Final Report
Research Project 930 - 537

# DEVELOPMENT OF A NON-SOLVENT BASED TEST METHOD FOR EVALUATING RECLAIMED ASPHALT PAVEMENT MIXES

*Prepared by*

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Sponsored by
Alabama Department of Transportation
Montgomery, AL

Sept. 26, 2004

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*DISCLAIMER*

## EXECUTIVE SUMMARY

The percent of reclaimed asphalt pavement (RAP) used in hot mix asphalt (HMA) is currently established either by arbitrarily setting maximum percent limits, or alternatively, by evaluating both the virgin and recovered binder properties. The first approach is based on engineering judgment and historical experience but is not quantitative. The second assumes that there is a linear change in binder properties between 0% and 100% RAP. It also consumes extensive amounts of time and solvents in the process of obtaining and testing the binder properties. The purpose of this research program is to develop a fundamentally sound, easily implemented non-solvent based test method for assessing performance-based binder properties using standard gyratory-compacted asphalt concrete mix samples.

Indirect tensile creep testing, such as that used for assessing thermal cracking potential, uses a complicated instrumentation and testing procedure to collect data only to mathematically convert it to stress relaxation modulus so that binder-dominated mix properties can be evaluated. This project developed a quick and simple stress relaxation test method that can be used directly to determine changes in the mix binder modulus and binder relaxation characteristics due to changes in either the PG binder grade or the percent of RAP. Testing uses standard gyratory samples (no trimming needed), two sets of mixes (one with and one without RAP), a controlled near-ambient test temperature (e.g., 25°C), a simple load frame with electronic load cell (no other sensors needed), and either a digital caliper or displacement sensor for confirming the vertical strain. Only 5 minutes is needed to test each compacted HMA sample.

Load and strain information with time is used to calculate the change in the stress relaxation modulus with time. A power law model is then fit through the data. The intercept in the model is the initial stress relaxation modulus and the exponent is a function of how fast the binder relaxes after the sample is strained. The exponent is referred to as the curvature coefficient in this study. Initial results showed that this test method can be used to:

- Assess RAP binder properties and monitor the consistency of the binder properties in the RAP stockpile.
- Estimate the percent RAP in a given mix.
- Determine when the grade of virgin asphalt needs to be lowered to compensate for the contribution of the RAP binder to the mix binder properties.

- Monitor the consistency of the binder properties of the HMA, with or without RAP, during HMA production and paving operations (i.e., quality control (QC) testing).

The following sections briefly outline the steps needed to obtain the desired information.

**Assessing and Monitoring RAP Stockpile Binder Properties**

A representative sample of RAP is obtained from the stockpile(s) to be used. This material is mixed and split down into a 4,500 gram sample size; this sample is then placed in a 160°C oven for 4 hours. A gyratory compactor, 100 gyrations, is used to compact a 100% RAP sample. A set of three samples should be prepared and tested. The stress relaxation test is conducted on the cooled sample. The stress relaxation modulus is the maximum value that will be obtained for a mix containing 50% or more of this RAP. The curvature coefficient represents the most decrease that can be expected in the binder's ability to relax with time (i.e., the most potential for cracking) when using 50% or more of the RAP.

Consistency of the RAP stockpile binder properties can be periodically assessed by following this sample preparation method and testing program

**Estimate the Percent RAP in a Given Mix**

Estimating the percent RAP in a given mix requires mixing and compacting one set of three samples using the target gradation, but without RAP, and the virgin aggregate and asphalt to be used in the RAP mix. A second set of three 50% RAP samples is prepared, and the stress relaxation modulus and curvature coefficient are determined. The change in modulus per percent change in RAP content, $b_{srm}$, is calculated by:

$$b_{srm} = (M_{SR50} - M_{SR0}) / 50$$

where:

$M_{SR50}$ = stress relaxation modulus with 50% RAP

$M_{SR0}$ = stress relaxation modulus with no RAP

The stress relaxation modulus for a mix with an unknown percent RAP $M_{SR??}$,, and estimate the percent RAP in the mix based on the stress relaxation modulus, $\%RAP_{srm}$, can then be calculated by:

$$\%RAP_{srm} = (M_{SR??} - M_{SR0}) / b_{srm}$$

The same process using the curvature coefficient, C, is repeated:

$$b_{cc} = (C_{50} - C_0)/50$$

where

$b_{cc}$ = change in curvature coefficient with a percent change in RAP

$C_{50}$ = curvature coefficient for 50% RAP mix

$C_o$ = curvature coefficient for 0% RAP mix

The percent RAP in the mix can be estimated by:

$$\%RAP_{cc} = (C_{??} - C_0)/b_{cc}$$

where

$\%RAP_{cc}$ = estimated % RAP from curvature coefficient data

The estimate of RAP in the mix is the average of $\%RAP_{srm}$ and $\%RAP_{cc}$.

**Selection of Virgin Asphalt PG Grade**

Based on the results from this study, a decrease in the virgin binder grade should be considered when there is more than a 75% increase in the stress relaxation modulus and a 20% or more decrease in the curvature coefficient.

**Quality Control Testing**

Daily HMA production samples obtained from East Alabama Paving showed that this test method can be used to construct control charts for stress relaxation modulus and the curvature coefficient. The coefficient of variation for each of these parameters is 16%, and 7%, respectively. Samples compacted at the field laboratory for volumetric testing can be used for this test, resulting in only about 5 more minutes of technician time per test per sample. The sample test temperature can be stabilized by placing the compacted sample in a zip lock bag, then stored in the temperature controlled water bath used for compacted bulk specific gravity testing.

**Recommendations**

The work for this study focus on the development of the test method and a preliminary evaluation of its applicability for use as a quick field test. A full field calibration and verification of the test method needs to be completed prior to consideration for adoption as either a mix design tool or a quality control test. Also, adaptation of existing Marshall stability load frames for conducting this test needs to refined and developed into a standard test method in AASHTO format. This will minimize any capital equipment costs for both agency and the contractor.

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## INTRODUCTION

Approximately 80% of asphalt pavement removed during highway rehabilitation or reconstruction is recycled back into new hot mix asphalt (HMA), disposing of only 20% through normal waste stream channels (FHWA, 1993). Not only does recycling asphalt concrete pavement minimize waste but also several states have shown it to be cost effective. For example, the Florida Department of Transportation reported savings of between 15 and 30% as a result of using RAP in fresh mix (Page, 1988). As of 1995, 32 states allowed a maximum of 50% reclaimed asphalt pavement (RAP) to be mixed with virgin materials to produce fresh HMA (Kandhal and Mallik, 1997).

Limits are usually set because of the nation-wide implementation of the new Superpave binder specifications (The Asphalt Institute, 1996). These specifications require binder in the mixture have rheological properties which will optimize long term pavement performance for a given set of environmental and traffic conditions. When RAP is added, the residual aged binder in the RAP commingles to some degree with the virgin binder. This produces a composite effective binder system with unknown material properties and hence unpredictable pavement performance. When the percentages of RAP in the mix are greater than 25%, the Federal Highway Administration (FHWA) recommends that the binder be extracted from the RAP and binder properties be determined (Bukowski, 1997). This information is used along with the properties for a range of neat asphalt cements to determine how to adjust PG specification requirements for the neat asphalt. Alabama currently allows 15% RAP so that this recycled material can be used without having to employ solvent-based extraction and recovery methods to evaluate the mixes. While this approach helps deal with hazardous waste disposal problems associated with the solvents, it does not address the need for a quantitative means of assessing if, or when, decreasing the virgin PG grade is desirable. Also, there is no current test method that can be used during construction for assessing the consistency of RAP mix material properties.

The purpose of this research program is to develop a fundamentally sound, easily implemented non-solvent based test method for assessing performance-based binder properties using standard gyratory-compacted asphalt concrete samples. This test method will also have the potential for being used for process control.

