Experimental Determination of Ultrasonic Wave Velocities in Plastics as Functions of Temperature.   III.   Rigid Epoxy Foam

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Synopsis

The velocity and attenuation of longitudinal bulk waves in a solid epoxy foam were measured by an acoustic pulse technique in the frequency range of 0.667–4.0 Mc./sec. and in the temperature range from ambient to 150°C. The measurements are reported with the density of the solid epoxy and with aluminum impurity loading as parameters. Over the indicated temperature and frequency ranges, complete attenuation and velocity measurements are reported for one foam corresponding to a density of 0.325 g./cc. In the density range of 0.088–0.325 g./cc. for the unloaded foams, attenuation is reported at room temperature. It is observed that the longitudinal velocities for all the densities decrease with temperature by about 40% in a span of 100°C. and that an approximately linear relation exists with temperature. The velocities in the foams loaded with small percentages of aluminum and heat-treated at 250°C. exhibit temperature behavior which is dependent upon the combined effects of loading, density change, and epoxy properties. For the loaded foam with the highest density (1.068 g./cc.), velocity is reported to a temperature of about 250°C. The velocities of all the various density samples with the exception of the loaded foams exhibit inflections at a temperature of about 110°C. The attenuation–temperature measurements on the 0.325 g./cc. sample show similar behavior at this temperature except that the effect is much more pronounced than the velocity inflection, hence a better indication of the transition. The precision of the measurement is about 2% for the relative longitudinal velocities and about 20% for the attenuation.

Introduction

This work is a continuation of ultrasonic studies which involve the investigation of longitudinal waves in plastics and several nose-cone materials at high temperatures.[1,2]

The purpose of the present investigation is to present data concerning the variation of longitudinal velocity as a function of temperature and density for several solid foams. DuRaFoam EA (prefoamed blocks of thermosetting resin produced by the D&R Pilot Plants, Inc., Hazardville, Conn.) is an epoxy-based formulation of various densities that has a fine-cell, uniform, nondirectional structure. The epoxy base used in these solid foams is Epon 834 (Shell Chemical Co.) which is a glycidyl polyether of a dihydric phenol having an epoxide equivalent weight of 225–290 (epoxide equivalent weight being the weight in grams which contains 1 gram-mole of

an epoxide group).[3]   This rigid material is completely free from grain and is characterized by excellent machinability and dimensional stability. The uniformity and homogeneity of structure allow fairly reproducible velocity measurements from one sample to the next.

The large attenuation of ultrasonic waves in viscoelastic solids generally requires that specimens only a few wavelengths in thickness be used for experimental work.   A convenient method for dealing with such a thin sample is to use solid transmission blocks and to observe the resulting change in amplitude and transit time of an ultrasonic signal with and without the sample inserted between the blocks.   The velocity and at tenuation of the ultrasonic bulk waves can then be readily calculated. In these experiments, it is observed that the bulk wave velocity of ultrasonic waves in an epoxy foam decreases with increasing temperature, and that the attenuation at constant frequency is rather sensitive to the density and type of impurity loading in the foam.   The attenuation is a strongly increasing function of frequency so that most of the information is limited to the frequencies of 0.667 and 1.5 Mc./sec.   There are intrinsic difficulties associated with the extension of these methods to higher frequencies, since, in order for the bulk velocity to be measured, the wavelength must be small with respect to the sample thickness.   However, due to the increased attenuation at these higher frequencies, unrealistically thin strips would be required.

Experimental Method

The electronic apparatus necessary for the generation and detection of pulsed ultrasonic signals is similar to the type used in the superposition method described elsewhere.[4]   In the present technique, due to the excessive attenuation of the samples, the equipment was used as a pulse-transmission apparatus with separate transmitting and receiving lead zirconate–titanate transducers.[5]

A block diagram of the apparatus is illustrated in Figure 1.   A time mark generator is used to trigger the high-frequency pulse oscillator and the oscilloscope.   A pulse a few microseconds in duration and about 500 v. in magnitude is applied to one of the transducers at the 2024 aluminum transmission blocks and simultaneously displayed in unrectified form on the dual-trace oscilloscope.   The acoustic signal transmitted through the sample assembly is detected by the second transducer, converted to an electrical signal, and also displayed on the oscilloscope.   The 93-ohm attenuators are used to prevent overloading the oscilloscope for constant amplitude input signals and for making the attenuation measurements.

