HRB SPECIAL REPORT 94

State of the Art:

Theory and Application of Sonic Testing to Bituminous Mixtures

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State of the Art:

Theory and Application of Sonic Testing to Bituminous Mixtures

Subject Area

31 Bituminous Materials and Mixes
32 Cement and Concrete

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Foreword

This Special Report was prepared to summarize and evaluate the theory and application of sonic testing to bituminous mixtures. It is a state-of-the-art report and contains no new test data. The report summarizes and evaluates contributions to the theory of sonic testing, the development of sonic test apparatus, and the application of sonic testing to bituminous mixtures.

Modulus of elasticity as determined by the sonic test is a measure of stiffness and is related to resistance to cracking of bituminous pavements, especially at low temperatures. Since the sonic test is a nondestructive type of test, it is useful in studying progressive deterioration and weathering of bituminous mixtures in the laboratory.

This report was written for the use of paving technologists in carrying on future research on bituminous mixtures and in developing standard test methods. It is hoped that this report will further stimulate application of sonic testing to research on bituminous paving mixtures.

—L. F. Rader

State of the Art

Theory and Application of Sonic Testing to Bituminous Mixtures

H. HONG*

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Ohio State University

THIS REVIEW of sonic testing is a state-of-the-art literature survey conducted by the Subcommittee on Summary and Evaluation of MC-A4 (Committee on Mechanical Properties of Bituminous Mixtures). The purpose of this survey is to provide a consolidated comparative study of a number of scattered research activities in a particular area or subarea of mechanical properties of bituminous mixtures so that (a) future research in this particular area or related areas will be facilitated and (b) assistance may be given to interested persons to keep abreast with the current state of the art in this particular area.

The sonic method of testing materials has been applied in the qualitative analysis of portland cement concrete beams for a number of years. This testing method is employed to determine the dynamic modulus of elasticity of a specimen in the laboratory by measuring the resonant frequency of a specimen. The advantages of this method are its simplicity of measurement and its nondestructive nature, which facilitates a repeated measurement of a certain physical property over a period of time. This test has been one of the important tools for studying the durability of portland cement concrete in the evaluation of the freeze-thaw test.

This dynamic testing method, utilizing sonic vibrations, has found very limited application in the field of bituminous mixtures to date. However, the advantages of this method and the potential of its use are such that it may be very desirable to explore the possibility of ever greater application to bituminous mixtures, in spite of some limitations.

DISCUSSION OF THE THEORY OF SONIC TESTING

The basic theory of sonic testing as developed in the study of the modulus of elasticity of portland cement concrete beams is discussed. This basic theory would be applicable to the study of some of the physical properties of bituminous-aggregate mixtures.

From the data on resonant frequency for the fundamental mode of flexural vibration of laboratory specimens of portland cement concrete and from the weight and dimensions of the specimen, Young's modulus of elasticity is determined by means of a formula such as

$$E = CWn^2 \tag{1}$$

where

E = Young's modulus,
W = weight of the specimen,
n = a resonant frequency, and

*Chairman, Subcommittee on Summary and Evaluation.

C = a factor which depends on the shape and size of specimen, the mode of vibration, and Poisson's ratio.

There has been considerable confusion in regard to the formulas used for computing C. An attempt to define factor C is made by (a) discussing the various differential equations that have been used for flexural (transverse) vibration of prisms, (b) discussing the shear constant K' in Timoshenko's differential equation, and (c) comparing the results from Goens's solution of Timoshenko's equation with results obtained by means of the theory of elasticity (1).

In the transverse vibration of prismatic bars, the following differential equations have been developed:

$$\frac{Er_z^2}{\rho}\frac{\partial^4 v}{\partial x^4}+\frac{\partial^2 v}{\partial t^2}=0 \tag{2}$$

$$\frac{Er_z^2}{\rho}\frac{\partial^4 v}{\partial x^4}+\frac{\partial^2 v}{\partial t^2}-r_z^2\frac{\partial^4 v}{\partial x^2\partial t^2}=0 \tag{3}$$

$$\frac{Er_z^2}{\rho}\frac{\partial^4 v}{\partial x^4}+\frac{\partial^2 v}{\partial t^2}-r_z^2\frac{\partial^4 v}{\partial x^2\partial t^2}+(r_z^2-r_y^2)\frac{\partial^4 v}{\partial x^2\partial t^2}=0 \tag{4}$$

$$\frac{Er_z^2}{\rho}\frac{\partial^4 v}{\partial x^4}+\frac{\partial^2 v}{\partial t^2}-r_z^2(1+\mu)\frac{\partial^4 v}{\partial x^2\partial t^2}=0 \tag{5}$$

$$\frac{Er_z^2}{\rho}\frac{\partial^4 v}{\partial x^4}+\frac{\partial^2 v}{\partial t^2}-r_z^2\left(1+\frac{E}{K'G}\right)\frac{\partial^4 v}{\partial x^2\partial t^2}+\frac{r_z^2}{K'G}\frac{\partial^4 v}{\partial t^4}=0 \tag{6}$$

where

ρ = mass per unit volume,
r_z, r_y = radii of gyration of the cross section with respect to centroidal z- and y-axes respectively,
v = displacement (deflection in y-direction),
x = the coordinate in the direction of length,
t = time,
μ = Poisson's ratio,
G = modulus of rigidity (modulus of elasticity in shear), and
K' = a constant introduced by Timoshenko to account for the effect of shear on the slope of the elastic line.

When a bar vibrates, a cross-sectional element may be thought of as executing two movements: a motion of translation laterally, and one of rotation relative to the position of the unbent neutral axis. In the derivation of Eq. 2 the effects of rotatory and lateral inertia and of shear are neglected. But if the thickness of the bar is a relatively large fraction of the length, as it is in most concrete specimens, the rotatory inertia must be taken into account.

Eq. 3, given by Lord Rayleigh (2), differs from Eq. 2 in that a term has been added to correct for the effect of rotatory inertia.

Eq. 4, given by Love (3), differs from Eq. 3 in that a term has been added to correct for the effect of another inertia, namely, that due to lateral contraction and expansion of the specimen. This term is never of much importance and is zero for prisms of square cross sections; therefore, its effect can be disregarded in most cases.

