Asphalt Mix Design: An Innovative Approach

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Using the results of Marshall and constant and cyclic load indirect tensile tests, it is shown that the indirect tensile tests can be used to infer the structural properties of compacted asphalt mixes without the need to use other expensive test apparatus. It is also shown that if the Marshall test is modified, the asphalt mix procedure can be tailored to optimize the structural properties of the mix. Correlations between the asphalt mix design parameters and the structural properties and the respective statistical matrix are presented and discussed. All tests were conducted on Marshall-sized specimens made from various asphalt concrete mixes.

Structural properties of asphalt mixes have a direct bearing on pavement performance under traffic loading and environmental conditions (*1–7*). Determining the relevant structural properties can be tedious and involved because these properties change with environmental conditions. Unlike the properties of mineral aggregate in the mix or in the base and subbase layers, which are relatively constant, physical and chemical properties of asphalt binder are dynamic in nature and are influenced by temperature, moisture, and time. In addition, the response of asphalt mixes to load is the result of three different mechanisms: elastic, viscoelastic, and plastic (*8–13*). Thus some of the relevant structural properties of asphalt mixes needed for the design of asphalt pavement include resilient characteristics, plastic (permanent) deformations, creep, and fatigue behavior.

Asphalt mixes are largely composed of coarse and fine aggregates, mineral filler, asphalt binder, and air voids. The proportions of these components in any given mix (the asphalt mix design) affect its structural properties and dictate its behavior under traffic loading. Existing practices divorce asphalt mix design procedures from those used to obtain structural properties. Thus a major problem facing the pavement engineer today is tailoring the asphalt mix design to optimize its structural properties to result in the best pavement performance under the anticipated traffic loading and environmental conditions.

In recognition of this need, researchers have developed several equations correlating the structural properties of the compacted mix and the mix design parameters. Some of these correlations were based only on the stiffness of the binder. Others were based on proportioning of the different materials in the mix. Still others were based on the Marshall stability and flow values (*14–23*). Each of these correlations was found to be limited to certain mixes or binder stiffness. In addition, fatigue properties of compacted asphalt mixes still need to be evaluated or estimated, or both.

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In recognition of these shortcomings, a research project sponsored by the FHWA was undertaken to identify, evaluate, and document a laboratory test procedure or procedures whereby asphalt mix design can be examined from the structural viewpoint. The results of the study should help the highway engineer to determine the structural properties of asphalt concrete mix that are needed in the design of flexible pavements.

EXPERIMENTAL PROGRAM

To accomplish the objectives of the study, an experimental program was undertaken to evaluate the structural and other parameters of compacted asphalt mixes. The test results of this study are tabulated elsewhere (*24*). This paper addresses the problems associated with Marshall and indirect tensile tests. Also, a new approach to obtaining the structural parameters of asphalt mixes needed in the pavement design methods is presented. A companion paper by Baladi et al. in this Record addresses variations of the structural properties with respect to variations in the specimen and test variables. To avoid unnecessary duplication, the reader is referred to the work of Baladi (*24*), Baladi et al. (*25*), and the other paper in this Record by Baladi et al. for sample preparation and test procedures and for a description of a new indirect tensile test apparatus that was developed during the course of the investigation. For completeness and convenience however, the test types and test materials are briefly described here.

Laboratory Tests

The following tests were conducted using the new indirect tensile test apparatus (*24*):

1. Indirect tensile tests (INTT) using a standard Marshall loading frame and deformation rate. Some of the test specimens were conditioned as standard Marshall specimens. Others were tested dry at 60°C, 25°C, and 5°C (140°F, 77°F, and 40°F).
2. Indirect constant peak cyclic load (INCCL) tests using an MTS hydraulic system. The specimens were subjected to a constant sustained load followed by a constant peak cyclic load of 500 lb. Some of the test specimens were subjected to a maximum of 500,000 cycles at a frequency of two cycles per second with a loading time of 0.1 sec and a relaxation period of 0.4 sec. Measurements of elastic, total, and plastic (permanent) deformations were collected along the vertical and horizontal diameters and the thickness of the specimen. The data were then analyzed to obtain the resilient and total characteristics of the specimens and their fatigue lives.

