ASPHALT RHEOLOGY

Relationship To Mixture

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editor

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ASPHALT RHEOLOGY: RELATIONSHIP TO MIXTURE

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NOTE

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Foreword

The papers in this publication, *Asphalt Rheology: Relationship to Mixture,* were presented at the symposium on Rheological Properties of Asphalts and Their Effects on the Mixture Properties and Pavement Performance held 11 December 1985, in Nashville, Tennessee. The symposium was sponsored by ASTM Committee D-4 on Road and Paving Materials. Oliver E. Briscoe, Maryland State Highway Department, presided as chairman of the symposium and editor of this publication.

A Note of Appreciation to Reviewers

The quality of the papers that appear in this publication reflects not only the obvious efforts of the authors but also the unheralded, though essential, work of the reviewers. On behalf of ASTM we acknowledge with appreciation their dedication to high professional standards and their sacrifice of time and effort.

ASTM Committee on Publications

Contents

Overview

Since the 1973 oil embargo numerous field construction and maintenance personnel throughout the United States have claimed that asphalt cements have changed and that these changes in asphalts have resulted in construction and early-life performance problems in asphalt concrete mixtures. The general belief of field personnel is that the oil companies are taking the "goodies" out of the asphalt and using them as feedstock for the petrochemical industry. Another widely held belief is that the oil embargo, this country's dependence on foreign crudes, the rapid development of new producing crude oil fields, and economic pressures have forced the oil companies to use less than desirable crudes to manufacture asphalt. Field personnel are convinced that the present asphalt specification tests, which are routinely performed, do not identify the important properties that control field construction and pavement performance.

As evidence of these statements, the field engineers cite a general increase in the occurrence of problems such as placement difficulties (tender mixes), excessive displacement under traffic (low stability), thermal cracking, raveling, and stripping (water susceptibility) of asphalt concrete pavements. These problems result in higher maintenance costs, shorter service life, higher life-cycle costs, and criticism by the driving public.

Certainly the opinions of these experienced field engineers must be heard; however, caution is in order. For example it was indicated that tenderness problems were evident in California pavements in the 1940s. Field engineers complained that asphalt "ain't as good as it use to be" as early as the 1930s, and asphalt cracking problems were evident early in the history of asphalt concrete use. In addition, these claims are often vague in nature and are not supported by definitive physical and chemical property data.

Most construction and early performance problems are associated with more than one potential cause. For example, raveling of an asphalt concrete surface course can be caused by one or a combination of the following factors: poor asphalt quality, low asphalt content, asphalt brittleness, high air void content of mixture, susceptibility to damage by moisture, shear forces due to traffic, and so forth. Clearly, the engineer should investigate all possible causes before "laying blame." Similarly, the properties of the asphalt cement should not necessarily be blamed for the recent increase in construction and early performance problems experienced on our nation's highways. Basic societal changes including increased weight and number of vehicles, air quality, and worker safety requirements and the development of equipment to increase production have placed ever changing demands on paving materials.

In an attempt to more adequately define historic changes in asphalt cements, research programs were initiated. The papers contained in this publication present information and techniques on the rheology of asphalts, their modification, and their effects. Those papers were presented during the symposium on Rheological Properties of Asphalts and Their Effects on the Mixture Properties and Pavement Performance, which was sponsored by ASTM Committee D-4 on Road and Paving Materials.

This publication is intended to create awareness and understanding of technology relating to asphalt rheology and its influence on pavements performance.

Most of the asphalt cracking problems have more than one cause; however, this publication deals primarily with asphalt and asphalt mixture rheological modifications. A portion of this publication deals with the precision testing of asphalt and asphalt mixtures as related to rheological properties.

The physical and chemical modifications of asphalt rheology allow for a different consideration of mix design and pavement structure since the performance level is indicated to be at a higher range after modification. Modifications, as indicated in the papers, have been accomplished through the use of various additives.

Although the information was largely gathered in laboratories, the information appears promising and needs a greater volume of field data to support the theory.

The information should be of tremendous value to design engineers, materials engineers, contractors, producers, and owners in their efforts to utilize materials of marginal quality, to improve mixture characteristics, and to improve pavement performance.

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Asphalt Rheology to Define the Properties of Asphalt Concrete Mixtures and the Performance of Pavements

REFERENCE: Roque, R., Tia, M., and Ruth, B. E., **"Asphalt Rheology to Define the Properties of Asphalt Concrete Mixtures and the Performance of Pavements,"** *Asphalt Rheology: Relationship to Mixture, ASTM STP 941,* O. E. Briscoe, Ed., American Society for Testing and Materials, Philadelphia, 1987, pp. 3–27.

