Dynamic Analysis of Asphaltic-Aggregate Mixtures

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Ultrasonic probes have been constructed for use in dynamic nondestructive testing of asphaltic concrete specimens. Use of the probe systems was superior to use of their main components alone, the piezoelectric crystals. The probes have the advantages of reducing ringing time, concentrating ultrasound in one direction, elimination of noise due to unshielded connections, and increased durability. The probes were used in a limited testing program. Compression and transverse wave velocities in the specimens tested were measured simultaneously. Sample conditions suitable for maximum wave velocity corresponded to conditions producing maximum strength and minimum voids in the mineral aggregate. A relationship of increasing wave velocity with increasing strength was noted. Wave velocity was observed to increase as the percentage of voids in mineral aggregate decreased. Various elastic constants were calculated from the wave velocities measured. Maximum values of E and G moduli as well as Poisson's ratio corresponded to minimum voids of the test specimens. Relative attenuation measurements were conducted by using water as a standard material. An evaluation of relative attenuation with changes in asphalt content indicated maximum damping at asphalt contents associated with high stability values.

Consideration of the dynamic behavior of a pavement system is becoming a very important part of pavement design practice. It is obvious that the thickness and mix design techniques currently used in the laboratory are not always applicable in the field because the techniques are based on static, destructive test methods. These methods do not accurately model the actual loading conditions occurring in the field.

Testing methods have been sought that evaluate the strength parameters of pavement components as they undergo the actual strain levels that will occur in the field. The parameters of Young's modulus E, shear modulus G, and Poisson's ratio μ are required in certain mathematical models to calculate design thicknesses for pavement layers.

Elastic theory has been used in the above-mentioned models. Because the asphaltic concrete layer of the pavement system conforms reasonably well to elastic theory for the strain levels in question, the use of elastic moduli for this particular layer may be justified. As dynamic loading conditions are reached, the behavior displayed by the asphaltic concrete layer tends to agree more reasonably with elastic theory. The behavior of other layers of the pavement system, such as the base and subgrade, deviates substantially from elastic theory.

The increasing interest in full-depth asphaltic pavements has added to the need for an even more rational design theory. One of the theories being considered involves modeling the pavement as a viscoelastic system. The theory behind this model uses the strength parameters previously mentioned plus a measure of the damping capacity (δ = logarithmic decrement) of the material. Thus a single testing method that evaluates these material characteristics dynamically would be very useful in pavement design.

Numerous testing methods have been developed that attempt to measure the needed design parameters. The test methods most desirable are those that approximate actual field conditions most closely. The ideal test should also be nondestructive so that a single specimen can be tested under a variety of loading conditions.

In this study a testing technique involving the generation and detection of ultrasonic waves in asphaltic concrete samples is used to measure the parameters in question. These values were determined by nondestructively measuring the propagation velocity of ultrasonic waves through the test material. The equipment required in this study was developed at the University of Missouri—Rolla. The main purpose of this study is to further the knowledge of this testing technique as applied to flexible pavement materials. In particular, an ultrasonic probe more suitable for attenuation measurements has been developed.

It was a goal of this study to measure the strength and damping parameters of the surface course of a flexible pavement system. The parameters E, G, μ, and δ depend on the properties of the asphalt-aggregate mixture. The effects of physical properties such as asphalt content, aggregate gradation, voids ratio, and density have, in the past, been evaluated by empirical testing procedures. An attempt has been made to correlate the results of one of these procedures, the Marshall method of mix design.

Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures to Meet Structural Requirements.

THEORY OF ULTRASOUND

The theory of ultrasound is very similar to that of audible sound. Sound is the result of mechanical disturbance of a material, i.e., a vibration. In general, three types of waves are generated by a source vibration: compression, shear, and Rayleigh waves.

