Introduction to Strategic Highway Research Program–Long-Term Pavement Performance Asphalt Concrete Resilient Modulus Testing Program

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Research is under way in the Strategic Highway Research Program's Long-Term Pavement Performance (SHRP-LTPP) project to develop and implement a test procedure for resilient modulus testing of asphalt concrete. A comprehensive test procedure has evolved over the past 3 years and is moving toward full-scale production testing in early 1992. Readers with limited exposure with the SHRP-LTPP program are provided with a feel for the test procedure that has been developed and the various activities that have been undertaken in this program to ensure consistent and reliable results.

The overall goal of the Strategic Highway Research Program's Long-Term Pavement Performance Program (SHRP-LTPP) studies is "to increase pavement life by investigation of various designs of pavement structures and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soil and maintenance practices" (*1*). A major component of the LTPP research effort is the establishment of a national pavement data base (NPDB) containing inventory information and performance histories of pavements with various design features, materials, traffic loads, environmental conditions, and maintenance practices. The primary source of the information stored in the NPDB will be the inventory and monitoring data collected on a large number of pavement test sections on existing or in-service pavements forming the general pavement studies (GPS) portion of LTPP, as well as newly constructed or rehabilitated test sections included in the specific pavement studies portion of LTPP, which allows for more-intensive evaluation of selected factors (*1*).

The LTPP study is being conducted under the central leadership of the SHRP staff with technical assistance provided by Texas Research and Development Foundation under SHRP Contract (P-001). The inventory and field monitoring data are being collected through the efforts and supervision of four regional coordination office contractors in cooperation with the state/province highway agencies. Information obtained through LTPP field material sampling and field testing and laboratory testing contracts includes in situ density and moisture data, visual pavement layer information, and laboratory test data (materials characterization) for each pavement section. This information will be included in the NPDB (*1*).

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A significant amount of data will be produced from the LTPP studies that can be used by the highway research community. One of the more important outputs from the materials characterization portion of the LTPP study will be resilient modulus (M_R) data from each layer of the pavement test sections. Relationships between this M_R data, other materials properties, and falling weight deflectometer data should be invaluable in evaluating the pavement performance of the LTPP sections.

This paper offers an overview of a specific SHRP-LTPP test procedure involving resilient modulus testing of asphalt concrete (AC) cores. It is intended to provide a discussion of the fundamentals of this test procedure and to identify the expected results to be achieved from the performance of this test.

OVERVIEW: SHRP-LTPP MATERIALS TESTING PROGRAM

The goal of the SHRP-LTPP field sampling and laboratory testing work is to recover, examine, and store pavement material samples obtained from designated pavement test sections and then to perform specified laboratory tests in order to define adequately the pavement layer structure and characterize material properties of the LTPP test sections. Laboratory tests are conducted for asphalt concrete, extracted aggregate from asphalt concrete, asphalt cement, bound base, subbase and subgrade, unbound granular base and subbase, subgrade, and portland cement concrete materials. The laboratory testing program includes a comprehensive testing process designed to produce an independent determination of pavement layering.

For each laboratory test, standard SHRP protocols have been developed for use by the laboratories. The intent of this process is to minimize the variability of material test data attributable to laboratory materials testing and handling techniques by standardizing these techniques as much as possible.

Many of the test procedures included in the SHRP program are based on standard AASHTO or ASTM specifications. However, several procedures, such as AC Core Examination and Thickness, were developed completely because AASHTO and ASTM lacked specifications. Still other protocols involve major modifications of the AASHTO or ASTM standards.

One such protocol, Resilient Modulus of Asphalt Concrete, represents a major modification to the existing ASTM D4123 procedure. The remainder of this paper will focus on this procedure.

AC RESILIENT MODULUS TESTING

Summary of Method

The SHRP protocol for AC resilient modulus testing (SHRP Protocol P07) describes procedures for determining M_R using repeated-load indirect tensile testing techniques. The procedure involves resilient modulus testing for a range of temperatures, loads, rest periods, and axis of loading. This test is completed on field cores obtained from SHRP test sections and is conducted through repetitive applications of compressive loads in a haversine waveform.