Eq. 5 is the differential equation used by Mason (4) and Thompson (5). They state that the term $-r_z^2(1+\mu)\left(\frac{\partial^4 v}{\partial x^2\partial t^2}\right)$ corrects for both rotatory and lateral inertia and quote

Love (3) and Timoshenko (6, 7) as authority. In these details Mason and Thompson are in error as may be verified by examining the references cited. Apparently, in obtaining Eq. 5 from Eq. 4, Mason assumed r_y^2 to be negligibly small and inadvertently used the wrong sign for $r_z^2\left(\frac{\partial^4 v}{\partial x^2 \partial t^2}\right)$. Therefore, all formulas based on Eq. 5 are of questionable value.

Eq. 6, given by Timoshenko (6, 7, 8), corrects for the effects of shear and of rotatory inertia. As none of the preceding equations correct for shear, they are therefore considered less accurate than Eq. 6.

The constant K' occurring in Eq. 6 has been a subject of discussion. Some investigators use the value $2/3$, the value suggested by Timoshenko for rectangular sections; others use $5/6$, the value suggested by Goens (9).

Since in his derivation of Eq. 6 Timoshenko defined K' as the ratio of the average unit shear across a section to the unit shear at the neutral axis, it follows on this basis that K' should be $2/3$ for rectangular sections and $3/4$ for circular sections. However, in the derivation, Timoshenko considered the effect of shear on the slope to be equal to the angle of shear at the neutral axis. Generally, in static loading the effect of shear on the slope is less than the angle of shear at the neutral axis and therefore one would expect K' to be more than $2/3$. The assumptions used in regard to loadings and supports would cause the value of K' to vary.

Also of importance in the study of the significance of K' is the fact that in his derivation of Eq. 6 Timoshenko neglected the effect of warping of a section on its rotatory inertia. When this effect is taken into consideration in the derivation, the result is an equation identical with Eq. 6, except that the second K' is then defined in terms of the effect of warping on rotatory inertia instead of the effect of shear on slope. However, it turns out that the second K' should have a value approximately equal to $5/6$, i.e., about the same value as the first K'.

From the preceding it appears that K' should be about $5/6$ for rectangular sections. Although these and still further refinements in the derivation of the differential equation would help to establish the best value for K', the most practical answer appears to be to use that empirical value that gives results most nearly in accord with those obtained by means of the mathematical theory of elasticity (1).

The equation giving the necessary relation between the resonant frequency and the dimensions, density, and elastic properties of a specimen is called a frequency equation.

The frequency equation that is found by mathematical derivation depends upon what differential equation (or equations) and what boundary conditions are assumed to hold. If the ends are free (or, in any case in which the boundary conditions are the same at the two ends), the frequency equation can be reduced to either of the following forms (1, 9):

$$\frac{M}{\tanh \alpha/2} + \frac{N}{\tan \beta/2} = 0 \tag{7}$$

$$\frac{M}{\coth \alpha/2} + \frac{N}{\cot \beta/2} = 0 \tag{8}$$

Eq. 7 applies to the first, third, fifth, etc., modes of vibration with respect to the plane midway between the two ends. Eq. 8 applies to the second, fourth, etc., modes of vibration, i.e., assymetrical vibration. The factors α and β in Eqs. 7 and 8 depend primarily on the ratio of depth in the direction of vibration to length. In Goens's solution (9), the expressions for α and β are determined on the basis of satisfying Eq. 6. The factors M and N are chosen so as to meet the requirement that the ends be free of resultant shear force and resultant moment.

Goens's solution gives the following expressions for α, β, M, and N in terms of r/L (reciprocal of slenderness ratio), μ, K', and k:

$$\alpha = k \left[\left(B^2k^4 + 1 \right)^{1/2} - Ak^2 \right]^{1/2} \tag{9}$$

$$\beta = K \left[\left(B^2k^4 + 1 \right)^{1/2} + Ak^2 \right]^{1/2} \tag{10}$$

$$M = \alpha/k^2 \left[\left(B^2k^4 + 1 \right)^{1/2} + Bk^2 \right] \tag{11}$$

$$N = \beta/k^2 \left[\left(B^2k^4 + 1 \right)^{1/2} - Bk^2 \right] \tag{12}$$

where

$A = (r/L)^2 \left[\frac{1+\mu}{K'} + 1/2 \right]$,

$B = (r/L)^2 \left[\frac{1+\mu}{K'} - 1/2 \right]$, and

K' = shear constant; should be $5/6$, $8/9$, and 0.85 respectively for μ equal to 0, $1/6$, and $1/3$.

The factor k has a value greater than α and less than β and is related to frequency and other properties by the equation

$$k = \left[\frac{4\pi^2 n^2 pL^4}{r^2 E} \right]^{1/4} \tag{13}$$

$$E = \frac{4\pi^2 n^2 pL^4}{r^2 k^4} \tag{14}$$

After the factors α, β, M, and N have been found in terms of k for particular values of r/L and μ, substitution can be made in either Eq. 7 or Eq. 8 as desired and k can be found by trial. The lowest value of k that satisfies Eq. 7 corresponds to the first mode of vibration, the next lowest to the third mode, etc.

If the ends of the beam were assumed to be hinged, then M = 0 and Eqs. 7 and 8 would reduce to $\tan \beta/2 = \infty$ and $\cot \beta/2 = \infty$. The solution of Eq. 6 for this case is given by Timoshenko (8).

Results have shown that for the same values of r/L and of μ, the values of k (and consequently the resonant frequencies of vibration) are only slightly less for plane stress (thin beams) than for plane strain (wide slab), both of which satisfy the requirement that the lateral surfaces be free of stress.

Although a solution based upon the equations of elasticity has not been obtained for a prism of rectangular section, it seems reasonable that the resonant frequency obtained by such a solution would lie between those for plane stress and plane strain. Probably if the section is nearly square, the frequency would be very close to that of a cylinder of the same r/L (1).