ABSTRACT: The behavior of asphalt concrete paving mixtures at low temperatures is primarily dependent upon the rheological properties of the asphalt binder. The Schweyer Constant Stress Rheometer was used to define the low-temperature rheological properties of asphalts recovered from laboratory-compacted mixtures and field cores. Asphalt viscosity relationships with resilient modulus, mix viscosity, static modulus, stiffness, fractures strain, fracture energy, and fracture stress of the mix were established using dynamic, static, and constant stress indirect tension testing procedures.

Resilient moduli predicted from the viscosity of asphalts recovered from pavements were used in elastic layer analyses to define deflection and strain basins produced by Dynaflect or plate tests. These deflection and strain basins compared favorably with those measured on a test pit pavement and on selected in-service pavements.

Relationships between asphalt viscosity and mix parameters are presented to illustrate the importance of asphalt viscosity and to suggest their potential use in the modeling of the thermal behavior of flexible pavements. It is shown that there is no appreciable difference between resilient and status moduli when asphalt viscosity exceeds about 400 MPa·s. The importance of shear susceptibility for both asphalt and mix viscosity determinations is discussed with recommendations for use of constant power viscosity to minimize errors induced by extrapolation of viscosity at shear rates outside those obtained in the test.

Parameters for thermal and load induced fracture include stress, strain, and energy. Laboratory test results were used to develop relationships between these parameters and the constant power viscosity of the asphalt binder. Tests on pavement cores produced fracture corresponding to that obtained in the laboratory tests. Comments are provided on the reliability of these parameters in defining fracture.

KEY WORDS: asphalt and mix rheology, Schweyer Constant Stress Rheometer, indirect tension test, low-temperature characterization, pavement response, temperature-asphalt viscosity effects, fracture

The importance of asphalt and mix properties on the low-temperature behavior of asphalt pavements is well recognized. Unfortunately, material

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specifications and pavement design methods generally neglect any consideration of material properties to enhance the low-temperature performance of flexible pavements. This situation exists because (1) the response of pavements to thermal and load-induced stresses are not clearly understood, (2) very little emphasis has been placed on the measurement of material properties at low temperature, and (3) suitable methods for analysis have not been developed.

The purpose of this discussion is to present a clear picture of how the asphalt rheological properties are related to mixture parameters determined by using static, dynamic, and constant stress modes of the indirect tension test. Some emphasis will be placed on the applicability of the Schweyer Constant Stress Rheometer for developing viscosity-temperature relationships and its use in predicting mixture parameters. Resilient modulus estimation for elastic layer analyses will also be discussed in relation to pavement deflection and strain measurements.

Resilient Modulus

Difficulties Encountered in Testing

The determination of resilient modulus from most laboratory tests is plagued with large differences in moduli values because of the characteristics of both materials and test methods. It should be recognized that modulus computations based on conventional elastic equations using deflections or diametral deformations apply only when creep is minimal or nonexistent. Therefore, the laboratory testing of asphalt mixtures requires lower test temperatures when asphalt viscosity is low or when shorter times of loading and lower applied stress are used.

Rather than elaborate on the relative shortcomings of test methods, we should address the problem of whether or not the laboratory-measured moduli correspond to that in the pavement. This means we must rely on the use of deflection basins from nondestructive testing equipment (for example, Road Rater, Dynaflect, or Falling Weight Deflectometer) and elastic layer theory to establish moduli for asphalt concrete pavements.

Recommended Laboratory Testing Procedures

The dynamic indirect tension test has been used to evaluate the moduli of both laboratory-compacted specimens and cores from existing pavements. Gyratory compacted specimens and cores, 10.16 cm (4 in.) in diameter, have been tested at different temperatures using 1.27-cm (0.5-in.) long bonded strain gages to evaluate either total or instantaneous resilient strain response of specimens subjected to a 0.1 s haversine loading with a 0.4 s rest period. The resilient modulus ($E_{0.1}$) is computed directly from the computed stress and total resilient strain without regard for Poisson's ratio, making it difficult if not impossible to determine for viscoelastic materials. The equation for computation of $E_{0.1}$ is

$$E_{0.1} = \frac{\sigma}{\epsilon_{TR}} = \frac{2P}{\pi l d(\epsilon_{TR})} \quad \text{(psi)} \tag{1}$$

where

σ_t = indirect tensile stress, psi,
P = applied load, lb,
l = thickness of test specimen, in.,
d = diameter of test specimen, in., and
ϵ_{TR} = total resilient strain