By using elastic theory, a relationship between the speed of propagation and amplitude of these waves and certain properties of the media through which they are traveling can be determined:

$$E = V_c^2 \rho \, [(1 + \mu)(1 - 2\mu)]/(1 - \mu) \quad (1)$$

$$G = V_s^2 \rho \quad (2)$$

$$\mu = \frac{1 - 1/2(V_c/V_s)^2}{1 - (V_c/V_s)^2} \quad (3)$$

and

$$\delta = (2.302/n) \log_{10}(A_o/A_n) \quad (4)$$

where

V_c = velocity of compression wave,
V_s = velocity of shear wave,
μ = Poisson's ratio,
E = Young's modulus,
G = shear modulus,
ρ = mass density = γ/g,
δ = logarithmic decrement (attenuation per cycle),
A_o = initial value of the amplitude, and
A_n = amplitude after n oscillations.

In this study, the method of direct transmission of ultrasonic waves was used to evaluate V_c, V_s, and A. The elastic constants were calculated from these measurements.

INSTRUMENTATION AND MATERIALS

Electronic Equipment

The electronic equipment used in this study was previously used, and partially developed at the University of Missouri—Rolla (1). The equipment necessary for conducting the tests includes a pulse generator, an oscilloscope, and two ultrasonic probes (transmitter and receiver).

The design of an ultrasonic probe suitable for dynamic evaluation of asphaltic concrete mixtures is hindered by various complications. The development of a probe that effectively overcomes these complications thus became a major part of this investigation.

Crystal Description

The crystals initially used were thickness expanders manufactured by Gulton Industries. The resonant frequency of these crystals is approximately 308 kHz/s in the thickness mode. They were 2.5 cm (1.0 in) in diameter and were made of lead piezoelectric zirconate titanate (PZT).

The second set of crystals used was the same size, and they were primarily radial expanders (shear mode) manufactured by Clevite. The crystal material was PZT and is identified as PZT-4 by the manufacturer. These crystals had a resonant frequency of 90 kHz in the radial mode and 640 kHz in the thickness mode.

Probe Construction

Previous work on the design of ultrasonic probes for flaw detection in metals has been published (2, 3). The basic characteristics of the probes used in flaw detection coincide with the properties of the probes used for ultrasonic testing in asphaltic concrete. Three of the main features considered in the probe design were (a) crystal selection, (b) mechanical damping of the crystals, and (c) concentration of ultrasonic waves in one direction.

The backing material suggested by Washington and used in this study is a mixture of tungsten powder and casting resin or Araldite. The tungsten and Araldite ratio suggested was 2:1 by weight. Figure 1 shows a section of the probe as built.

The ultrasonic probe has two additional advantages. First, the probe design offers complete electronic shielding. This eliminates noise that often hinders ultrasonic measurements. Second and more practical, the durability of the probe system has been increased.

Sample Preparation

The asphaltic concrete samples used in this study were prepared according to Marshall test procedures. These procedures are given by ASTM Designation D 1559.

The aggregates used in preparation of these samples were obtained from aggregate stockpiles at the University of Missouri—Rolla, which stocks the aggregates (crushed stone and Meramec River sand) for laboratory and research purposes. The sand and crushed stone were sieved into various sizes and recombined to conform to the Missouri State Highway Department gradation specifications for type D asphaltic concrete.

The asphaltic cement used in this study was 85 to 100 penetration grade and was obtained for research from the Shell Oil Company. The specific gravity of the asphalt is 1.010 (4).

Three Marshall specimens at each asphalt content were prepared. Identical combinations of aggregates were used for each specimen. The specimens were compacted by 50 blows of a standard Marshall hammer on each face of the specimen. The compacted specimens had a diameter of 10.2 cm (4 in) and a height of approximately 6.4 cm (2.5 in).

TESTING TECHNIQUES

The ultrasonic testing technique used in this study is known as the direct transmission method. The use of this method was necessary because of the significant amount of scatter associated with the multiple reflections and longer path lengths typical of other methods.

Sample Supporting Devices and Acoustic Coupling

The sample supporting device initially used was a testing frame normally used for unconfined compressive strength soil tests. The proving ring normally used for load measurement was replaced by a much lighter ring constructed from plexiglass. This smaller ring was used to obtain constant pressure between the probes and the test sample.

The main advantage of this sample holding device is its simplicity. Samples can be mounted, tested, and removed quickly and with little effort. The constant pressure obtained is also advantageous in that it minimizes any deviations due to changes in coupling pressures.

