

Can LMLC mixtures simulate field production?

The data in Table 11 showed that the laboratory manufactured mixtures (LMLC) also have some limitations in simulating field produced (FMLC) mixtures. The discrepancy between the LMLC and FMLC properties seems to be inconsistent among the various mixtures.

Predict mixtures performance based on FMLC properties.

The data in Table 11 indicate that the #2513 FMLC mixtures would not meet NDOT moisture sensitivity specifications on the TS dry value. The ISI OG FMLC mixtures would barely meet the minimum TS dry value specified by NDOT while the FNF and #2623 FMLC mixtures would surpass the minimum required TS dry value.

In the case of the retained strength ratio, only the #2513 FMLC mxitures would meet the NDOT minimum requirement of 70%. This provides a clear example as to why a moisture sensitivity specification should include both a minimum absolute value and a minimum retained strength ratio.

By imposing both the minimum absolute TS value of 65 psi and the minimum retained strength ratio of 70% on both the tensile strength and M_r, it can be concluded that each one of the four FMLC mixtures (i.e. #2513, ISI OG, FNF, and #2623) would fail at least one of the two criterion. Therefore, this data indicate that the moisture sensitivity is a serious problem with CRM modified HMA mixtures. It is anticipated that the majority of the CRM mixtures would suffer from premature moisture damage. This kind of limitation is very serious for Nevada since good quality aggregates are in short supply throughout the state.

5.3 Permanent Deformation Characteristics

The triaxial repeated load test was used to evaluate the permanent deformation characteristics of the FMLC and LMLC mixtures from NDOT contracts #2513, #2680, and #2623. In summary, this test applies a 45 psi deviator stress (0.1 second duration) and 30 psi confining pressure. The sample is 4" diameter by 8" high with air voids between 6 and 8 percent.

The permanent deformation test was conducted on the mixtures from contracts #2513 and #2623 under the following conditions:

Temperature (F)	Moisture
104	None
104	Conditioned
140	None

While the mixtures from contract #2680 were tested under 104°F without any conditioning. Figure 9 show a typical permanent deformation data on a FMLC mixture. Table 12 summarizes the permanent strains measured under the various testing conditions for the #2513 and #22623 mixtures while Table 13 summarizes the permanent deformation data for the #2680 mixtures.

The data on the #2513 mixtures indicate that the properties of the FMLC and LMLC mixtures differ significantly under all conditions. This agrees with the observations based on the temperature susceptibility and moisture sensitivity data. However, in both cases the moisture conditioning significantly reduces the rutting resistance of the mixtures. Also the higher the temperature, the lower the resistance of mixtures to permanent deformation will be.

The failure criteria for the triaxial permanent deformation is to maintain less than 1% permanent strain under 12,000 cycles. The data in Table 12 indicate that the field produced mixtures from contracts #2513 and #2623 do not possess good resistance to permanent deformation. These mixtures are expected to encounter premature rutting failures in the field.

The data in Table 13 indicate that the ISI mixtures have relatively low resistance to permanent deformation while the FNF mixtures have excellent resistance to permanent deformation. The differences between the LMLC and FMLC mixtures are not as noticeable as in the case of the #2513 mixtures.

In summary, the #2513, ISI OG, and the #2623 mixtures are expected to have problems with premature rutting while the FNF mixtures are expected to perform well in resisting rutting under the Las Vegas environment. These observations coincide very well with the recommendations based on the resilient modulus properties at 104°F.

5.4 Low Temperature Cracking

The resistance of the CRM mixtures to low temperature cracking was measured using the Thermal Stress Restrained Specimen Test (TSRST). The TSRST is a direct tension used to measure the fracture stress and the fracture temperature of an HMA beam as it is cooled down at rate of -5°C/hour. Thermal tensile stresses are generated throughout the length of the specimen as it is cooled because it is restrained at a constant length. As the temperature of the HMA beam decreases, the tensile stresses increase until they surpass the strength of the mixture after which the specimen breaks. At the breaking point, the temperature is referred to as the fracture temperature and the tensile stress is referred to as the fracture stress. The TSRST sample consists of a 50mm x 50mm x 250mm HMA beam sawn on all four sides and two ends.

Table 14 summarizes the fracture stresses and temperatures for the CRM HMA mixtures. The fracture stress is an indication of the spacing of the low temperature cracks while the fracture temperature is an indication of the occurrence of the low temperature cracking. The fracture temperature is a better indicator of the mixtures resistance to low temperature cracking since it directly measures the temperature at which cracking is expected to occur. The data in Table 14 indicate that FNF mixtures exhibit extremely good resistance to low temperature cracking followed by the #2623 mixtures. The #2513 and the ISI OG mixtures have similar resistances to low temperature cracking which are lower than the FAF and the #2623 mixtures.

6.0 SUMMARY AND RECOMMENDATIONS

This report summarizes the findings of a research project which evaluated CRM HMA mixtures in Nevada. The research developed a mix design procedure, a binder evaluation system, and measured the characteristics of CRM mixtures used on Nevada's projects.

The existing mix design procedure for CRM mixtures were reviewed and design procedures for gap and dense graded mixtures were recommended. The recommended mix design process for gap graded CRM mixtures was implemented on an actual NDOT project and modifications were made as necessary.

Three binder characterization systems were evaluated on nine different CRM binders. The data generated from this experiment were used to evaluate the suitability of each grading system in grading CRM binders.