Development of Test Method

The development of the SHRP AC M_R test procedure has been under way for some time. An outline and a draft test procedure were originally developed by a group of materials-testing experts under the direction of SHRP (*2*). The first draft of Protocol P07 was essentially based on ASTM D4123-82 (1987) and preliminary findings of the asphalt-aggregate mixture analysis system study. The first production version of P07 was issued in July 1989. Subsequent revisions were instituted by the SHRP technical assistance contractor in November 1989, and the version currently in use for the resilient modulus pilot study was issued in July 1991. Further refinement of the test procedure, based on the results of a pilot study, is expected. This protocol was to be issued in its final form in early 1992. Resilient modulus testing of all LTPP AC specimens should be complete by middle to late 1992.

SHRP PROFICIENCY TESTING

Expert task group recommendations led to a decision in 1988 that a vital element in laboratory quality assurance would be the AASHTO accreditation program (AAP) (*3*). The laboratories under contract to SHRP were required to be accredited by AAP. Since the resilient modulus testing of asphalt is not covered under this program, it was decided that a separate proficiency-testing program would be developed to ensure the quality of the test data being collected (*3*).

Seventeen laboratories are participating in an asphalt concrete resilient modulus testing program that involves two separate test series for the verification of M_R system calibration and proficiency. The first portion involves the verification of the system calibration and proficiency by testing a set of four synthetic reference specimens (i.e., rubber, Teflon, polyurethane, and Lucite) provided by SHRP; the second portion involves establishment of further M_R proficiency on actual asphalt field cores.

In the first series, laboratory-generated M_R results for the synthetic specimens are compared with the anticipated range in M_R results to identify acceptable or unacceptable results. If the measured responses do not fall within the anticipated range, the agencies are advised to inspect their test system for problems with equipment (load cell, transducers, etc.), alignment, or specimen placement. Once system problems are corrected and acceptable M_R values are obtained, the testing agency is released to begin the second series of the proficiency program involving asphalt core proficiency testing. It should be noted that a number of laboratories had considerable difficulty in completing the initial proficiency test series.

The second proficiency test series involves M_R testing of asphalt cores obtained from the Pennsylvania State University test track. The participating laboratories were given two sets of core specimens and were asked to conduct resilient modulus testing using the SHRP Protocol P07 procedures including testing at 41, 77, and 104°F (5, 25, and 40°C). Similarly to the initial series, the M_R values generated by the participating laboratories were compared to a range of expected M_R values developed by SHRP quality-control personnel. If measured responses fall outside this range, the agencies are advised to inspect their load apparatus, transducer placement, and location for needed adjustments and to evaluate specimen marking, location, and placement techniques of laboratory personnel.

The initial round of testing within the synthetic proficiency series produced a range of resilient modulus values from 25 percent to an order of magnitude greater than the accepted values for the reference specimens. This illustrates that this testing program was indeed necessary and vital to the success of the LTPP program. The experience indicates that a less vigorous course of action may have resulted in the collection of unusable data at great cost to the highway community (*3*).

PILOT STUDY TESTING

The SHRP AC M_R pilot study was initiated to provide SHRP with answers to several questions concerning the AC M_R program. The objectives of this study are as follows:

- Provide SHRP laboratories with general resilient modulus testing experience before production testing of the specimens;
- Allow the laboratories a chance to institute and evaluate their inhouse quality-assurance and quality-control program before production testing;
- Encourage uniformity in M_R testing between the three SHRP contract laboratories;
- Determine the extent of construction variability present between ends of a test section;
- Determine areas in which Protocol P07 may be streamlined; and
- Determine if additional asphalt concrete property tests are required on samples undergoing resilient modulus testing.

As part of this pilot study, AC specimens were selected from 40 SHRP test sections representing all four SHRP regions, including 24 states and 4 Canadian provinces (see Figure 1). Approximately 480 specimens will undergo a battery of standard SHRP tests, including

- Core examination and thickness measurements,
- Bulk specific gravity,
- Maximum specific gravity,
- Asphalt content, and
- Resilient modulus.

Through the performance of this study and the analysis of the corresponding data, the objectives mentioned previously will be achieved.

Each SHRP contract laboratory must pass the AC proficiency and calibration testing program before they are cleared to begin pilot study testing. After clearance, each laboratory is given a list of the designated specimens for pilot testing. The order of testing of these samples has been randomized to minimize bias in the test results. The laboratory proceeds by testing each specimen in accordance with a defined process. The data from all of the samples will then be gathered and analyzed by the SHRP technical assistance contractor to achieve the stated objectives. It is anticipated that the results of this pilot study will have a significant chance of altering Protocol P07, since a critical analysis is going to be made of differences in modulus values for different rest periods on the same sample and of the effect of testing two axes of each sample. This pilot study testing program should yield valuable results and insights into the asphalt concrete resilient modulus test procedure.

