

Influence of Test Parameters in SHRP P07 Procedure on Resilient Moduli of Asphalt Concrete Field Cores

Y. R. KIM, K. A. SHAH, AND N. P. KHOSLA

The results of resilient modulus (M_R) testing at North Carolina State University as a part of the Strategic Highway Research Program (SHRP) asphalt concrete core proficiency testing program are presented. As a requirement of participating in this proficiency testing, thorough calibration was conducted on the M_R testing system at NCSU before the commencement of any testing. Then four synthetic specimens were tested within the framework of ASTM D4123-82. After the M_R values of the synthetic specimens were verified to be within the acceptable range, the M_R testing was performed on field cores supplied by the proficiency testing program. The MTS Systems Corp. M_R testing fixture was used with the MTS servohydraulic closed-loop loading system. The mountable measurement device consisting of two extensometers with springs was used in measuring the horizontal deformation. Load and deformation data were acquired by a 12-bit data acquisition board and the LabWindows data acquisition program. A computer program that automatically calculates the instantaneous and total deformation values from the raw data was developed on the basis of regression analysis. The M_R testing of field cores was performed in accordance with the SHRP P07 protocol (September 1990 version). The test results indicated that the effects of testing axis and rest period are relatively small compared with the influence of Poisson's ratio. The M_R values from the assumed Poisson's ratio were as much as five times larger than those calculated by using Poisson's ratio calculated from the vertical and horizontal deformations.

A characterization of various highway materials is one of the most influencing steps involved in pavement design schemes. Material properties are usually obtained from laboratory testing by simulating the field conditions as close as possible. These material properties are input to constitutive models of different design analyses to predict stresses, strains, and deflections induced in a layered pavement structure under moving wheel loads.

As a major constituent of the flexible pavement, the resilient properties of asphalt concrete have been continuously studied using various types of test methods. All of these efforts have led ASTM to standardize the resilient modulus testing method of asphalt concrete (ASTM D4123-82). However, as demonstrated in the Workshop on Resilient Modulus Testing held in Oregon State University in March 1989, there was strong consensus among pavement engineers that ASTM D4123 is unnecessarily time-consuming and that the test results are difficult to reproduce. Furthermore, although the resilient modulus is considered to be a material property, the value of resilient modulus seems to depend on the load history applied.

Department of Civil Engineering, North Carolina State University, P.O. Box 7908, Raleigh, N.C. 27695.

In recognition of the importance and existing problems of resilient modulus testing of asphalt concrete, the Strategic Highway Research Program's (SHRP) material testing program is developing a resilient modulus test procedure for asphalt concrete (SHRP Protocol P07). This procedure incorporates recent findings on resilient modulus testing into the existing ASTM D4123-82.

Another effort by SHRP in the evaluation of the resilient moduli values of field cores is being undertaken as a part of SHRP's Long-Term Pavement Performance program (LTPP). This project is entitled *SHRP Asphalt Concrete Core Proficiency Sample Program for Resilient Modulus Testing*. More than 50 laboratories in the United States are voluntarily participating in this project, including North Carolina State University (NCSU).

The objectives of this paper are first to describe the SHRP asphalt concrete core proficiency testing activities at NCSU (hereafter called proficiency testing); second, to introduce the data acquisition and analysis program developed for the resilient modulus testing; and third, to summarize findings from the resilient modulus testing of LTPP field cores.

RESILIENT MODULUS TESTING FIXTURE

The testing apparatus used in this study was provided by MTS Systems Corp. The schematic presentation of this fixture is shown in Figure 1. The fixture was installed inside an environmental chamber in which temperature could be maintained within $\pm 1^\circ\text{F}$ for extended periods.

Horizontal displacements were measured by extensometers designed by MTS Systems with full-scale travels of 0.15 in. (0.381 cm). Ranging the transducers to 10 percent of full scale calibrates the output to a finer-scale travel and allows higher-resolution measurements of small deformations. Vertical deformations were measured directly from the actuator movement using the stroke reading in the MTS microconsole.

The diametral device consists of two extensometers with gauge length extenders and two specimen adapter brackets as shown in Figure 1. The brackets are machined to the same radius as the specimen and remain in contact with the specimen all along the thickness. This design allows each bracket to measure the maximum deformation instead of measuring local deformation due to point contact with a linear variable differential transducer (LVDT) that is used in some diametral tensile test fixtures. The mounting method of these extensometers can be found elsewhere (1,2).