The basic procedure is to compact specimens or obtain cores that are representative of the pavement being evaluated. Generally, it is preferable to have specimens between 5.08 and 7.62 cm (2 and 3 in.) in thickness. Poor coring equipment or procedures or both may result in an irregular or skewed surface where the curved 1.27-cm (0.5-in.) indirect tension test loading plates contact the specimen. These specimens should be discarded if possible. Gyratory compaction is preferred over kneading or Marshall compaction because the aggregate orientation is comparable to that achieved by field compaction methods.

The instrumentation of the specimen with a strain gage requires surface preparation on any specimen not having a sawed face. Chill specimens in a freezer, use a belt sander to remove asphalt, and polish exposed aggregate surfaces. Care must be taken to prevent overheating, which will result in asphalt smearing of exposed aggregate. Surfaces can be cleaned with a bristle brush or with high-pressure air, provided no oil or water contaminants are present in the air supply. Orient the specimen to obtain the most uniform distribution of exposed aggregate for bonding of the 1.27-cm (0.5-in.) long strain gage. The gage is epoxyed in place along this axis (horizontal) and centered about the loading axis (vertical). A 0.625-cm. (0.25-in.) offset of the strain gage above or below the center of the specimen does not appear to have any effect on the strain measurement. Note that the strain gage is long enough to result in an average strain corresponding to a 95 to 100% stress level; again, this is not considered detrimental to the accuracy and precision of the test.

Test temperatures recommended for resilient modulus testing are 25, 15, 5, and −5°C (77, 59, 41, and 23°F) although other temperatures may be derived to bracket in-service low pavement temperatures. Testing at or above 25°C (77°F) may produce questionable results depending on the degree of compaction and asphalt viscosity. For example, the stiffness of the strain gage is often too high for testing of specimens prepared with an AC-20 above 25°C (77°F).

The key to reproducible results is to properly precondition the test specimen. This is accomplished by applying a low level constant stress to the specimen at 25°C (77°F) until a creep strain of about 100 to 150 μm/m (100 to 150 μin./in.) are obtained in 4 to 8 min. If necessary, the applied load may be increased if the creep rate is too slow. Remove the applied load and allow time for recovery of elastic and delayed elastic strain. Dynamic testing can then be initiated.

Five or more stress levels should be selected for resilient modulus testing. The maximum stress must be carefully selected to prevent excessive accumulation of creep strains. Usually 20 cycles at each stress level is adequate for evaluation of the total resilient strain. Allow for strain recovery after testing at each stress level. This will minimize the total accumulated strain and aid in preventing early failure of the specimen, particularly at extremely low temperatures. Testing can proceed at sequentially lower temperatures following the same procedure without any additional preconditioning. Numerous specimens can be tested at a given temperature prior to the testing at a lower temperature without any apparent loss of the preconditioning treatment.

At extremely low temperatures where $E_{0.1}$ is approaching or greater than 6.9E9 Pa (1E6 psi) the strain tolerance of the specimen is extremely low. Overstressing resulting in brittle fracture of the specimen is quite possible unless stress levels are limited to 1379 kPa (200 psi) or less for specimens that have a maximum low tensile strength of 2758 to 3447 kPa (400 to 500 psi). In general, stress levels should not exceed 50% of the maximum low-temperature tensile strength.

Correlation to Asphalt Viscosity

Asphalt cements recovered from pavement cores and laboratory compacted specimens using the Abson procedure were tested at different temperatures using the Schweyer Constant Stress Rheometer. The computed values of viscosity at a shear rate of 1.0 s^{-1} and the C-value (shear susceptibility factor or complex flow value) were used to compute the constant power viscosity (η_j)

$$\eta_j \text{ (where } j = \tau_j \dot{\gamma}_j = 100 \text{ W/m}^3) = \eta_{100}$$

$$\eta_{100} = \eta_{1.0} \left(\frac{100}{\eta_{1.0}}\right)^{C-1/C+1} \tag{2}$$

where

η_{100} = viscosity at a constant power of 100 W/m^3, Pa·s,
τ_j = applied shear stress, Pa,
$\dot{\gamma}_j$ = shear rate response, s^{-1},

$\eta_{1.0}$ = viscosity at 1.0 s^{-1}, Pa·s, and
C = shear susceptibility factor.