The acoustic portion of the apparatus consists of PZT longitudinal transducers (0.6 and 3.0 Mc./sec. resonant frequencies), 2024 aluminum buffer rods, the foam sample, and interfacial joint layers.   The buffer rods were used to separate the transmitted and received signals sufficiently in time so that noise generated by the transmitting transducer did not affect the signal on the receiving transducer.   The samples were approximately 5
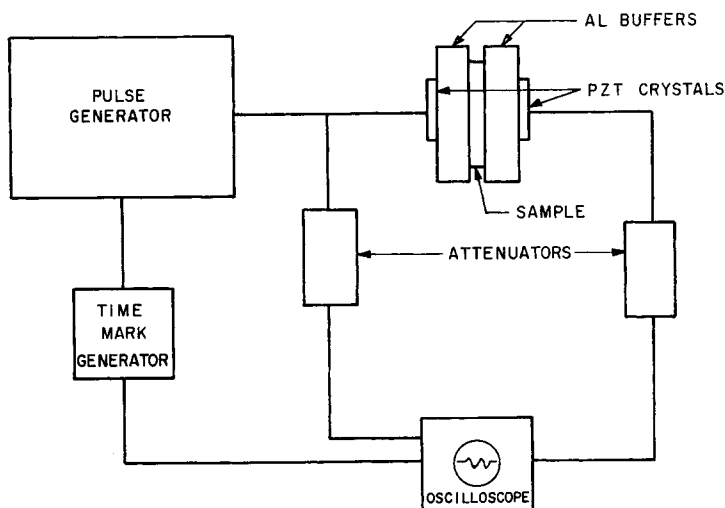
Fig. 1. Block diagram of apparatus for measuring bulk-wave velocity in solid epoxy
foams by ultrasonic pulse transmission.

mm. thick and were bonded to the transmission blocks by a thin layer of
silicone stopcock grease. The grease (F&M DC silicone grease) was used
in place of thinner coupling agents because it provided greater transmission
of the acoustic signal and because it was found not to diffuse into the sample
over a wide temperature range. The entire assembly as used for longi-
tudinal velocity measurements was then held together by light spring ten-
sion (about $1/3$ lb./in.^{2}).

The time required for a signal to traverse the entire assembly less the
time of travel through the aluminum buffers represents the travel time for
a longitudinal wave in the sample and is calculated by counting the number
of time marks between reference peaks on the transmitted and received
signals.[1] The difference between the relative levels in decibels of the trans-
mitted signal for samples of two different thicknesses represents the at-
tenuation of the acoustic signal in the sample. The velocity in millimeters
per microsecond and the attenuation in decibels per centimeter are easily
computed when the sample thickness is known. The velocity measure-
ments, and especially the attenuation measurements, are greatly affected
by the interfacial layers of grease. The effect was minimized by using the
same amount of bond for each sample, ensuring a uniform layer over the
entire sample surface, and by applying the same amount of compression
for each different assembly.

For the temperature measurements, the entire acoustic assembly was
then placed in an oven with a high air flow. Temperature was maintained
constant with a thermocouple controller system and measured at the
sample assembly with a separate chromel–alumel thermocouple. The
temperature in the immediate vicinity of the sample was found to be uni-
form to within 1°C. with a maximum fluctuation of 2°C. at 150°C.

due to the controller system.   Measurements on various kinds and thick-
nesses of samples indicated that approximately 1 hr. was necessary for the
sample to obtain a uniform temperature.[1]   Considering this, it is estimated
that the temperature of the sample itself was uniform to within 1°C. to a
temperature of 150°C.