Some advantages of the device are as follows:

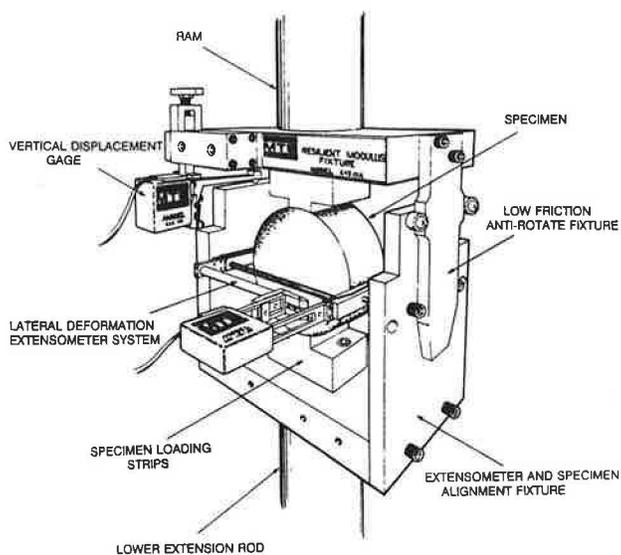


FIGURE 1 Resilient modulus testing fixture and extensometers.

1. Because the brackets are placed at the sides of the specimen guided by pin screws through the holes in fixed side walls, this fixture gives more precise control over the vertical locations of the brackets.

2. Once the test starts, the low-friction antirotate bar in the upper fixture (Figure 1) prevents rotation of the actuator due to repetitive loading.

3. Another advantage of this fixture is that the improper measurements due to "rocking" of the specimen can be minimized. Because the extensometers are attached to the specimen by springs, extraneous deformation due to rigid-body rotation cannot affect the deformation measurements.

TESTING PROTOCOL

Calibration with Synthetic Specimens

Participation in the SHRP proficiency testing required calibration of the resilient modulus testing system before the commencement of any testing. The calibration procedure included alignment of the top and bottom loading rams, calibration of extensometers and load cell, and adjustment of gain settings in the MTS console to check the shape and timing of wave form.

Then four types of synthetic specimens were tested to verify the calibration of the system. The synthetic specimens were made from polyacrylate (Lucite), polyethylene, Teflon, and cast synthetic rubber used for Hveem stabilometer calibration. The testing protocol that was required to determine the resilient modulus, within the framework of ASTM D4123, called for

- Test temperature— $77 \pm 0.9^\circ\text{F}$ ($25 \pm 0.5^\circ\text{C}$);
- Applied load—50 lb;
- Record deflection—after 15 conditioning cycles; and
- Determination of resilient modulus—twice for each sample, second replication done after rotating the sample through 90 degrees.

Results were then submitted to the researchers of the proficiency testing program for analysis.

Resilient Modulus Testing of Field Cores

After the M_R values of the synthetic specimens were found to be within the acceptable range of known M_R values, testing was conducted on the asphalt concrete cores obtained from the test sections at the Pennsylvania State University and sent by the SHRP proficiency testing project. Two sets of cores, consisting of five samples each, were supplied with the labels "O" or "N" followed by a two-digit number. The samples labeled N and O are the cores from a new and a 5-year old pavement, respectively. Two mutually perpendicular diametral lines were drawn on the sample and marked either "A" or "B". The cores were not trafficked; consequently, traffic direction was not marked on the cores. Indirect tensile strength at 77°F was 223 psi for cores marked "N" and 61 psi for cores marked "O".

All the samples were tested in accordance with the SHRP P07 procedure (September 1990 version) along both axes. Each time a core was tested, Direction A or B was chosen randomly for the first set of readings. The differences and modifications between this procedure and ASTM D4123 are listed in Table 1.

DATA ACQUISITION AND ANALYSIS PROGRAM

Noise in Data Acquisition

At NCSU, LabWindows (Version 1.2) is being used to acquire the data from the MTS. The programs used for data acquisition have been written in Quick Basic within the LabWindows. To acquire the data, an AT-MIO-16 board has been set up. The AT-MIO-16 is a high-performance multifunction analog, digital, and timing input and output board. The input voltage range for the AT-MIO-16 has been set up to remain between -10 and 10 V. Therefore, the precision of the input signal measured by the AT-MIO-16 twelve-bit analog-to-digital converter can be calculated by dividing the total voltage range (20 V) by 2^{12} , which results in 4.88 mV. Thus, when displacement cartridges of 0.5 in. (for vertical deformation) and 0.015 in. (for horizontal deformation) maximum capacity were used, the minimum values of deformation measured were $(0.5/10) \times (4.88/1,000) = 2.44 \times 10^{-3}$ in. and $(0.015/10) \times (4.88/1,000) = 7.32 \times 10^{-6}$ in., respectively. Similarly, for a 2,000-lb. load cartridge, the minimum value of load that could be read was 0.976 lb. This accounts for most of the fluctuation in the output deformation curves. As can be seen from Figures 2 and 3, the values of the deformations are seen to fluctuate between two precision levels. The "noise" in the data can be easily accounted for from the minimum precision values as explained. It is not claimed here that there is no fluctuation at all in the actual data, but it is believed that the small fluctuations can be amplified because of the limitation of the acquisition board.