This constant power viscosity has the advantage of minimizing extrapolation errors since the shear rate ($\dot{\gamma}_i$) is within or close to the shear rates obtained from the rheometer tests. In effect, an error or variability in the C-factor will have very little effect on the computed viscosity regardless of temperature as compared to extrapolation of the viscosity to any fixed shear rate.

Viscosity-temperature relationships generally used in regression analysis are

$$\log \eta_{100} = a + b \log(K) \tag{3}$$

$$\log \eta_{100} = a + b \log(°R) \tag{4}$$

or

$$\log \eta_{100} = a + b \log(°C) \tag{5}$$

Both Eqs 4 and 5 may be used exclusively for low-temperature [≤ 25°C (77°F)] viscosity predictions or often the 60°C (140°F) absolute viscosity can be incorporated to achieve excellent correlation and predictive accuracy. Occasionally, when predicting viscosities below 25°C (77°F), Eq 6 can be used effectively. Figure 1 illustrates the asphalt viscosity-temperature relationship obtained from two sample sites on a section of U.S. Route 27 at Palm Beach, Florida.

The resilient moduli for U.S. 27 are plotted in Fig. 2 for comparison to the resilient modulus-constant power asphalt viscosity relationship developed previously by Ruth and Bloy [*1*]. The regression lines essentially superimpose although some variation between the plotted data and Ruth and Bloy's relationship exists in the viscosity range of 1.0E10 Pa·s. Also, the test results from a test pit pavement are shown to illustrate that higher air void content mixtures (7.0 versus 3% to 4%) result in a greater reduction in resilient modulus as the asphalt viscosity decreases with increased temperatures.