Results

Figures 2–7 show the relationship between attenuation and velocity with
density, frequency, and temperature as parameters.   The longitudinal
bulk velocity with density as parameter is plotted as a function of tempera-
ture for two different frequencies in Figures 2 and 3.   The density in this
range was controlled by varying the amount of epoxy resin and blowing
agent in the original formulation of the foam.[3]   Since thermal expansion
data were not available for these particular foams, the curves are not
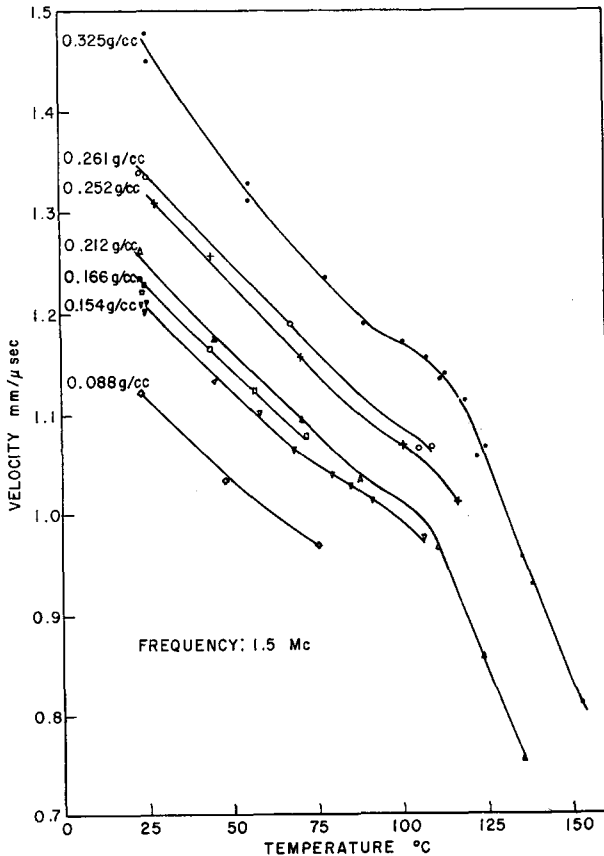corrected for thermal expansion.   However,   comparison   with   solid

Fig. 2. Longitudinal velocity vs. temperature with density as a parameter for a frequency
of 1.5 Mc./sec.

phenolic[6] and silicone[7] foams in the same density range indicates that the resulting error due to expansion would be less than 1% at temperatures to 150°C. For the range of densities shown in Figures 2 and 3, the samples had not been previously heat-treated, and the same general shape of the velocity curve is apparent for all densities. Of particular interest is the existence of an inflection point in the velocity curve at a temperature of about 110°C., where the curve definitely changes slope. Velocity inflections are generally associated with some sort of phase transition, with an accompanying transition in one of the moduli. In this case, a permanent change in the color, density, and velocity was observed when the foams in the density range indicated in Figures 2 and 3 were exposed to temperatures higher than about 110°C. and then remeasured at room temperature. Up to this temperature, the velocity and density assumed the original values within experimental error when the temperature was
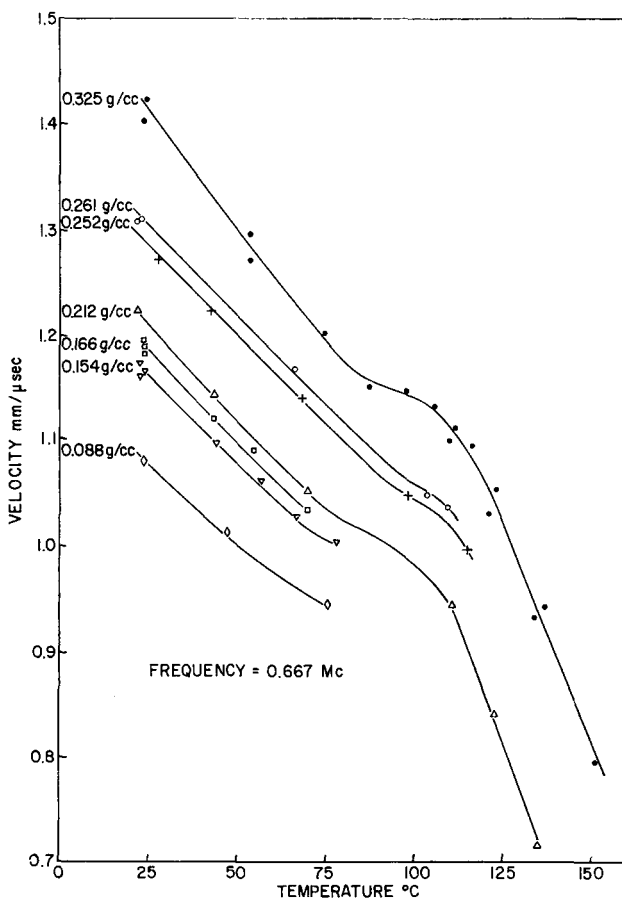