CRM mixtures from NDOT contracts #2513, #2680, and #2623 were evaluated in terms of their temperature susceptibility, moisture sensitivity, permanent deformation resistance , and low temperature cracking resistance. The data from this experiment will be used to correlate between laboratory and field performance of CRM mixtures in the state of Nevada.

Based on the results of this research effort, the following recommendation can be made:

- The design of gap graded CRM mixtures can be conducted using a modified version of the Hveem mix design process. The most significant modification is in the area of compaction of the mixtures. It was discovered that the normal Hveem compaction procedure was inadequate for CRM mixtures. Therefore, a new method was recommended which calls for compacting the CRM samples in two lifts to avoid the separation of the sample. The impact of curing period on the stability of CRM mixtures was evaluated and proven to be insignificant. In the case of mixing, higher mixing temperatures must be maintained when dealing with CRM mixtures.

- The standard SHRP binder grading system (i.e. parallel plate) has some limitations in grading CRM Binders. These limitations become very significant when dealing with CRM binders containing rubber particles larger than #200. Therefore, it is recommended to use the plate and cup system in conjunction with the BBR to grade CRM binders that contain any rubber particles larger than #200.

- The temperature susceptibility of all the CRM mixtures used in Nevada is poor except for the FNF mixtures used on contract #2680.

- The moisture sensitivity of all the CRM mixtures used in Nevada is very poor.

- The permanent deformation resistance of all the CRM mixtures used in Nevada is very poor except for the FNF mixtures used on contract #2680.

- The resistance to low temperature cracking of the CRM mixtures is acceptable with the FNF mixtures providing the best resistance.

In summary, the FNF mixture on contract #2680 represents the best CRM mixtures used in Nevada. However, the FNF mixture still suffers from poor moisture sensitivity and poor construction control. It is recommended that NDOT monitors the field performance of all these projects and use these performance in conjunction with the laboratory evaluations presented in this report to make decisions regarding the future use of CRM mixtures in Nevada.

REFERENCES

1. Bahia, H.U. and Davies, R., "Effects of Crumb Rubber Type and Content on Performance Related Properties of Asphalt Binders".

2. Bahia, H.U. and Davies, R., "Effect of Crumb Rubber Modifiers (CRM) on Performance Related Properties of Asphalt Binders", presented to Association of Asphalt Paving Technologists, 1994.

3. McGennis, R.B. and Quinn, W.J., "Performance Graded Asphalt Binders Using Fine Mesh Crumb Rubber", prepared for Rouse Rubber Industries, Inc., 1994.

4. Blakely, S.D., "The Classification of Nevada's 1993 Asphalt Binders Using SHRP's Performance-Based Grading System", University of Nevada, Reno, Master Thesis, 1994.

5. Heitzman, M.A., "State of the Practice - Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier", Federal Highway Administration, Report No. FHWA-SA-92-022, May 1992.

6. Chehovits, J.G., Hicks, R.G. and Lundy, J., "Mix Design Procedures", Workshops on Crumb Rubber Modifiers, FHWA and Nevada Transportation Technology Transfer Center, March 1993.

7. Chehovits, J.G., "Design of Asphalt and Crumb Rubber Modifier Blends for Highway Applications", Workshops on Asphalt Rubber, Federal Highway Administration, Publication No. FHWA-SA-93-007.

8. Vallerga, B.A., "Design and Specification of Changes for Paving Mixtures with Asphalt Rubber Binders", Proceedings: National Seminar on Asphalt Rubber, San Antonio, Texas, October, 1981.

9. Schuler, S., et,al., "Investigation of Material and Structural Properties of Asphalt Rubber Paving Mixtures", FHWA Report No. FHWA-RD-86-027.

10. Chehovits, J.G., "Binder Design Procedures", Workshops on Crumb Rubber Modifiers, Nevada Transportation Technology Transfer Center and FHWA, March 1993.

11. Stroup-Gardiner, M., Krutz, N. and Epps, J.A., "Comparison of Mix Design Methods for Rubberized Asphalt Concrete Mixtures", The Asphalt Rubber Producers Group, October 1989.

12. Roberts, F.L., et.al., "Hot Mix Asphalt Materials, Mixture Design, and Construction", National Center for Asphalt Technology, First Edition, 1991.

13. Krutz, N.C., and Stroup-Gardiner, M., "Permanent Deformation Characteristics of Recycled Tire Rubber Modified and Unmodified Asphalt Concrete Mixtures", Transportation Research Board, 71st Annual Meeting, January, 1992.

14. Krutz, N.C., and Stroup-Gardiner, M., "Low Temperature Cracking Characteristics of Ground Tire Rubber Modified and Unmodified Asphalt Concrete Mixtures", the Asphalt Rubber Producers Group, September, 1991.

Table 1. Hveem stability at various CRM binder contents and cooling periods.

CRM Binder Content (%)	Cooling Period (hrs) 4	16	24
		Hveem stability	
7	28	23	20
8	18	19	27
9	19	18	21
9.5	19	18	17
10	18	17	17
10.5	9	11	13

Table 2. Mix design data for NDOT Contract #2513.

Test	Sample ID						
	7%	8%	9%	9.5%	10%	10.5%	11%
Bulk Sp. Gr.	2.127	2.139	2.132	2.125	2.134	2.132	2.184
Air Voids	8.6	7.2	6.5	6.3	5.5	4.9	2.2
Max. Sp. Gr.	2.327	2.306	2.280	2.268	2.258	2.243	2.232
Stability	28	18	19	19	18	9	14

Table 3. Flash point, Brookfiled viscosity, and RTFO loss for CRM binders.