As stated previously, the factor C in Eq. 1 depends on the shape and size of specimen, Poisson's ratio, and mode of vibration. From Eqs. 1 and 14:

$$C = \frac{4\pi^2 L^3}{gIk^4} \tag{15}$$

where

g = the acceleration of gravity, and
I = the moment of inertia of the cross section.

In the limit as r/L approaches zero, $\alpha = \beta = k$. Furthermore M = N in this limit if both ends are free. For this limiting case of r/L approaching zero, Eqs. 7, 8, and 15 reduce to:

$$\tan\frac{m}{2} + \tanh\frac{m}{2} = 0 \tag{16}$$

$$\cot\frac{m}{2} - \cot\frac{m}{2} = 0 \tag{17}$$

and

$$C' = \frac{4\pi^2 L^3}{gIm^4} \tag{18}$$

respectively, where C' is written for C and m is written for the limiting value of k.

Thus, C may be expressed as

$$C = C'T \tag{19}$$

where T (= m^4/k^4) is the correction factor introduced by Goens (9). From Eq. 19 it may be seen that T is the factor by which values of C based on Eq. 2, i.e., C', should be multiplied in order that C based on a more accurate differential equation may be found. Consequently, T is the factor by which the values of E based on Eq. 2 should be multiplied in order to obtain the E based upon the more accurate differential equation under consideration.

Thus, Eq. 1 may be written:

$$E = CWn^2 = C'TWn^2 = [C'Wn^2]\ T \tag{20}$$

or as expressed by Obert and Duvall (10):

$$E = \left[\frac{4\pi^2 L^4 f^2 p}{r^2 m^4}\right] T \tag{21}$$

where

- f = frequency of vibration,
- E = modulus of elasticity,
- p = density,
- L = length of specimens,
- r = radius of gyration of the section about an axis perpendicular to the plane of bending, and
- m = a constant depending on the mode of vibration (4.73 for fundamental).

The value of T as expressed in terms of μ and r/L may be approximated by mathematical equations, but graphical solutions expressed in t/L (depth to length ratio) are often employed (Fig. 1).

After T has been determined, the factor C may be obtained by means of Eqs. 18 and 19. Then for the first mode of vibration:

$$C_1 = 0.00020436\ \frac{L^3}{I}\ T_1\ \text{sec}^2\ \text{psi} \tag{22}$$

or

$$C_1 b = 0.0024523\ \left(\frac{L}{t}\right)^3\ T_1\ \text{sec}^2\ \text{per in.} \tag{23}$$

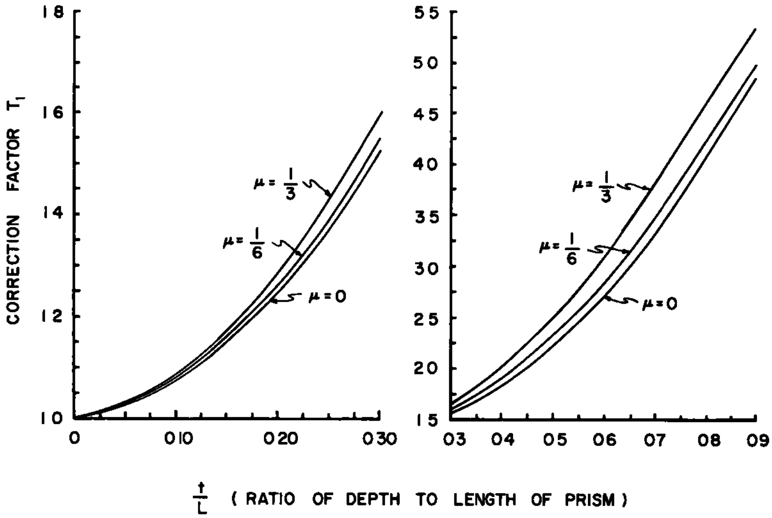

Figure 1. Goens's correction factor T_1 vs ratio of depth to length of prism.

for a prism of rectangular section, and

$$C_1d = 0.0041632 \left(\frac{L}{d}\right)^3 T_1 \sec^2 \text{ per in.} \tag{24}$$

for a circular cylinder, where t, b = dimensions of rectangular section, t being in the direction of vibration, and d = diameter of cylinder. Subscript 1 denotes the first mode of vibration.

Graphs of C_1b and C_1d vs L/t and L/d respectively are shown in Figure 2. With the value of C known, the Young's modulus as originally expressed in Eq. 1 ($E = CWn^2$) can be obtained for the resonant frequencies of various modes of flexural vibration.

Dynamic modulus of rigidity (sometimes designated as "the modulus of elasticity in shear") may be calculated from the fundamental torsional frequency, weight, and dimensions of the test specimen as follows:

$$\text{Dynamic } G = BW(n'')^2$$

where

Dynamic G = dynamic modulus of rigidity in psi;
W = weight of specimen in pounds;
n'' = fundamental torsional frequency in cycles per sec;
$B = \dfrac{4LR}{gA} \sec^2$ per sq in.;
L = length of specimen in in.;
R = shape factor:
= 1.183 for a square cross section prism;
$= \dfrac{a/b + b/a}{4a/b - 2.52(a/b)^2 + 0.21(a/b)^6}$ for a rectangular prism whose cross-sectional dimensions are a and b in., with a < b;
g = gravitational acceleration; and
A = cross-sectional area of test specimen in sq in.

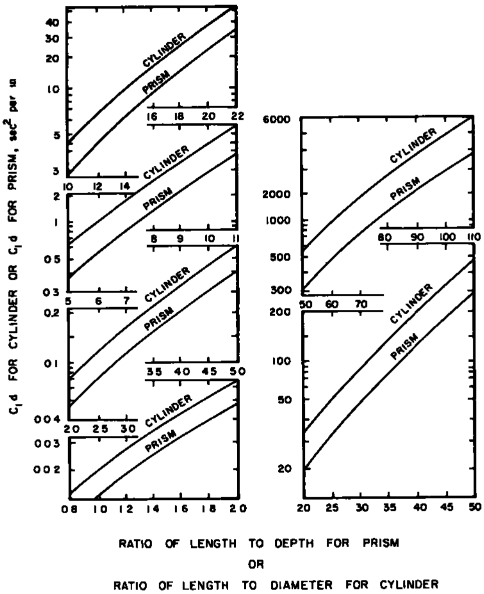

Figure 2. Curves for the graphical determination of C for prisms and cylinders.