As in other studies (4, 5), pressure coupling of the probes to the samples did not always prove adequate. Better quality results were obtained by using an inter-

mediate coupling material. Silicone grease as a coupling medium proved adequate for measurements involving velocity determinations.

Grease coupling was not adequate for tests measuring wave amplitude. Therefore, a second coupling material and sample supporting device were selected. The device consisted of a plexiglass tank constructed such that acoustic coupling could be obtained by using water as the coupling medium. The two ultrasonic probes were positioned and sealed into holes on opposite faces of the tank. Dimensions of the tank were such that the Marshall samples could be placed between the probes without any probe-sample contact. The distance between the receiving and transmitting probes was then kept constant during the tests.

Compression wave velocities measured by using this technique were identical to values from the pressure coupling method. Disadvantages of the method for velocity measurement were apparent. More calculations were involved because the time of wave travel through the water had to be taken into consideration. Transverse waves are not transmitted through water; thus, with this method, measurement of transverse wave velocities is impossible.

The water coupling method did result in more accurate measurements of the amplitude of the transmitted wave. This was expected and resulted partially from the fact that pressure coupling effects were eliminated completely. Better quality signals also resulted from using water as a coupling medium. As opposed to grease, the water quickly and effectively filled all air voids between the probe and sample and diminished the effects of sample roughness on the quality of acoustic coupling.

Velocity Measurements

All major velocity measurements were obtained from the pressure coupling method using silicone grease as a coupling medium. A major advantage was that the initial compression wave and shear wave arrivals could be detected on the same trace.

Velocities of the compression wave and shear wave were easily obtained by dividing the length of the sample by the respective arrival times. This exposed the least accurate measurement in the velocity determinations, the measurement of sample thickness. Thickness measurements were made with a micrometer and were taken a number of times to ensure the highest accuracy possible.

Damping Measurements

Tests involving amplitude measurements were initially conducted by using pressure coupling with grease as a coupling medium. The object of these measurements was to determine the decrease in energy of the wave per length of travel through the specimen, i.e., the attenuation per length.

A sample submersion tank was used to measure relative damping in samples using water as the coupling agent. The ultrasonic probes were sealed into holes in the sides of the tank with a flexible, easily removed sealant. The dimensions of the tank were such that, when the Marshall specimens were placed inside, the sample was centered between the probes. At this point, the tank was filled with water at a constant temperature. A constant pulse width, pulse interval, and pulse voltage were chosen, and testing was begun. The distance between the probes was held constant throughout the testing program.

Amplitude measurements on the sample using water coupling were reproducible. There was, however, a small increase in amplitude of the compression wave as the specimen became saturated. Increased energy transmission with increased saturation of the sample resulted from the decrease of air voids with saturation. This increase in amplitude was easily controlled by either testing the samples as soon as possible after submersion or allowing them to become saturated before amplitude was measured. The results with the least scatter came from testing the samples just after submersion.

Another advantage of this testing technique was using the tank filled with water as a standard for relative attenuation measurements. The distance between the probes was varied, and the amplitude of the compression wave through the water was measured at each setting. From these data, the damping capacity of the water was determined and expressed in volts per centimeter. This value is essentially the slope of a line representing amplitude versus distance between probes. The assumption of linearity of this relationship may be questioned but was of no consequence since the same assumption was made when the specimens were in place. Any nonlinearity would be constant between sample and standard, thus cancelling when relative measurements were considered.

The asphaltic concrete samples were tested, and a value of compression wave amplitude was determined. This amplitude was always much less than the amplitude through water alone. The amplitude loss due to the sample was evaluated and expressed in volts per centimeter of sample length. Relative attenuation of the specimens was then expressed as the dimensionless ratio of amplitude loss per unit length of sample to amplitude loss per unit length of water.

Destructive Testing of Asphaltic Concrete Specimens

Marshall specimens are normally tested destructively according to specifications outlined by ASTM D 1559-73. These testing specifications include a test temperature of 60°C (140°F) and a constant strain rate of 5.1 cm/min (2 in/min). The testing program used in this study conformed to those specifications with the following exceptions.