Resilient Modulus Analysis Program

An effort has also been made at NCSU to develop a program that automatically calculates the M_R values from the data file obtained using the data acquisition program. This program

TABLE 1 Comparison of ASTM D4123 and SHRP P07 Protocol

Criteria	ASTM D 4123	SHRP P07
Testing machine	It should have the capability of applying a load pulse over a range of frequencies, load duration and load levels. Note 2 suggests use of electrohydraulic m/c's or other m/c's such as those using pneumatic devices.	It shall be a top-loading, closed loop electrohydraulic testing m/c with a function generator capable of applying a haversine shaped load pulse over a range of load durations, load levels and rest period.
Deformation measurements	<ul style="list-style-type: none"> * By LVDT's or other suitable devices. * Positive contact between the specimen and measuring device by spring loading or gluing attachments. * Gauges wired to preclude the effects of eccentric loading so as to give algebraic sum of movement of each side of the specimen. Alternatively, each gauge can be read independently and results summed independently. 	<p>By LVDT's.</p> <p>Positive contact by using a spring loaded LVDT and attaching a flat head (3/8" x 1/4") as a contact point.</p> <p>The two LVDT's shall be wired so that each transducer can be read independently and the results summed during the test program.</p>
Temperatures recommended	41,77 (or ambient laboratory temperature) & 104°F.	41,77 & 104°F
Measurement of indirect tensile strength	Destructive test on a specimen and the use of equation 8.3 in ASTM D 4123.	According to the procedure in attachment A to protocol P07 at $77 \pm 2^\circ\text{F}$.
Recommended load for testing and preconditioning	10 to 50% of indirect tensile strength.	30, 15 & 5% of indirect tensile strength for test temperatures of 41 ± 2 , 77 ± 2 & $104 \pm 2^\circ\text{F}$ respectively.
Seating load	ASTM remains silent.	3, 1.5 & 0.5% of indirect tensile strength for test temperatures of 41 ± 2 , 77 ± 2 & $104 \pm 2^\circ\text{F}$ respectively.
Axis of loading	Sample to be rotated 90° each time a test with a different variable is done on the same specimen.	Testing is to be performed along two mutually perpendicular diametral axis (latest version, July 1991, requires testing along two axes 45° apart).
Wave form Loading pattern & preconditioning	Haversine or suitable waveform; Load duration 0.1 to 0.4 sec, Frequency of load: 0.33, 0.5 & 1 Hz. suggested.	Haversine; Load duration 0.1 sec; Rest periods 0.9, 1.9 & 2.9 secs.
Period of preconditioning	Until the deformations are stable.	Until a minimum of 10 successive readings of horizontal deformation agree within 10%.
Expected load repetitions	A minimum of 50 to 200 load repetitions is typical.	Expected ranges are 50-150, 50-100, & 20-50 for 41 ± 2 , 77 ± 2 , $104 \pm 2^\circ\text{F}$ resp.
If cumulative vertical deformation exceeds (x)"	here $x = 0.001$ " Reduce the test temperature, the applied load, or both.	here $x = 0.025$ " for 41°F $= 0.050$ " for 77 & 104°F Reduce applied load to min. possible retaining adequate deformation. If not possible to retain adequate deformation for measurements, stop the preconditioning and generate 10 load pulses for M_R determination and so indicate on test report.

(continued on next page)

TABLE 1 (continued)

Criteria	ASTM D 4123	SHRP P07
Number of load pulses to be applied for M_r	Measure the avg. recoverable horizontal and vertical deformations over at least 3 loading cycles after the repeated resilient deformations are stable.	Minimum of 30 load pulses to be applied. Continued beyond 30 until the range in deformation values of five successive horiz. deformation values is less than 10% of the avg. Then M_r is the avg. of the M_r values measured individually from 5 load cycles after deformations are stable.
Poisson's ratio	0.35 suggested to be reasonable at 77°F.	0.2, 0.35 & 0.5 to be assumed for temperatures of 41±2, 77±2, and 104±2°F respectively.
Specimens	Lab-molded: prepare as per 6.1 core specimens: as per 6.2.	Lab molded specimens: no suggestions Core specimens: as per ASTM.
Test sequence	Testing to begin at the lowest temperature, shortest load duration and smallest load. Subsequent testing on the same specimen should be so as to provide progressively lower moduli.	The sequence shall consist of initial testing at 41°F, followed by intermediate testing at 77°F and final testing at 104°F.

Additions in SHRP P07:

Section 6 gives a description about specimen requirements and measurements.
Section 7.2 describes the procedures related to alignment and specimen seating.

determines the peak values of load applied at each consecutive load cycle after compensating for the level of precision (which has been discussed earlier) of load measured. The program also calculates instantaneous and total values of horizontal and vertical deformations.