## BACKGROUND

The primary hypothesis for this research is that the tensile stiffness of mixtures within the linear viscoelastic range is primarily an indication of binder properties. Changes in mixture stiffness due to the inclusion of RAP in the mixture should therefore reflect the contribution of the RAP binder to effective (combination of both neat and RAP binder) binder content. This section of the paper is separated in two parts. The first part gives a brief overview of the use of RAP in HMA and the second parts give a short description of indirect tension testing as used to represent predominately binder-related performance properties (i.e., thermal cracking).

### *RAP in HMA*

The method used to add RAP in a new mixture depends on the quantity of RAP added. According to McDaniel et al. (2000), if less than 15%of RAP is used, there is no need to change the binder grade. If between 15 and 25% of RAP is used, simply decreased the virgin binder grade of one grade (6°C) on both ends. If more than 25% of RAP is used, then both the upper and lower PG temperature needs to be determined using blending charts. Table 1 shows the recommendations for the selection of the virgin binder grade based upon the grading of the recovered RAP binder properties.

**Table 1. Selection of virgin binder PG for different RAP binder properties (McDaniel et al, 2000).**

| Selection of Virgin Binder | RAP Percentage | | |
|---|---|---|---|
| | Recovered RAP Grade | | |
| Recommended Virgin Asphalt Binder Grade | PG xx-22 or lower | PG xx-16 | PG xx-10 or higher |
| No change in binder selection | < 20% | < 15% | < 10% |
| Select virgin binder one grade softer than normal (ex.: PG58-28 instead of PG64-22) | 20-30% | 15-25% | 10-15% |
| Follow recommendations from blending charts | >30% | >25% | >15% |

### *Indirect Tension (IDT) Testing*

IDT tests are simple to perform, however one needs to estimate or to determine Poisson's ratio in order to calculate a precise modulus (Roque and Buttlar, 1992). In an IDT test, the horizontal and vertical strain can be measured externally or internally. When the vertical displacement is measured by an LVDT on the ram, it is called external. The horizontal strain is then calculated using an estimated Poisson's ratio. An internal measurement uses strain gages glued to the center of one or both flat faces of the sample. The main disadvantage of using external measurement is that the strain near the point of contact on the specimen will be taken into account in the calculation even if it is not representative of the failure plane (Roque and Buttlar, 1992). External measurement will also measure any rocking of the samples. Internal measurement will measure only what happens in the center part, but the strain gage lengths are so small that any segregation in that section of the sample will results in erroneous results (Wallace and Monismith, 1980). Poisson's ratio is usually assumed to be 0.35, but this change depending on the mix, test temperature, and loading frequency used for the test (Tayebali et al, 1995). Assumptions of Poisson's ratio are commonly made to simplify the required equipment, sample set-up, and limit testing variability. It is generally accepted in HMA analysis that Poisson's ratio is assumed to be 0.2 at temperatures lower than 10°C, 0.35 between 10 and 30 °C, and 0.5 above 30 °C.

The IDT creep test used to estimate thermal cracking potential by constructing the master creep compliance curve, which is then transformed into the master stress relaxation modulus curve by a Laplace transformation. This transformation is used to compute the thermal stresses in the pavement according to a constitutive equation (Lytton et al, 1993). The creep test was preferred to the relaxation test because, according to Lytton et al. (1993), it is easier to conduct and more reliable than relaxation test.

## RESEARCH PROGRAM

### Objectives

The main objectives of this research were to:

- Develop and validate a simple, quick indirect tension stress relaxation test for assessing binder properties using compacted HMA samples.
- Evaluate the effect of adding RAP to HMA mixtures on relaxation modulus and rate of relaxation.
- Provide a preliminary evaluation of the test method in process control of HMA mix properties.

### *Scope*

This research is based on the hypothesis that if the indirect tensile stress relaxation test represents primarily binder properties, then there should be a good correlation between binder and mix stress relaxation modulus. Additionally, there should be a limited influence of gradation on the mix stress relaxation. Stress relaxation modulus master curves were constructed for each of two binders (PG 67-22, PG 76-22) and each of four mixes (fine with PG 67-22; coarse with PG 67-22; fine with PG 76-22; coarse with PG 76-22).

A second and larger experiment was designed to determine if the stress relaxation test results were sensitive to changes in the mix binder, such as those anticipated with increasing percentages of RAP. A Superpave gyratory compactor was used to prepare samples at mix design air voids (i.e., 4%) for both binders, both gradations (fine, coarse), two aggregate types (granite, gravel), and two sources of RAP (Alabama, Minnesota) at one of five concentrations (0, 15, 25, 50, and 100%). The 100% RAP mixtures were used as a mixture representation of the recovered binder properties used in the blending charts recommended by McDaniel et al. (2000). Stress relaxation testing was conducted at two temperatures (5 and 22°C). A power law model was fit through the data for each test and the intercept (zero-time stress relaxation modulus) and exponent (a function of the relaxation time) were calculated. Statistical differences in these two parameters were used to determine the influence of various percentages of RAP on binder properties.

A limited field application of the test method was conducted using one week of plant produced HMA to establish the repeatability of the test using actual field mixes.

## MATERIALS

### *Asphalt Binder*

Two binders were selected as those commonly used in Alabama. They are a PG 76-22 (polymer-modified) and a PG 67-22 (neat binder). Table 2 shows the standard PG binder specification properties for both of these asphalt binders. Figure 1 shows master curves constructed from dynamic shear rheometer (DSR) results for both of these binders (22°C reference temperature). Note that there is little difference in the binder modulus at the colder temperatures (i.e., higher frequencies). Only at the warmer temperatures is there any appreciable difference in the modulus. Given these data, little difference is expected in the mix modulus when tested at the colder 5°C temperature, and only a slight increase in modulus for the PG 76-22 at the 22C temperature

**Table 2. Virgin and RAP binder properties.**

| Properties | | PG 67-22 | PG 76-22 | Recovered Minnesota RAP Binder | Recovered Alabama RAP Binder |
|---|---|---|---|---|---|
| G* / sin δ, kPa (RTFOT) | 64C | 4.228 | - | - | - |
| | 76C | - | 3.558 | - | - |
| | 88C | - | - | 4.65 | 2.613 |
| Bending Beam Stiffness, S, MPa | 0C | - | - | 101 | - |
| | -12C | 179 | 127 | - | 169 |
| Bending Beam Slope, m | 0C | - | - | 0.315 | - |
| | -6C | - | - | - | 0.348 |
| | -12C | 0.323 | 0.363 | - | - |
| | PG Grading | PG 67-22 | PG 76-22 | PG 88-10 | PG 88-16 |

NA = not available

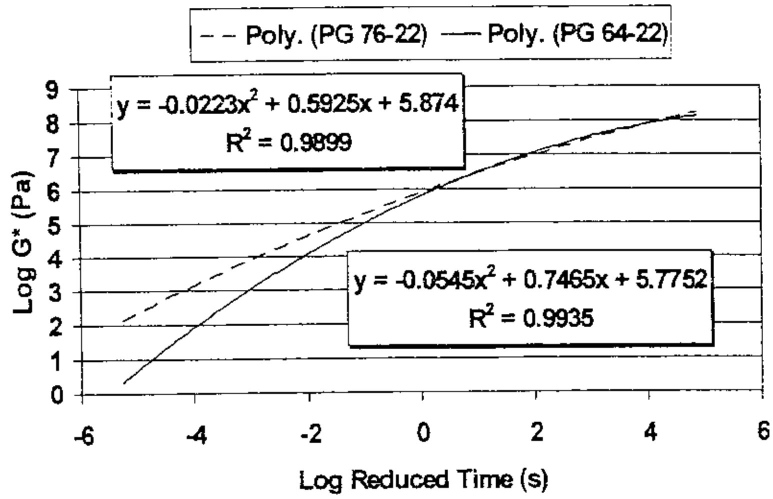



**Figure 1. Binder G* master curves at 22°C.**

*Aggregates*

A granite and a partially crushed river gravel were selected to provide a range of aggregate shape and level of water absorption (Table 3). Each of these aggregate stockpiles were sieved into individual fractions, and then recombined to produce one of two gradations (Table 4).