Binder Type	Flash Point (C)	Brookfield Visc. at 135 °C (Pa*s)	RTFO Mass Loss (%)
CRM Binder 1	271	2.2	0.525
CRM Binder 2	302	7.4	0.201
CRM Binder 3	305	7.1	0.289
CRM Binder 4	317	NA	0.453
CRM Binder 5	294	12.6	0.033

Table 4. Limiting temperatures for CRM binders as measured by the three systems.

Temperature	System 1	System 2	System 3
	Parallel Plate with BBR	Plate and Cup only	Plate and Cup with BBR
	CRM Binder 1		
Tmax(virgin)	74.2	75.8	75.8
Tmax(RTFO)	69.5	69.4	69.4
Tint(PAV)	8.2	11.0	11.0
Tmin(PAV)	-27.6	-15	-27.6
	CRM Binder 2		
Tmax(virgin)	81.1	81.5	81.5
Tmax(RTFO)	67.7	65.9	65.9
Tint(PAV)	17.1	18.3	18.3
Tmin(PAV)	-21.8	-14	-21.8
	CRM Binder 3		
Tmax(virgin)	91.7	105.6	105.6
Tmax(RTFO)	79.9	76.0	76.0
Tint(PAV)	8.6	10.6	10.6
Tmin(PAV)	-16.1	-13	-16.1
	CRM Binder 4		
Tmax(virgin)	97.8	83.9	83.9
Tmax(RTFO)	90.2	83.9	83.9
Tint(PAV)	14.9	15.1	15.1
Tmin(PAV)	-15.4	-11	-15.4
	CRM Binder 5		
Tmax(virgin)	84.8	79.9	79.9
Tmax(RTFO)	78.2	74.2	74.2
Tint(PAV)	6.0	12.1	12.1
Tmin(PAV)	-33.6	-15	-33.6

Table 5. Results of the parallel plate (system 1) trials for CRM binder 4.

Binder	Temp (C)	$G^*/\sin(\delta)$		
		Trial 1	Trial 2	Trial 3
Original	58	12.501	40.541	NA
	64	38.080	35.250	8.540
	70	5.830	34.700	NA
RTFO Aged	58	20.153	49.806	41.560
	64	39.992	39.870	27.780
	70	44.720	25.820	15.620

Table 6. Performance grading of CRM asphalt binders.

Binder	Parallel Plate with BBR (System 1)	Plate and Cup alone (System 2)	Plate and Cup with BBR (System 3)
CRM Binder 1	PG 64-34	PG 64-22	PG 64-34
CRM Binder 2	PG 64-28	PG 64-22	PG 64-28
CRM Binder 3	PG 76-22	PG 76-22	PG 76-22
CRM Binder 4	PG 82-22	PG 82-16	PG 82-22
CRM Binder 5	PG 76-34	PG 70-22	PG 70-34

Table 7. Limiting temperatures for the #2680 CRM binders as measured by the three systems.

Temperature	**System 1**	**System 2**	**System 3**
	Parallel Plate with BBR	**Plate and Cup only**	**Plate and Cup with BBR**
ISI Base AC-20			
Tmax(virgin)	66.7	66.1	68.3
Tmax(RTFO)	64.7	64.5	66.5
Tint(PAV)	24.8	24.8	NA
Tmin(PAV)	-6.2	-6.2	-6.2
ISI CRM Binder (GG)			
Tmax(virgin)	116.4	86.7	80.0
Tmax(RTFO)	102.2	84.1	77.4
Tint(PAV)	18.0	18.0	24.4
Tmin(PAV)	-17.3	-17.3	-17.3
ISI CRM Binder (OG)			
Tmax(virgin)	118.7	89.2	85.2
Tmax(RTFO)	111.1	86.4	82.9
Tint(PAV)	20.5	20.5	22.1
Tmin(PAV)	-14.6	-14.6	-14.6
FNF Base AC-10			
Tmax(virgin)	64.3	65.5	66.9
Tmax(RTFO)	64.9	64.8	67.5
Tint(PAV)	19.8	19.8	23.6
Tmin(PAV)	-15.3	-15.3	-15.3
FNF CRM Binder			
Tmax(virgin)	141.4	97.7	92.8
Tmax(RTFO)	102.3	99.3	92.4
Tint(PAV)	8.2	8.2	22.9
Tmin(PAV)	-16.1	-16.1	-16.1

Table 8. Performance grading of binders for contract #2680.

Binder	Parallel Plate with BBR (System 1)	Plate and Cup alone (System 2)	Plate and Cup with BBR (System 3)
ISI Base AC-20	PG 64-16	PG 64-16	PG 64-16
ISI CRM Binder (GG)	PG 100-22	PG 82-22	PG 76-22
ISI CRM Binder (OG)	PG 106-22	PG 82-22	PG 82-22
FNF Base AC-10	PG 64-22	PG 64-22	PG 64-22
FNF CRM Binder	PG 118-22	PG 94-22	PG 88-22

Table 9. PG grades of CRM binders sampled at various times for contract #2680.

Sample Type	Time of Sampling	PG-Grade
ISI CRM	3:00 a.m.	76-22
ISI CRM	4:00 a.m.	76-22
ISI CRM	8:00 p.m.	76-22
FNF CRM	1:20 a.m.	88-22
FNF CRM	12:10 a.m.	94-22
FNF CRM	7:30 p.m.	94-22
FNF CRM	8:20 p.m.	82-22
FNF CRM	9:40 p.m.	88-22

Table 10. Temperature susceptibility data of CRM mixtures.