The program first picks up the peak values of load and deformations at each cycle and compensates for repeated peaks (which result because of the limitation of the level of precision, as discussed earlier) using the following equation:

$$\delta_A = \delta_O + (R - 1) \times PL/C$$

where

δ_A = adjusted peak value,

δ_O = peak value obtained from the raw data,

R = number of times the same peak value appeared,

PL = half of the precision level (0.488 lb, 3.66 μ in., and 122 μ in. for 2,000-lb load cell, 0.015-in. maximum capacity horizontal deformation cartridge, and 0.5-in. maximum capacity vertical deformation cartridge, respectively), and

C = weighting factor (1, 2, and 7 for load, horizontal deformation, and vertical deformation, respectively).

This equation was developed from the comparison of peak values obtained from the data acquisition program and a Hewlett-Packard Model 7090A plotter. Average seating load was then calculated and subtracted from peak values of load.

To get the instantaneous and total deformation values, regression is done in three portions of the deformation curve:

1. Linear regression in the straight portion of the unloading path.
2. Regression in the curved portion that connects the unloading path and the recovery portion to yield the following hyperbolic equation:

$$Y = a + (b/X)$$

where

Y = deformation value,

X = time, and

a, b = regression constants.

3. Regression in the recovery portion between 40 and 90 percent of rest period to yield a hyperbolic equation. A tangent was drawn to this hyperbola at the point corresponding to 55 percent of rest period. The portion used for regression and the point for calculating a tangent were selected after examining deformation-versus-time curves from various test conditions.

Two linear equations, one from the unloading path and the other from the tangent of the hyperbola in the recovery period, are solved to determine the intersection. Then the point on the hyperbolic curve corresponding to the time coordinate of the intersection (for convenience, say Point A) is selected

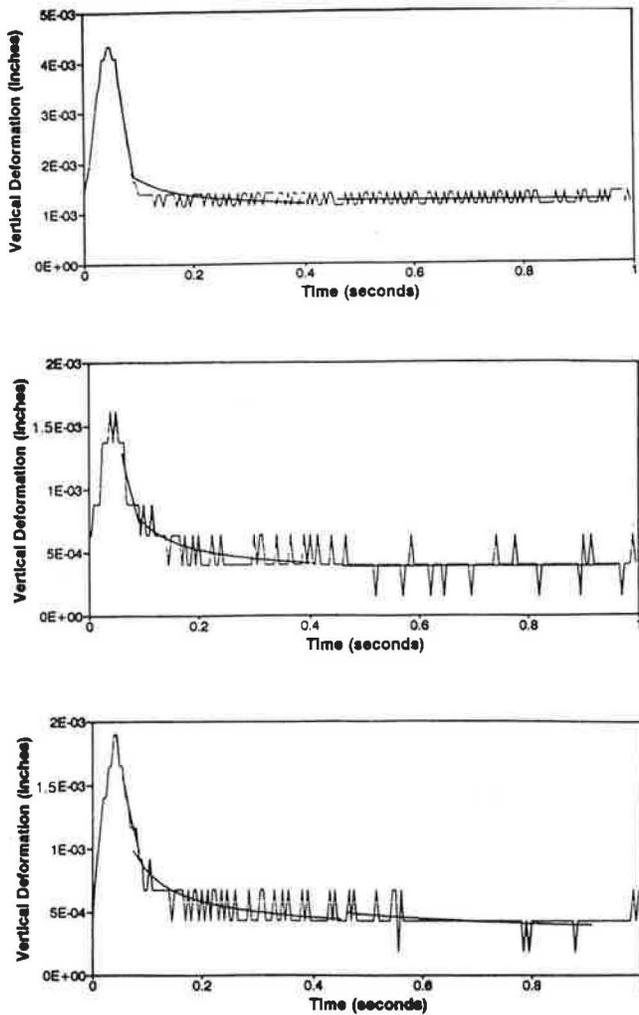


FIGURE 2 Actual vertical deformations and prediction from regression: *top*, N-core at 41°F; *middle*, O-core at 77°F; *bottom*, N-core at 104°F.

to determine the instantaneous deformation by subtracting the deformation at Point A from the peak deformation. Subtracting the deformation value at the end of the rest period (calculated from the regressed hyperbolic equation) from the peak deformation yields the total deformation value.

The program was checked for random cases to see how accurately the regression equations fit the actual data. The comparison was very satisfactory in the region where the accuracy of the curves and lines was most significant. Some of the results at different testing conditions are shown in Figures 2 and 3. The equations in ASTM D4123 were used to calculate the resilient modulus and Poisson's ratio from the deformation measurements.