Because of the large variations in behavior of asphaltic concrete with changes in temperature, it was desirable to hold temperature constant through all phases of this study. Testing was thus conducted on Marshall specimens at room temperature, 23°C (73°F). At that temperature, the Marshall stability values exceeded 44.5 kN (10 000 lbf). These values were above the load limit for any constant strain rate testing machine available. Therefore, a testing machine was used that applied a constant rate of load application.

The testing machine used for the destructive tests was a Tinius Olsen model 200 D. A constant loading rate was chosen that resulted in a strain rate close to 5.1 cm/min (2 in/min). This strain rate was estimated by timing revolutions of a dial gauge attached to the loading head. This constant strain rate was then used for each test.

Limitations in the accuracy of this method of obtaining constant strain rate were considered. The slope of the load-deformation curve and the failure load were known to be highly dependent on strain rate. Because of this, the accuracy of estimating constant strain rate with the constant loading rate mentioned was evaluated.

Five identical asphaltic concrete samples were compacted. One of these samples was tested at room temperature in a normal Marshall testing device. This test was terminated at a 44.5-kN (10 000-lbf) load without completely failing the sample, 44.5 kN (10 000 lbf) being the limit of the machine. Three of the five samples were tested in the Tinius Olsen testing machine at the loading

Figure 1. Section of the ultrasonic probe.

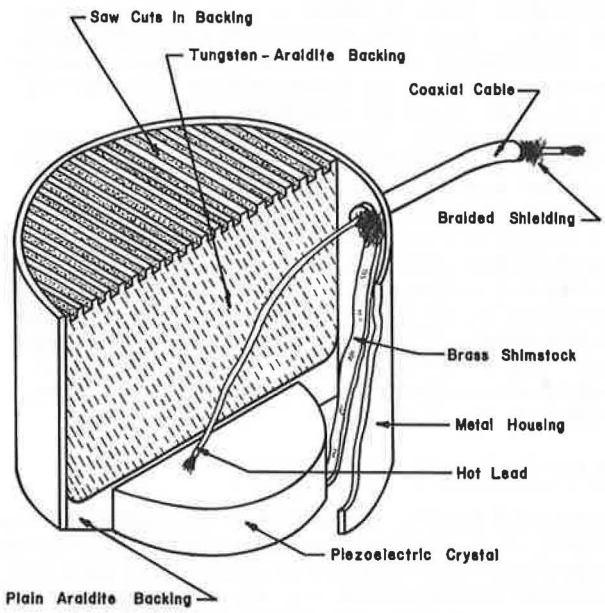


Figure 2. Modified stability versus asphalt content.

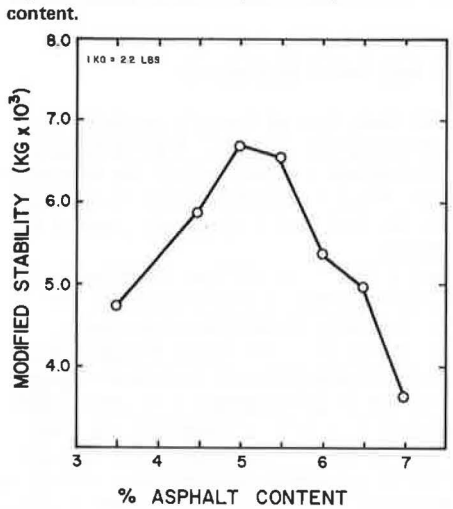
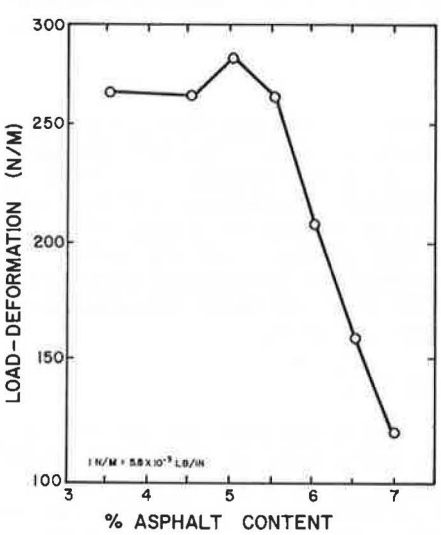