**Table 3. Aggregate properties.**

| Properties | Granite | Gravel | MN RAP* | AL RAP* |
|---|---|---|---|---|
| Bulk specific gravity | 2.658 | 2.598 | 2.126 | 2.340 |
| Bulk specific gravity, SSD | 2.676 | 2.618 | 2.161 | 2.428 |
| Apparent specific gravity | 2.707 | 2.652 | 2.204 | 2.470 |
| Water absorption, % | 0.7 | 1.2 | 1.7 | 1.2 |
| % Crushed Faces | 100% | 100% | 100% | 100% |
| Flat and elongated, % (5:1) | 0% | 0% | 0% | 0% |
| % Asphalt Binder | NA | NA | 5.6% | 4.3% |

NA = not applicable
* Values obtained on the RAP aggregate after solvent extraction.

**Table 4. Gradations used in this study.**

| Gradation | Cumulative Percent Passing, % | | | | | |
|---|---|---|---|---|---|---|
| Sieve Size | Coarse gradation | Coarse 50% AL RAP | Coarse 50% MN RAP | Fine gradation | MN RAP | AL RAP |
| 19.0 mm | 100 | 100 | 100 | 100 | 100 | 100 |
| 12.5 mm | 95 | 92 | 98 | 95 | 97 | 84 |
| 9.5 mm | 85 | 82 | 92 | 85 | 92 | 76 |
| 4.75 mm | 50 | 48 | 60 | 69 | 79 | 50 |
| 2.36 mm | 31 | 31 | 40 | 55 | 66 | 32 |
| 1.18 mm | 20 | 20 | 28 | 40 | 51 | 25 |
| 0.6 mm | 15 | 15 | 19 | 30 | 33 | 19 |
| 0.3 mm | 11 | 11 | 10 | 20 | 15 | 14 |
| 0.15 mm | 9 | 8 | 6 | 9 | 7 | 9 |
| 0.075 mm | 5 | 5 | 4 | 5 | 4 | 6 |

*Reclaimed Asphalt Pavement (RAP)*

Two different sources of RAP were used in order to evaluate the sensitivity of the test method to a range of RAP properties. Alabama RAP was selected to represent a region of the country that typically uses a PG 67-22 grade and Minnesota RAP to represent a softer binder (e.g., PG 58-22). The Alabama RAP source was visually more variable than the Minnesota RAP source. In order to minimize the non-uniformity of the RAP, three bags of RAP were mixed together before the RAP was sampled.

Table 2 shows binder properties for RAP binder extracted by ASTM D2172 (centrifuge) and recovered with a Rotavapor distillation process. The recovered AL RAP binder was graded as a PG 88-16; the Minnesota RAP was graded as a PG 88-10. The lower cold temperature value for the AL RAP is a function of the variability of this RAP source. In reality, the AL RAP grading varied between a PG 88-16 and a PG 88-10 classification.

Table 3 presents the aggregates properties of the RAP; Table 4 presents the after-extraction RAP aggregate gradations. Aggregate blends of each aggregate source were prepared at each of three concentrations of RAP (15, 25 and 50%). Mixtures without RAP were used as the control mixtures (i.e., 0 % RAP).

*HMA Mixtures*

HMA samples, with and without RAP, were compacted with a Superpave gyratory compactor following the ASTM D4013 standard using 100 gyrations. All specimens have a diameter of 150 mm and a height of around 115mm. Three replicates of each mix were prepared and tested.

The 100% RAP samples were prepared by heating the RAP at 160°C for four hours, then compacting the RAP mix with 100 gyrations.

## INITIAL TESTING

### Binder Stress Relaxation

The relaxation modulus should only be calculated from the moment at which the constant strain is achieved (Chen 2000). About 0.35 seconds was needed, at most, to reach a constant strain for the DSR used in this study (Figure 2). Therefore, 0.35 seconds was selected as the starting point for the calculation of the stress relaxation modulus modeling for the binder testing. The strain was maintained for a maximum of two minutes; preliminary testing indicates that the stress relaxation will be substantially achieved within that time, regardless of temperature. Measurable loads were not obtainable at test times longer than 2 minutes.

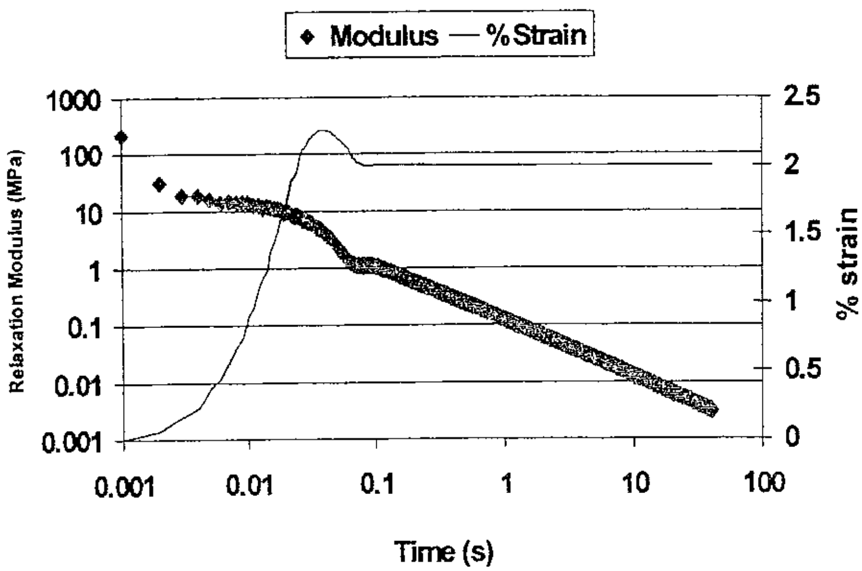



**Figure 2. Example of time needed to reach constant strain for binder relaxation test (PG67-22 at 22°C).**

## HMA Stress Relaxation

An Instron 8501 was used to conduct the IDT stress relaxation test on HMA specimens. The strain was set using the ram control displacement sensor, and a 22KN load cell was used to measure stress relaxation every 0.1 seconds over a time interval of up to two minutes. Eventually, the test time was limited to 45 seconds because only minimally measurable decreasing changes in stress, regardless of temperature, are obtained after this time.

Originally, the jig used for indirect tensile strength testing when evaluating the moisture sensitivity of HMA mixtures (ASTM D4867) was used. However, the posts appeared to generate some friction so the first modification was to refit the load frame so that the upper and lower platens were vertically aligned but not mounted on guide posts.

The test method development included defining a range of strain levels within the linear viscoelastic range, evaluation of the time needed to achieve a constant strain level, evaluation of the time needed for data collection, and developing an analysis approach for estimating initial modulus and the rate of stress relaxation.

### *HMA Stress Relaxation Method Development*

As with the binder experiment, it was necessary to establish the limit of the linear viscoelastic range for the different HMA mixtures for different test temperatures. Tests were performed at different strain levels and the relaxation modulus was calculated. The limit was considered attained when the relaxation modulus has decreased of 10% compared to the modulus measured at the lowest strain level.

The ramp speed had a large influence on the precision of the level of strain achieved. The faster the ram moved, the less control there was on the level of strain. Since in a relaxation experiment it is desirable to reach a known, a ram speed of 100 mm/min was chosen as being the best compromise between achieving a constant strain as fast as possible without over-shooting the target strain.

The drift in the measured strain that could be attributed to the equipment set up was also assessed by evaluating the stress relaxation data obtained when testing a steel cylinder. Steel, under the low level of stress used in this experiment, should not show any relaxation since it is a perfectly elastic material. Figure 3 shows that it took less than 3 seconds to reach a modulus that is constant for the steel cylinder; a difference of 1% or less was considered as not significant.