SONIC TEST APPARATUS

The sonic measurement of the modulus of elasticity requires first, a method of supporting the specimen so that it will vibrate in some prescribed mode of vibration; second, a method of vibrating the specimen in that mode; third, a means of measuring the frequency of vibration; and fourth, a measurement of the dimensions and density of the specimen.

The dimensions and density of the specimen can be readily obtained, but the natural frequency is somewhat more difficult to evaluate. Not too many years ago the natural frequency was found by striking a specimen with a mallet and comparing the sound emitted with that produced by various tuning forks. This method led to errors of comparison besides being limited by the small range of vibrations heard by the human ear. Today, the determination of the natural frequency is done almost entirely by electrical instruments such as the sonometer.

The method of mounting the specimen determines the mode in which it will vibrate. For the fundamental tone of the longitudinal vibration, the specimen should be mounted at the center. For the transverse fundamental tone and free-free mode of vibration, the beam should be mounted at the nodal points, which are 0.224L (L = length of specimen) from each end in order that no dampening of the vibrations occur at the supports. For the same reason narrow rubber or wooden balls free to rotate are used as supports (Fig. 3).

The electrical apparatus serves a twofold purpose: to produce a sustained vibration in the specimen and to serve as a means of determining the frequency of this vibration. The apparatus consists of a mechanism for vibrating the driver at known frequencies.

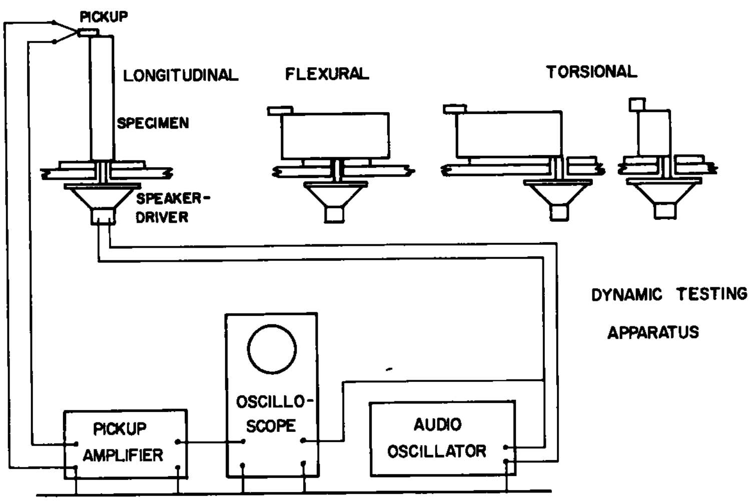

Figure 3. Diagram of apparatus and beam positions.

The specimen is set against this driver and is set in vibration by it. A pickup system, much like that used in a phonograph, is attached to one end of the beam to measure its energy output. When the frequency of the driving force is equal to the fundamental frequency of the beam, the systems are in resonance, i.e., the beam vibrates with maximum amplitude. Other details of the apparatus are well described elsewhere (11). Additional details of usage of sonic apparatus given by Davidson (12), Stauss (13), and Goetz (16) are recommended.

APPLICATION OF THE SONIC TESTING TO BITUMINOUS MIXTURES

In the sonic testing of portland cement concrete beams, because this material is essentially elastic over the whole range of temperature to which it is normally subjected, the application of the elastic theory is reasonably valid. Various results indicate that the moduli of elasticity determined by sonic and other mechanical means are in reasonable agreement. However, the physical properties of bituminous mixtures are very much subject to temperature. Bituminous mixtures may be considered elastic-plastic materials, depending on the specific temperature level. At substantially low temperatures, bituminous mixtures become rigid and behave elastically. However, at sufficiently high temperatures, bituminous mixtures are essentially plastic. In this plastic state, a continuous deformation may occur without fracture or a continuous deformation may occur without increase in stress. For these reasons of temperature susceptibility it is very important to realize the limitations of the sonic testing method as applied to the study of the physical properties of bituminous paving mixtures.

The earliest known application of sonic testing to bituminous mixtures was made by Davidson (12) and Stauss (13) in 1949 under the direction of L. F. Rader at the University of Wisconsin. Davidson and Stauss utilized the sonic test in the study of physical properties of asphaltic concrete at low temperatures. They concluded that the sonic method of determining the modulus of elasticity is a suitable test for determining the E of asphalt paving mixtures chilled to low temperatures. They also concluded that at room temperatures the sonic method is not applicable for determining the modulus of elasticity. They further showed that the sonic modulus of elasticity was increased as the density of mixture and bitumen content increased (Fig. 4). The effect of moisture on the sonic modulus of elasticity decreased as the density of the mixture increased. The effect of moisture on the sonic modulus was insignificant at temperatures above 32 F (Fig. 5). The size of aggregates did not seem to have any influence on the sonic modulus of elasticity.

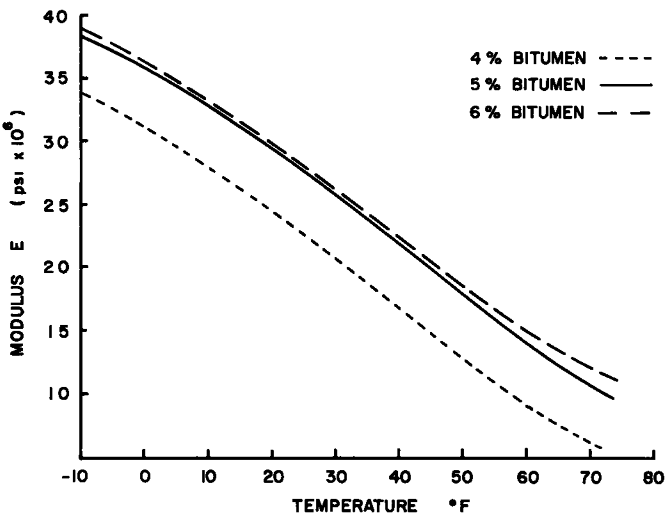

Figure 4. Sonic modulus showing the influence of bitumen content.

