ULTRASONIC MODULI OF ASPHALT CONCRETE

Richard W. Stephenson and Phillip G. Manke, Oklahoma State University

There has been a need for a nondestructive, dynamic technique for evaluating certain "elastic" constants of asphalt paving materials. In this study, a method is developed by which the dynamic E-modulus, G-modulus, and Poisson's ratio of compacted asphalt-aggregate specimens are determined from measurement of the propagation velocities of pulsed ultrasonic shear and compressional waves through the test material. This test procedure proved to be easily and rapidly performed on standard Hveem-gyratory specimens. The results obtained compared favorably with those reported by other investigators using different procedures. A brief study of a single asphalt-aggregate mixture, using a variety of asphalt and void contents, resulted in the following observations: (a) An increase in the temperature of the test material resulted in a decrease of the values of both the dynamic E- and G-moduli; (b) maximum moduli occurred at an "optimum" asphalt content for wave transmission of 6 percent; (c) the dynamic Poisson's ratio increased directly with increased asphalt content of the specimens; (d) at temperatures greater than approximately 100 F, Poisson's ratios increased rapidly toward the theoretical maximum of 0.50; and (e) the amount of voids contained in a compacted specimen had only a minor influence on the rate of wave transmission through the specimens at low temperatures, but above 80 F this influence was more pronounced.

•IN an effort to standardize flexible pavement design techniques, researchers have focused on procedures that treat the pavement system as a structural assembly. Because asphalt pavements are treated in this way, the major obstacle to overcome is that of determining the parameters defining the respective material's behavior under load. Although it is recognized that the system is not elastic, elastic theory has been utilized. Strength parameters predicted from various tests that have evolved over the years, in conjunction with modifications of elastic theory, have been used in pavement design.

One problem with using standard methods to determine material constants lies in the fact that most of these tests involve static loading conditions, whereas an in situ pavement is subjected primarily to dynamic loading. Another problem arises from the destructive nature of these tests. A laboratory specimen can be tested only once. This, coupled with the gross nonhomogeneity of the material under study, introduces a large degree of variation from test sample to test sample.

A testing method for road construction materials is needed, which permits the determination of material constants from evaluative procedures that more closely approximate the type of loading and the loading conditions that exist under actual use. This test should be such that a single material sample could be tested many times under varying conditions by using a repetitive or dynamic type of loading technique; i.e., a nondestructive, dynamic test procedure is desired.

In this study, a test technique used by acoustic engineers in their study of more homogeneous materials such as metals, plastics, ceramics, and glass has been applied to asphaltic paving materials. By measuring the propagation velocity of high-frequency sound waves through the material, various material constants can be determined. The advantages of this technique are threefold. First, the test procedure is nondestructive, which enables many measurements to be made on the same specimen. Second, the test

Sponsored by Committee on Mechanical Properties of Bituminous Pavement Mixtures.

procedure is dynamic and more closely corresponds to the type of loading that occurs on the in situ structure. Third, the test is easily and rapidly performed.

The primary objective of this work was to develop a test procedure by which the propagation velocity of both the ultrasonic shear and compressional waves could be directly determined. In support of this development, the ability of the testing technique to reveal the relations of certain dynamic elastic constants (E-modulus, G-modulus, and Poisson's ratio) of a compacted asphalt-aggregate mixture to changes in temperature and asphalt content was examined. The effect of void content on the shear and compressional wave velocity was also studied.

RELATION BETWEEN WAVE VELOCITIES AND MATERIAL PROPERTIES

Measurements of ultrasonic longitudinal wave velocity in asphalt concrete have been made by several investigators (1, 2, 3). However, up to this time, no pulse technique for measuring transverse wave velocities in asphalt concrete has been devised, or at least no reference to such a technique was found in a rather extensive literature review. The need for such procedures has been pointed out in various studies. Measurement of the velocity of the transverse wave through asphalt concrete, in conjunction with similar measurements of the longitudinal wave velocities, would allow the calculation of several important elastic constants that are descriptive of the dynamic nature of the test material. The technique presented in this study should provide the highway engineer with a new means to analyze nondestructively the dynamic behavioral tendencies of asphalt-aggregate mixtures.

The following relations between wave velocities and material constants can be derived from elastic theory for an extended elastic solid (4):

$$G = \rho V_s^2 \tag{1}$$

$$E = 3 - [1/(V_c/V_s)^2 - 1]\ \rho V_s^2 \tag{2}$$

$$\nu = [1 - \tfrac{1}{2} (V_c/V_s)^2]/[1 - (V_c/V_s)^2] \tag{3}$$

where

- E = E-modulus,
- G = G-modulus,
- ν = Poisson's ratio,
- V_c = longitudinal wave velocity,
- V_s = transverse wave velocity, and
- ρ = mass density of the medium.

In this investigation, the technique known as direct transmission was utilized to measure the time of travel of an ultrasonic wave through the test material. This method employs a cathode ray oscilloscope to measure the time lapse between the actuation of the wave source and the detection of the generated wave at a receiver.

EQUIPMENT

Electronic Equipment

The electronic equipment utilized to generate and detect ultrasonic waves consisted of a pulse generator, source and receiver piezoelectric ceramic transducers, and an oscilloscope. The pulse generator delivered a 1,100-Vdc spike pulse at a frequency of 60 Hz to the source transducer by the discharge of a condenser through an RCA 6130 hydrogen thyratron tube. Concurrently with the main voltage spike, the generator actuated a trigger pulse to the horizontal time base of the oscilloscope.

Two sets of transducers were utilized. One set generated primarily shear waves, and the other set generated primarily compressional waves. Both sets were constructed from a composition of lead zirconate titanate (PZT) manufactured by Gulton Industries.

The compressional ceramic discs had a diameter of 1.0 in. and a thickness of 0.25 in. and were poled to be thickness expanders. The resonant frequency for these discs was 308 kc/sec.