Property	Rep 1 (ksi)	Rep 2 (ksi)	Rep 3 (ksi)	Average (ksi)	STD*	COV* (%)
Contract #2513 Field Mixed-Lab Compacted						
M_r at 34F	863	1116	1071	1017	135	13
M_r at 77F	114	128	108	117	10.5	9
M_r at 104F	16	17	16	16	1.0	6
Contract #2513 Lab Mixed-Lab Compacted						
M_r at 34F	1203	1074		1139	418	30
M_r at 77F	182	161		172	41.1	21
M_r at 104F	23	25		24	3.8	15
Contract #2680 ISI GG Lab Mixed-Lab Compacted						
M_r at 34F	2309	2146	2465	2307	159.9	7
M_r at 77F	276	261	312	283	26.4	9
M_r at 104F	31	41	41	38	6.0	16
Contract #2680 ISI OG Field Mixed-Lab Compacted						
M_r at 34F	2698	2469	2256	2474	221.0	9
M_r at 77F	226	193	207	209	16.6	8
M_r at 104F	34	28	29	30	3.2	11

Table 10. Temperature susceptibility data of CRM mixtures (continued).

Property	Rep 1 (ksi)	Rep 2 (ksi)	Rep 3 (ksi)	Average (ksi)	STD[*]	COV[*] (%)
Contract #2680 ISI OG Lab Mixed-Lab Compacted						
M_r at 34F	1881	1828	1906	1872	39.8	2
M_r at 77F	259	251	262	257	5.9	2
M_r at 104F	30	30	32	31	0.9	3
Contract #2680 FNF Field Mixed-Lab Compacted						
M_r at 34F	2481	2156	2300	2312	162.9	7
M_r at 77F	674	576	645	632	50.3	9
M_r at 104F	251	215	216	227	20.5	9
Contract #2680 FNF Lab Mixed-Lab Compacted						
M_r at 34F	1128	1145	1332	1202	113.5	9
M_r at 77F	246	236	238	240	5.0	2
M_r at 104F	37	50	50	46	7.7	17
Contract #2623 Field Mixed-Lab Compacted						
M_r at 34F	1154	1495	1638	1429	249.0	17
M_r at 77F	232	201	209	214	16.0	7.5
M_r at 104F	22	23	25	23	1.5	7

Table 11. Moisture sensitivity data of CRM mixtures.

	Mr Dry (ksi)	Mr Wet (ksi)	Mr Ratio (%)	TS Dry (psi)	TS Wet (psi)	TS Ratio (%)
Contract #2513 Field Mixed-Lab Compacted						
Rep1	114	101	89	60	50	83
Rep2	128	99	77	56	43	77
Rep3	108	107	99	53	44	83
Contract #2513 Lab Mixed-Lab Compacted						
Rep1	182	72	40	65	50	76
Rep2	161	112	70	73	49	67
Rep3				80	51	63
Contract #2680 ISI GG Lab Mixed-Lab Compacted						
Rep1	276	185	67	122	58	48
Rep2	261	182	70	114	60	53
Rep3	312	194	62	118	52	44
Contract #2680 ISI OG Field Mixed-Lab Compacted						
Rep1	226	154	68	65	43	66
Rep2	193	137	71	64	37	58
Rep3	207	170	82	65	37	57

Table 11. Moisture sensitivity data of CRM mixtures (continued).

	Mr Dry (ksi)	Mr Wet (ksi)	Mr Ratio (%)	TS Dry (psi)	TS Wet (psi)	TS Ratio (%)
Contract #2680ISI OG Lab Mixed-Lab Compacted						
Rep1	259	173	67	94	67	71
Rep2	251	165	66	103	65	63
Rep3	262	171	65	107	71	66
Contract #2680 FNF Field Mixed-Lab Compacted						
Rep1	674	401	59	103	64	62
Rep2	576	337	59	113	60	53
Rep3	645	342	53	91	68	75
Contract #2680 FNF Lab Mixed-Lab Compacted						
Rep1	246	178	72	79	47	59
Rep2	236	172	73	90	50	56
Rep3	238	187	79	93	48	52
Contract #2623 Field Mixed-Lab Compacted						
Rep1	232	67	29	87	42	49
Rep2	201	81	40	90	46	51
Rep3	209	74	35	88	48	50

Table 12. Summary of permanent deformation data for NDOT contract # 2513.

Test Conditions	Mixtures	Sample	Air Voids (%)	Permanent Strain (%) AT 12,000 CYCLES
104° F Dry	#2513 LMLC	1	6.9	0.570
		2	7.2	0.428
	#2513 FMLC	1	7.0	5.229 (8000)*
		2	6.9	4.783 (7000)
	#2623 FMLC	1	6.1	1.609
		2	7.9	2.198
104°F Conditioned	#2513 LMLC	1	7.4	2.569
		2	6.5	1.670
	#2513 FMLC	1	7.2	3.878 (1000)
		2	6.2	3.877 (2000)
	#2623 FMLC	1	6.6	4.580 (4000)
		2	7.7	2.814 (6000)
140°F Dry	#2513 LMLC	1	6.4	4.683 (10000)
		2	6.4	1.175
	#2513 FMLC	1	6.9	2.477 (200)
		2	7.4	0.266 (100)
	#2623 FMLC	1	6.2	5.624 (5000)
		2	7.0	5.515 (3000)

* The number represent the cycles to failure in the cases where the sample fail prior to 12,000 cycles.