Figure 3. Load-deformation values versus asphalt content.



rate previously mentioned. The initial tangent slopes of these three load-deformation curves ranged from 35.0 to 40.3 MN/m (200 000 to 230 000 lbf/in). The maximum load or failure load of these three tests ranged from 48.9 to 53.4 kN (11 000 to 12 000 lbf). The deviations of these samples seemed insignificant when compared to the test results of the final sample. The fifth specimen was failed at a slower load rate than the previous three specimens. The slope of its load-deformation curve was 28.0 MN/m (160 000 lbf/in) and the failure load was 30.7 kN (6900 lbf). This analysis led to the conclusion that the constant loading rate applied resulted in a reasonably constant strain rate. Any significant deviations in slope were due to variations in characteristics of the specimens rather than strain rate differences.

TEST RESULTS AND DISCUSSION

Ultrasonic velocity tests were performed on the asphaltic concrete samples. Twenty 10.2-cm-diameter (4-in), 6.4-cm-high ($2\frac{1}{2}$-in) samples were prepared at seven asphalt contents and identical aggregate gradations.

Density-Voids Analysis

The percentage of air voids (percentage of total volume) decreased from a maximum of 9.68 at 3.5 percent asphalt content to a minimum of 2.21 at an asphalt content of 7.0 percent. The maximum unit weight of 234 g/cm^3 (146.1 lb/ft^3) occurred at 6.5 percent asphalt content. At 5.0 percent asphalt content, the minimum percentage of air voids was measured at 14.8.

Static Strength and Deformation Tests

The results of the modified Marshall stability tests discussed in the previous chapter are shown in Figures 2 and 3. The tests were conducted at a specimen temperature of 23°C (73°F) and at a constant loading rate that resulted in a strain rate of about 5.1 cm/min (2 in/min).

Figure 2 shows the modified stability (Pm) values versus asphalt content. The modified stability value is the failure load (strength) resulting from the testing procedure mentioned above. The maximum stability of 51.2 kN (11 500 lbf) occurred at 5.0 percent asphalt content.

Because of the empirical nature of the Marshall test, the state of stress and strain in the specimen is difficult to evaluate. This difficulty results from the mode of sample failure and the nonuniform stress distribution that occurs on a partially loaded disk. Krokosky and Chen (4), in their viscoelastic analysis of the Marshall test, encountered the same problem. In their study, the above researchers developed a shape factor, Φ, which related the Marshall load-deformation ratio $P(t)/f$ to the static modulus $E(t)$ by the equation

$$E(t) = \Phi[P(t)/f] \tag{5}$$

where

Φ = shape factor,
$P(t)$ = Marshall stability,
f = flow value or deformation corresponding to $P(t)$, and
$E(t)$ = modulus obtained from unconfined tests.

It should be noted that the Marshall stability P and Young's modulus E are given as a function of loading time. According to Krokosky and Chen, Φ seemed to be independent of asphalt content. The variation of this value with changes in aggregate gradation was not determined. This statement and the differences in aggre-

gate gradations used in the two studies prohibited the use of the actual factor used by these researchers. However, the fact that the shape factor did not seem to be affected by changes in asphalt content was useful in this study. From the previous equation it can be seen that, if Φ is constant, any decrease or increase in modulus due to change in asphalt content should result in a relative change in the load-deformation ratio, Pm/f. From this statement it can be concluded that any change in the load-deformation values shown in Figure 3 would be an indication of changes in static modulus.

Wave Velocity Tests

Ultrasonic wave velocities were measured by using the ultrasonic testing technique that specifies pressure coupling of probes to the sample. Both compression wave and transverse wave transmission times were measured simultaneously for each specimen.

Compression Wave Velocity

Figure 4 shows compression wave velocity versus asphalt content. Asphalt content is expressed in percentage by weight of aggregate. Moderate amounts of data scatter occurred. Thus, for purposes of clarity, the average velocities at each asphalt content have been plotted. One possible reason for this scatter could have been differences in particle orientation between samples of equal asphalt content. The values of compression wave velocity obtained in these tests agreed with those obtained by other investigators (5) using similar methods. An optimum asphalt content for compression wave transmission occurred at approximately 5 percent asphalt content. The compression wave velocity at this optimum condition was approximately 3.96 km/s (13 000 ft/s).