3. Indirect variable peak cyclic load (INVCL) tests using an MTS hydraulic system. Basically, the test procedure is the same as that of the INCCL test except that after the application of the sustained load, the specimen was subjected to 100-, 200-, and 500-lb peak cyclic loads; each load was applied for only 1,000 cycles.

4. Marshall tests at the design asphalt content. Some of the test specimens were conditioned as specified by the standard Marshall test procedures. Others were conditioned dry at 40° F and then tested at the same temperature. For all of the Marshall tests, an equivalent Marshall stiffness (ES) was defined using the load-deformation record and Equation 1.

$$ES = S/2\,[F_{0.5(s)}] \qquad (1)$$

where

ES = equivalent stiffness (lb/in.),
S = Marshall stability (lb), and
$F_{0.5(s)}$ = flow at half the value of Marshall stability (in.).

A total of 125 samples (375 specimens) were made and tested using the new indirect test apparatus (75 for each of the INCCL, INVCL, and Marshall tests, and 150 for the INTT). In the remaining parts of this paper, the term "sample" is used to describe one test sample that was later cut to three (triplicate) test specimens. It should be noted that

1. All samples were made using several materials as described in the next section.
2. All indirect tests were conducted using a new indirect tensile test apparatus.
3. For all of the tests and for each combination of the test materials, a constant (design) asphalt content was used. This design asphalt content corresponds to that at 3 percent air voids as determined by using separate standard Marshall mix design procedures.

Test Materials

The test materials used in this study were

1. Three different types of aggregate were used: crushed (angular) limestone, rounded natural (river deposit) aggregate, and a mix of 50 percent by weight per sieve of crushed limestone and natural aggregate;
2. Fly ash mineral filler;
3. Two aggregate gradations (*24* and the other paper in this Record by Baladi et al.); and
4. Three viscosity-graded asphalt cements (AC-10, AC-5, and AC-2.5).

For each material combination, a constant percentage of asphalt content was used (the percentage of asphalt content at 3 percent air voids as determined from the standard Marshall mix design procedures). The samples were compacted near three values of percentage of air voids (3, 5, and 7 percent) by varying the foot pressure and number of tampings of a kneading compactor. For each material combination and percentage of air voids, a cylindrical sample 10.16 cm in diameter and 22 cm high (4 in. by 8.5 in.) was made. Later, the sample was cut into three 6.3-cm-high (2.5-in.) specimens. The three specimens (a triplicate) were then tested under the same conditions (test temperature and test type) using the new indirect tensile test apparatus for the INTT, INCCL, and INVCL tests and a standard Marshall apparatus for the Marshall tests.

ANALYTICAL MODELS

The analytical models used to calculate the resilient and total moduli and Poisson's ratios and the tensile and compressive strengths were developed on the basis of linear, homogeneous, and isotropic elastic models. Details of these models may be found elsewhere (*24*). Equations 2 and 3, to calculate the compressive and tensile strengths of compacted asphalt mixes, are relevant to the following discussion.

$$INCS = 0.475386\ (P/L) \qquad (2)$$

$$INTS = 0.156241\ (P/L) \qquad (3)$$

where

$INCS$ = indirect compressive strength (psi),
$INTS$ = indirect tensile strength (psi),
P = maximum load (lb), and
L = specimen thickness (in.).