Table 13. Summary of permanent deformation data for NDOT contract #2680.

Mixture	Replicate	Permanent Strain at 12,000 cycles (%)*
ISI GG LMLC	1	1.49 (9000)
	2	5.27
	3	5.12
	4	5.48 (10000)
	5	3.95
ISI OG FMLC	1	3.07 (1000)
	2	5.20 (3000)
	3	5.491 (5000)
	4	5.00 (4000)
	5	5.017 (4000)
ISI OG LMLC	1	5.33 (4000)
	2	5.55 (7000)
	3	5.00 (6000)
	4	5.40 (7000)
	5	5.46 (6000)
FNF FMLC	1	0.213
	2	0.307
	3	0.260
	4	0.258
	5	0.270
FNF LMLC	1	0.553
	2	0.280
	3	0.377
	4	0.514
	5	0.521

Table 14. Summary of the low temperature properties of CRM mixtures.

Property	Rep1	Rep2	Rep3	Average	STD	COV
Contract #2513 FMLC						
Fracture Stress (psi)	191	215	188	198	14.8	8
Fracture Temperature (C)	-32.4	-34.4	-31.2	-32.7	-1.6	5
Contract #2680 ISI OG FMLC						
Fracture Stress (psi)	297	272	359	309	44.8	15
Fracture Temperature (C)	-28	-29	-32	-30	-2.1	7
Contract #2680 FNF FMLC						
Fracture Stress (psi)	214	204	213	210	5.5	3
Fracture Temperature (C)	-38	-52	-48	-46	-7.2	16
Contract #2623 FMLC						
Fracture Stress (psi)	242	235		239	5.0	2
Fracture Temperature (C)	-35.5	-37.2		-36	-1.2	3

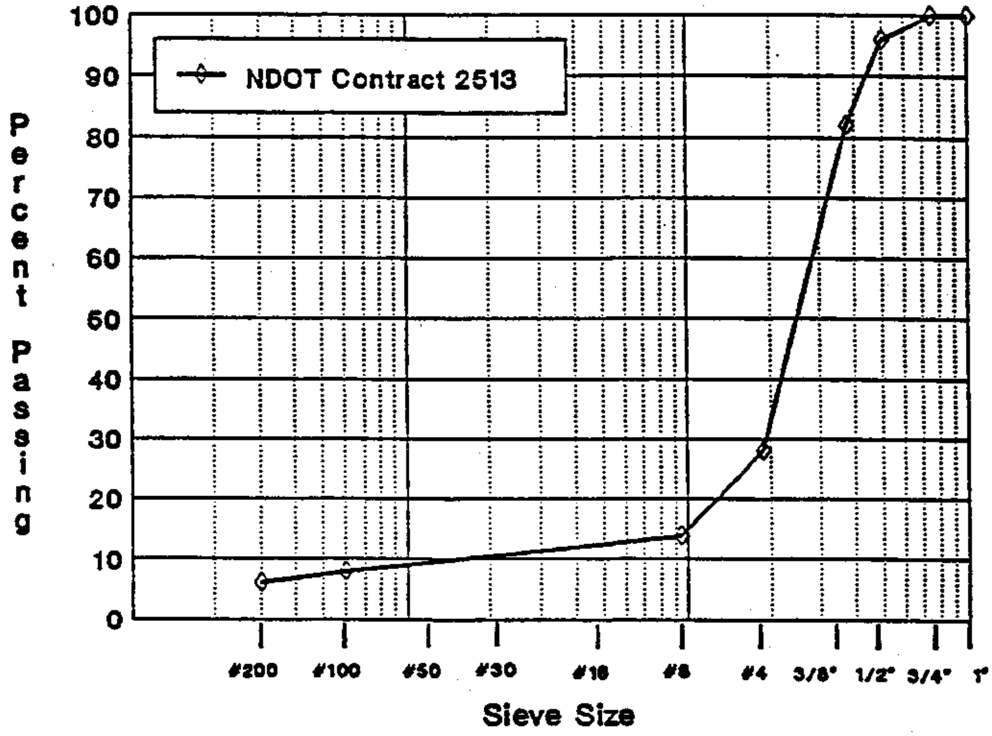

Figure 1 - Aggregate gradation for NDOT contract #2513

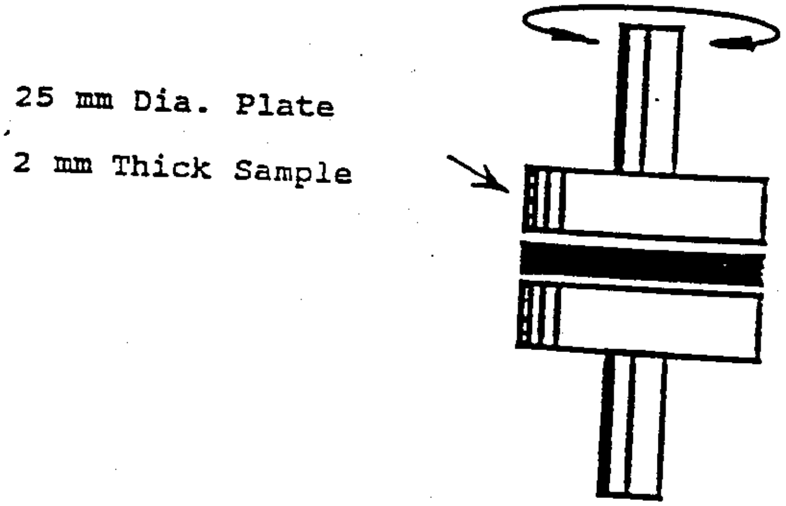

Figure 2a. The Parallel Plate Test Configuration for Rheological Testing of Asphalt Binder.