RESILIENT MODULUS TEST

The repeated-load resilient modulus test of asphalt concrete cores is conducted through repetitive applications of compressive loads in a haversine waveform. The compressive load is applied along a vertical diametral plane of a cylindrical core of asphalt concrete (Figure 2). The resulting horizontal and vertical deformations of the core are measured, and resilient modulus is calculated using the applied load, specimen dimensions, and measured horizontal deformation information. In the current version of the M_R protocol, Poisson's ratios are assumed for the three test temperatures. However, the use of calculated Poisson's ratios developed from measured horizontal and vertical deformations in calculating the resilient modulus will be investigated in the pilot study.

Two separate resilient modulus values are obtained. One, defined as instantaneous resilient modulus, is calculated using

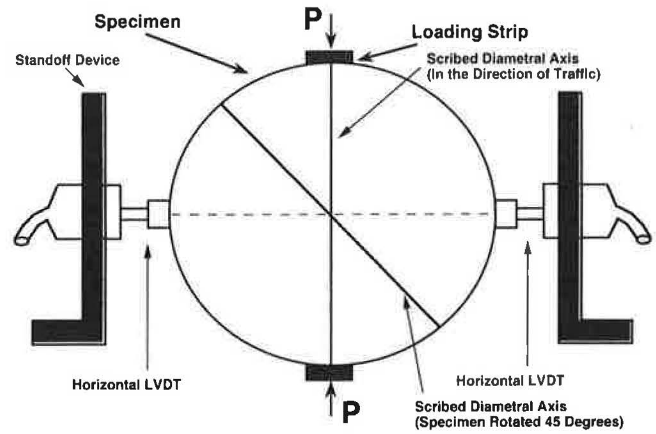

FIGURE 2 Proper loading and placement of horizontal transducers.

MOISTURE / TEMPERATURE / SUBGRADE TYPE / BASE THICKNESS	WET				DRY			
	FREEZE		NO FREEZE		FREEZE		NO FREEZE	
	F	C	F	C	F	C	F	C
LO	242401 (MD) 512004 (VA) 182008 (IN) 196150 (IA)	341638 (NJ) 541640 (WV) 261013 (MI) 271023 (MN)	223056 (LA) 052042 (AR) 412002 (AR)	124108 (FL) 479025 (TN)	382001 (ND) 836454 (MB) 307076 (MT) 901802 (SK)	322027 (NV) 829017 (BC) 201009 (KS) 327000 (NV)	067491 (CA) 404163 (OK) 062053 (CA) 062051 (CA)	321030 (NV) 404165 (OK) 371645 (NC) 068149 (CA)
HI	872811 (ON) 872812 (ON) 182009 (IN)	341033 (NJ) 341034 (NJ)	053071 (AR) 482108 (TX)	134112 (GA) 134113 (GA)	562017 (WY) 469187 (SD) 562020 (WY)	562019 (WY) 567772 (WY) 562037 (WY)	404154 (OK) 062004 (CA) 062647 (CA)	068201 (CA) 041062 (AZ) 041065 (AZ)

FIGURE 1 Pilot study experimental design.

the recoverable horizontal deformation that occurs during the unloading portion of one load-unload cycle. The other, defined as total resilient modulus, is calculated using the total recoverable deformation, which includes both the instantaneous recoverable and the continuing recoverable deformation during the rest period of one cycle.

For each resilient modulus test, the following general procedures are followed:

- The tensile strength is determined for a selected test specimen at 77 ± 2°F using the procedures described in this paper. The value of tensile strength determined by this procedure is then used to estimate the indirect tensile stress and the corresponding compressive load to be repetitively applied to the designated test specimens during the resilient modulus determinations.
- The test specimens are tested along two diametral axes at three rest periods (i.e., 0.9, 1.9, and 2.9 sec) and at testing temperatures of 41, 77, and 104 ± 2°F (5, 25, and 40°C ± 1°C). For each test temperature, repetitive haversine load pulses of 0.1-sec duration are applied to the individual test specimens with rest periods of varying duration between load pulses as described herein. The magnitude of load to be applied is based on a predefined percentage of the indirect tensile strength of a specimen. The general testing sequence includes initial testing at 41°F followed by testing at 77°F and final testing at 104°F.
- After completion of resilient modulus testing at 104°F, the test specimen is returned to 77°F and an indirect tensile strength test is performed in accordance with standard procedures to be outlined later. This test is performed to determine the tensile strength of the specific specimen actually used in resilient modulus testing.