The shear mode crystals were constructed as 1.0-in. square plates with a 0.25-in. thickness. The shear plate thickness deformed into a rhombus on excitation such that a shearing action was input into the test material. The resonant frequency of the shear plates was 172 kc/sec.

The cathode ray oscilloscope was a Tectronix Type 545B with a type B wide-band, high gain preamplifier plug-in unit. The instrument had two time-base generators (A and B) with delayed sweep operation ability. Time measurements were made using the delayed sweep operation. This technique allowed time measurements to be made to an error of ±2 division of the delay-time multiplier dial on the oscilloscope. The preamplifier had a vertical deflection sensitivity of 0.005 to 20 V/cm and a horizontal time-base sweep rate of 2 μsec/cm to 1 sec/cm with an accuracy of ±3 percent. The rise time of the preamplifier unit was 18 nsec (18×10^{-12} sec).

Temperature Monitoring Equipment

Internal specimen temperatures were monitored by implanting a thermistor in the material. The thermistor's small size and adaptability to remote readout devices made it ideally suited to the needs of this study. Preliminary work revealed that the temperature gradients between the center and the outer edges of the test specimens were insignificant. This was determined by implanting thermistors at varying depths and locations within the specimen and observing the temperatures as the specimen temperature was varied over the entire testing range. Consequently, it was decided that one thermistor located at middepth and just off center of the specimen would yield sufficiently accurate temperatures. It was also determined that a thermistor placed in this location would not interfere significantly with the transmission of the sound pulse.

The thermistors and display equipment chosen for this work were manufactured by Yellow Springs Instrument Company. They had a working range of -12 to 270 F.

MATERIALS AND SAMPLE PREPARATION

Three different aggregates were utilized in the asphalt concrete. All three (fine sand, coarse sand, and crushed limestone) were obtained from a local hot-mix asphalt plant. The asphalt cement used in this mixture was a 60- to 70-penetration grade steam and vacuum refined material. The material had a specific gravity (at 77 F) of 1.005 and a softening point of 118 F. The aggregates were sized on U. S. standard sieves and then recombined according to the Oklahoma Department of Highways' specifications for a type C surface course mixture (5). The asphalt and aggregate were combined by using standard mixing procedures to produce a uniform mix. Figure 1 shows the combined grading of the aggregate mixture and the type C specification.

The compacted asphalt concrete specimens were 4 in. in diameter and 2 in. high. These Hveem-gyratory specimens were molded by using a motorized gyratory-shear compactor in which the compactive effort is applied by hydraulic pressure and gyration of the compaction mold. This method of compacting test specimens of bituminous mixtures has been standardized by the Texas Highway Department (Test Method Tex-206-F, Part II) (6).

Hveem specimens were made with asphalt contents varying from 4 to 8 percent by total weight of the mixture. Specimens at 5 percent asphalt content were compacted at void contents ranging from 1 to 11 percent by volume. Different densities, i.e., void contents in the compacted specimens, were achieved by varying the compactive effort expended in the molding process.

TESTING PROCEDURE

The inherent nonhomogeneity of asphalt concrete and the high attenuation of ultrasonic waves passing through this material, as well as the self-imposed restriction of testing specimens compacted by standard methods to standard sizes, necessitated techniques

that differed from the standard procedures used with other, more homogeneous materials. The large grain sizes of some of the aggregate in the specimen required longer wave lengths than are usually employed. The scattering caused by the large aggregate grains and the viscous nature of the asphalt binder required a wave of relatively large amplitude to overcome the attenuation tendencies of the material. The longer wave length, in turn, does not allow sharply collimated sound beams as is customary in metal testing. In addition, all three types of wave modes (compression, shear, and surface) are excited regardless of the polarity of the source transducer. This occurs because of the elastic nature of the piezoelectric crystal and the surface irregularities at the transducer-specimen interface. Because of the high attenuation and scatter in the material, identical source and receiver transducers were used. The receiving transducer was placed directly opposite to the source transducer (direct transmission method) on the top and bottom faces of the test specimen (Fig. 2).

The ultrasonic compressional wave travels with a greater velocity than any of the other wave modes. If an ultrasonic wave is input at one face of the test specimen, the first motion detected by the receiver on the diametrically opposite face will be the arrival of the compressional wave. Other wave modes, as well as reflected and refracted compressional waves, will arrive later in time than the original wave traveling a direct path between the two transducers. This is because of their longer path lengths and/or slower characteristic velocities. Figure 2 shows the test setup and the first pulses of different waves. The reception of the direct path longitudinal wave, L_1, is followed by the reception of the transverse wave, T_1, and surface wave, S_1. These waves may be distorted by the reflected and refracted longitudinal waves (L_2, L_3, etc.). The numerous large aggregate grains further complicate the output pattern because of multiple-wave reflections and refractions at their boundaries.

The sample is supported such that the two faces are essentially free; therefore, the primary wave will be reflected at the material-air interfaces. The wave will travel back and forth between the interfaces, arriving at the receiver in odd multiples of the direct path travel time. Reflection continues in this manner until the wave source is shut down and the wave itself is damped to zero amplitude.

Two separate types of wave velocity determinations were made in this study. The first type employed the longitudinally poled transducers to generate a relatively high-amplitude compressional wave and lesser amplitude waves of other modes. The second type of test used the transversely poled transducers to input primarily a shearing mode wave form.

The operation of the test equipment in recording the travel time of the ultrasonic pulse was basically quite simple. The test specimen was placed on a holding device with its bottom face resting on the source transducer, and the receiver transducer was positioned on the top or opposite face of the specimen. The pulse generator activated both the source transducer and the horizontal trace of the oscilloscope simultaneously. When a signal was perceived by the receiver, it generated a small voltage that was pre-amplified and fed to the vertical plates of the oscilloscope, which caused a vertical deflection of the trace. A measurement of the time lapse between the activiation of the source transducer and the vertical deflection of the trace on the oscilloscope screen yielded the travel time. The velocity of the wave was simply the known specimen height divided by the observed travel time.