STATISTICAL MATRICES

The main objective of the statistical analysis was to determine if results from one type of test (e.g., the Marshall test) can or cannot be used to infer the results from other tests (e.g., cyclic load indirect tensile tests). Traditionally, this was accomplished by a simple statistical correlation between one set of results and another. Such correlations ignore the physical interpretation of the data and simply relate one set of numbers to another. Consequently, the resulting correlation equations are naturally limited to a specific set of data. A better method is to independently examine each set of data and analyze its variations with the given set of variables. For example, if the Marshall results show that stability and flow are related to one variable (e.g., the percentage of air voids) and the INCCL results show dependency on another variable or other variables, then perhaps the results from the latter tests cannot be related to stability and flow. If the results from both tests are not satisfactory, any correlation between them is problematic.

To this end, results from each test were examined for specific patterns with regard to the independent variables. The factors that influence the test results are summarized in Table 1. Numbers under the variables indicate the order of significance of that variable for the test results. For example, the percentage of air voids is the second most significant factor affecting Marshall stability for all tests that were conducted at the design asphalt content but different percentages of air voids. Flow value, on the other hand, is influenced by (in order of decreasing significance) load (stability), gradation, percentage of air voids, and aggregate angularity. Equations 4–10 relate Marshall stability, flow, equivalent stiffness, indirect compressive strength, indirect tensile strength, resilient modulus, and total modulus to the specimen and test variables, respectively. It resulting equations. Nevertheless, results from INTT (Equations 7 and 8) were statistically related to those from INCCL tests (Equation 9), which resulted in the following equations:

$$\ln(MR) = 7.1949 + 1.01341 \times \ln(INCS) - 0.0003409 \times CL \quad (12)$$

$R^2 = 0.974$; $SE = 0.220$

$$\ln(MR) = 8.3145 + 1.01511 \times \ln(INTS) - 0.0003409 \times CL \quad (13)$$

$R^2 = 0.974$; $SE = 0.220$

where all variables are as before.

The estimated values of the resilient modulus, using Equations 12 and 13, were found to vary by 13 percent from the measured ones. The equation overestimated the resilient modulus for the 3 percent air voids specimens and underestimated it for the 7 percent air voids specimens. These observations suggested that a correction to Equation 12 should be derived to account for the percentage of air voids. Examination of the regression coefficients of Equations 7–9 indicated that *AV* affects the values of ln(*INCS*) and ln(*INTS*) by a factor of about –0.26 and the values of ln(*MR*) by a factor of –0.14. This implies that the effect of *AV* is much greater on *INCS* than on *MR*. This was expected because, as noted previously, *INCS*-values are based on the load at failure (Equation 2); the values of *MR* are based on smaller loads and the elastic component of the deformation. Thus the relationship between *MR* and *INCS* should also account for the effects of *AV*. A second regression was done in which the percentage of air voids was included as one of the independent variables. This yielded the following equations:

$$\ln(MR) = 6.1776 + 1.08108 \times \ln(INCS) + 0.14145 \times AV - 0.0003409 \times CL \quad (14)$$

$R^2 = 0.996$; $SE = 0.085$

$$\ln(MR) = 7.3667 + 1.08335 \times \ln(INTS) + 0.14218 \times AV - 0.0003409 \times CL \quad (15)$$

$R^2 = 0.996$; $SE = 0.083$

where all variables are as before.

It should be noted that *INCS* in Equations 14 and 15 is also dependent, in part, on the percentage of air voids. That is, a collinearity is introduced into the equation. Also, the positive values of the regression coefficient of the percentage of air voids (0.14145 and 0.14218) does not mean that increasing *AV* increases *MR*. On the contrary, increasing *AV* yields a decrease in *MR*. This is mainly related, as stated earlier, to the interpretation of the equation. The *AV* term in Equations 14 and 15 accounts for the difference between the effects of the air voids on *INCS* and the effects on *MR*. Stated differently, the percentage decrease in the value of *INCS* due to an increase in *AV* from 3 to 7 percent is greater than the percentage decrease of *MR* for the same range of *AV*. To relate the *INCS*- and *MR*-values, this difference has to be accounted for; the *AV* term in the equations accounts for this difference. From an engineering viewpoint, Equations 14 and 15 should not be used because interpretation of the equation may mislead the user (higher values of the percentage of air voids cause higher resilient modulus). The equations are introduced here for one reason, to be able to estimate the resilient modulus for the same specimen subjected to the indirect tensile test. Hence laboratory costs are minimized. Again, the equations should not be used for physical or mathematical interpretations of the sensitivity of the test results to the independent variables or other interpretations. This is simply a tool for estimating the resilient modulus of specimens subjected to INTT.