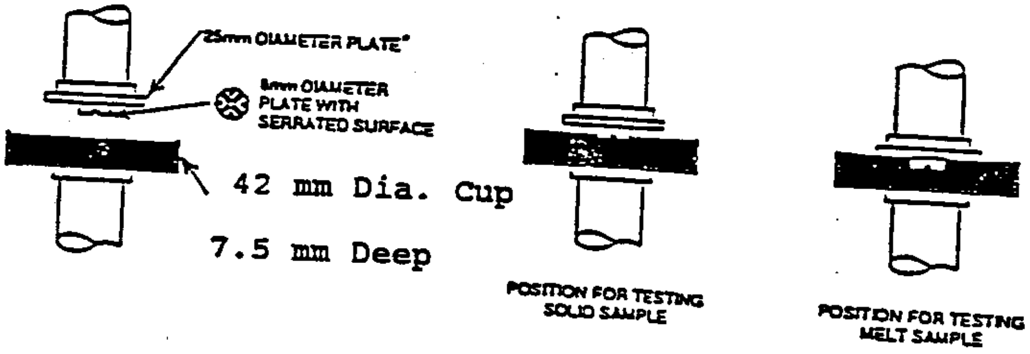

Figure 2b. The Cup and Plate Test Configuration for Rheological Testing of Asphalt Binder.

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 (TP1)																					
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 3. SHRP binder grading form.

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	>-34
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(130)				
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, TP2:[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 3. SHRP binder grading form (Continued).

Contract #	2513	SHRP PG Grade
Sample ID.	parallel plate 2mm gap	
Asphalt Type	ARC	76-28
Mass Loss, %	0.4598	
Brookfield Vis., cp	NA	
Flash Pt., C	> 230	
Limiting Temp. for Tmax, C	81.0	
Limiting Temp. for Tint, C	13.8	
Limiting Temp. for Tmin, C	-20.0	

DSR-Original						DSR-RTFOT					
Temp, C	Plate Diam., mm	Strain, %	G^*, kPa	Phase angle δ	$G^*/\sin\delta$ kPa	Temp, C	Plate Diam., mm	Strain, %	G^*, kPa	Phase angle δ	$G^*/\sin\delta$ kPa
70	25	6	5.85	50.9	7.54	70	25	6	7.13	60.6	8.19
64	"	"	9.39	49.6	12.36	64	"	"	12.13	58.0	14.29
58	"	"	18.91	50.4	24.53	58	"	"	25.19	50.4	32.69
52	"	"				52	"	"			

DSR-PAV						BBR-PAV			DT-PAV		
Temp, C	Plate Diam., mm	Strain, %	G^*, MPa	Phase angle δ	$G^*\sin\delta$ MPa	Temp, C	S(t), MPa	m	Temp, C	Avg. Failure Strain, %	Avg. Failure Stress, Pa
25	8	1				-10	44	0.36			
22	"	"	2.03	40.6	1.32	-20	152	0.30			
19	"	"	4.15	38.9	2.61						
16	"	"	5.46	37.5	3.32						

1. Original: Tmax
   Temperature at which $G^*/\sin\delta$ = 1.0 KPa 90.2

2. RTFOT: Tmax
   Temperature at which $G^*/\sin\delta$ = 2.2 KPa 81.0

3. DSR-PAV: Tint
   Temperature at which $G^*(\sin\delta)$ = 5.0 KPa 13.8

4. BBR-PAV: Tmin
   Temperature at which S(t) = 300 MPa -33.7
   Temperature at which m = 0.30 -20.0

Figure 4. Rheological properties of CRM binder from NDOT Contract #2513, parallel plate system.

Contract #	2513	SHRP PG Grade
Sample ID	PLATE/CUP	
Asphalt Type	ARC	76-28
Mass Loss %	0.4598	
Brookfield Pa*s	NA	
Flash Point, °C	> 230	
Limiting Temp for Tmax, °C	76.9	
Limiting Temp for Tint, °C	11.6	
Limiting Temp for Tmin, °C	-20.0	

DSR- Original

Temp, C	Plate Diam, mm	G*, kPa	Phase angle δ	G*/sinδ kPa
75	25	1.21	82.1	1.22
65	25	3.84	75.3	3.97
60	25	6.57	72.1	6.90
55	25	10.83	69.1	11.60
45	25			

DSR- RTFOT

Temp, C	Plate Diam, mm	G*, kPa	Phase angle δ	G*/sinδ kPa
75	25	2.79	61.7	3.17
65	25	5.64	49.8	7.38
60	25	11.75	44.8	16.68
55	25	21.47	45.8	29.95
45	25			

DSR-PAV

Temp,C	Plate Diam, mm	G* MPa	Phase Angle δ	G*sinδ MPa
45	25			
40	8	0.32	44.3	0.22
25	8	2.01	39.3	1.27
10	8	11.09	31.2	5.74

1. Original : Tmax is temp at which G*/sinδ = 1.0 kPa 76.9

2. RTFOT : Tmax is temp at which G*/sinδ = 2.2 kPa 77.4

3. PAV : Tint is temp at which G*(sinδ) = 5.0 MPa 11.6

4. BBR - PAV : temp at which S(t) = 300 MPa -33.7
temp at which m = 0.30 -20.0

Figure 5. Rheological properties of CRM binder from NDOT Contract #2513, plate and cup system.