Longitudinal Wave Velocity Measurements

Figure 3 shows the oscilloscope trace of a wave transmitted through a 4 percent asphalt concrete specimen using the compressional transducers. The major particle motion occurs in the longitudinal mode due to the crystal polarity; hence, the compressional wave travels through the test material with a relatively large amplitude. Therefore, the receiver, also poled longitudinally, detects the longitudinal wave not only as the initial particle motion but also as a large-amplitude disturbance. By this reasoning, point A on Figure 3 is the point in time when the direct path compressional wave arrives at the receiver, t_{L1}. As previously discussed, the wave reflects between the two parallel surfaces. Consequently, points D and E in Figure 3 correspond to 3 times t_{L1} and 5 times t_{L1} respectively.

Figure 1. Combined aggregate grading chart.

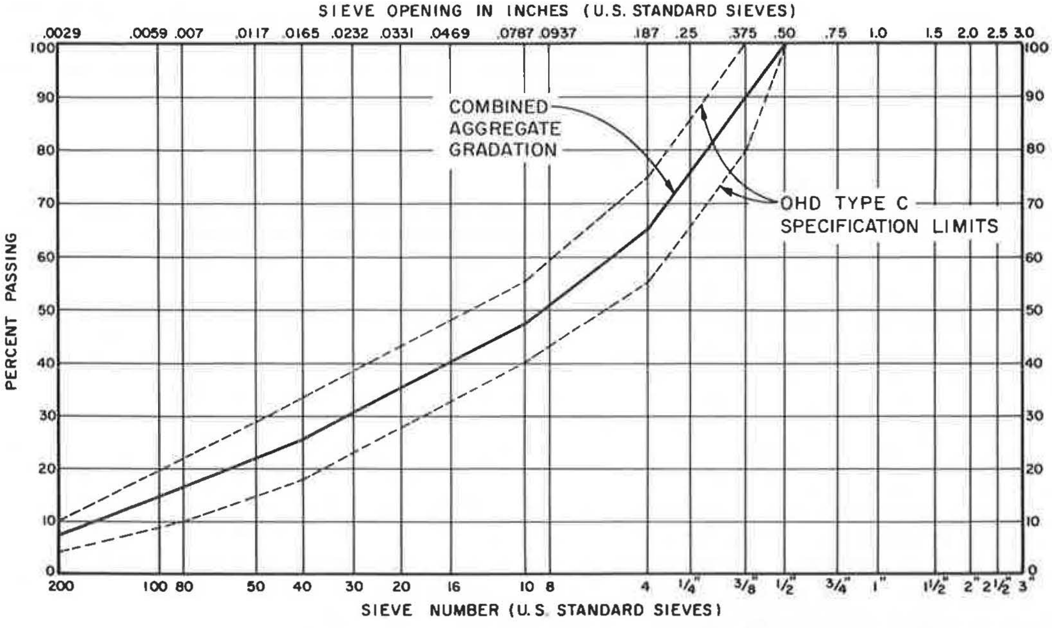


Figure 2. Ultrasonic wave paths and trace indication of their reception.

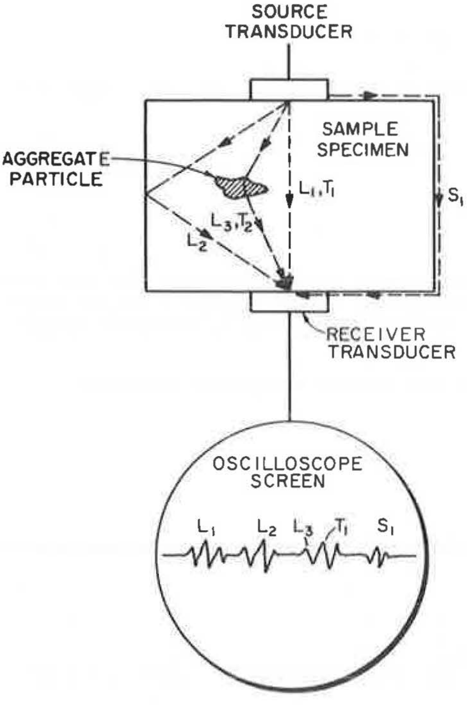
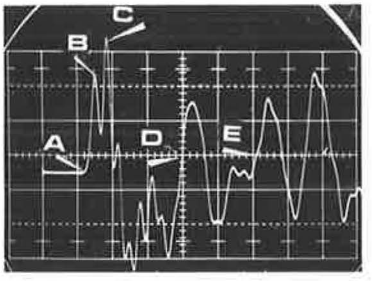


Figure 3. Oscilloscope trace of transverse wave, 4 percent asphalt content specimen.



Because of the length of the driving pulse, the source crystal is resonating simultaneously with the longitudinal reflections in the material. This behavior inputs a low-amplitude wave with a frequency approximately equal to the resonant frequency of the crystal. The period of the high-frequency wave as measured from point B to point C (Fig. 3) is approximately 3.3×10^{-6}. This corresponds to a frequency of 303 kc/sec. This frequency agrees well with the calculated resonant frequency for the transducers of 308 kc/sec. During this time, both reflected and refracted waves of different modes, as well as the direct path shear wave, are striking the receiver. However, the arrival of the direct path shear wave was sufficiently masked by the extraneous indications so that it was not definitely distinguishable on the trace.

Transverse Wave Velocity Measurements

Shear wave velocities were more difficult to determine than were the compressional wave velocities. The basic problem in the measurement of shear wave velocity stems from the high attenuation of the shear wave in asphalt concrete, the consequent necessity of inputting a high-amplitude wave, and the difficulty of securing good transducer-test specimen coupling. Therefore, piezoelectric transducers operating in primarily a shear mode were needed to enable generation and detection of the shear wave.