Davidson and Stauss related that hand temper plus static loading was not quite satisfactory in obtaining uniform density. The beam size was specified as 4 in. by 2¼ in. by 18 in. after a number of experiments with several different dimensions.

Later, at Purdue University, Bawa (14) indicated that a sonic modulus of elasticity could be obtained for beam specimens using the theory of sonic vibrations. Yong (15) also found that the sonic method of testing would be a useful tool in determining and following the relative deterioration of bitumen-aggregate mixtures subject to weathering tests.

Bawa and Yong used the following equation for the determination of Young's modulus of elasticity:

$$E = CWn^2$$

where

$C = 0.00323 \dfrac{L^3}{bt^3}$,

b = width of beam, in., and

t = thickness of beam, in.

This equation is basically correct. However, the coefficient 0.00323 of C is correct only when the value of T (correction factor proposed by Goens) is 1.3172. As previously indicated, the value of T is dependent upon the depth to length ratio (t/L) and Poisson's ratio. Therefore, for any value of T other than 1.3172, the coefficient proposed by Bawa and Yong is in error. Thus, it is desirable to calculate the value of coefficient by considering the dimensions of specimen and Poisson's ratio in order to avoid the error that may be introduced by Bawa's proposed coefficient of 0.00323.

Goetz (16) in 1955 showed that even though the modulus of elasticity values calculated from the fundamental frequency measurements with the aid of elastic theory may not be strictly valid, particularly at temperatures above 40 F, such measurements do provide valuable information concerning the elastic-plastic characteristics of bituminous

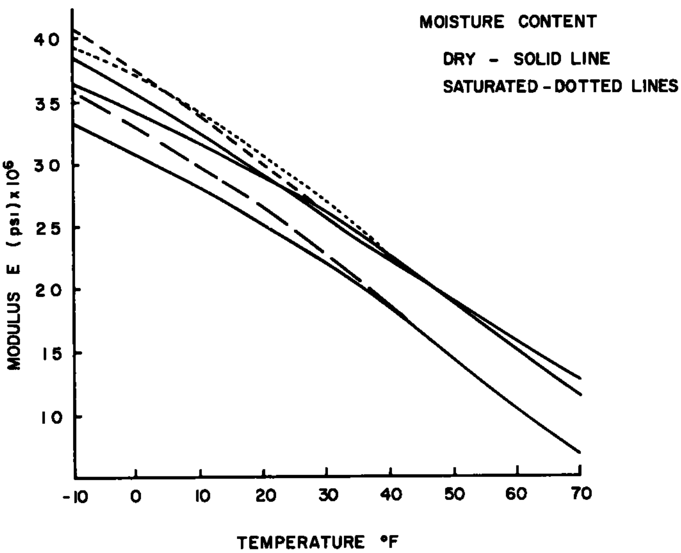

Figure 5. Sonic modulus showing the influence of moisture content.

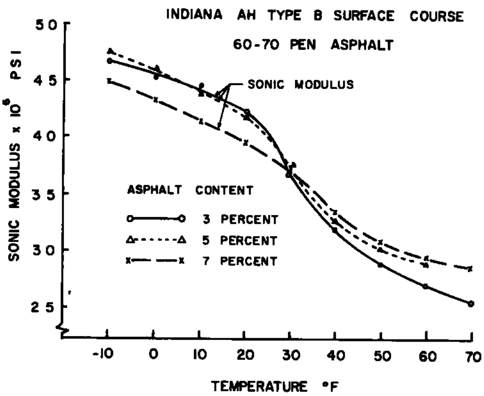

Figure 6. Variation of sonic modulus with temperature.

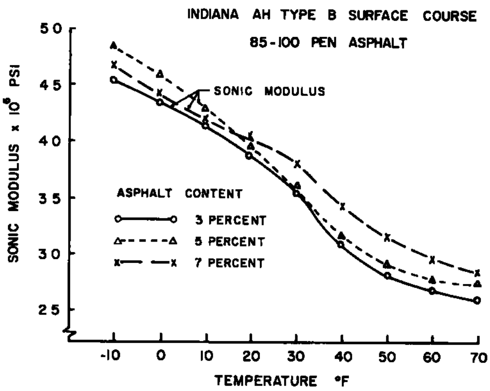

Figure 7. Variation of sonic modulus with temperature.

aggregate mixtures and appear to be sufficiently valid at lower temperatures so as to provide a measure of stiffness. He emphasized that the nondestructive test is useful for the study of accelerated weathering of bituminous mixtures.

Goetz further showed that the sonic modulus of elasticity increases as the temperature decreases; that there is no consistent relationship between the sonic test values and the amount of asphalt in the mixtures; and that the influence of asphalt penetration on sonic modulus is very small (Figs. 6, 7, 8, 9). In comparing the modulus of elasticity values determined by sonic method and conventional mechanical means, Goetz indicated that at 40 F there is a general lack of correlation between results from sonic tests and flexure tests. The sonic modulus of elasticity values are somewhat more than ten times as large as modulus values obtained from the flexure test (Fig. 10). This discrepancy might have been due to the difference in the rate of strain and the level of temperature, which is not sufficiently low. At 70 F the differences in modulus of elasticity determined by the sonic test, unconfined compression test, and flexure test are in even more serious disagreement than was the case for tests made at 40 F. In this case the modulus values determined from the sonic test are as much as 1,000 times as great as the values determined from the flexure tests. Therefore, it is quite clear that the temperature of the specimen and the rate of strain are of critical importance with respect to the modulus of elasticity.

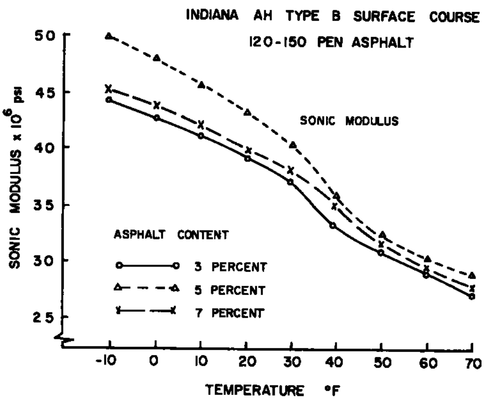

Figure 8. Variation of sonic modulus with temperature.