At the present time, the best prediction of resilient modulus is obtained using

For $\eta_{100} \leq 9.19E8$ Pa·s

$$\log E_{0.1}(\text{Pa}) = 7.1866 + 0.3068 \log \eta_{100} \tag{6}$$

and for $\eta_{100} > 9.19E8$ Pa·s

$$\log E_{0.1}(\text{Pa}) = 9.5135 + 0.0472 \log \eta_{100} \tag{7}$$

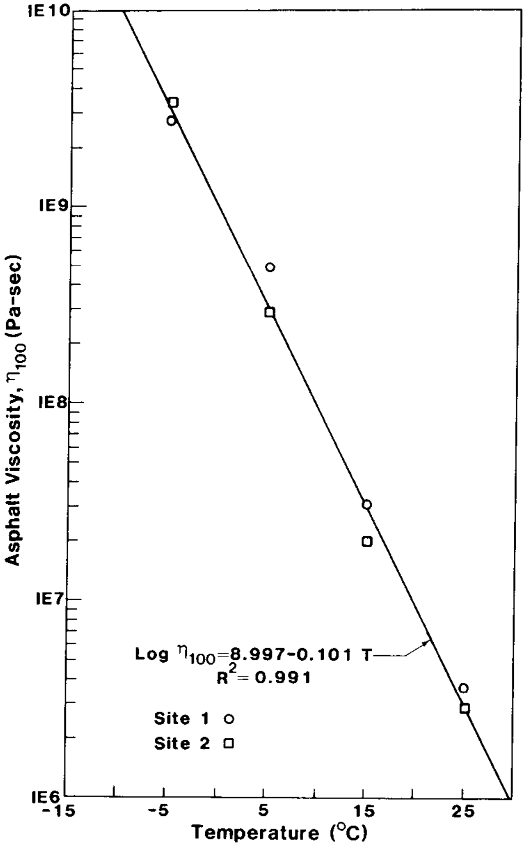

FIG. 1—*Low temperature asphalt rheology.*

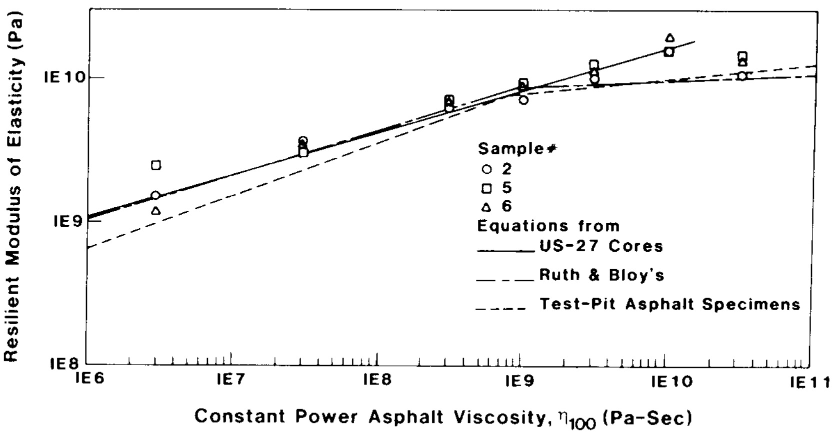

FIG. 2—*Resilient modulus-asphalt viscosity relationship.*

These equations have been used to predict the resilient moduli of in-service pavements with reasonable accuracy.

Pavement Response-Predictions of E_1

Pavement evaluation investigations in Florida usually rely on Dynaflect or Falling Weight Deflectometer data to determine uniformity, structural adequacy, and layer moduli. Layer moduli are computed either from empirical correlations with plate bearing moduli or from iteration of moduli in an elastic multilayer stress analysis program. The use of recovered asphalt viscosity to predict the resilient modulus ($E_{0.1}$) of the pavement has proven to yield good results in elastic layer programs for analysis of both field and test pit pavements.

Figure 3 is an illustration of a pavement section as constructed in the Florida Department of Transportation's test pit. Asphalt recovered from samples of hot mix were tested to establish the η_{100} versus temperature relationship which in turn was used to predict the viscosity at the 20°C (69°F) pavement test temperature. Using Eq 7, a resilient modulus (E_1) of 857 738 kPa (124 400 psi) was obtained for use in the elastic layer analysis program.

Strain gages and linear variable differential transformers (LVDTs) installed at various positions from the 30.48-cm (12-in.) diameter plate, illustrated in Fig. 4, provided response measurements to the imposed dynamic loads. The measured response is compared to the predicted response for deflection and pavement surface strains in Figs. 5 and 6, respectively. In both cases, the predicted response corresponds very closely

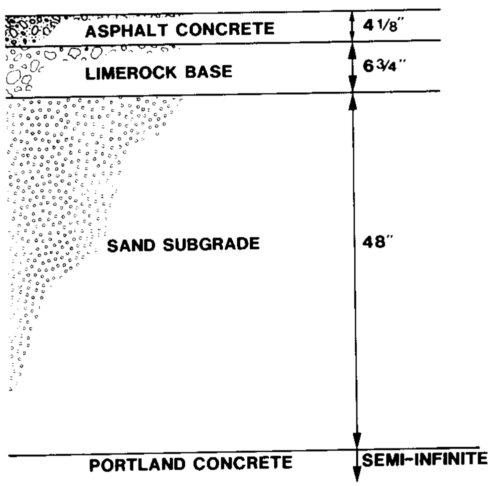

FIG. 3—*Pavement system in the test pit as modeled for elastic layer analysis.*

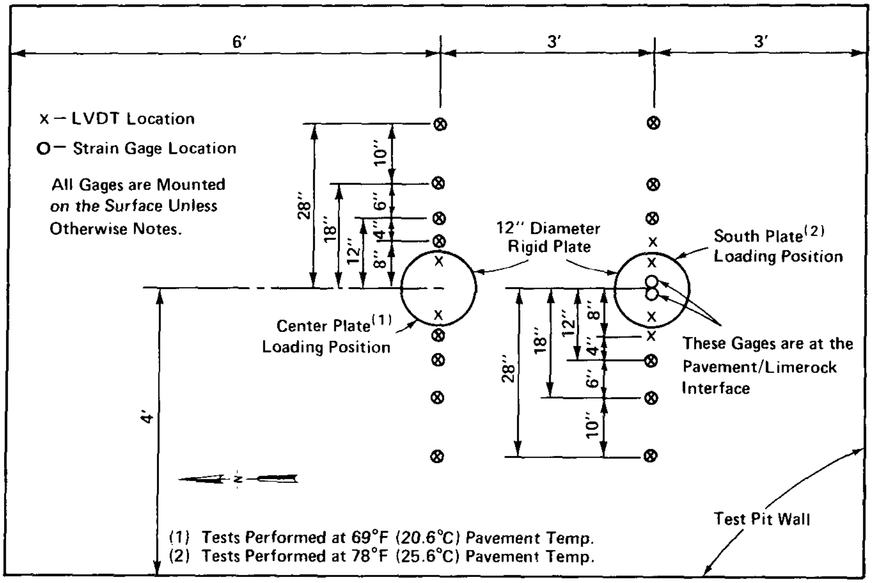

FIG. 4—*Location of plate loading positions and strain and deflection measurements.*

to the measured response. As a point of interest, this pavement was retained after initial testing and two years later tested with a dual wheel assembly using a 690-kPa (100-psi) tire pressure. Measured and predicted responses were substantially different. Asphalt recovered from samples of the asphalt concrete taken during removal of the test pavement indicated that hardening almost identical to that observed in the field had occurred