Unlike the compressional wave reception, the first particle motion to arrive at the receiver will not be the same mode as the major input. Although the major input mode is shear, Poisson's effect will also cause small-amplitude compressional waves to be introduced into the specimen. These waves, traveling with a greater velocity, will arrive at the receiver before the larger amplitude shear wave. Other compressional waves, originating through mode conversion as the shear wave impinges on materials having different acoustic impedences, will also arrive ahead of the shear wave. If the original shear wave amplitude is not great enough, its arrival at the receiver will be masked by the other extraneous indications.

Figure 4 shows an oscilloscope trace output from an asphalt concrete specimen tested with the shear transducers. The low-amplitude, high-frequency precursor displayed in the initial portion of the trace is not fully understood at this time. The precursor remained constant throughout the various tests and was not noticeably affected by temperature or the physical makeup of the specimen.

Because the major input wave particle motion occurs transversely and the receiver is poled to be most sensitive to the shearing mode, the direct transmission transverse wave appears on the output trace with a relatively large amplitude. While the direct transmission longitudinal wave precedes in time the arrival of the transverse wave because of its higher characteristic velocity, the amplitude of the longitudinal wave is smaller compared to that of the transverse wave. Point A on the trace (Fig. 4) is considered to be the point in time of the arrival of the longitudinal wave. Peaks B and C define a period of 6.0×10^{-6} sec, corresponding to a frequency of 166 kc/sec. This frequency compares favorably with the resonant frequency of the transducers (172 kc/sec) indicating that these signals are caused by the reasonating of the shear transducers. At first observation, point C appears to be a likely choice for the arrival of the transverse wave. However, it was found that increasing the test specimen temperature resulted in variations in this point. The point in time where the trace crossed the zero axis (point D) was selected to be the time of arrival of the transverse wave (t_{T1}). This point was easily identifiable throughout the testing procedure. To determine if this point actually indicated the transverse wave arrival, we conducted tests on specimens of steel, Lucite, and concrete and compared the results with results published by other investigators. Table 1 shows that the procedure outlined above provided excellent agreement with published results.

Reflection of the transverse wave from the test material-air interface occurred in a manner similar to the reflection of the longitudinal wave. The amplitude of the reflected wave was much reduced because of the attenuation of the shear wave in the test media. Point E in Figure 4 is believed to be the arrival of the first reflected shear wave (3 times t_{T1}).

TEST RESULTS AND DISCUSSION

General

The testing technique employed in this study would be advantageous only if it yielded results indicative of the actual dynamic properties of the material being tested. It was believed that, if test results obtained in the manner previously described were compatible with the expected or predictable behavioral tendencies, and if they were consistent with the results obtained by other investigators using different testing procedures, the usefulness of this technique would be confirmed.

Admittedly, asphalt concrete can be thought of as an elastic material only under certain conditions. Primarily, these conditions are low temperature of the material, where the plastic properties of the matrix are reduced, and low magnitudes of loading. The assumption of homogeneity, also necessary for elastic theory, can be made only in the generalization that the matrix is equally nonhomogeneous in all directions. However, most engineers are so familiar with such material parameters as Poisson's ratio, Young's modulus, and the shear modulus that there does seem to be some value in determining these or similar parameters, i.e., dynamic E-modulus, G-modulus, and Poisson's ratio from wave velocity measurements. Such values should characterize a material and its behavior under varying conditions as well as the more fundamental factors rooted in the classical theory of elasticity.

The effects of variations in temperature and asphalt content on the dynamic E-modulus, G-modulus, and Poisson's ratio in a specific asphalt-aggregate mixture were investigated. The relations between the ultrasonic wave velocities and both the specimen asphalt content and specimen void content were also determined.

Ten specimens, two each with asphalt contents of 4, 5, 6, 7, and 8 percent by total weight, were continuously tested for both ultrasonic compressional wave velocity and ultrasonic shear wave velocity as their temperature was increased from -15 to 160 F. Internal specimen temperatures were monitored via the implanted thermistors, and velocity readings were made at increments of 5 F.

"Elastic" Constants

Plots of E-modulus (psi) and G-modulus (psi) values versus temperature of the respective asphalt content mixtures are shown in Figures 5 and 6 respectively. The values were calculated by using the equations presented earlier. For clarity, the actual data points are not shown, but the uneven nature of the plots indicates a certain amount of scatter in the readings. This data scatter can be attributed to several factors. Nonhomogeneity of the aggregate particle sizes, shape, and orientation in the compacted specimens is, perhaps, the most obvious source of error. Random errors inherent in the measurement procedure, i.e., those related to the instrumentation and those pertaining to operator techniques, could also be responsible for or have some influence on the scatter.

Despite the scatter, specimens at each of the asphalt contents exhibited the same general trend. As shown in the figures, both moduli values decreased with increasing temperature. The rate of decrease in both plots also increased as the specimen temperature was raised. The moduli values increased with asphalt content up to 6 percent. Above this limit the moduli decrease. E-modulus values ranged from a high of 5.03×10^6 psi for the 6 percent asphalt content specimens at -15 F to a low of 0.35×10^6 psi for the 8 percent asphalt content specimen at 160 F. The amount of decrease in the E-modulus values between -15 F and 160 F was in the range of 86 percent. The decrease in E-modulus with temperature was an expected occurrence. Similar findings have been reported by Goetz (1), Kallas and Riley (9), and Kingham and Reseigh (10).

The G-modulus values ranged from a maximum of 1.81×10^6 psi for the 6 percent asphalt content specimen at -15 F to 0.117×10^6 psi for the 8 percent asphalt content specimen at 160 F. The average decrease in G-modulus exhibited by the respective mixtures was approximately 87 percent of the maximum (low-temperature) modulus. As with the E-modulus plots, the G-modulus is a maximum throughout the temperature range for the 6 percent asphalt content mix.

Figure 4. Oscilloscope trace of transverse wave, 6 percent asphalt content specimen.