TEST RESULTS AND DISCUSSION OF RESULTS

Effect of Testing Axis

Results from the proficiency testing indicated that the M_R values were slightly higher along the diametral axis that was tested first as shown in Figures 4 and 5. Figures 4 and 5 present

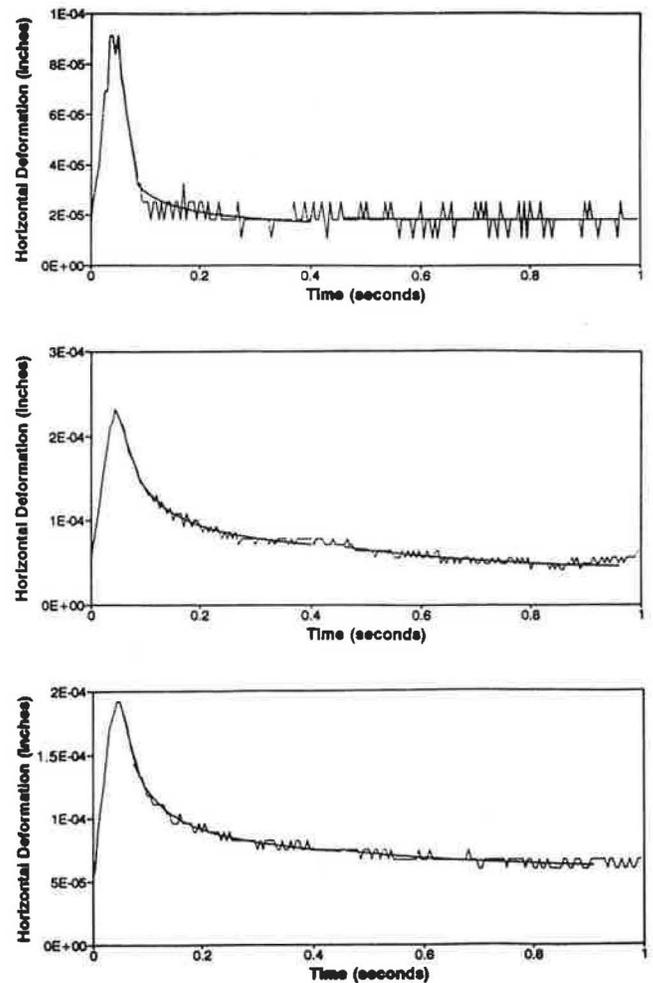


FIGURE 3 Actual horizontal deformations and prediction from regression: *top*, N-core at 41°F; *middle*, O-core at 77°F; *bottom*, N-core at 104°F.

the total M_R values calculated from assumed and calculated Poisson's ratios, respectively. Comparison of Figures 4 and 5 revealed that the axis dependency became more significant when M_R values were determined from Poisson's ratios calculated from vertical and horizontal deformations than from assumed Poisson's ratios.

Fairhurst et al. (2) studied the change in M_R values based on calculated Poisson's ratios at different specimen rotations using laboratory-compacted specimens. It was reported that M_R values at a 0-degree specimen position were larger than those at 90 degrees. Since the 90-degree position was always tested after the initial 0-degree position, they suggested that the decrease in the M_R values at the 90-degree position could be due to internal damage done to the specimen during testing in the initial position.

The same data used in Fairhurst's paper were plotted in Figure 5 under the legend of "lab.specimens" with the M_R values from the field cores. The axis dependency from the field cores was not as prominent as that obtained by Fairhurst et al. (2). This might be a direct consequence of the load level applied. If higher load levels were used, damage would be more and hence the difference in M_R values would be larger.

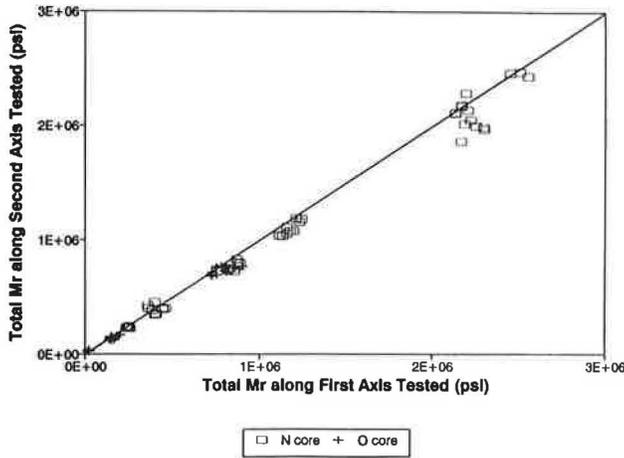


FIGURE 4 Axis dependency of M_R values from assumed Poisson's ratio.

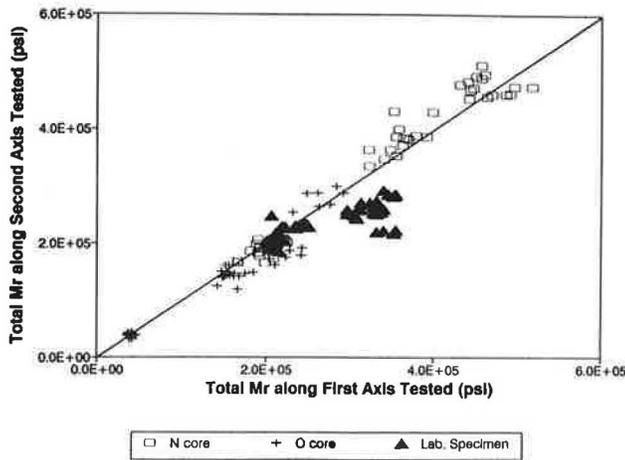


FIGURE 5 Axis dependency of M_R values from calculated Poisson's ratio.