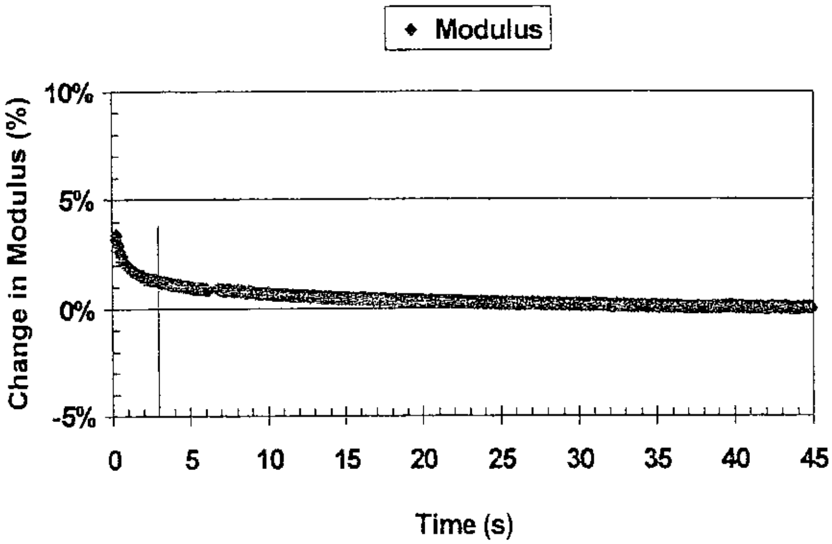



**Figure 3. Setup time with steel cylinder in HMA stress relaxation equipment.**

*Analysis approach*

The first step in the analysis was the conversion of displacement of the ram to an estimate of the horizontal strain. The vertical displacement of the ram was divided by the diameter of the sample to calculate the vertical strain. The horizontal strain was then estimated with assumed Poisson's ratio according to the temperature; 0.35 for 22°C and 0.2 for 5°C. Figure 4 shows a typical stress relaxation modulus curve with time. A power curve was, in every case, the best fit curve with an $R^2$ of 0.9 or above, regardless of the test temperature.

As noted in the Background section, previous researchers considered data at very early times during a stress relaxation test to have a significant influence on the test results. The research for this project shows that as long as there is sufficient data to capture the stress relaxation characteristics of the mix, then the choice of the starting point in the data acquisition does not make a significant difference in the data. Figure 4 shows two power curves, each using data at different starting points (2 and 5 seconds). The resulting power law equations have a difference of less than 1% in either the intercepts or exponents.

Two key parameters, the intercept and the exponent, can be used to estimate the stress relaxation characteristics of the mix. The intercept represent the maximum relaxation modulus at a time of zero. The exponent, which is function of the degree of curvature, represents the ability of the mix binder to relax with time. The higher the value of the exponent, the more the sample relaxes in a given period of time.

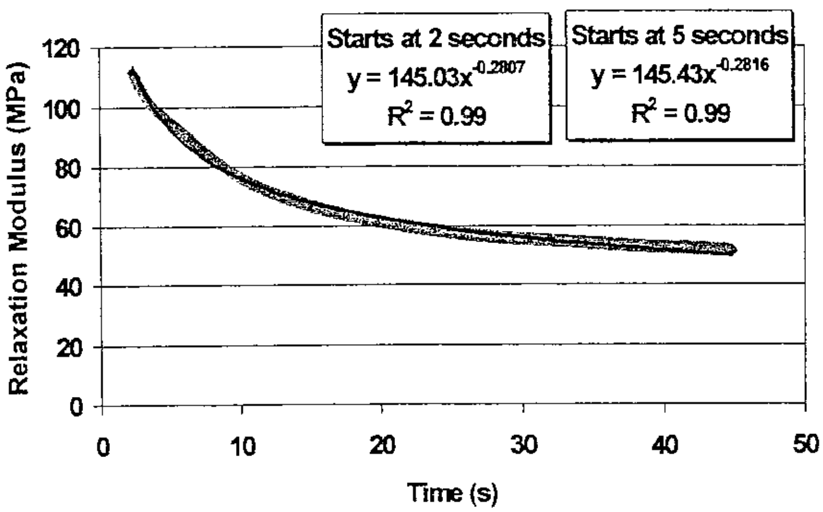



**Figure 4. Typical relaxation curve and best fit curves.**

## RESULTS AND DISCUSSION

### Binder and Mix Stress Relaxation Comparison

Figure 5 compares the binder and mix stress relaxation modulus for both the fine and coarse gradations using the gravel mixes (no RAP). Although not shown, the granite mixes showed similar trends. This figure indicates that there is a good relation between the binder and HMA stress relaxation modulus, however the HMA stress relaxation modulus is consistently stiffer. The inclusion of solid particles in any liquid increases the viscosity of the liquid, therefore the higher stiffness for the mixes is assumed to be a function of the percentage of fines that is incorporated into the combined binder-aggregate film (Buttlar, et al 2001). Figure 5a shows that there is little difference in the slope, intercept, or $R^2$ due to gradation differences when the PG

67-22 (unmodified) asphalt binder was used. Figure 5b shows that when the polymer modified PG 76-22 was used, the stress relaxation modulus almost doubled when the fine gradation was used.

Although the stress relaxation modulus is influenced by mix variables such as the binder grade and the fineness of the gradation, changes in the HMA mix stress relaxation modulus is well correlated with binder stress relaxation modulus. Therefore, it can be stated that a change in the HMA stress relaxation behavior will indicate a corresponding change in the binder stress relaxation modulus.

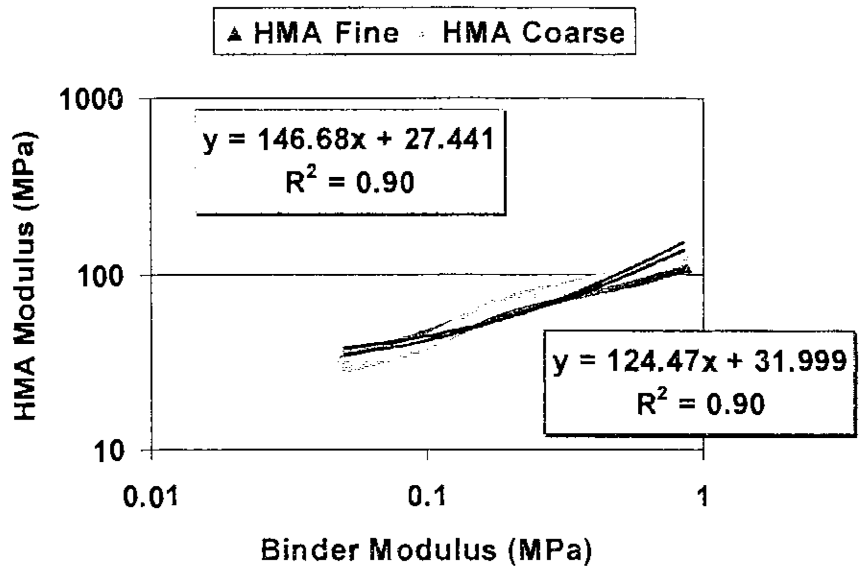
## Influence of RAP on HMA Stress Relaxation

The first statistical evaluation calculated a Pearson's correlation matrix to determine if there were any well-correlated single variable comparisons. The analysis showed there were only two fair correlations found for each of the two test temperatures:

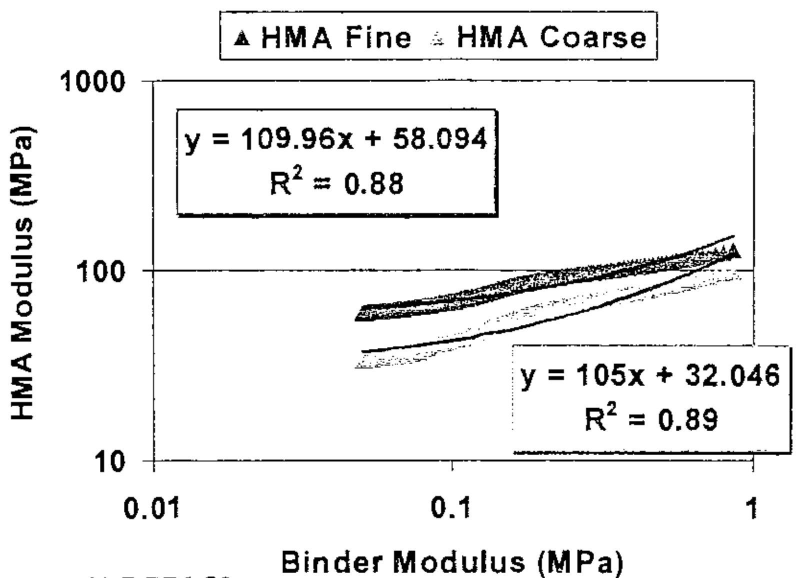
- Modulus increased with the addition of RAP (R=0.59 at 5°C and 0.65 at 22°C).
- Curvature coefficient decreased with the addition of RAP (R=0.76 at 5°C and 0.66 at 22°C).