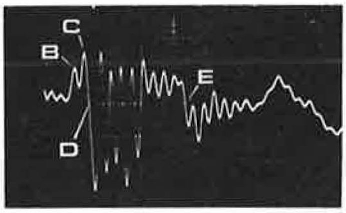


Table 1. Comparison of transverse wave velocity measurements.

Source	Transverse Wave Velocity (fps) Steel	Lucite	Concrete
Krautkramer and Krautkramer (7)	10,600	4,700	7,500[a]
Filipczynski et al. (8)	10,600	3,700	7,000[a]
Stephenson and Manke	9,500	4,200	7,200

[a]The transverse velocity in concrete equals approximately one-half of the published values of longitudinal velocity.

Figure 5. Effect of temperature on E-modulus.

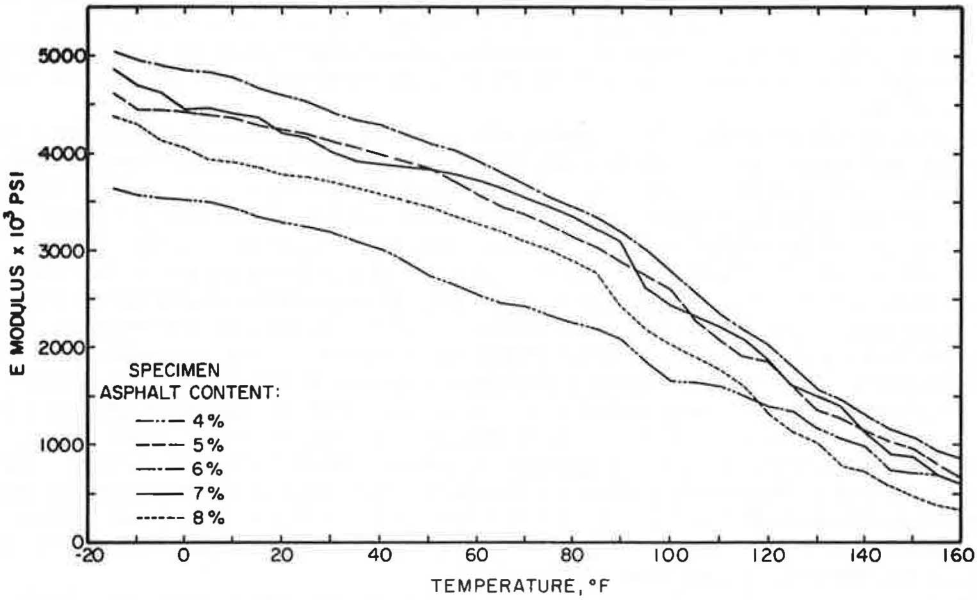
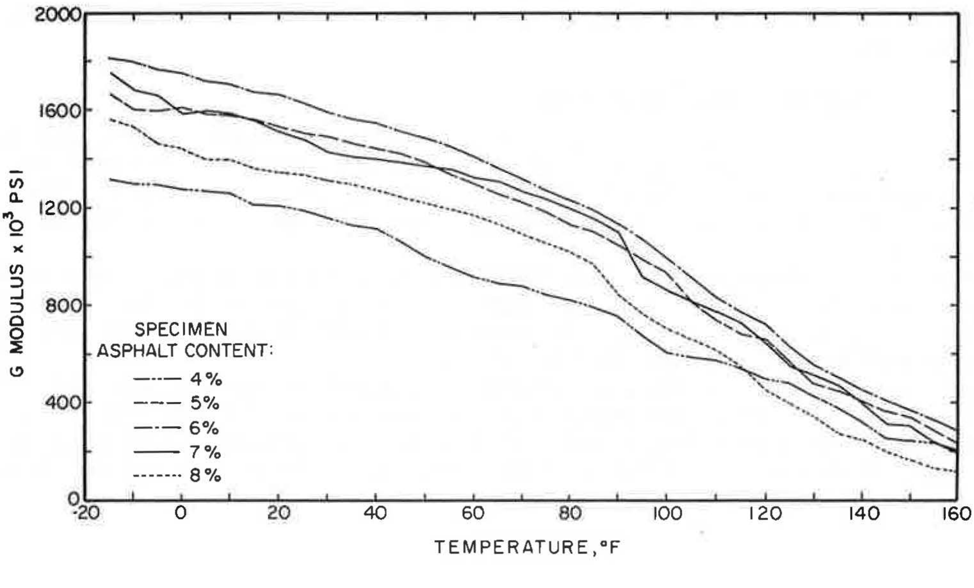


Figure 6. Effect of temperature on G-modulus.



It was expected that at some low temperature the moduli would attain a limiting value. Although the curves do indicate a leveling off at lower temperatures, limitations of the temperature-monitoring equipment prevented examinations below -15 F.

At the other temperature extreme some minimum moduli value was also expected. However, beyond the temperature of 160 F the specimens softened to such an extent that they fractured and spalled during the testing operation. Consequently, velocity measurements and therefore moduli determinations could not be made above this temperature.

Various investigators (9, 11) have demonstrated the relationship of the so-called E-modulus to both the frequency of loading and the loading stress for asphalt concrete material. They have shown that the E-modulus values vary directly with frequency and inversely with loading stress. The values of the E-modulus presented here are in excellent agreement with the sonic modulus values reported by Goetz (1). Monismith et al. (11), using repeated-load compression tests, reported values of the modulus of resilient deformation (E_e) in the range of 8×10^5 psi. Their tests used a deviator stress of 20 to 40 psi; however, a much greater level was used in the ultrasonic technique. Gregg et al. (12), utilizing a triaxial testing method with low-frequency repetition, reported moduli of resilient deformation for bituminous stabilized sand bases in the range of 2.2×10^5 psi.