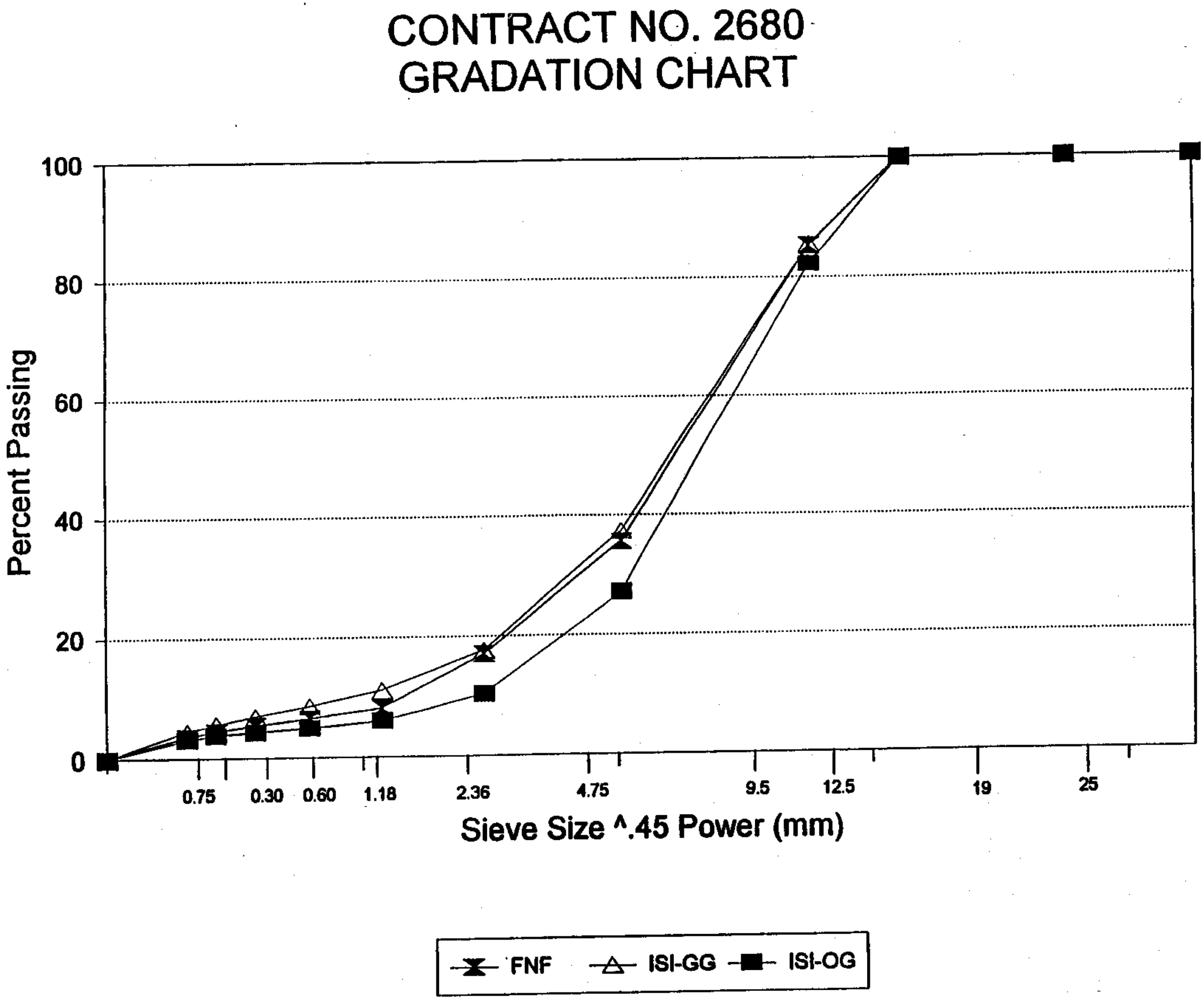

Figure 6 - Gradation curves for the mixtures on contract #2680.