Transverse Wave Velocity

A plot of the transverse wave velocities versus asphalt content is shown in Figure 5. Again, average wave velocities for each asphalt content have been plotted. The magnitude of transverse wave velocities also agreed with the values obtained in other investigations. Optimum wave transmission was observed at an asphalt content of approximately 5 percent. The transverse wave velocity occurring at this optimum condition was 1.94 km/s (6370 ft/s).

Wave Velocity Results

Figures 4 and 5 show that optimum wave transmission of both compression and transverse waves existed at an asphalt content of 5.0 percent. Consideration of what conditions are favorable for wave transmission was based on observations of certain density-voids data. The data used were the percentage of air voids and the percentage of voids in the mineral aggregate (VMA). Percentage of VMA is defined as the percentage of voids in the compacted specimen inclusive of air voids and asphalt binder.

Percentage of VMA did undergo a significant change at this optimum asphalt content. A trend of decreasing wave velocities with increasing VMA was apparent. So much scatter occurred that a unique straight-line relationship could not be shown. However, a range of values was indicated that include the major portion of the data points.

In general, optimum conditions for wave transmission seemed to correlate with minimum VMA. Minimum VMA logically indicated a highly dense aggregate network. Minimum VMA thus suggested a maximum ratio of aggregate volume to volume of voids inclusive of asphalt binder. This ratio indicated high acoustic impedance of the sample because air voids and asphalt binder were lumped together as low-impedance materials and the aggregate was a high-impedance material.

Maximum stability corresponded to maximum wave velocities, and a trend of increasing pulse velocity with increasing strength was noted. The dense aggregate network associated with minimum VMA and maximum wave velocity suggested large amounts of grain contact. High amounts of grain contact are in turn indicative of high internal friction and, logically, greater strength.

In summary, optimum conditions for wave transmission correspond with minimum VMA and maximum stability. These relationships are best explained by the resulting dense aggregate network, high grain contact, and high internal friction.

Dynamic Moduli and Poisson's Ratio

As discussed earlier, certain elastic constants (Young's modulus, shear modulus, and Poisson's ratio) can be determined from measurements of compression wave and transverse wave velocities in an elastic material. The assumption of elasticity in asphaltic concrete is obviously questionable. Deviations from this assumption, however, are minimized when low temperature and dynamic loads are approached.

Young's Modulus E and Shear Modulus G

Figures 6 and 7 show the plots of Young's modulus and shear modulus versus asphalt content. The variations of these moduli with asphalt content reflect the behavior of the wave velocities from which they were calculated. This is indicated by the fact that both curves peak at 5 percent asphalt content.

Through the assumption of a constant shape factor as discussed earlier, the dynamic Young's modulus was compared to the measured load-deformation values. Comparing the two curves (Figures 6 and 3) shows that both plots possess a breaking point at 5 percent asphalt content. Because of the large amounts of scatter a definite relationship between E and P_m/f (dynamic E and static E) was difficult to infer. By considering the constant differences in loading times between the two testing procedures a general relationship between static modulus (load-deformation ratio) and dynamic modulus was observed. The dynamic Young's modulus increased with increasing load-deformation ratio. However, this trend did not seem to hold true for the lowest asphalt content.

Poisson's Ratio μ

Poisson's ratio, also calculated from the wave velocities versus asphalt content, is shown in Figure 8. Poisson's ratio increased up to an asphalt content of 5.5 percent. At this point the values began to decrease with increasing asphalt content. This behavior seemed to be the result of the sensitivity of the values of Poisson's ratio to changes in the wave velocities from which they were calculated. A unit change in wave velocity can result in a tenfold change in Poisson's ratio.

Attenuation Measurements

Relative damping or attenuation measurements were made using water as the coupling medium. Water at 23°C (73°F) was used as a standard, and relative damping was expressed as the dimensionless ratio of amplitude loss per unit length of sample to amplitude loss per unit length of

Figure 4. Compression wave velocity versus asphalt content.