It should be noted that SHRP P07 limits the load to 30, 15, and 5 percent of the indirect tensile strength at 77°F for testing temperatures of 41, 77, and 104°F, respectively, whereas the load level used in Fairhurst's paper was 20 percent of the indirect tensile strength at 73°F that was allowed in ASTM D4123. The load levels required by SHRP P07 probably yield less damage, hence causing less axis dependency. A sensitivity analysis must be done to determine whether these differences are significant in pavement design.

Effect of Rest Period

Several researchers have studied the effect of rest period on the resilient modulus of asphalt concrete (3-5). Terrel et al. suggested that the computed value of resilient modulus would depend on the rest period between the individual stress pulses as the asphalt mixes exhibit viscoelastic behavior (4). At low temperatures and short stress durations the dependency is not significant, but that is not the case with warm temperatures and long stress durations. For that case, the viscoelastic response should be included as a factor in the material characterization.

Monismith also stated that the rest period has a great influence on the value of resilient modulus because of the viscoelastic behavior of the asphalt concrete (5). However, it was suggested to be important to consider the ratio of the rest period (time OFF) to the time of loading (time ON), because it would directly affect the amount of recoverable strain and hence the resilient modulus. The smaller the ratio, the smaller will be the recoverable strain and hence larger the values of resilient modulus (Figure 6). This dependence is also temperature-dependent: dependence decreases with decrease in temperature.

Fairhurst et al. investigated the effect of cycle frequency which is directly related to the rest period duration on the magnitude of resilient modulus (2). The results indicated that M_R increased slightly with the shorter rest periods. This was not surprising, because shorter rest periods for the specimen between loading pulses resulted in less time for rebound strain and thus higher M_R values.

The results from the proficiency testing on cores indicated that there was very little effect of rest period on the values of resilient modulus as shown in Figure 7. In some cases the M_R values even increased slightly with increasing rest periods. The increase was seen more often in O-specimens than in N-specimens.

The apparent contradiction in the obtained results to the expectations can be easily explained. First, as is clear from Figure 6, the beneficial effect of rest period is not very significant after a certain time-OFF/time-On ratio (close to 8 in Figure 6). The time-OFF/time-ON ratios in the proficiency testing were 9, 19, and 29; therefore, we can expect very little effect of rest period. Second, the order of testing the specimens at different rest periods was in the direction of causing lesser damage; that is, the case in which the worst damage was expected (0.9-sec rest period) was tested before the case with minimum damage (2.9-sec rest period). This order of testing might have increased the fatigue damage as the test progressed, resulting in lesser recoverable deformation and a slight increase in the M_R values. All the observations made

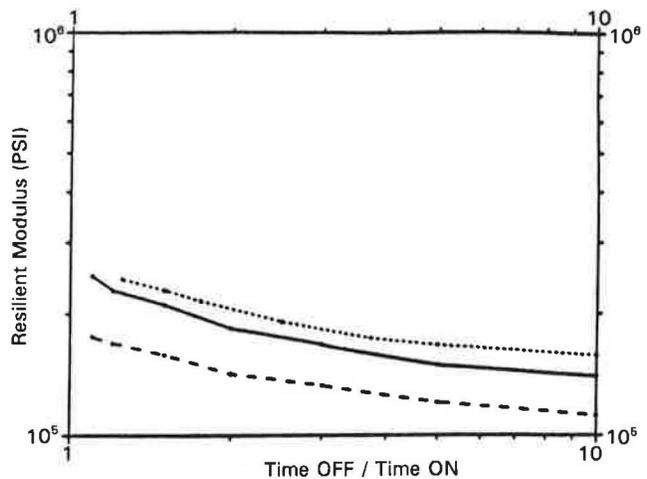


FIGURE 6 Influence of time interval between load applications on M_R determined in repeated loading in compression at 25°C: solid line = Specimen R7, Time ON = 1.0 sec; dashed line = Specimen R6, Time ON = 1.0 sec; dotted line = Specimen R6, Time ON = 0.4 sec (5).