In the pilot study, the resilient modulus test specimens subsequently are subjected to testing for maximum specific gravity and asphalt content using standard SHRP testing procedures.

TEST EQUIPMENT

Testing Machine

The machine used for SHRP resilient modulus testing is a top-loading, closed-loop, electrohydraulic testing machine with a function generator capable of applying a haversine-shaped load pulse over a range of load durations, load levels, and rest periods.

Temperature-Control System

The temperature-control systems are capable of attaining temperature control ranging from 41°F (5°C) to 104°F (40°C) while maintaining the specified temperature within ± 2°F (± 1.1°C). The system includes a temperature-controlled cabinet large enough to hold the load frame, one sample, and the horizontal and vertical deformation transducers. In most of the systems used by the SHRP testing laboratories, carbon dioxide is used to cool the chamber and electric heating elements are used to heat the chamber.

Specimen Holding and Loading Device

In addition to the closed-loop system, a diametral load guide device has been designed for SHRP testing. The loading device is a modified, commercially available (through special order) die set with upper and lower platens constrained to remain parallel during testing. The top platen is counterbalanced to minimize load effects for tests at elevated test temperatures. Attached to this load frame are two horizontal transducer holders positioned to provide a contact point of the transducer at the midheight of the specimen. These transducer holders are adjustable in order to "zero" the transducers before testing. Steel loading strips with a concave surface having a radius of curvature equal to a nominal 4.0-in.-diameter specimen are attached to the load frame to apply uniform loading to the diametral axis of the core. The outer edges of the loading strips have been rounded to remove sharp edges that might cut the core during testing.

This loading system has been designed to ensure that the load is applied evenly to the test specimen with no sample rocking or equipment flexure during testing.

Measuring and Recording System

The measuring and recording system includes sensors for measuring and recording horizontal and vertical deformations. The system is capable of recording horizontal deformations in the range of 0.000005 in. (0.00015 mm) of deformation (see Table 1).

The measuring or recording devices also provide real-time deformation and load information and are capable of monitoring readings on tests conducted to 1 Hz. Computer monitoring systems are used to generate real-time plots for viewing as the test progresses.

TABLE 1 Recommended Response Characteristics for Load Cell and Transducers

	Vertical	Horizontal
Measurement Transducers		
Max. Linear Stroke, mm	± 1.3	± 0.5
Max. Mechanical Travel, mm	4.0	1.5
Minimum Sensitivity, mv/v/mm	280	280
Nonlinearity, %FS	± 0.5	± 0.25
Min. Temperature Range, C	0 - 50	0 - 50
Load Cell		
Minimum Sensitivity, mv/v	2	
Nonlinearity, %FS	0.25	
Hysteresis, %FS	0.25	
Repeatability, %FS	0.10	
Maximum Deflection, mm	0.125	
Maximum Capacity, lb	800	

Horizontal Deformation Measurement

The transducers used to measure horizontal deformations are located at midheight and opposite each other along the specimen's horizontal diameter (Figure 2). Positive contact between the transducer tip and specimen is maintained during the test procedure. This is ensured by the use of spring-loaded transducers and the attachment of a suitable head as a contact point. In addition, the two horizontal transducers are wired so that each transducer can be read independently and the results summed during the test program.

Vertical Deformation Measurement

The two transducers used to measure vertical deformations are located on opposite sides of the upper platen of the load frame (Figure 3). These two transducers are equidistant from the actuator shaft and on a line coincident with the center of the two guideposts of the load frame and the center of the actuator shaft. The sensitivity of these measurement devices has been selected to provide the required level of deformation readout. A positive contact between the vertical transducers and the upper platen of the load frame is maintained during the test procedure. In addition, the two transducers are wired so that each transducer can be read independently and the results averaged during the test program.

Load Measurement

The repetitive loads are measured with an electronic load cell that meets the load requirements necessary for resilient testing (see Table 1).