Similarly, Equations 16 and 17 express the total modulus (Equation 10) in terms of *INCS* and *INTS*, respectively.

$$\ln(E) = 7.0327 + 1.0205 \times \ln(INCS) - 0.1108 \times AV - 0.0003339 \times CL \quad (16)$$

$R^2 = 0.996$; $SE= 0.080$

$$\ln(E) = 8.1552 + 1.0227 \times \ln(INTS) - 0.1153 \times AV - 0.0003339 \times CL \quad (17)$$

$R^2 = 0.996$; $SE= 0.078$

where all variables are as before.

As was the case for Equations 14 and 15, introducing the *AV* term in Equations 16 and 17 introduces collinearity because *INCS* is also a function of *AV*. Again, the *AV* term in the equation simply accounts for the difference in its effects on *INCS*, *INTS*, and *E*. It is strongly recommended that Equations 14–17 be used only for estimation of the values of *MR* and *E* and not for mathematical or physical interpretations and manipulation.

Figure 1 shows the measured and calculated values (using Equation 14) of the resilient modulus. The figure is divided into two quarters for results at 77°F and 40°F. The straight line in the figure represents equality between the calculated and measured values. It was found that the maximum percentage difference between the measure and the calculated values (of Equation 14) is 3.2 percent for the 77°F tests and 9.2 percent for those at 40°F. These percentage differences are, respectively, 6.0 and 4.1 percent for Equation 16. It should be noted that the measured values of the resilient and total moduli were found to be dependent on the number of load applications (a higher number of load applications yields lower values of the moduli). The values of *MR* and *E* at cycle 500 were used to derive Equations 14–17. The reason is that, in practice, the resilient modulus tests are conducted for only 500 cycles at which the value of the modulus is calculated and the test is terminated. Nevertheless, the effects of the number of load repetitions can be incorporated into the equations without any complications. The calculated and measured values of the total modulus showed a trend similar to that of Figure 1.

Analysis of the deformations along the vertical (*DV*) and horizontal (*DH*) diameters (Table 1) indicated that