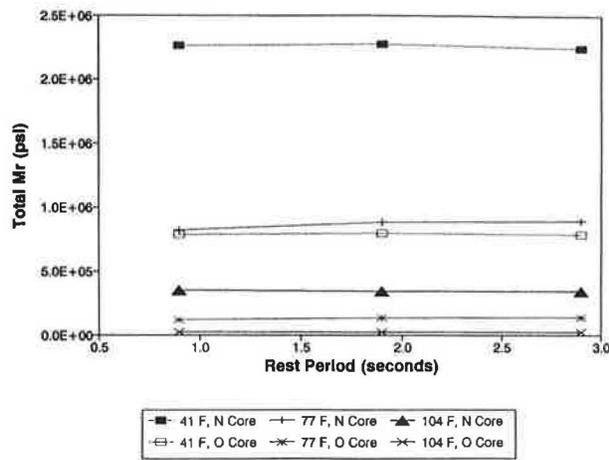


FIGURE 7 Effect of rest period on total M_R using assumed Poisson's ratio.

can explain the lack of a definite pattern in the effect of rest period on the M_R values.

Effect of Temperature

The role that the temperature plays in material response for pavements built with viscoelastic binders is the most significant variable affecting the choice of test and condition of test as well as the ultimate performance of the pavement. Kennedy et al. stated that the effect of temperature on pavement materials should be thought of not only in terms of high and low temperature but also in terms of the complete temperature range the pavement will experience (6). This may vary from -22 to 140°F. However, as far as resilient modulus is concerned, testing below the glass transition temperature, which ranges from -10 to 0°F, is not necessary.

Actual test data indicated that the resilient modulus depends a great deal on the temperature at which the specimen is tested (Figure 8). It was also observed by Cochran (7) and Furber (8) that with increase in temperature the resilient modulus decreases notably.

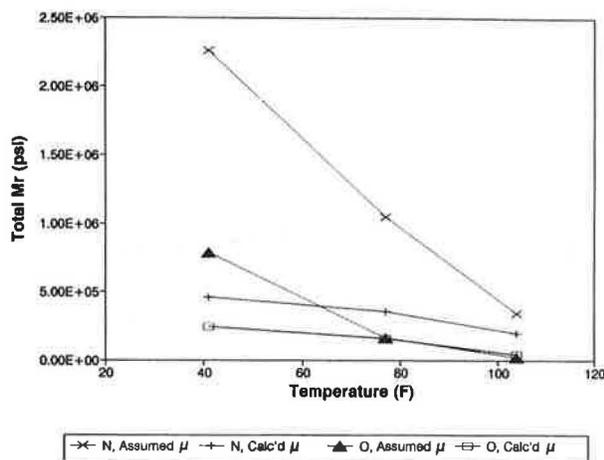


FIGURE 8 Effect of temperature on total M_R .

Effect of Poisson's Ratio

Figure 8 clearly demonstrates the magnitude of difference in the M_R values depending on whether assumed or calculated Poisson's ratio has been used in calculating the M_R values. The largest discrepancy occurred with N-cores at 41°F, the M_R from assumed Poisson's ratio being about five times the size of the M_R from calculated Poisson's ratio. Also the temperature susceptibility (tangential slope of M_R -versus-temperature curve) was lessened by using the calculated Poisson's ratio. Actual Poisson's ratio as determined from the total vertical and horizontal deformations was found to vary between negative values and 1.5 (Figure 9), which is definitely out of the theoretical range of 0 to 0.5 for elastic materials.

The significance of Poisson's ratio on M_R values has been reported by several researchers. From the experience of the Minnesota Department of Transportation (7), it was found that using the assumed value of 0.35 for Poisson's ratio resulted in 1.5 to 2 times higher values of resilient modulus than those obtained by using the "actual" Poisson's ratio calculated from measured horizontal and vertical deformations. Similar observation was made by Baladi and Harichandran, that the resilient moduli values with Poisson's ratio of 0.35 were different by as much as a factor of two or more than those with calculated Poisson's ratio (9).

Fairhurst et al. investigated the influence of temperature on Poisson's ratio and concluded that Poisson's ratio increased with increase in the temperature, which resulted in a decrease in M_R values (2). These results appear reasonable because the plastic portion of the asphalt binder increases with temperature. They concluded that Poisson's ratio near 0.5, the theoretical maximum for elastic materials, suggested that the applied load might be too high. Another interesting finding was that Poisson's ratio at the 90-degree position is slightly higher than that at 0 degrees. This could be due to a redistribution of the applied load into the region outside the center (as a result of the "weakened" central zone), causing greater overall horizontal deformation, hence a higher Poisson's ratio. These observations drew a conclusion that Poisson's ratio could serve as an indicator for excessive damage in the specimen during the resilient modulus testing.

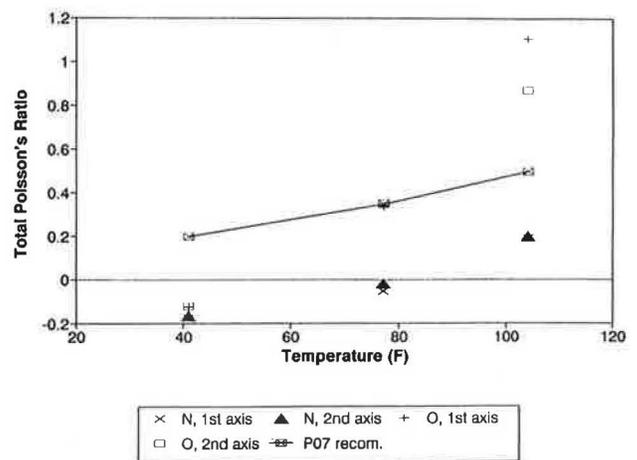


FIGURE 9 Poisson's ratio as function of temperature.