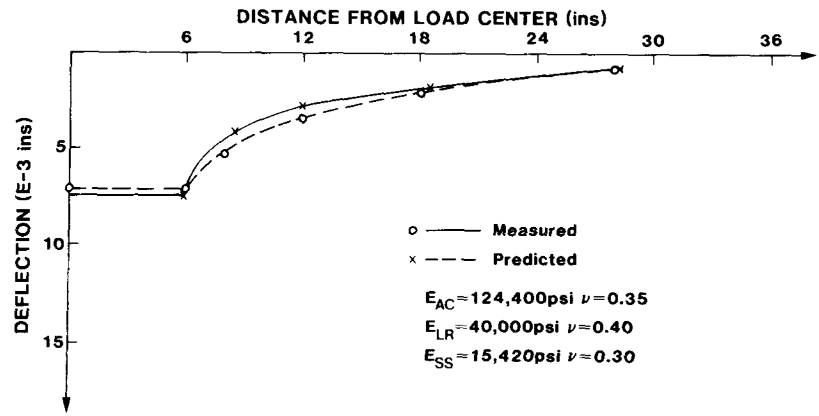

FIG. 5—*Measured versus predicted deflections,* E_2 *= 40 000 [20.6°C (69°F)], 1814 kg (4000 lb).*

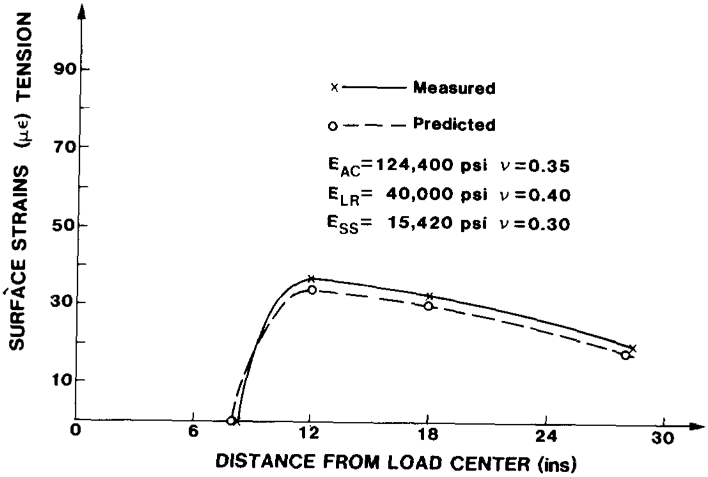

FIG. 6—*Measured versus predicted strains,* E_2 = *40 000 [20.6°C (69°F)], 1814 kg (4000 lb).*

over the two-year period. A new resilient modulus was computed which provided predicted deflection and strain response values which closely match those measured immediately prior to removal of the pavement.

Test Parameters for Thermal Response Modeling

Conceptual and Observed Response

The thermal response of an infinitely long segment of asphalt concrete highway pavement can be conceptualized in two ways. One is to consider full bonding to a high quality granular base having a relatively low coefficient of thermal expansion. The second way is to assume little bonding or friction which can easily be overcome by the contraction or expansion of the asphalt pavement.

In the first case, the contraction strain (ϵ_{con}) produced by cooling of the pavement will be equal to the elastic, delayed elastic, and creep strains. A strain gage bonded on the pavement would indicate no strain unless this bond was overcome and the pavement cracked in the vicinity of the gage. However, the imposed thermal stress is dependent upon the rate of cooling and the amount of creep. At warmer temperatures, the creep rate may be sufficient to keep tensile stress and elastic strain relatively low. At lower temperatures, the creep strain rate decreases rapidly, resulting in higher levels of tensile stress. Therefore, higher rates of cooling and lower minimum temperatures in relation to asphalt viscosity (or viscosity of the mix) increase the potential for development of tensile stresses and creep strains that are of sufficient magnitude to crack the asphalt concrete pavement.