Because, in this procedure, both moduli are determined from evaluation of the compressional and shear wave velocities, any factor influencing these velocities are mirrored in the moduli values. The behavior of an asphalt-aggregate mixture is complicated by the material deformation characteristics at various temperatures related to the consistency of the asphalt binder. At relatively high temperatures, the mixture may be a highly plastic (tending to viscous) material and at lower temperatures the mixture may be considered as an elastic material. Between these temperature extremes the material will probably exhibit both elastic and plastic characteristics.

Figure 7 is a plot of Poisson's ratio versus temperature for the 5 percent and 8 percent specimens. The behavior is typical of the specimens at other asphalt contents. The plot shows that at low temperatures Poisson's ratio for the 5 percent specimen is approximately 0.385 whereas that for the 8 percent specimen is 0.405. Both values hold reasonably constant until a temperature of between 80 and 100 F is reached. Between 80 and 100 F, Poisson's ratio for both specimens begins to increase rapidly until a value of 0.449 and 0.477 is reached at 160 F for the 5 and 8 percent asphalt content specimens respectively. As would be expected, the ratios at the higher temperatures approach the theoretical maximum ratio of 0.50.

The figure also shows the effect of asphalt content on Poisson's ratio; i.e., Poisson's ratio increased monotonically with increasing asphalt content of the specimens. This further reflects the behavioral dependency of the material on the visoelastic nature of the binder. When the test specimen was heated to the point at which the asphalt binder began to soften, the change in asphalt consistency caused a significant loss of rigidity in the material.

Temperature Effects on Wave Velocities

Figure 8 shows compressional wave traces for a 4 percent asphalt content specimen. It is easily seen in these photographs that the arrival of the initial vertical deflection takes almost twice as long in the hotter specimen than in the colder specimen. The amplitude of the received wave is greatly reduced when the specimen is at the higher temperature.

Figure 9 shows three photographs of shear wave traces for a 6 percent asphalt content specimen. The arrival time of the large-amplitude shear wave is readily seen to increase as temperature increases. Another unique feature is the increased wave amplitude at 90 F in relation to the other two traces.

As temperature is increased, the viscosity of an asphalt cement will decrease. The material characteristics change from a brittle solid to a semisolid and, finally, to a viscous liquid. In an asphalt-aggregate mixture, the films of asphalt surrounding the aggregate particles serve as a binder or cementing agent. As the nature of the films

Figure 7. Effect of temperature on Poisson's ratio.

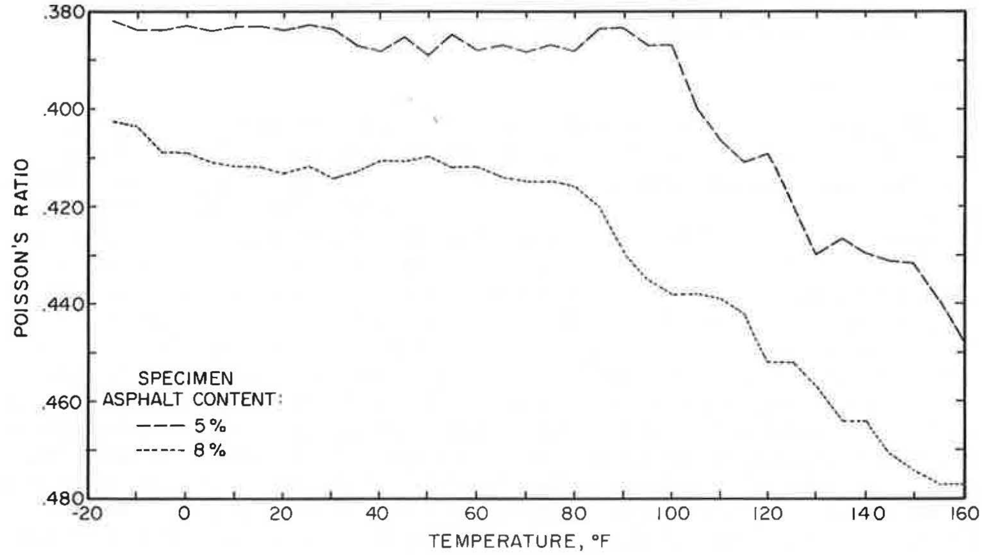
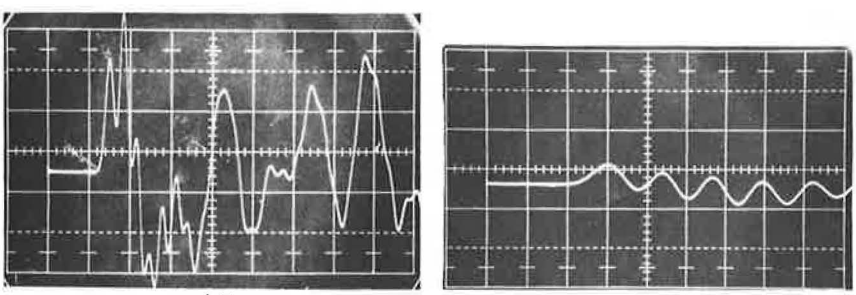
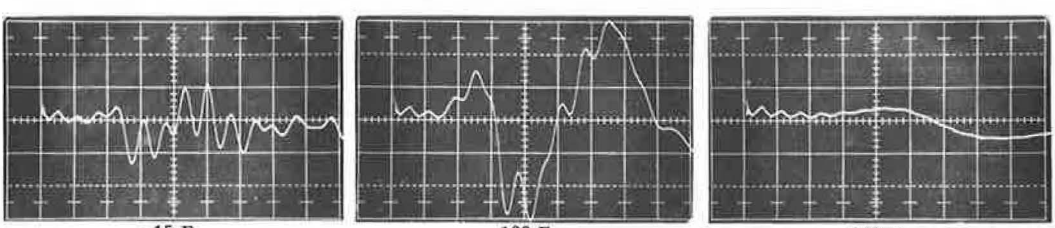


Figure 8. Effect of temperature on longitudinal wave, 4 percent asphalt content specimen.