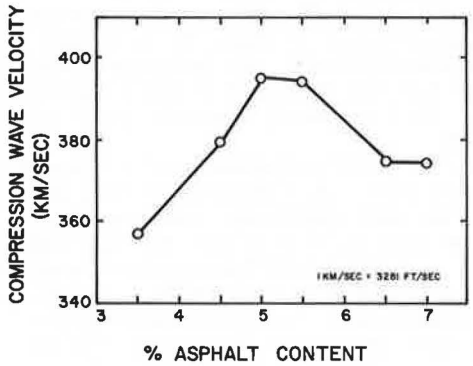


Figure 5. Transverse wave velocity versus asphalt content.

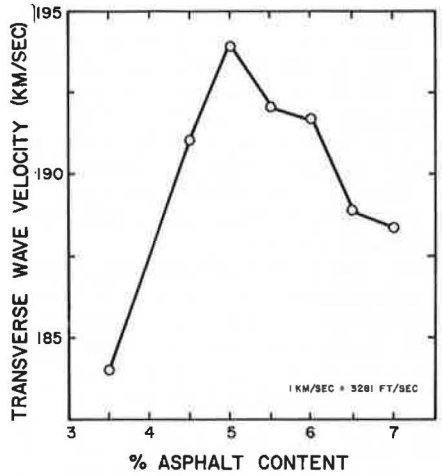


Figure 6. Young's modulus E versus asphalt content.

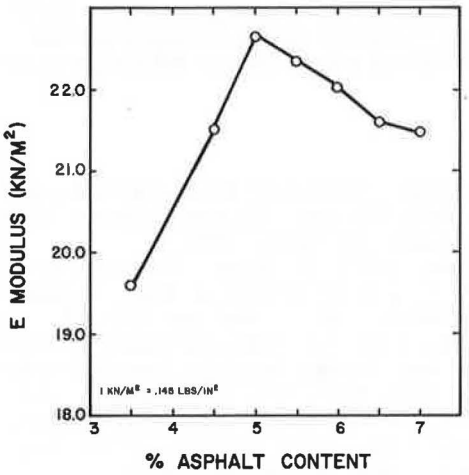


Figure 7. Shear modulus G versus aphalt content.

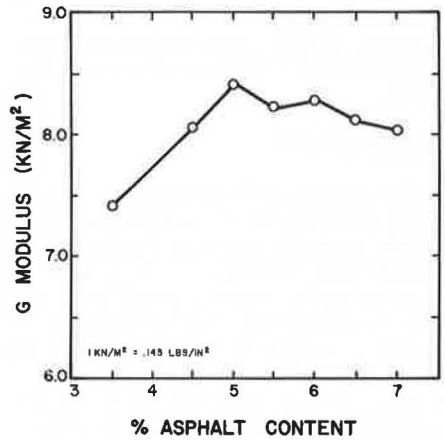


Figure 8. Poisson's ratio μ versus asphalt content.

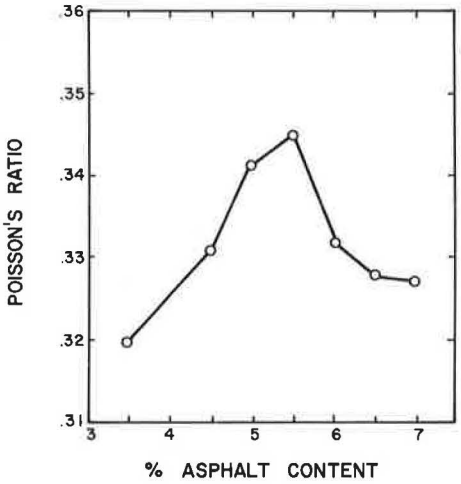
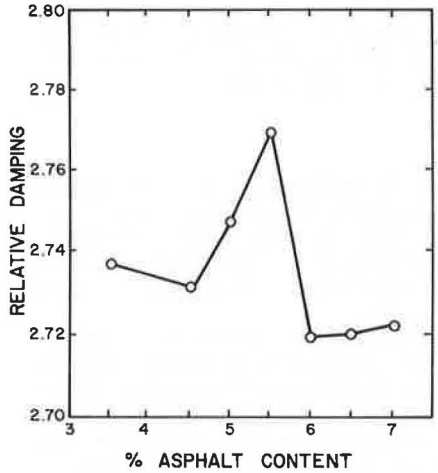