SAMPLE HANDLING: PREPARATION AND MARKING

Size Requirements

Resilient modulus testing is being conducted on asphalt concrete specimens that are extracted from a single pavement layer and are more than 1.5 in. but less than 3.0 in. thick. The desired thickness for testing is 2.0 in. If the thickness of a particular AC layer scheduled for testing is 1 in. or more greater than the desired testing thickness of 2 in., then the 2-in. specimen to be used for testing is obtained from the middle of the AC layer by sawing the specimen. SHRP test samples that have projections or depressions higher or deeper than 0.1 in. are not tested unless no other suitable cores are available. In addition, specimens with ends that are skewed (either end of the specimen departs from perpendicularity to the axis by more than 0.5 degrees, or ⅛ in. in 12 in.) are not tested. Cores that have smooth, uniform curved surfaces as well as smooth and parallel top and bottom diametral faces are desired.

Specimens To Be Tested

Eight AC core locations have been designated for the P07 test on every flexible pavement test section in GPS study. If any of the test specimens obtained from the specified core locations are damaged or untestable, other cores that are in the same grouping but that have not been identified for other testing are substituted for M_R testing. Care is taken to ensure that high heat or other adverse conditions during storage do not deform the specimen or otherwise render it unfit for testing.

Preparation of Specimens Before Testing

Two diametral axes are marked on each test specimen to be tested using a suitable marking device (Figure 4). One axis shall be marked parallel to the traffic direction symbol (arrow) or "T" marked during the field coring operations. The other axis is marked at a 45-degree angle from the arrow (or T) placed on the specimen during field-coring operations. Slight adjustments in the marking locations are allowed to prevent the placement of the loading strips directly on exposed large-aggregate particles. The thickness of each specimen is then measured to the nearest 0.01 in. (0.25 mm). This thickness is determined by averaging three measurements taken equally spaced around the test specimen with a single center measurement.

The diameter of each test specimen is determined to the nearest 0.01 in. (0.25 mm) by averaging a minimum of two diametral measurements. The diameter of the axis parallel to the direction of traffic is measured first. Subsequently, the diameter of the axis perpendicular to this axis is measured.

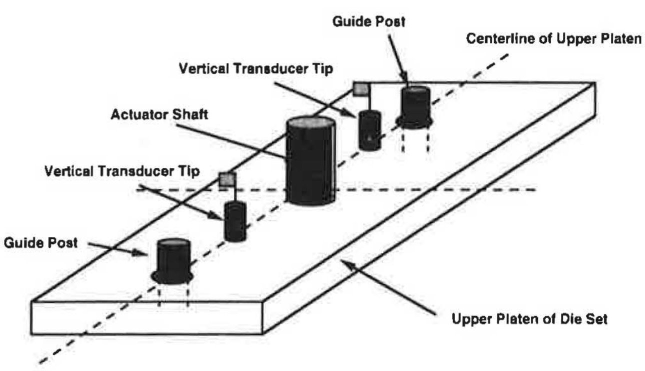

FIGURE 3 Placement of vertical transducers.

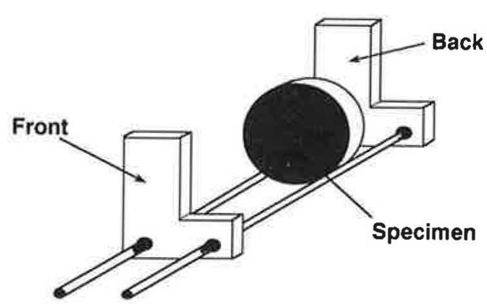

FIGURE 4 Specimen marking device.

These two measurements are averaged to determine the diameter of the test specimen. If the average diameter of the core is less than 3.85 in. or exceeds 4.15 in., the core is not to be tested. In this case, a replacement core is selected for the resilient modulus test.

TEST PROCEDURE

General

The asphalt cores are placed in a controlled temperature cabinet or chamber and brought to the specified test temperatures. Unless the core specimen temperature is monitored in some manner and the actual temperature known, the core samples remain in the cabinet for a minimum of 24 hr before testing.