These correlations are as expected. That is, the stress relaxation modulus should increase as more RAP binder is incorporated into the HMA effective binder. Also, as more aged (RAP) binder is included in the overall HMA binder properties, the ability of the mix to deform with time (i.e., relax) should be reduced.

The next step in the statistical analysis was to do an analysis of variance (ANOVA) followed by the Duncan multiple range test. With the Duncan analysis, it is possible to separate the data into groups that have significant difference in their means. The effect of PG grade, percentage of RAP, gradation, aggregate source, and RAP source on the modulus and the curvature coefficient were analyzed. No statistical differences were found for any of these variables. This is in agreement with the preliminary findings that showed minimal influence of the gradation. As for the aggregates sources, it was also expected since the IDT stress relaxation test is primarily an indicator of the binder properties. Finally, the RAP source did not make any statistical difference because there was little difference between the PG grades of both RAP. It should be noted that the high variability in the Alabama RAP may have produced enough variability in the mix testing to hide any statistical difference that could have been seen otherwise.




a) PG 67-22




b) PG76-22

**Figure 5. Relation between Binder relaxation modulus and HMA**

*Effect of PG Grade*

The effect of the PG grade on the stress relaxation modulus and the curvature coefficient used only data from the specimens without RAP (Table 5). The Duncan multiple means test shows that neither the average modulus nor average curvature coefficient were significantly different at either of the two test temperatures used in this study. However, the trends in both terms are consistent with expectations. The modulus increases with decreasing temperature, with little difference between the binders at the cold temperatures and a slight, but not statistically different, change at the warmer temperature. This agrees with the differences seen in the binder master curves (Figure 1). The curvature coefficient is lower at the colder temperature, and dependent upon the binder grade at the warmer temperature. The curvature coefficient is less for the polymer modified PG 76-22 than for the PG 64-22 at 22C, indicating that the polymer modified asphalt will take longer to relax at the warmer temperature.

*Effect of Percent RAP*

At 5°C, adding any percentage of RAP at least doubled the stress relaxation modulus; the modulus is similar for mixes with 15, 25, and 50% RAP (Table 6). The curvature coefficient was more sensitive to the percentage of RAP as is seen by the continually decreasing ability of the HMA to dissipate stress over time with an increasing percentage of RAP. Both the no RAP and 15% RAP mixtures have statistically similar curvature coefficients. At least 25% RAP is needed to produce a statistically significant decrease. The curvature coefficient is similar for both the 50 and 100% RAP mixtures, and both are significantly different from the no RAP option. All of the test results shown in Table 7 were used for this analysis.

At 22°C, the modulus again more than doubles with the inclusion of 15% RAP in the mixes. There is a statistically significant increase in the modulus when using as little as 15% RAP at this temperature. There is no difference between mixes with either 15 or 25% RAP. Mixes with either 50 or 100% RAP have similar modulus and both are significantly higher than mixes with lower percentages of RAP. These same trends are seen for the curvature coefficient at this temperature.

**Table 5. Influence of the PG grade on stress relaxation modulus and curvature coefficient.**

| | Temp. (°C) | Duncan Grouping | Mean | n | Binder Grade |
|---|---|---|---|---|---|
| Modulus (MPa) | 5 | A | 220.6 | 24 | PG 67-22 |
| | | | 206.6 | 24 | PG 76-22 |
| | 22 | A | 112.7 | 24 | PG 67-22 |
| | | | 103.3 | 24 | PG 76-22 |
| Curvature Coefficient | 5 | A | 0.123 | 24 | PG 67-22 |
| | | | 0.116 | 24 | PG 76-22 |
| | 22 | A | 0.371 | 24 | PG 67-22 |
| | | B | 0.267 | 24 | PG 76-22 |

The results shown in Table 5 indicate that monitoring both the stress relaxation modulus and curvature coefficient can be used to differentiate between mixes prepared with a PG 67-22 and a PG 76-22. Therefore, this test has the potential for being used to determine if the desired binder grade was used in the production of an HMA mix.

**Table 6. Influence of the percentage of RAP on the modulus and the curvature coefficient**

| | Temp. (°C) | Duncan Grouping | | %RAP | Mean | n |
|---|---|---|---|---|---|---|
| **Modulus (MPa)** | **5** | | **A** | 0 | 213.6 | 48 |
| | | | **B** | 15 | 507.9 | 48 |
| | | | | 25 | 513.1 | 48 |
| | | | | 50 | 517.1 | 48 |
| | | | | 100 | 443.6 | 11 |
| | **22** | | **A** | 0 | 108.0 | 48 |
| | | | **C** | 15 | 190.0 | 48 |
| | | **B** | | 25 | 204.9 | 48 |
| | | | **D** | 50 | 237.6 | 48 |
| | | | | 100 | 258.8 | 11 |
| **Curvature coefficient** | **5** | | **A** | 0 | 0.318 | 48 |
| | | **B** | | 15 | 0.281 | 48 |
| | | | | 25 | 0.242 | 48 |
| | | | **C** | 50 | 0.148 | 48 |
| | | | | 100 | 0.153 | 11 |
| | **22** | | **A** | 0 | 0.119 | 48 |
| | | | **B** | 15 | 0.097 | 48 |
| | | | | 25 | 0.082 | 48 |
| | | | **C** | 50 | 0.051 | 48 |
| | | | | 100 | 0.057 | 11 |

**Evaluation of Current Blending Chart Practices for Estimating the Percent of RAP or Grade of Virgin Binder**

The current practice for mixing RAP in a new mix uses blending charts. With blending charts, it is assumed that there is a linear relation between the amount of RAP and the binder properties of the new mix. A linear relation between the amount of RAP and the relaxation characteristics is shown on Figure 6. When mixtures with a range of RAP from 0 to 50% are considered, the assumption of linearity between modulus and the percent of RAP is valid. Figure 6 shows only the relation for mix containing Minnesota RAP and PG 67-22 binder tested at 22°C; the other mixes, while not shown, have similar relationships.

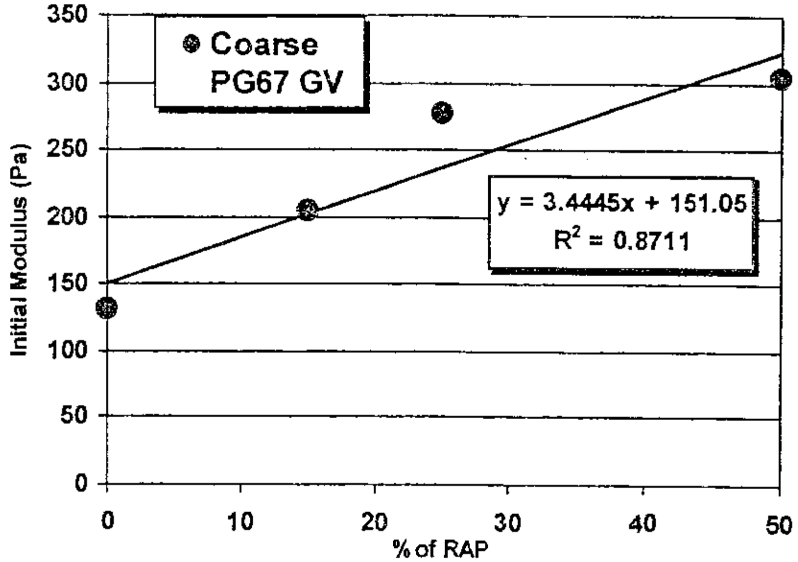



**Figure 6. Linear relationship between initial modulus and percent of RAP (PG 67-22, 22°C).**

Stress relaxation modulus results from the 100% RAP mix samples were used to represent the 100% recovered binder in the blending charts. There is little difference between the initial stress relaxation modulus for either the 50 or 100% RAP mixes. This means that there is a non-linear relationship between modulus and the percent of RAP when the full range of percent RAP mixes are considered (Figure 7a). Figure 7b shows that the curvature coefficient also has a non-linear relationship with the percent RAP. These results show that at 50% RAP, the mix binder is predominately influenced by the RAP binder and not the virgin binder.