Vinson (10) concluded from a theoretical study using a finite element program that the increase in Poisson's ratio from 0.15 to 0.45 did not affect the results very much. It was also concluded that for a resilient modulus test performed under typical loading conditions (i.e., a steel-asphalt concrete interface) the resilient modulus with an assumed Poisson's ratio is more accurate because of induced shear stresses in the specimen. However, better results were obtained with calculated values of Poisson's ratio when a soft modulus material is placed between the steel platen and asphalt concrete.

McGee, however, concluded from the experimental study that resilient modulus values calculated with an assumed value of 0.35 have shown more scattering than those calculated by using calculated values (11). It has also been found that Poisson's ratio increases with increase in loading level, temperature, and asphalt content.

CONCLUSIONS

On the basis of the resilient modulus testing of field cores in accordance with the SHRP P07 procedure, the following conclusions were made:

1. The M_R values from the second axis testing were slightly smaller than those from the first axis testing. The load levels recommended by SHRP P07 seemed to reduce the testing axis dependency significantly by minimizing the damage from the first axis testing.
2. The effect of rest period was not significant for the loading history required by SHRP P07 (0.1-sec loading with 0.9-, 1.9-, and 2.9-sec rest periods).
3. The resilient modulus decreased as temperature increased. The temperature dependency of the M_R values were reduced when the M_R values were calculated from the calculated Poisson's ratios.
4. The most influencing parameter on the M_R values was Poisson's ratio. The discrepancies in M_R values due to the testing axis dependency and different lengths of rest periods were almost negligible compared to the magnitude of difference in the M_R values from assumed and calculated Poisson's ratios.

ACKNOWLEDGMENTS

The authors are grateful to NCHRP for its support and sponsorship of this research. Special thanks are due to G. Steele for his most constructive information.

REFERENCES

1. Y. R. Kim, N. P. Khosla, and N. Kim. Effect of Temperature and Mixture Variables on Fatigue Life Predicted by Diametral Fatigue Testing. In *Transportation Research Record 1317*, TRB, National Research Council, Washington, D.C., 1991.
2. C. E. Fairhurst, Y. R. Kim, and N. P. Khosla. Resilient Modulus Testing of Asphalt Specimens in Accordance with ASTM D4123-82. *Proc. 4th International RILEM Symposium*, Budapest, Hungary, Oct. 1990.
3. F. P. Bonnaure, A. H. J. J. Huibers, and A. Boonders. A Laboratory Investigation of the Influence of Rest Periods on the Fatigue Characteristics of Bituminous Mixes. *Proc., Association of Asphalt Paving Technologists*, Vol. 51, Kansas City, Mo., 1982.
4. R. L. Terrel, I. S. Awad, and L. R. Foss. *Techniques for Characterizing Bituminous Materials Using a Versatile Triaxial Testing System*. ASTM Special Technical Publication 561. ASTM, Philadelphia, Pa., 1974.
5. C. L. Monismith. Resilient Modulus Testing: Interpretation of Laboratory Results for Design Purposes. *Proc., Workshop on Resilient Modulus Testing*, Oregon State University, Corvallis, 1989.
6. T. W. Kennedy, T. D. White, and J. A. Epps. Use of Material Tests and Pavement Design Procedures to Evaluate New Paving Binders. In *Properties of Flexible Pavement Materials*. ASTM Special Technical Publication 807 (J. J. Emery, ed.). ASTM, Philadelphia, Pa., 1983.
7. G. R. Cochran. Minnesota Department of Transportation Experience with Laboratory MR Testing. *Proc., Workshop on Resilient Modulus Testing*, Oregon State University, Corvallis, 1989.
8. A. B. Furber. Strain and Temperature Effects on Resilient Moduli. *Proc., Workshop on Resilient Modulus Testing*, Oregon State University, Corvallis, 1989.
9. G. Y. Baladi and R. S. Harichandran. Asphalt Mix Design and the Indirect Test: A New Horizon. In *Asphalt Concrete Mix Design: Development of More Rational Approaches*. ASTM Special Technical Publication 1041 (W. Gartner, Jr., ed.). ASTM, Philadelphia, Pa., 1989.
10. T. S. Vinson. Fundamentals of Resilient Modulus Testing. *Proc., Workshop on Resilient Modulus Testing*, Oregon State University, Corvallis, 1989.
11. N. McGee. Laboratory MR Investigation of 2331 Mix. *Proc., Workshop on Resilient Modulus Testing*, Oregon State University, Corvallis, 1989.