1. The *DH* measured from the indirect tensile tests can be used to estimate the magnitude of the permissible maximum

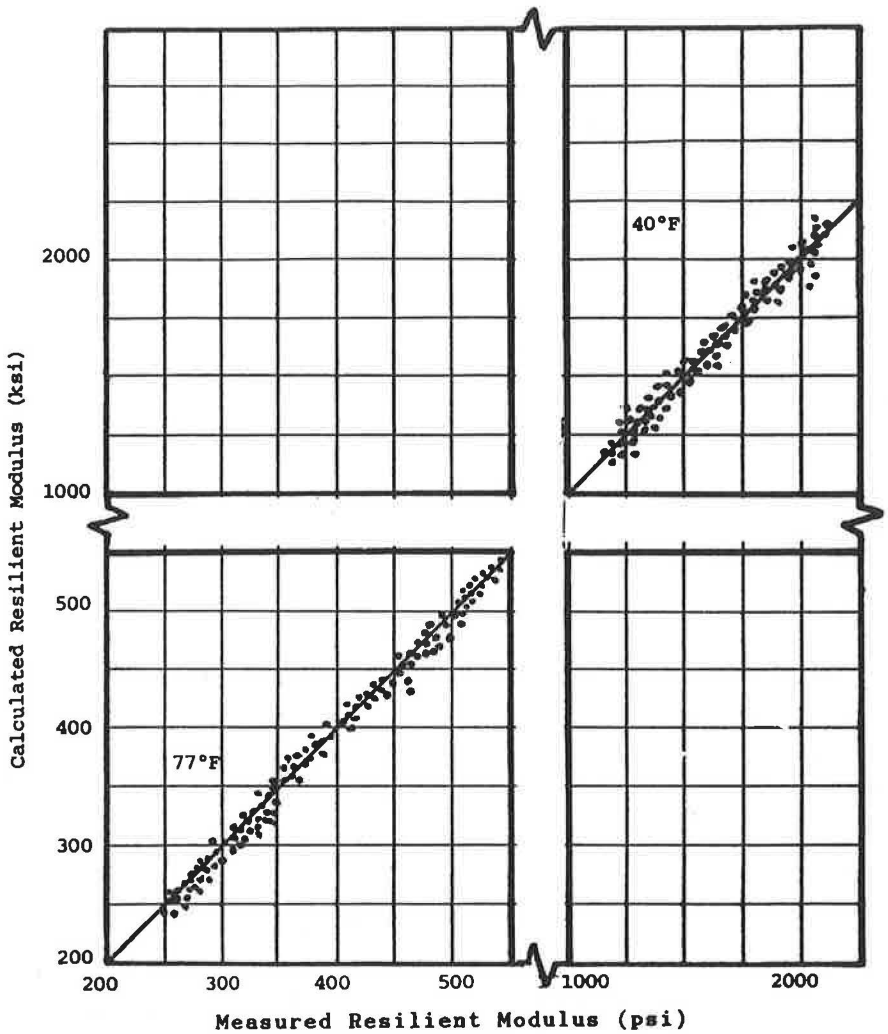

FIGURE 1 Calculated (using Equation 14) versus measured resilient modulus for three magnitudes of cyclic loads and two test temperatures.

cumulative tensile plastic strain to control fatigue cracking. In most specimens subjected to the INCCL test, a hair-sized tensile crack was initiated when the value of the measured cumulative plastic tensile *DH* was about 95 percent of the value of *DH* of a compatible specimen subjected to INTT. This observation implies that the fatigue life of the mix can be defined by the number of load applications at which the cumulative plastic tensile strain reaches a value of 95 percent of the *DH*.

2. The vertical deformation (*DV*) measured from the indirect tensile test is a measure of the compressibility of the asphalt mix. Again, the completed analysis has indicated that the *DV* can be related to the permanent deformation measured in the INCCL tests.

Because the final analysis was completed after this paper was submitted, the findings and equations (fatigue life and permanent deformation) will be published elsewhere and may be found in Baladi (*24*).

ASPHALT MIX DESIGN

As noted previously, statistical analyses indicated a poor correlation between Marshall stability and *MR*. A better and more accurate correlation was obtained between *MR* and *ES*, and *MR* and *INCS* or *INTS*. This implies that Marshall stability cannot be used to accurately estimate the structural properties of a mix. Because the objective of the study is to tailor the asphalt mix design procedure to optimize the structural properties of the mix, the rejection or acceptance of an asphalt mix design should not be partly based on Marshall stability. Given this scenario and these findings, what criteria should be used to accept or reject a design of an asphalt mix? Two alternatives are offered here. The first is based on a slightly modified version of Marshall mix design. The second is based on the indirect tensile test.

In the first alternative, two modifications to the standard Marshall mix design procedures are suggested:

1. Replace Marshall stability by the equivalent Marshall stiffness (*ES*) to select the optimum asphalt content. That is, replace the plot of Marshall stability versus asphalt content by equivalent stiffness versus asphalt content. The design asphalt content can then be determined using, for example, the Asphalt Institute criteria except that the asphalt content corresponding to the optimum value of *ES* should be used rather than that at optimum stability.