Fig. 3. Longitudinal velocity vs. temperature with density as a parameter for a frequency of 0.667 Mc./sec.
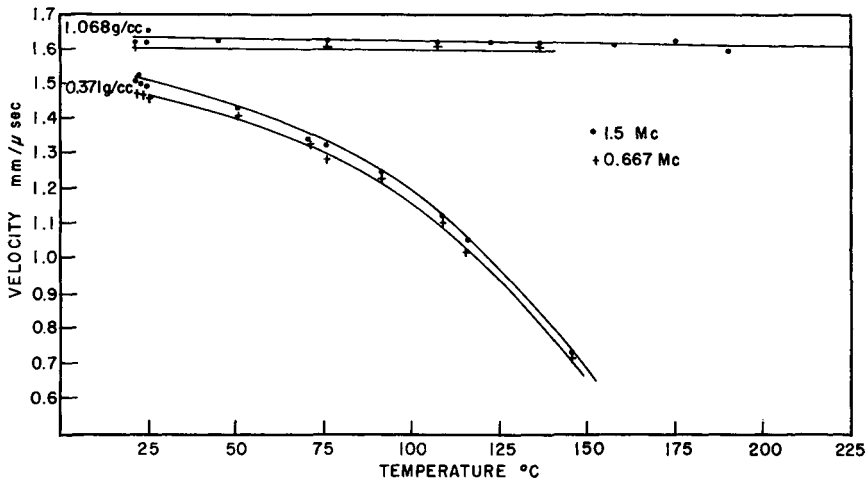
Fig. 4. Longitudinal velocity vs. temperature for aluminum-loaded foams at frequencies of 0.667 and 1.5 Mc./sec.

lowered. However, when the samples had been exposed to a higher temperature, a permanent dimensional change occurred, with a consequent density increase in the range of 5–15% which was demonstrated by redeterminations of sample thicknesses. The actual percentage increase was a function of the density of the sample and the temperature to which it had been exposed. In conjunction with the density increase under these conditions, a remeasurement of the velocity at room temperature showed a corresponding decrease in the range of 5–10% from the original values. The decrease in velocity with increased density due to temperature effects is contradictory to the experimental observation for the original samples where the velocity increases with increasing density, and is probably related to permanent chemical or physical changes. The color also changed from the original neutral color to shades of brown, depending on the temperatures to which the samples had been exposed.

Figure 4 shows the bulk velocity variation with temperature of two high-density foams that had been heat-treated and were loaded with different amounts of aluminum. The bottom curve corresponds to a light gray epoxy foam (density 0.371 g./cc.) prepared in the same fashion as the lower density materials but loaded with 8% aluminum by weight. The top curve represents a darker gray material (density 1.068 g./cc.) prepared by mixing equal parts by weight of the finely powdered 8% loaded foam and solid resin. The aluminum filler used in these foams was in the form of a finely ground powder so that the majority of the particles was less than 25μ in size,[3] thus ensuring the nondimensional characteristics of the foams. Both materials had been heat-treated at 250°C. for several hours. Data for the lower density material were limited to a temperature of about 150°C. because of excessive attenuation of the signal at higher temperatures. Neither curve has an inflection point, probably because of the heat treat-
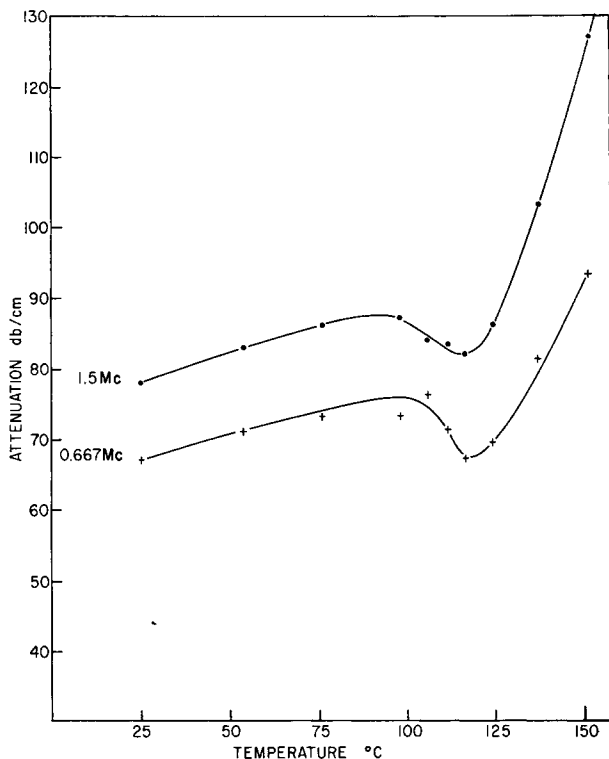
Fig. 5. Attenuation vs. temperature for a 0.325 g./cc. sample at frequencies of 0.667 and 1.5 Mc./sec.

ment, and the velocity and density for these materials were reproducible within experimental error at room temperature after several exposures to high temperatures.