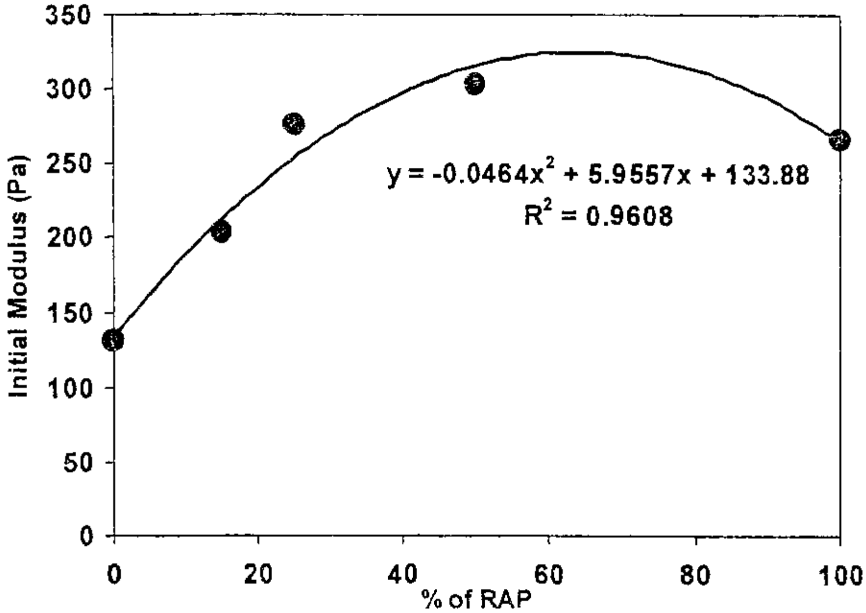



**Figure 7a. Non-linear relation between percent of RAP and modulus (MN RAP, Gravel, PG 67-22, 22°C )**

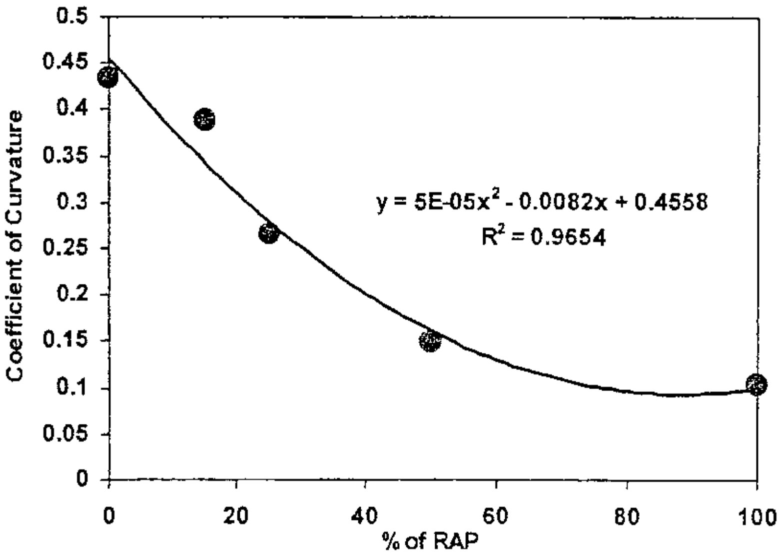



**Figure 7b. Non-linear relation between percent of RAP and modulus (MN RAP, Gravel, PG 67-22, 22°C )**

## TABLE 7a
## RELAXATION CHARACTERISTICS (MODULUS / CURVATURE COEFFICIENT) FOR HMA MIXES AT 5C

| Temp. °C | Asphalt | Source of RAP | % of RAP | Granite | | | | Gravel | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Fine Grad. | | Coarse Grad. | | Fine Grad. | | Coarse Grad. | |
| | | | | Modulus (MPa) | Curvature coefficient | Modulus (MPa) | Curvature coefficient | Modulus (MPa) | Curvature coefficient | Modulus (MPa) | Curvature coefficient |
| 5 | PG 67-22 | None | None | 255 | 0.135 | 211 | 0.111 | 235 | 0.117 | 237 | 0.144 |
| | | AL RAP | 15% | 525 | 0.078 | 528 | 0.071 | 554 | 0.102 | 632 | 0.099 |
| | | | 25% | 564 | 0.068 | 487 | 0.087 | 527 | 0.094 | 604 | 0.066 |
| | | | 50% | 468 | 0.084 | 606 | 0.067 | 428 | 0.081 | 614 | 0.062 |
| | | | 100% | 595 | 0.036 | 575 | 0.036 | 595 | 0.036 | 575 | 0.036 |
| | | MN RAP | 15% | 516 | 0.126 | 521 | 0.100 | 557 | 0.108 | 499 | 0.138 |
| | | | 25% | 486 | 0.080 | 401 | 0.096 | 523 | 0.064 | 494 | 0.077 |
| | | | 50% | 475 | 0.042 | 375 | 0.060 | 521 | 0.047 | 504 | 0.036 |
| | | | 100% | 625 | 0.018 | 625 | 0.018 | 625 | 0.018 | 625 | 0.018 |
| | PG 76-22 | None | None | 224 | 0.116 | 227 | 0.131 | 211 | 0.099 | 210 | 0.117 |
| | | AL RAP | 15% | 413 | 0.071 | 494 | 0.096 | 635 | 0.054 | 617 | 0.094 |
| | | | 25% | 669 | 0.081 | 479 | 0.105 | 498 | 0.059 | 519 | 0.055 |
| | | | 50% | 574 | 0.063 | 629 | 0.064 | 565 | 0.055 | 701 | 0.036 |
| | | | 100% | 595 | 0.036 | 575 | 0.036 | 595 | 0.036 | 575 | 0.036 |
| | | MN RAP | 15% | 357 | 0.135 | 349 | 0.138 | 421 | 0.071 | 507 | 0.073 |
| | | | 25% | 444 | 0.103 | 602 | 0.096 | 472 | 0.078 | 441 | 0.102 |
| | | | 50% | 363 | 0.027 | 316 | 0.034 | 632 | 0.026 | 504 | 0.036 |
| | | | 100% | 625 | 0.018 | 625 | 0.018 | 625 | 0.018 | 625 | 0.018 |