The tensile strength of the designated test specimens are determined at 77 ± 2°F using the following procedure:

- The test specimen is marked, placed in the loading apparatus and positioned (this is a critical alignment and it is conducted with great care).
- A compressive load is applied at a controlled deformation rate along the axis marked parallel to traffic. A deformation rate of 2 in./min (50.8 mm/min) is used.
- The load is monitored during the entire loading time, or until the load sustained by the specimen begins to decrease. The indirect tensile strength is then calculated using the following equation:

$$S_t = \frac{(1.273 \times P_o)}{t} \times \left[\sin\left(\frac{57.2958}{D}\right) - \frac{1}{2 \times D}\right]$$

or

$$S_t = 0.156 \times P_o/t \text{ for a 4.00-in.-diameter core} \qquad (1)$$

where

P_o = maximum load sustained by the specimen (lb),
t = specimen thickness (in.), and
D = specimen diameter (in.).

Alignment and Specimen Seating

At each temperature, the test specimen is placed in the loading apparatus and positioned so that the diametral markings are centered top to bottom within the loading strips on both the front and back face of the specimen along the axis parallel to the direction of traffic (Figure 2). A check is also made to ensure that the midpoint of the specimen in the lengthwise (or thickness) direction is located and coincident with a vertical line of action through the test machine actuator shaft and the shank of the load guide device. The alignment of the front face of the specimen can be checked by ensuring that the diametral marking is centered on the top and bottom loading strips. With the use of a mirror, the back face can be similarly aligned. The first axis to be tested is the axis parallel to the direction of traffic (i.e., the load is being applied along the axis parallel to traffic). The head of the arrow should always be located at the top (12 o'clock) position and the upper surface (i.e., the newer pavement surface facing to the front).

The second axis tested is the axis 45 degrees from the initial axis parallel to the direction of traffic. The core specimen is similarly aligned along this axis before resilient modulus testing. The electronic measuring system is adjusted and balanced as necessary. Before testing and after the horizontal deformation transducers are mounted in the holding device, adjustments are required in the relative position of the transducers in order to match the mechanical "null" position with the electrical null or a near-zero voltage position (a similar null position is required for the transducers used to measure the vertical deformations during testing). When starting from the null position, the "travel" of the transducer shaft should be sufficient to require no further adjustment in the transducer position for the duration of a test.

Preconditioning

Preconditioning and testing are conducted while the specimen is in the temperature-control cabinet. Selection of the applied loads for preconditioning and testing at the three test temperatures is based on the tensile strength at 77°F, determined as specified previously. Tensile stress levels of 30, 15, and 5 percent of the tensile strength, measured at 77°F (25°C), are used in conducting the resilient modulus determinations at the test temperatures of 41, 77, and 104 ± 2°F (5, 25, and 40°C ± 1°C), respectively. Minimum specimen contact loads of 3, 1.5, and 0.5 percent of the 77°F tensile strength value shall be maintained during resilient testing for test temperatures, respectively, of 41, 77, and 104 ± 2°F (5, 25, and 40 ± 1°C).

The sequence of resilient modulus testing consists of initial testing at 41°F, intermediate testing at 77°F, and final testing at 104°F. The test specimens are brought to the specified temperature before each test. The test specimen is preconditioned along the axis by the application of a repeated haversine-shaped load pulse of 0.1-sec duration with a rest period of 0.9 sec, until a minimum of 10 successive horizontal deformation readings agree within 10 percent. The number of load applications to be applied depends on the test temperature. The expected ranges in number of load applications for preconditioning are 50 to 150 for 41 ± 2°F, 50 to 100 for 77 ± 2°F, and 20 to 50 for 104 ± 2°F. The minimum number of load applications for a given situation must be such that the resilient deformations are stable. If adequate horizontal deformations (greater than 0.0001 in.) are not recorded using 5, 15, and 30 percent of the tensile strength measured at 77°F (25°C), then the loads can be increased in increments of 5 (i.e., 10, 15, 20, 25 percent). If load levels different from 5, 15, and 30 percent of the tensile strength measured at 77°F (25°C) are used, they are noted on the data sheet.

Both the horizontal and vertical deformations are monitored during preconditioning of the test specimen. If total cumulative vertical deformations greater than 0.025 in. (0.625 mm) for 41°F or 0.050 in. (1.25 mm) for 77 and 104°F occur, the applied load is reduced to the minimum value possible and still maintain adequate deformations for measurement purposes. If use of smaller load levels does not yield adequate deformations for measurement purposes, the preconditioning is discontinued and an additional 10 load pulses are generated to use in the resilient modulus determination.