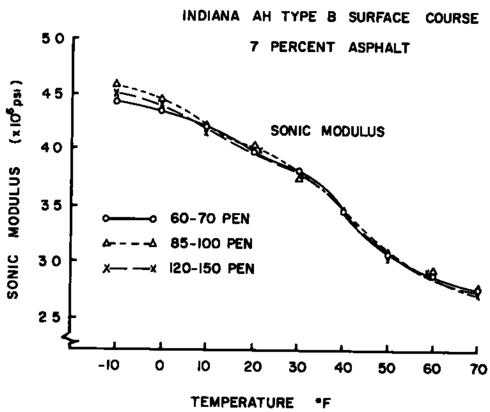

Figure 9. Variation of sonic modulus with temperature.

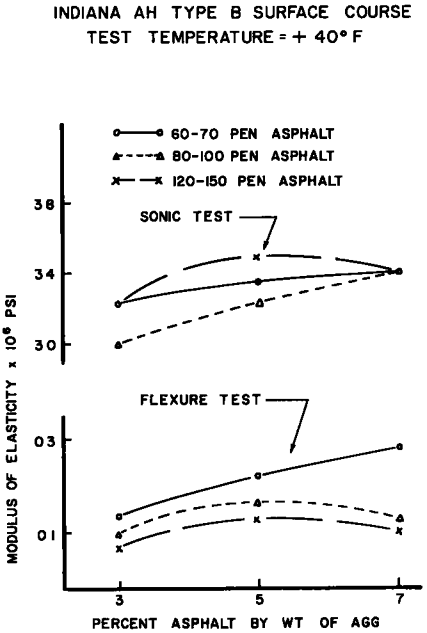

Figure 10. Comparison of modulus of elasticity from sonic and flexural tests.

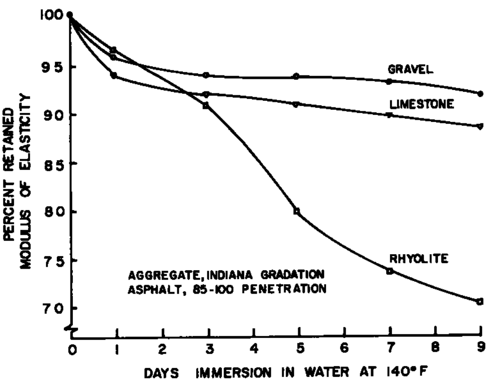

Figure 11. Immersion period vs retained modulus of elasticity using sonic test.

In the fabrication of specimens Goetz utilized both cylindrical and beam specimens. It was found that cylindrical specimens could be vibrated transversely if their length was not less than about three times their diameter, but vibration in other fundamental modes was not possible. Furthermore, more power was required to vibrate the cylindrical specimens than was the case for corresponding beam specimens, and calculation of sonic modulus was more involved. The beam specimens were from 14 to 18 in. long with a cross section of 4 by 3 in. Some difference in modulus value was noted depending upon direction of vibration with respect to the 4- or 3-in. thickness, which probably was due to direction of compaction. As a result of these tests, the dimensions of beam were standardized at 12 in. by 2$\frac{1}{2}$ in. by 2 in. for maximum size aggregate of $\frac{1}{2}$ in.

In compacting specimens, 4-in. diameter cylindrical specimens were molded by a double-plunger compaction method. Beam specimens were formed by impact compaction followed by static load. However, Goetz noted the need for an improved compaction method and suggested the rolling action for compacting beam specimens. Based on the author's experience (17), the kneading compactor method appears to be by far the most suitable for beam specimens.

Andersland and Goetz (18) utilized sonic testing for the evaluation of stripping resistance in compacted bituminous mixtures. They indicated that the sonic test gave results that revealed the stripping qualities of the aggregates employed as well as or better than either the immersion-compression test or the visual stripping resistance test. Since specimens for the sonic test contained materials of the same kind, gradations, and proportions compacted in a similar manner as would be used in actual field construction, the sonic test has inherent advantages over both the immersion-compression test and the visual stripping test. The sonic test permitted observation of progressive stripping on the same specimen (Figs. 11, 12). This procedure eliminates errors caused by duplicate specimens having different characteristics as experienced in the immersion-compression test. The sonic test appears to have a further application in evaluating whether the stripping tendency of a specific aggregate or bitumen might be improved by the use of an anti-stripping agent.

Abbott and Craig (19) indicated that, in the determination of age-hardening tendencies and water susceptibility of paving asphalt by the sonic method, the sonic method is not an effective tool for evaluating the stripping characteristics of cutback paving mixes because of the long time required for the sample to reach an elastic state by evaporation of solvent (Fig. 13). The hardening of a paving mixture after aging can be followed by

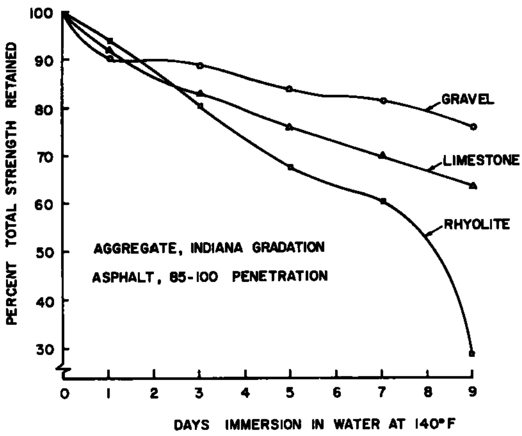

Figure 12. Immersion period vs percent total strength retained using immersion-compression test.

the increase in sonic moduli of the test specimens (Fig. 14). The increase in sonic modulus parallels the increase in unconfined compressive strength. For a given mix design and a given asphalt, a straight-line plot of sonic modulus vs compressive strength can be obtained (Fig. 15). Water susceptibility of hot-mix pavements can be readily determined by the sonic method and the effectiveness of adhesion-promoting additives evaluated (Figs. 16, 17, 18). Sonic modulus is a good indicator of loss of adhesion and compressive strength even though their relationships are not linear. The relationship of penetration of extracted asphalt with sonic modulus and compressive strength of beams during oven aging cycle is shown in Figure 19.