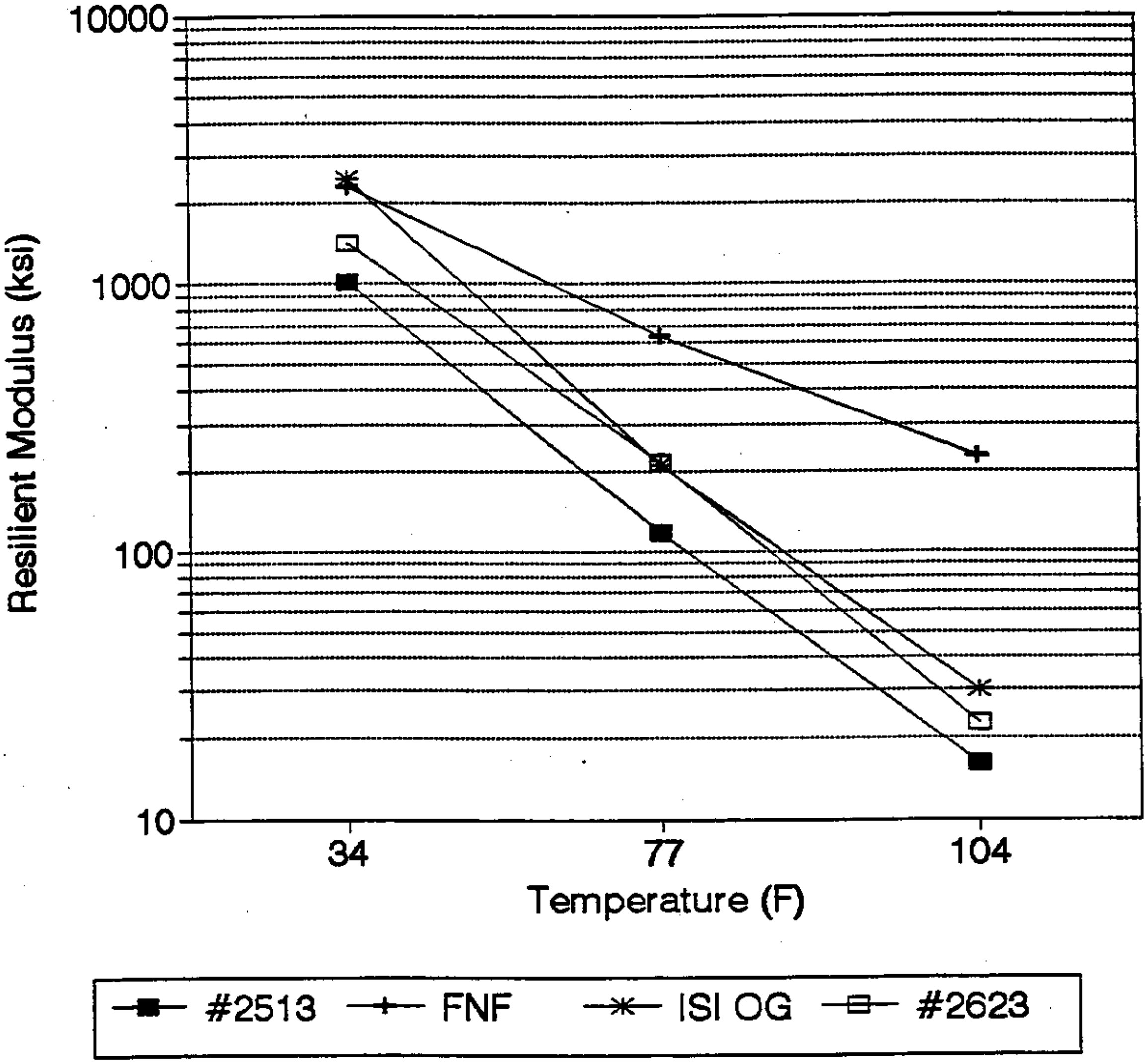

Figure 8 - Temperature susceptibility of the FMLC mixtures.

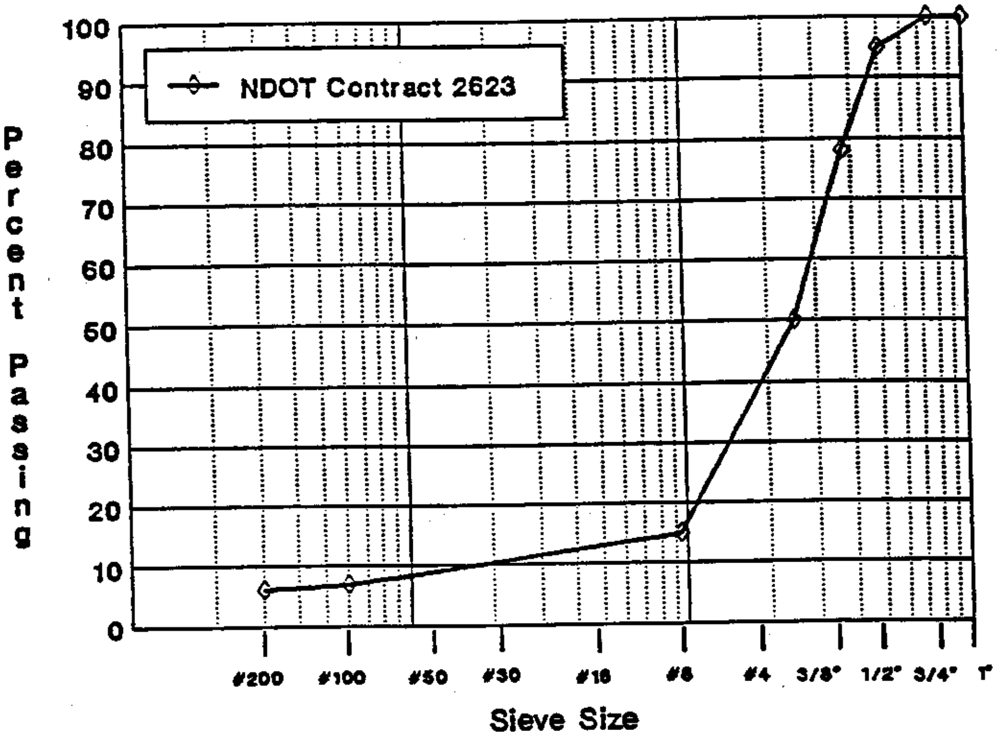

Figure 7 - Aggregate gradation for NDOT contract #2623

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