Testing

After preconditioning a specimen at a specific test temperature, the resilient modulus test is conducted as follows:

- A minimum of 30 load pulses (each 0.1-sec load pulse with a rest period of 0.9 sec) are applied and measured deformations are recorded. The application of load pulses continues beyond 30 until the range in deformation values of five successive horizontal deformation values (i.e. from lowest to highest value) is less than 10 percent of the average of the five deformation values. The rest period is then increased to 1.9 sec and a minimum of 30 load repetitions are applied. The rest period is then increased to 2.9 sec and a minimum of 30 load repetitions are applied.
- The recoverable horizontal and vertical deformations over the last five loading cycles are measured and recorded after the repeated resilient deformations have become stable. One loading cycle consists of one load pulse and a subsequent rest period. The vertical deformation measurements are also measured and reported. The resilient modulus will be calculated along each axis for each test period and temperature by averaging the deformations measured for the last five load cycles.
- After testing is completed for the first axis (load applied along the axis parallel to the direction of traffic), the specimen is rotated to the axis 45 degrees from the axis parallel to traffic and the preceding steps are repeated.
- When the specimen has been tested along both axes at a specific test temperature, it is raised to the next high temperature.
- After testing is completed at 104°F, the specimen is brought to a temperature of 77 ± 2°F and an indirect tensile strength test is conducted.

Calculations

The M_R equation used in ASTM D4123 is based to some extent on work by Hadley et al. (*4*) in which the equations for the indirect tensile test developed by Hondros (*5*) were used to develop a direct method of estimating modulus. These equations, however, are based on uniform contact pressure or a "flexible" loading condition. The resilient modulus equation used in SHRP's P07 Protocol was developed by Hadley to account for the use of the "rigid" curved steel applied loading strips used in applying the repeatedly applied load to the specimen (*6*). The P07 equation generally produces M_R values 20 to 25 percent greater than the ASTM equation.

The resilient modulus of elasticity, E, in pounds-force per square inch is calculated as follows:

$$E_{RI} = \frac{P \times D(0.080 + 0.297\nu + 0.0425\nu^2)}{H_I \times t} \quad (2)$$

$$E_{RT} = \frac{P \times D(0.080 + 0.297\nu + 0.0425\nu^2)}{H_T \times t} \quad (3)$$

where

E_{RI} = instantaneous resilient modulus of elasticity (psi),
E_{RT} = total resilient modulus of elasticity (psi),
P = repeated load (lbf) (P = applied load − minimum contact load),
t = thickness of test specimen (in.),
D = diameter of specimen (in.),
H_I = instantaneous recoverable horizontal deformation (in.),
H_T = total recoverable horizontal deformation (in.), and
ν = Poisson's ratio.

If calculated and not assumed, ν is as follows:

$$\nu_{RI} = \frac{0.859 - 0.08R_i}{0.285R_i - 0.040} \quad (4)$$

$$\nu_{RT} = \frac{0.859 - 0.08R_t}{0.285R_t - 0.040} \quad (5)$$

and

$$R_i = V_i/H_i \quad (6)$$

$$R_T = V_T/H_t \quad (7)$$

where V_i is instantaneous recoverable vertical deformation (in inches) and V_T is total recoverable vertical deformation (in inches).

QUALITY ASSURANCE AND QUALITY-CONTROL PROCEDURES

During the course of pilot study and production resilient modulus testing, the SHRP contract laboratories must follow very specific quality-assurance and quality-control (QA/QC) checks. These tests are meant to ensure consistent, repeatable results for the testing program.

Unscheduled Calibration Checks

The laboratories performing this testing have been issued a set of four synthetic reference samples. The moduli of these samples are known, and they are used for in-house quality assurance and quality control. To ensure that the test equipment is properly calibrated, these reference samples must be tested when

- The testing program is initiated;
- Start-up follows a 5-day delay;
- Equipment is replaced or repaired;
- Controller settings are adjusted; and
- Measurement problems are discovered.

Scheduled Calibration Checks

The following scheduled checks must be completed by each SHRP contract laboratory. Transducers must be calibrated daily to ensure proper deformation measurements. This calibration process can be conducted by the operator or technician performing the modulus testing. The load cell must also be checked weekly by the use of a proving ring. The transducers and load cell shall be sent to the manufacturer for calibration and inspection every 6 months.