-4 F   160 F

Figure 9. Effect of temperature on transverse wave, 6 percent asphalt content specimen.



-15 F   100 F   160 F

changes with increasing temperature, the aggregate matrix is less tightly bound together; i.e., it becomes less rigid. Consequently, the mixture is unable to transmit the compressional wave at as high a velocity as it can at low temperatures.

Asphalt Content Effects

Figures 10 and 11 show both compressional wave velocity and shear wave velocity versus percentage of asphalt content at temperatures of 0, 80, and 160 F. In all of the plots, the velocities increased with asphalt content up to a limiting value of either 6 or 7 percent. For the aggregate mixture used in this study, optimum asphalt content was 6.2 percent. However, no direct correlation of optimum asphalt content and maximum wave velocity could be made. These curves, although not conclusive for defining optimum asphalt content as determined by a standard test procedure, do give an indication of the percentage of asphalt that yields the best conditions of interparticle contact and minimum path length for the transmission of the wave. In a series of specimens compacted from a design mixture, conditions should exist where there is a sufficient quantity of asphalt cement to achieve optimum particle orientation and reduction of void content so that the pulsed wave can travel from aggregate particle to aggregate particle with only minimal travel distance through the acoustically slower asphalt binder. The use of lesser quantities of the asphalt binder should result in lower densities, increased voids, and more random particle orientation—all of which combine to reduce the velocity of the mechanical wave. Asphalt contents above this "optimum" will tend to force the aggregate particles apart, reduce interparticle contact, and force the wave to travel through the acoustically slower asphalt cement for longer periods. This will increase the travel time of the wave and greatly reduce its velocity.

Void Content Effects

In an attempt to define the relation between the percentage of voids in the test material and the velocity of an ultrasonic wave through it, 15 specimens were compacted by using the Hveem-gyratory technique. The void contents ranging from 0.84 to 11.22 percent by volume were obtained by varying the total compactive effort applied to the specimen. Compressional wave and shear wave velocity measurements were then made at -15 and 80 F.

Figure 12 shows both compressional wave velocity and shear wave velocity versus void content. Although a considerable amount of data scatter is evident, the apparent linear relationship between the variables prompted computation of the linear regression line for the data sets. The low slopes of both the compressional and shear plots at -15 F indicate a negligible effect of the voids contained in the test material on the wave velocities at that temperature. However, the linear regression line slope of both wave types at 80 F was considerably greater than those at the lower temperature. This, of course, indicates that an increase in the amount of voids in a specimen at 80 F caused a decrease in the rates of transmission of the ultrasonic waves through the material.

The data scatter in both the compression and the shear wave tests is probably attributable to the fact that the size of the aggregate particles as well as their orientation in the asphalt-aggregate mixture has a large influence on the rate of transmission of an elastic wave through the material. The aggregate used in the mix had a tip size of ½ in. Orientation of several of these larger particles such that most of the travel path (± 2.0 in.) of the elastic wave was through these particles would result in high velocities. The velocities of waves having travel paths through more of the asphalt cement rather than the aggregate constituent would have slower travel velocities.

Figure 12 shows that the amount of voids in a material specimen at low temperature had little, if any, effect on the rate of transmission of the ultrasonic wave. The increased viscosity of the asphalt binder at these temperatures seems to be a primary influence. At the higher temperatures, where the asphalt viscosity and the asphalt volume are greater, the amount of voids included in the matrix is relatively more important. This indicates that the nature of the binder has a smaller influence on interparticle contact in the more dense specimens than in the less dense specimens. That is, the better aggregate-to-aggregate contact in the denser or more highly compacted material results in a relatively higher rate of transmission of the acoustic wave.

Figure 10. Effect of asphalt content on compressional wave velocity.

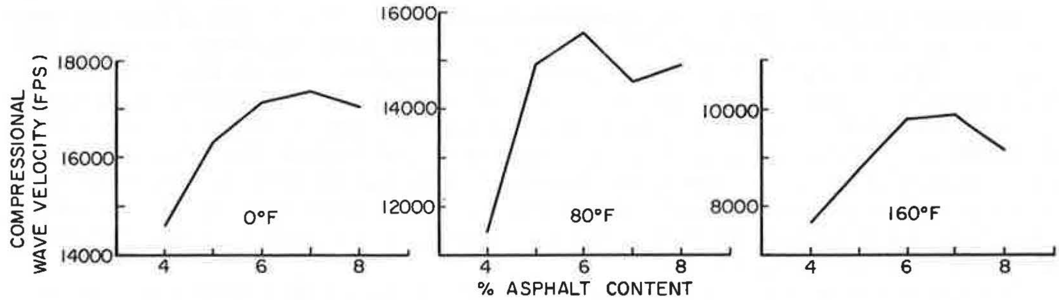


Figure 11. Effect of asphalt content on shear wave velocity.