The difference between some of the curves of Figures 2–4 is approximately 2–3%. The technique used here has been found to give absolute accuracies on the order of 1% under favorable conditions such as sufficient sample thicknesses, homogeneous, linear, nondispersive samples, and the use of thin coupling agents such as transformer oil. In the present application, the accuracy is limited by four major causes. First, as previously indicated, the thickness of the interfacial layer of silicone grease was a critical factor in the reproducibility of the transit time from one assembly to the next. However, this error was partially reduced by standard techniques of assembling so that transit times on any one sample could be reproduced to better than 1% when reassembled.

The second source of error arises because of the very small thicknesses of the samples. However, as previously noted, the foam material was easily machinable, so that for most of the samples the thickness was uniform to within 0.25–0.50% over the entire surface. In one case, a variation of 0.75% was observed from one side of the sample to the other.
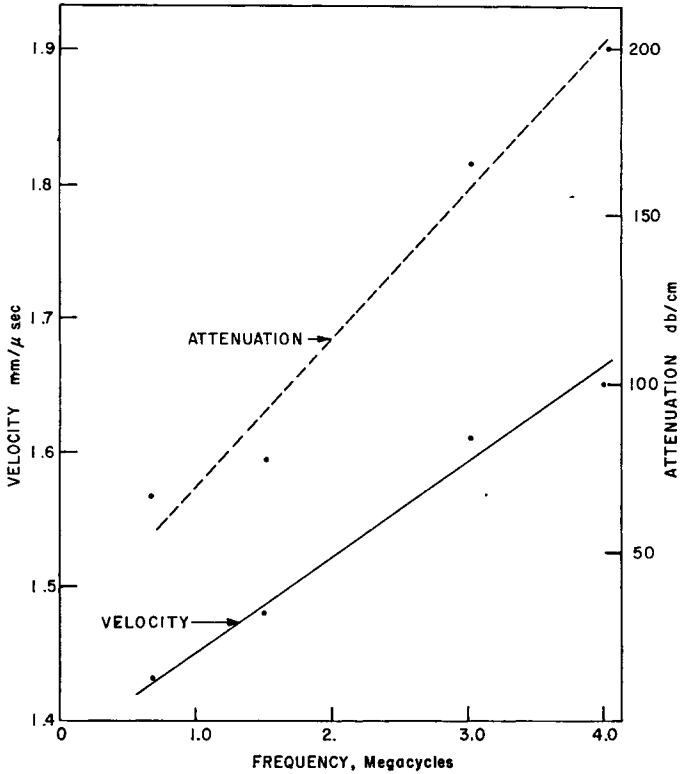
Fig. 6. Velocity and attenuation for a 0.325 g./cc. sample at a temperature of 22°C. as a function of frequency.

Also, the samples did not distort in parallelism beyond the original limits of the variation when exposed to high temperatures. Considering these factors and the transit times through the samples, this source of error is negligible.

The third source of error is concerned with sampling, resulting from the fact that the samples are thin and that relatively large voids could sometimes be observed. The top curve of Figure 2 is for a composite of two different samples of the same measured density showing agreement within 2% (this result is also a function of the first two sources of error). Some of the other curves of Figure 2 represent samples cut from two different blocks marked as the same density but showing a slight difference in density for the individual samples, justifying the plot of different curves for each sample. These observations indicate that sampling errors alone are less than 2%.

The last source of error is probably the largest and depends upon the definition used in the calculation of velocity. These materials are obviously dispersive as indicated by the difference in velocity for frequencies of 0.667 and 1.5 Mc./sec., as shown in Figures 2–4. Dispersion in elastic
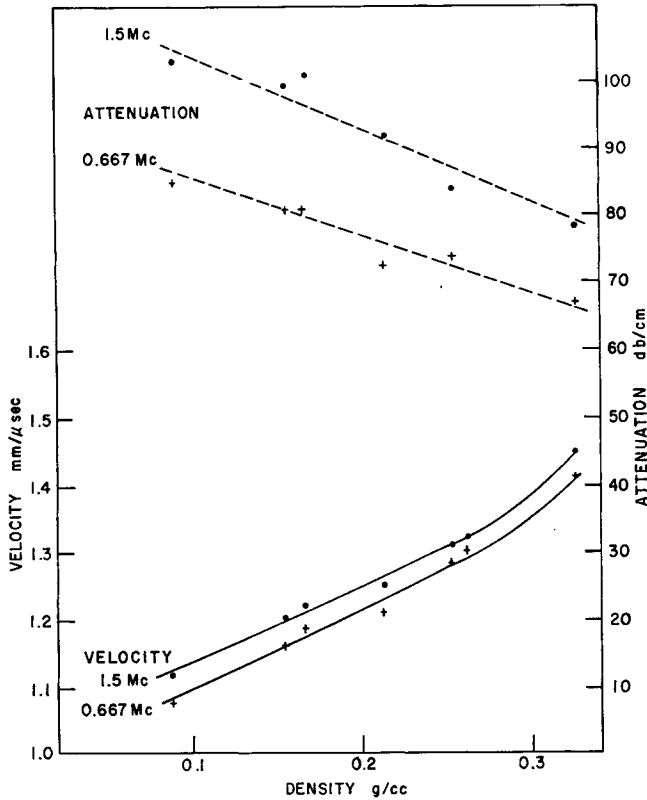
Fig. 7. Longitudinal velocity and attenuation vs. density at 25°C. for frequencies of 0.667 and 1.5 Mc./sec.