Ongoing Operator Quality-Control Checks

During the actual testing of the SHRP samples, the operators must be aware of many simple checks that may be performed to ensure reasonable test results (Figure 5). During testing, the output from the vertical and horizontal transducers should be checked to identify specimen misalignment or rocking. Additionally, the response should be checked to identify "noise" (electrical disturbances in the signal output) in the system. Response curves should be smooth and free of erratic peaks and valleys. If these peaks and valleys are present, it is a sure sign that electrical disturbance is present too. The minimization of this noise is essential in order to record accurate results.

Upon initiation of M_R testing, the deformation values between the two vertical transducers must be checked primarily to identify improper specimen placement within the load guide device. In completing this check the greater vertical deformation reading should not exceed the lesser vertical deformation reading by more than 50 percent (i.e., $Y_G \leq 1.5\ Y_L$). If this limitation is exceeded, the test should be stopped and the contributing problem identified and corrected. Misalignment of the midpoint of the asphalt core thickness (or centroid of specimen) with respect to the system actuator–load guide device line of action is the usual cause of observed differences in vertical deformation readouts from the two transducers.

Deformation values between the two horizontal transducers must be checked to determine if the specimen is rocking. The

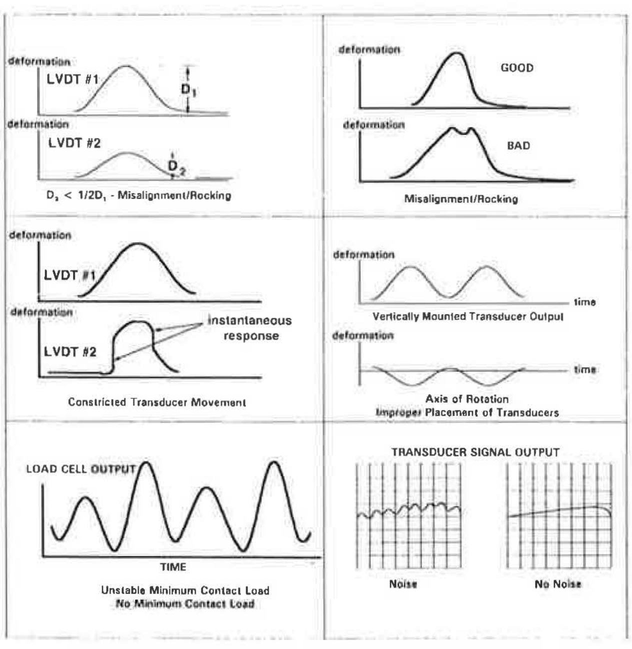

FIGURE 5 Ongoing QA/QC procedures.

deformation values should be compared, and the greater output should not exceed the lesser value by more than 50 percent (i.e., $X_G \leq 1.5\ X_L$). If this is not so, the test should be stopped and the problem identified and corrected. The problem is usually indicative of improper alignment of the test specimen (i.e., diametral markings) between the loading strips.

Horizontal transducer output should be checked to make sure that negative values are not obtained. If negative values are obtained, this is a sure sign of specimen misalignment or placement in the diametral load guide device.

Load cell output must be monitored to ensure that a consistent and appropriate load is being applied to the specimen. Nonconsistent load outputs can indicate that the contact load is unstable or that no minimum contact load is being applied.

The operator is the key person involved with resilient modulus QA/QC procedures. It is imperative that the system operators are aware of the warning signs and that action be taken to alleviate any of these problems as they occur.

CONCLUSION

Significant progress has been achieved in the development of the SHRP-LTPP asphalt concrete resilient modulus testing procedure. However, much must still be learned about actual production testing using this procedure. Testing to date has been accomplished on a limited basis on few samples. This project has the potential to bring the AC resilient modulus test procedures now being used out of the university laboratories and into the mainstream. This will be accomplished only by proceeding with production type testing for a long period of time. During this time, many factors will be evaluated and the procedure may be streamlined or modified to decrease the complexity of the test and its many processes.

Through the resilient modulus of asphalt concrete testing program, it is believed that many things will be learned about pavement performance due to various materials and procedures currently in use. This test has the potential to go a long way in reaching the objectives set for the SHRP-LTPP program in 1987.

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