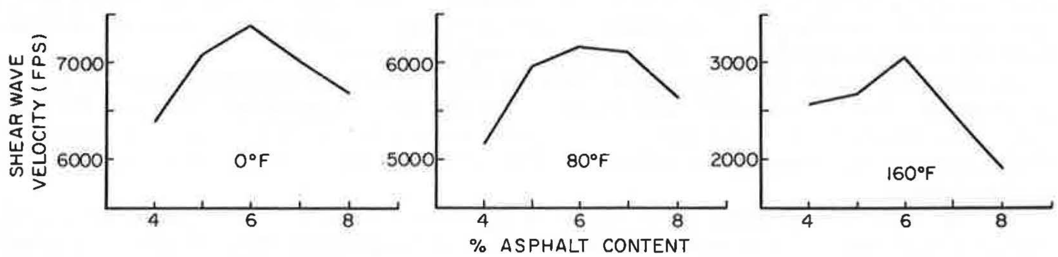
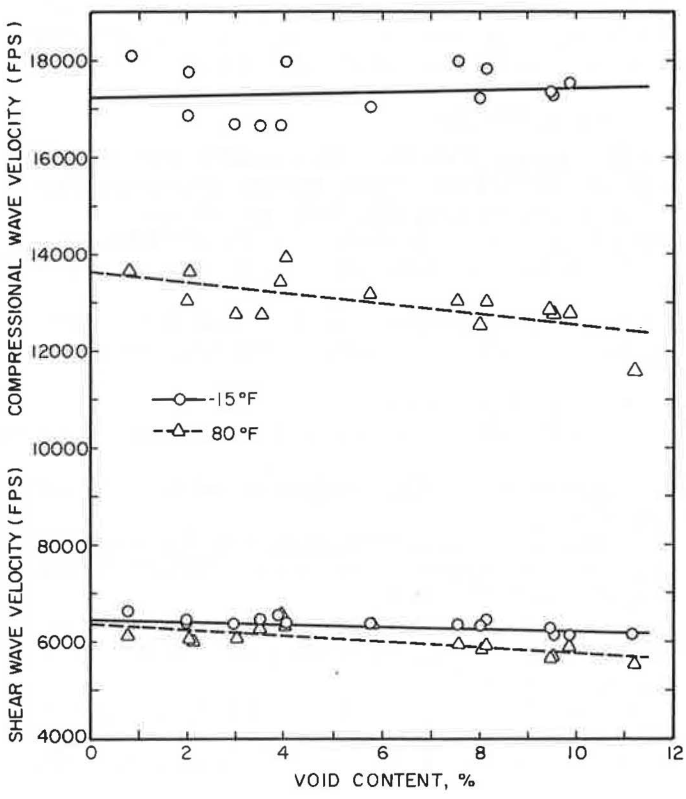


Figure 12. Effect of void content on wave velocities.



CONCLUSIONS

It can be concluded from these preliminary tests that it is possible to directly measure ultrasonic shear wave velocities through standard-sized specimens of compacted asphalt-aggregate material at temperatures representative of in-service conditions. In addition, the study has demonstrated that ultrasonic testing procedures can yield useful information regarding the dynamic properties of asphalt concrete. This nondestructive testing procedure shows great promise for determining the behavioral characteristics of other types of pavement construction materials as well. The possibility also exists that material parameters determined by this or similar techniques will have some application in the area of design, control, and subsequent in situ evaluation of flexible pavement components.

A brief, nonstatistical study of a single asphalt-aggregate mixture resulted in the following observations concerning the behavior of the material.

1. The temperature of the asphalt-aggregate test material had a great influence on both the dynamic E- and G-moduli calculated from the wave velocity measurements. Both moduli decreased with increasing temperature. The rate of decrease of the moduli increased with increasing temperature. The maximum moduli values were associated with the test specimens containing 6 percent asphalt cement.

2. Poisson's ratio increased monotonically with increasing asphalt content of the specimens. The values were essentially constant until a temperature between 80 and 100 F was reached. Beyond this limit, Poisson's ratio increased to approximately 0.50. This behavior was considered indicative of the influence of the viscous properties of the asphalt binder.

3. Maximum wave velocities occurred in specimens compacted with asphalt contents of 6 and 7 percent. An increase above 7 percent or a decrease below 6 percent asphalt content resulted in reduced velocities throughout the range of test temperatures. Thus, an "optimum" asphalt content for wave transmission existed at or between these limits.

4. At -15 F, the amount of voids contained in a compacted asphalt-aggregate specimen had little or no effect on either the compressional or shear wave velocity. At laboratory temperature (80 F), however, an increase in voids resulted in a decrease in wave velocity. This trend was most evident for the compressional wave.

REFERENCES

1. Goetz, W. H. Sonic Testing of Bituminous Mixtures. Proc. AAPT, Vol. 24, 1955.
2. Manke, P. G., and Gallaway, B. M. Pulse Velocities in Flexible Pavement Construction Materials. Highway Research Record, 131, 1966, pp. 128-153.
3. Stephenson, R. W. Temperature Effects on the Compressional Wave Velocities of Asphalt-Aggregate Mixtures. Oklahoma State University, M.Sc. thesis, July 1968 (unpublished).
4. Kolsky, H. Stress Waves in Solids. Dover Publications, Inc., New York, 1963.
5. Standard Specifications for Highway Construction. Oklahoma Dept. of Highways, 1967.
6. Manual of Testing Procedures. Texas Highway Dept., Vol. 1.
7. Krautkramer, J., and Krautkramer, H. Ultrasonic Testing of Materials. Springer-Verlag, New York, 1969.
8. Filipczynski, L., Pawlowski, Z., and Wehr, J. Ultrasonic Methods of Testing Materials. Butterworth, London, 1966.
9. Kallas, B. F., and Riley, J. C. Mechanical Properties of Asphalt Pavement Materials. Proc. Second Internat. Conf. on Structural Design of Asphalt Pavements, Univ. of Michigan, Ann Arbor, August 7-11, 1967.
10. Kingham, R. I., and Reseigh, T. C. A Field Study of Asphalt-Treated Bases in Colorado. Proc. Second Internat. Conf. on Structural Design of Asphalt Pavements, Univ. of Michigan, Ann Arbor, August 7-11, 1967.
11. Monismith, C. L., Terrel, R. L., and Chan, C. K. Load Transmission Characteristics of Asphalt-Treated Base Courses. Proc. Second Internat. Conf. on Structural Design of Asphalt Pavements, Univ. of Michigan, Ann Arbor, August 7-11, 1967.

12. Gregg, J. S., Dehlen, G. L., and Rigden, P. J. On the Properties, Behavior and Design of Bituminous Stabilized Sand Bases. Proc. Second Internat. Conf. on Structural Design of Asphalt Pavements, Univ. of Michigan, Ann Arbor, August 7-11, 1967.