Figure 9. Relative damping versus asphalt content.



water. Significant amounts of scatter occurred, and Figure 9 shows average attenuation versus asphalt content. The damping values shown in Figure 9 indicate that systematic deviations (e.g., linear decrease or increase) of damping with changes in asphalt content did not occur. However, there was a peak in damping at an asphalt content of approximately 5.5 percent. This peak corresponded roughly to the optimum conditions resulting in the peak velocity and peak stability discussed previously. Again, if we ignore the extreme lower and higher asphalt content points, an increase in stability corresponded to increased damping.

The damping values measured resulted from the decrease in intensity of the compression wave as it traveled through the sample being tested. This decrease in energy was due to three major sources: (a) scattering of the wave by reflections at aggregate-particle interfaces, (b) divergences of the wave with distance, and (c) absorption of the wave energy due to heat losses. Inasmuch as this study used samples of uniform size and aggregate gradation, the effects of the first two sources should remain constant. Any major deviations in damping should thus be the result of a change in the magnitude of energy loss due to absorption.

Peak damping of the ultrasonic wave seemed to occur at an optimum condition of high grain-to-grain contact (associated with minimum VMA). Definite conclusions regarding damping were difficult because of the numerous influencing factors.

SUMMARY AND CONCLUSIONS

The key purpose of this study was to develop and construct a probe suitable for velocity and amplitude measurements of ultrasonic acoustic waves in asphaltic concrete specimens. From these values, E, G, μ, and damping properties of the material were evaluated. It was concluded that these properties may be of importance in the dynamic design of asphaltic concrete systems.

The following are the results and conclusions observed from the design, construction, and use of the ultrasonic probes in question. It should be stressed that the test results came from a limited testing program. A larger and more complete testing program should be conducted before definite conclusions can be drawn.

Probe Design

An ultrasonic probe having the following properties was designed and constructed: (a) short ringing time, (b) high electronic shielding, and (c) durability.

Test Results

1. The results of the testing program indicated that values of longitudinal and transverse wave velocities could be measured simultaneously. This concurrent measurement of both velocities on the same electronic trace was a result of the better quality signal produced by the constructed probes.
2. Wave velocities were evaluated versus asphalt content. An optimum condition for wave transmission was noticed at an asphalt content of 5 percent. The relationships of wave velocity with ultimate strength and wave velocity with percentage of VMA were observed. Wave velocity appeared to increase with increasing strength and to decrease with increasing percentage of VMA. Maximum wave velocity, maximum strength, and minimum percentage of VMA occurred at the 5 percent optimum.
3. Various parameters were calculated from the wave velocities according to elastic theory. The curves of dynamic moduli (E and G) versus asphalt content indicated peak values at 5 percent asphalt content.
4. Poisson's ratio increased with asphalt content until a value of 5.5 percent was reached. Above 5.5 percent, Poisson's ratio decreased. The behavior was felt to be the result of material deviations from the assumptions of elasticity and homogeneity necessary for calculations of the value.
5. The values of E mentioned above were compared to load-deformation values (P_s/f) from destructive tests conducted on the Marshall specimens. Changes in load-deformation values were considered indicative of changes in engineering modulus through the assumption of a shape factor (Φ). By this assumption similarities of engineering modulus with the dynamic modulus calculated from the ultrasonic method were observed. A general trend of increasing dynamic Young's modulus with increasing load-deformation values was observed.
6. Relative damping measurements were made by using water as a standard material. Large and systematic deviations of damping with changes in asphalt content did not occur. However, there was an indication of peak damping conditions at an asphalt content of 5.5 percent. The closeness of this peak to the peak corresponding to that of maximum stability suggested a correlation between high damping capacity and high strength. Possible theoretical explanations of this relationship were proposed, but statistical proof from the testing program was limited.

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