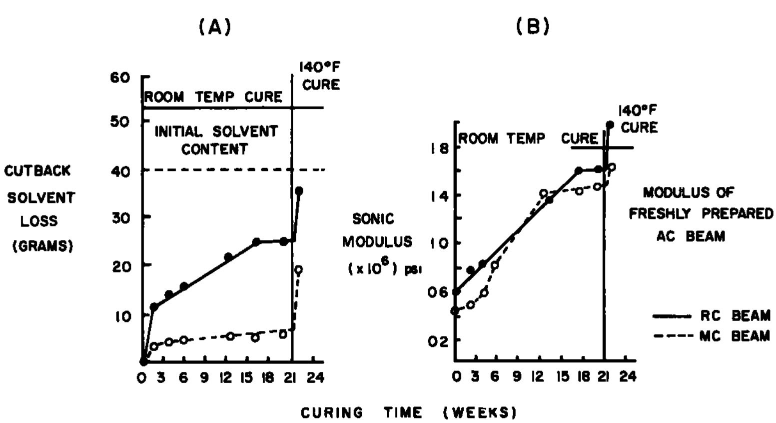

Figure 13. Changes during curing of RC and MC cutback beams showing (A) rate of cutback solvent loss, and (B) sonic modulus increase.

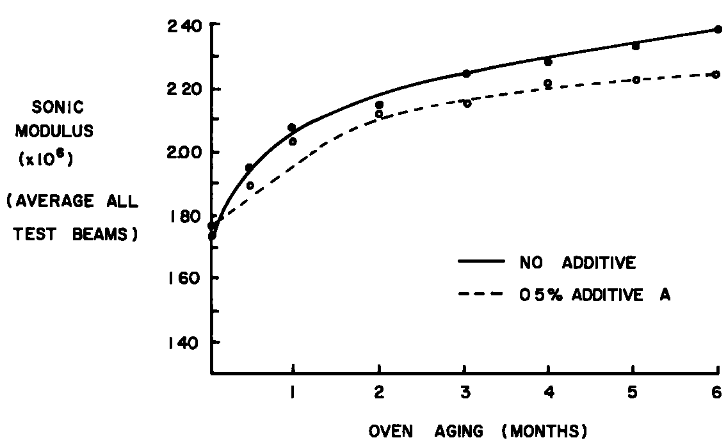

Figure 14. Sonic modulus changes occurring in Lloydminster AC-rhyolite beams during aging at 140 F.

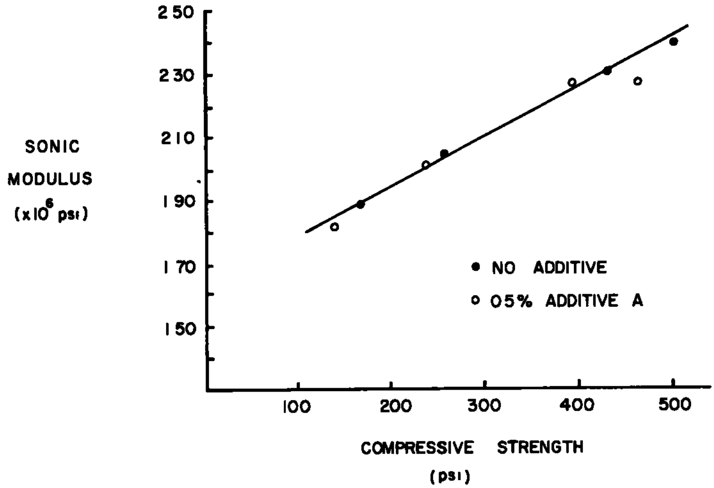

Figure 15. Sonic modulus and strength relationship during 6-month age-hardening of Lloydminster AC-rhyolite beams.

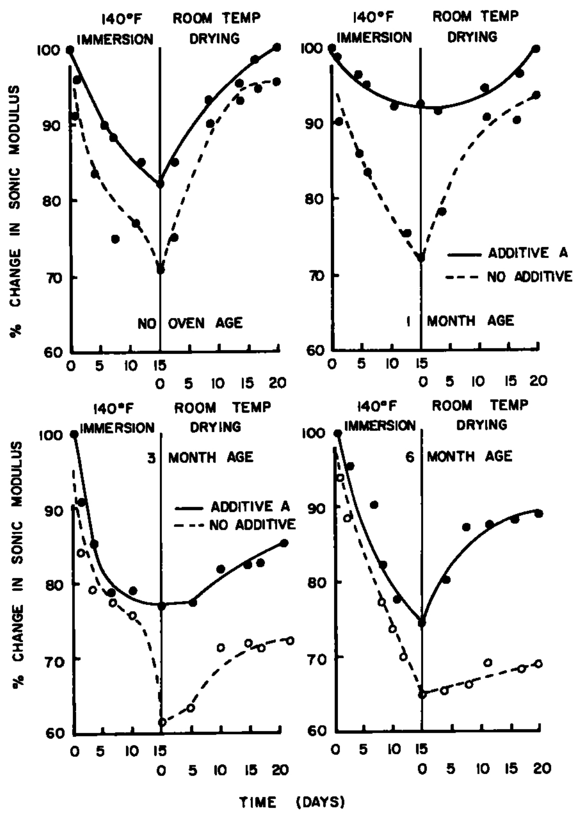

Figure 16. Sonic modulus changes during water immersion and drying of Lloydminster AC-rhyolite beams after various periods of oven aging.