2. Marshall tests can be conducted at room temperature thus eliminating the need for a water bath.

After the design asphalt content has been determined, the values of *ES* and *AV* that correspond to design asphalt content should be used in Equation 11 to estimate the resilient modulus of the mix.

In the second alternative, the INTT is highly recommended. In these tests, the specimen deformations in two directions should be measured. The design asphalt content should then be selected on the basis of the values of *INCS*, *INTS*, *DV*, *DH*, and the median limits given in Article 3.14 of the Asphalt Institute Manual Series 2 for the percentage of air voids. A detailed sample preparation and test procedure may be found in Baladi (*24*).

The INTT requires neither expensive and complex equipment nor a new training or personnel. The INTT can be conducted at room or any other temperatures. Indeed, the test and test procedures are similar to the Marshall test. The AASHTO T 245-82 procedure can be followed step by step except as noted in the following list.

1. After the test specimens (triplicate for each combination of material and asphalt content) have been prepared, bring their temperature to the test temperature (room temperature is recommended). If other temperatures are desired, a temperature-controlled chamber is required.
2. Place the indirect tensile test apparatus under the loading head of a standard Marshall loading frame.
3. Place the test specimen on the lower curved platen of the apparatus and lower the loading strip to make contact with the specimen (5 lb of load will ensure a good contact).
4. Adjust and balance the electronic measuring system as necessary. This includes the load cell and the vertical and horizontal linear variable differential transformer or transformers.
5. Apply the load to the specimen by means of the constant rate of movement of the Marshall machine head (2 in./min) until the maximum load is reached and the load decreases as indicated by the measuring system.
6. Calculate the indirect compressive and tensile strengths (*INCS* and *INTS*) using Equations 2 and 3, respectively.
7. Calculate the resilient and total moduli using Equations 14 and 16 or 15 and 17, respectively.
8. The tests can be conducted at different temperatures to infer the effects of test temperature on test results.
9. As in the standard Marshall mix design, analyze the *INCS*, *INTS* (or *MR* and *E*), *DV*, *DH*, the percentage of air voids, the percentage of voids in mineral aggregate, and the density of the specimens as a function of the percentage of asphalt content.
10. The design asphalt content should be selected on the basis of the optimum structural properties and the specified percentage of air voids.

The values of the optimum structural properties vary and depend on the particular project under consideration. Nevertheless, the results of these tests can be directly used to establish the mix design and to obtain the structural properties for the pavement design. Further, the procedure eliminates the need for a water bath. Tests at 140°F or any other temperature can be conducted on specimens conditioned dry in a temperature-controlled chamber.

It should be noted that because the recommended equations are based on a limited data base, verification of the estimated values of the resilient and total moduli is strongly recommended. Such verification should also help the engineer to calibrate the equations.

CONCLUSIONS

The following conclusions, based on laboratory test results and analytical and statistical analyses, can be drawn:

1. The resilient and total moduli of asphalt mixes can be expressed in terms of the indirect compressive strength of the mix, the test temperature, and the magnitude of the applied cyclic load.
2. The need for complex tests and testing equipment to estimate the resilient modulus of asphalt mixes can be eliminated.
3. Marshall stability cannot be used to properly characterize the structural parameters required in the mechanistic pavement design models. The equivalent Marshall stiffness is a better descriptor of these parameters.
4. The asphalt mix design procedure can be tailored to optimize the structural properties of asphalt mixes.
5. Indirect tensile tests can be used to obtain an asphalt mix design based on the structural properties of the mix.

SUMMARY

Structural properties of asphalt mixes have direct bearing on pavement performance. Knowledge of these properties is essential for the structural design of pavements. Existing asphalt mix design procedures are divorced from those used to obtain structural properties. It was shown that the Marshall mix design method can be tailored to optimize the structural properties of a mix. Modifications of the method are suggested. Further, relationships to estimate the total and resilient moduli from the indirect tensile test results are presented. Hence, the need for complex and expensive tests can be eliminated.

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