## TABLE 7b
## RELAXATION CHARACTERISTICS (MODULUS / CURVATURE COEFFICIENT) FOR HMA MIXES AT 22C

| Temp. °C | Asphalt | Source of RAP | % of RAP | Granite | | | | Gravel | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Fine Grad. | | Coarse Grad. | | Fine Grad. | | Coarse Grad. | |
| | | | | Modulus (MPa) | Curvature coefficient | Modulus (MPa) | Curvature coefficient | Modulus (MPa) | Curvature coefficient | Modulus (MPa) | Curvature coefficient |
| 22 | PG 67-22 | None | None | 101 | 0.349 | 86 | 0.376 | 120 | 0.334 | 131 | 0.434 |
| | | AL RAP | 15% | 322 | 0.268 | 189 | 0.267 | 139 | 0.318 | 166 | 0.401 |
| | | | 25% | 304 | 0.244 | 246 | 0.256 | 191 | 0.318 | 152 | 0.301 |
| | | | 50% | 231 | 0.253 | 245 | 0.226 | 203 | 0.255 | 163 | 0.318 |
| | | | 100% | 217 | 0.209 | 274 | 0.201 | 217 | 0.209 | 274 | 0.201 |
| | | MN RAP | 15% | 211 | 0.360 | 181 | 0.289 | 219 | 0.325 | 203 | 0.388 |
| | | | 25% | 210 | 0.210 | 175 | 0.249 | 307 | 0.255 | 276 | 0.265 |
| | | | 50% | 257 | 0.068 | 305 | 0.165 | 236 | 0.184 | 303 | 0.148 |
| | | | 100% | 267 | 0.103 | 267 | 0.013 | 267 | 0.103 | 267 | 0.103 |
| | PG 76-22 | None | None | 94 | 0.220 | 79 | 0.268 | 120 | 0.207 | 103 | 0.290 |
| | | AL RAP | 15% | 150 | 0.200 | 180 | 0.226 | 221 | 0.212 | 169 | 0.258 |
| | | | 25% | 173 | 0.199 | 140 | 0.225 | 233 | 0.210 | 208 | 0.235 |
| | | | 50% | 270 | 0.118 | 165 | 0.186 | 253 | 0.136 | 169 | 0.109 |
| | | | 100% | 217 | 0.209 | 274 | 0.201 | 217 | 0.209 | 274 | 0.201 |
| | | MN RAP | 15% | 127 | 0.273 | 116 | 0.233 | 260 | 0.020 | 187 | 0.257 |
| | | | 25% | 194 | 0.266 | 100 | 0.231 | 191 | 0.188 | 176 | 0.219 |
| | | | 50% | 280 | 0.091 | 266 | 0.091 | 237 | 0.050 | 192 | 0.067 |
| | | | 100% | 267 | 0.103 | 267 | 0.103 | 267 | 0.103 | 267 | 0.103 |

## Practical Application of Findings

### *When to Change Virgin PG Binder Grade*

Guidelines for when to reduce the PG grade, shown in Table 1, are based on the grade of the recovered RAP binder (McDaniel, 2000). The AL RAP and MN RAP were graded as PG88-16, and PG88-10, respectively, therefore, at the current ALDOT maximum of 15% RAP, mixes with either RAP source should have the PG binder grade reduced. However, since ALDOT uses a midpoint PG grade (PG 67-22 instead of a PG 64-22) for specifying unmodified asphalt binders, this would mean that the grade would have to be reduced to a PG 58-28 to keep with the standard PG grading system. This may be too much of a reduction in the upper temperature stiffness, and could result in a substantial increase in rutting problems. RAP used in ALDOT mixes with a specified PG 76-22 would be bumped to a PG 70-28 (modified binder).

An alternative approach can be developed based on the results from this study. Table 8 shows how the stress relaxation test parameters can be used to replace the recovered binder NCHRP guideline recommendations. The data in Tables and 7 were used to estimate the percent change in the properties when 10% RAP, for the NCHRP guidelines, and 15% RAP, for the current ALDOT maximum allowable RAP. Estimated changes in properties assumed that changes are linear between 0 and 50% RAP.

**Table 8. Alternative guidelines for when to consider changing PG grades.**

| | NCHRP Guidelines | | Current ALDOT Practices | |
|---|---|---|---|---|
| | Stress Relaxation Modulus, MPa | Curvature Coefficient | Stress Relaxation Modulus, MPa | Curvature Coefficient |
| Allowable Change in Mix Properties Before Grade of Virgin Binder Needs to be Changed | No More Than 50% Increase | No More Than 12% Decrease | No More Than 75% Increase | No More Than 19% Decrease |

% Changes expressed as changes in the mix properties with no RAP (same virgin aggregate and asphalt as to be used in RAP mixes)
* Conditions for both the stress relaxation modulus and the curvature coefficient need to be met.

These guidelines suggest that the current ALDOT practice of allowing up to 15% RAP in any HMA dense graded lift should also consider reducing the PG grade of the virgin binder from PG 67-22 to a PG 58-28

*Determining the Percent RAP Actually Used in Construction*

A practical application of this information is the determination of the percent RAP in a given mix. Using the information that there is a linear relationship between the percent of RAP from 0 to 50%, and both the stress relaxation modulus and curvature coefficient, the percent RAP in a given mix can be determined as follows:

1. Mix and compact three samples for a control mix and three samples for a mix with the same aggregates and binder but with 50% RAP. The control gradation should be similar to that in the mix with the RAP. Use the same virgin asphalt binder for both sets of samples.
2. Determine the stress relaxation modulus and curvature coefficient for a mix with no RAP and one with 50% RAP.
3. Determine, b, the change in modulus for a percent change in RAP:

   $b = (M_{SR50} - M_{SR0}) / 50$

where:

   $M_{SR50}$ = stress relaxation modulus with 50% RAP

   $M_{SR0}$ = stress relaxation modulus with no RAP

4. Determine, $M_{SR??}$, the stress relaxation modulus for a mix with an unknown percent RAP.
5. Estimate the percent RAP in the mix:

   $\%RAP = (M_{SR??} - M_{SR0}) / b$

**Test Method Refinements – Field Study**

An evaluation of the initial test results showed that the standard deviation of both the modulus and curvature coefficient were dependent upon the mean value. The coefficient of variation (COV) was about 30% for the stress relaxation modulus and about 15% for the curvature coefficient. It was felt that the variability of both parameters could be reduced by conducting three tests per sample, then using the average of these three tests per sample as the single test result reported for each sample. Three tests per sample were accomplished by rotating the sample 30 degrees between each of the three tests so that a different area of the sample was evaluated with each loading. Since the time from start of loading the sample to the completion of one loading cycle takes less than 2 minutes, testing the same sample three times should only increase the testing time by about 3 to 4 minutes.

This change in the test method was combined with a preliminary evaluation of field mixes obtained from East Alabama Paving (EAP), a local paving company. One bag of HMA, sampled by the plant staff during the day's production, was picked up by Auburn University researchers daily. The mix was reheated, split, and used to prepare five gyratory samples. A standard number of gyrations (100) was used to compact all samples. Four days of paving were sampled, which means that a total of 20 samples were tested (Table 9). The same mix (coarse gradation, PG 67-22, no RAP) was produced on all four days of paving.

The stress relaxation test was performed for this last portion of the research with the following test parameters:

- ramp speed of 100 mm/min
- strain level of 0.001
- test duration of 45 seconds
- data acquisition every 0.1 second
- first three seconds of the test were not included in the analysis.

Figure 8 shows the process control chart that is obtained for stress relaxation modulus for four days of paving as well as the plus and minus two standard deviation limits. All of the modulus values are well within the upper and lower limits. Figure 9 shows the process control chart for the daily results for the curvature coefficient. The per bag variability, rather than per sample variability, is used to set the limits. While all of the values are within the limits, the curvature coefficient is more variable for the fourth day (samples 16 through 20), and once the outlier is removed, day 4 data show a tendency to be higher than the other days.

By doing three tests on each plant-produced sample without RAP, the COV was brought down to 18% (from 30%) for the stress relaxation modulus and 7% (from 15%) for the coefficient of curvature.