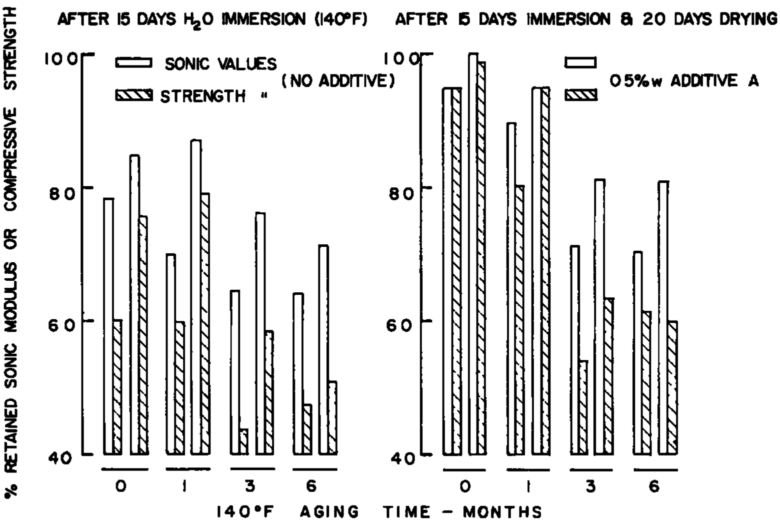

Figure 17. Effect of aging followed by soaking and drying cycles on sonic modulus and compressive strength.

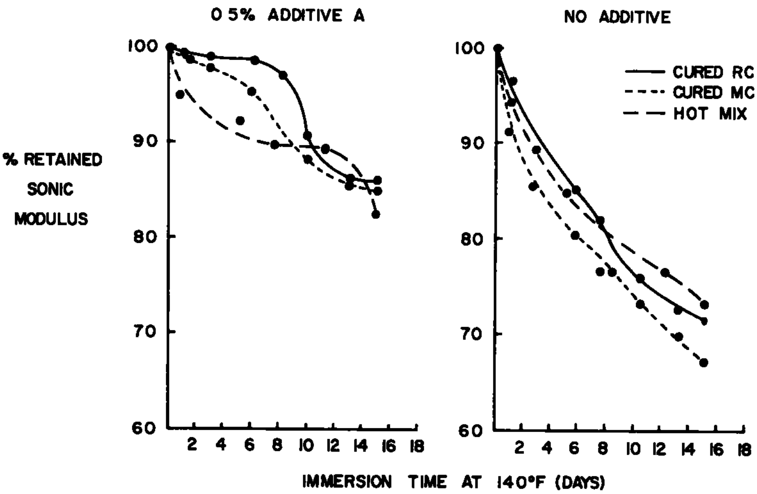

Figure 18. Effect of additive on sonic modulus during water immersion of cutback and hot beam mix.

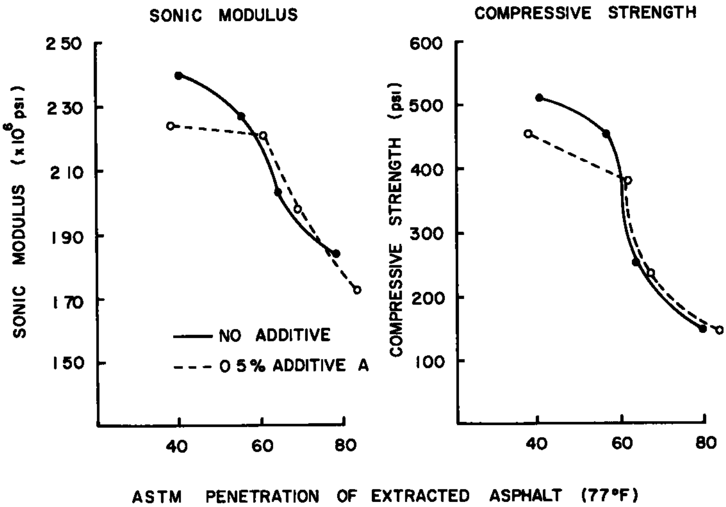

Figure 19. Relationship of penetration of extracted asphalt with sonic modulus and compressive strength of beams during oven aging cycle.

In the WASHO Road Test (20), a California Division of Highways study indicates that the pulse velocity increases with a decrease in temperature. It is seen from Figure 20 that the pulse velocity between 20 and 70 F is practically constant and that it decreases as the temperature increases above 70 F.

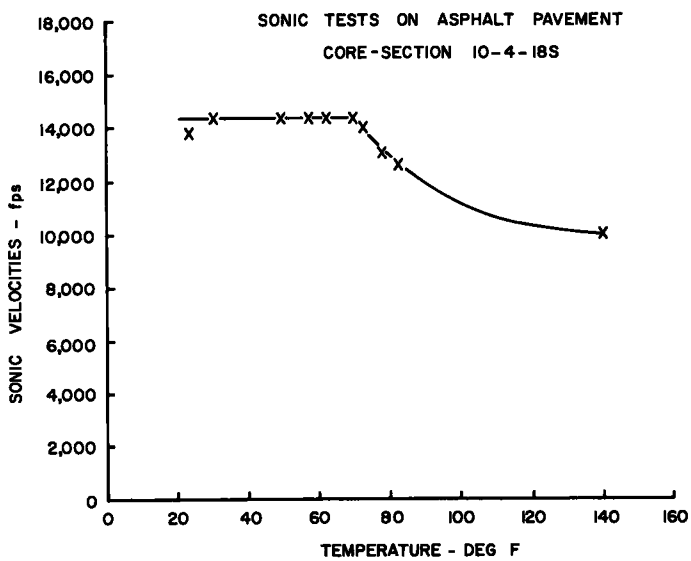

Figure 20. Soniscope tests on pavement core, Section 10-4-18S, WASHO Road Test.

CONCLUSIONS

The dynamic method as described in this review is believed to give the modulus of elasticity of that class of materials which exhibits permanent set and plastic flow because it is not complicated by these factors. The usefulness of the dynamic method would seem to be confined, therefore, to whatever use can be made of a knowledge of the true elasticity of a material.

The advantages of the sonic testing are (a) that it does not destroy the specimen nor alter it by the effect of high stress, and thus the specimen may be reused for vari ous other tests or even the same test where the effects of some deteriorating agent are to be studied; (b) that the test may be performed with simplicity, accuracy, and speed; and (c) that very little time and expenditure of money are necessary to complete the test. One disadvantage is that this testing method is limited in its application to a temperature range below 40 F. Further improvement of the testing method and greater knowledge may widen the applicability to all temperature levels.

In view of the potential of the sonic testing method for the study of physical properties of bituminous mixtures, it is deemed necessary to explore the possibility of a greater use and to standardize the test method in the future.

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