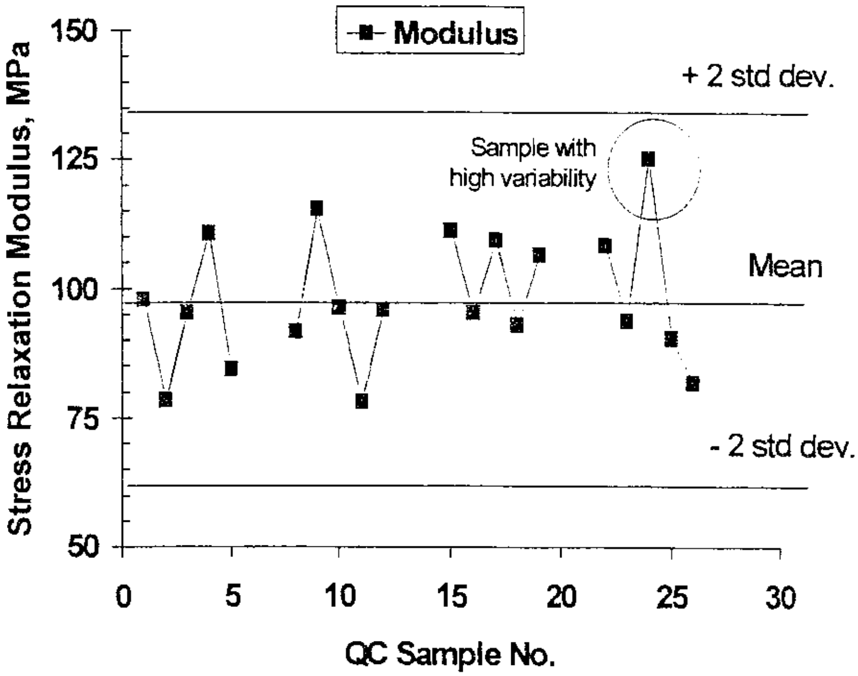



**Figure 8. Stress relaxation modulus process control chart for field study.**

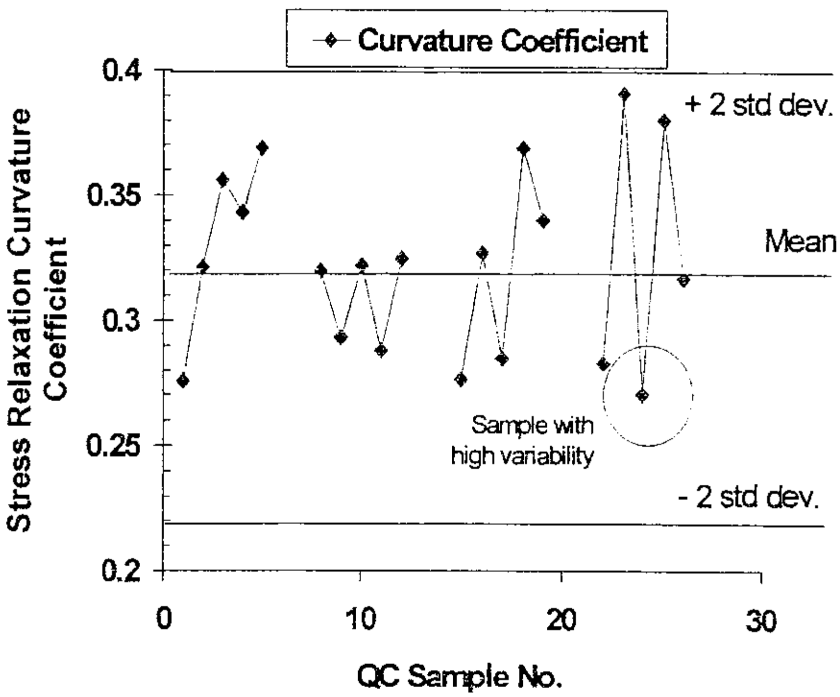



**Figure 9. Coefficient of curvature process control chart for field study.**

**TABLE 9**
**RESULTS FROM FIELD TESTING**

| | Modulus (MPa) | | | | | | Curvature | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| bag | 1 | 2 | 3 | average | std deviation | COV | 1 | 2 | 3 | average | std deviation | COV |
| 1 | 112.0 | 86.3 | 95.2 | 97.8 | 13.1 | 13.4% | 0.278 | 0.267 | 0.281 | 0.275 | 0.007 | 2.7% |
| 1 | 103.9 | 79.8 | 50.9 | 78.2 | 26.5 | 33.9% | 0.341 | 0.352 | 0.271 | 0.321 | 0.044 | 13.7% |
| 1 | 87.1 | 112.7 | 85.8 | 95.2 | 15.1 | 15.9% | 0.376 | 0.352 | 0.339 | 0.356 | 0.019 | 5.3% |
| 1 | 146.5 | 74.0 | 110.8 | 110.4 | 36.3 | 32.9% | 0.316 | 0.346 | 0.368 | 0.343 | 0.026 | 7.6% |
| 1 | 100.4 | 87.3 | 65.4 | 84.4 | 17.7 | 20.9% | 0.359 | 0.356 | 0.391 | 0.369 | 0.019 | 5.3% |
| 2 | 106.5 | 93.2 | 74.8 | 91.5 | 15.9 | 17.4% | 0.346 | 0.307 | 0.306 | 0.320 | 0.023 | 7.1% |
| 2 | 120.3 | 109.6 | 115.9 | 115.3 | 5.4 | 4.7% | 0.270 | 0.304 | 0.305 | 0.293 | 0.020 | 6.8% |
| 2 | 96.7 | 103.4 | 88.2 | 96.1 | 7.6 | 7.9% | 0.346 | 0.315 | 0.305 | 0.322 | 0.021 | 6.6% |
| 2 | 97.1 | 51.4 | 85.7 | 78.1 | 23.8 | 30.5% | 0.271 | 0.330 | 0.262 | 0.288 | 0.037 | 12.8% |
| 2 | 117.9 | 97.4 | 71.6 | 95.6 | 23.2 | 24.2% | 0.348 | 0.299 | 0.327 | 0.325 | 0.025 | 7.6% |
| 3 | 103.1 | 125.0 | 104.6 | 110.9 | 12.2 | 11.0% | 0.291 | 0.271 | 0.266 | 0.276 | 0.013 | 4.8% |
| 3 | 122.2 | 90.9 | 72.9 | 95.3 | 24.9 | 26.2% | 0.339 | 0.281 | 0.360 | 0.327 | 0.041 | 12.5% |
| 3 | 94.9 | 118.9 | 113.9 | 109.2 | 12.7 | 11.6% | 0.310 | 0.273 | 0.270 | 0.284 | 0.022 | 7.8% |
| 3 | 86.0 | 93.6 | 99.1 | 92.9 | 6.6 | 7.1% | 0.381 | 0.345 | 0.380 | 0.369 | 0.021 | 5.6% |
| 3 | 120.5 | 92.7 | 106.1 | 106.4 | 13.9 | 13.0% | 0.332 | 0.318 | 0.369 | 0.340 | 0.026 | 7.8% |
| 4 | 122.2 | 114.6 | 87.6 | 108.1 | 18.2 | 16.8% | 0.294 | 0.269 | 0.285 | 0.283 | 0.013 | 4.5% |
| 4 | 88.8 | 80.3 | 111.6 | 93.5 | 16.2 | 17.3% | 0.360 | 0.402 | 0.410 | 0.391 | 0.027 | 6.9% |
| 4 | 182.8 | 92.6 | 99.6 | 125.0 | 50.2 | 40.1% | 0.293 | 0.248 | 0.269 | 0.270 | 0.023 | 8.3% |
| 4 | 94.2 | 93.3 | 83.4 | 90.3 | 6.0 | 6.6% | 0.382 | 0.371 | 0.387 | 0.380 | 0.008 | 2.2% |
| 4 | 68.1 | 103.4 | 73.9 | 81.8 | 18.9 | 23.1% | 0.250 | 0.357 | 0.342 | 0.316 | 0.058 | 18.3% |

## CONCLUSIONS

Indirect tension stress relaxation testing can be used to evaluate changes in the binder-dominated mix properties. The test method developed for this study is quick, simple, and repeatable. The total testing time, not including sample preparation or conditioning at the test temperature, is less than 5 minutes. Since this test was designed to used gyratory compacted samples, without trimming, samples prepared for volumetric testing either during mix design or in field laboratories during production can be used. This means that no additional samples need to be prepared in order to include this test into the current mix design and quality control/quality acceptance testing.

The coefficient of variation for the initial stress relaxation modulus and curvature coefficient is 16% and 7%, respectively. At ambient temperature (22°C), these parameters can be used to:

- Differentiate between mixes with a PG 67-22 and a PG 76-22.
- Estimate the percent RAP in a mix, or alternatively, be used to establish threshold values

for needing to change the virgin asphalt binder grade.

- Monitor the consistency of the mix binder during production (i.e., process control).

## RECOMMENDATIONS

The key elements of the stress relaxation test method have been developed and initially validated in this study. Work that remains to be done includes:

- Development of instructions and details on how to adapt Marshall stability load frames already fitted with electronic load cells to conduct stress relaxation testing.
- Collection of sufficient data from a wide range of HMA mixes from construction projects, with and without RAP, to confirm the initial estimates of repeatability and to develop reproducibility information.
- Field verification of the usefulness of this test method for monitoring the consistency of RAP stockpile binder properties.

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