materials is generally due to purely geometrical considerations, whereas in viscoelastic materials the dispersion is produced by the properties of the solid.[8a] In the latter case, high-frequency waves travel faster than low-frequency waves, which is consistent with the present experimental data. When the elastic properties vary with frequency, as in a dispersive medium, the interpretation of the results becomes uncertain, since there is not a unique velocity of propagation and the velocity at which energy is transferred is the group velocity c_g, which differs from the phase velocity c_p, by an amount $\lambda(dc_p/d\lambda)$. In the present experiments, the first peak of the transmitted and received pulses was used as reference in computing the transit time and consequently the velocity. By using the second peak instead of the first as reference, a velocity decrease of about 8% resulted for the 0.667 and 1.5 Mc./sec. cases, and this difference increased with increasing temperature. The remaining peaks were generally too distorted to be used in calculating the transit times so that further comparisons could not be made.

The difference noted above was due to the fact that the output frequency was in general lower than the input. For input frequencies ranging from

0.667 to 4.0 Mc./sec., the output frequencies ranged from 0.5 to 2.0 Mc./sec. in corresponding order. For the temperature measurements with the 0.667 and 1.5 Mc./sec. input frequencies, the output frequencies in both cases were observed to slowly decrease with increasing temperature. For an input frequency of 0.333 Mc./sec., the output frequency was comparable, although velocity information could not be obtained because of distortion of both input and output waveforms. The basic premise for the use of the first peak as a reference was that it was the first accurate reference point at which the transit time of a disturbance could be detected. Also, since the major objective of the experiment was to determine the relationship between the longitudinal bulk velocity and the density of the solid foam, relative, rather than absolute, velocities were required. Accounting for these factors, relative velocities are considered reliable since the same situation was observed for all specimens.

Figure 5 shows the attenuation plotted as a function of temperature for the 0.325 g./cc. sample. The attenuation is calculated from the relation

$$\alpha = (X_2 - X_1 - C)/d \qquad (1)$$

where X_1 and X_2 are, respectively, the attenuator settings of the signal with and without the sample inserted for a standard height on the oscilloscope, and d is the thickness of the sample. C is a correction factor which accounts for the impedance mismatch at the two buffer–sample interfaces and is given by

$$C = 20 \log \left[(Z_1 + Z_2)^2/4Z_1Z_2\right] \qquad (2)$$

where Z_1 and Z_2 are the acoustic impedances of the sample and aluminum buffer rods, respectively. Equation (1) does not take into account interfacial effects, such as the impedance of the silicone grease or the reproducibility of the bonding surface. The former effect could be minimized by using samples of different thicknesses and applying eq. (1) with d as the difference in thicknesses, X_1 and X_2 as the attenuator settings for the two different thicknesses, and C equal to 0. This was performed for four different sample thicknesses, and the attenuation calculated in this way agreed within experimental variation with that calculated by the direct use of eq. (1). For the attenuation measurements, the bond between the sample and the buffer was found to be the limiting factor on the accuracy and was experimentally observed to cause a variation of about 20%. Of interest in Figure 5 is the fact that an inversion in the attenuation occurs at approximately the same temperature as the inflection in velocity, and that the slope of the attenuation curve changes much more than the slope of the velocity curve at this temperature.

Figure 6 shows the variation of velocity and attenuation as a function of frequency for the 0.325 g./cc. sample at a constant temperature of 22°C. First, it is noted that extending the frequency to 4.0 Mc./sec. increases the velocity about 20%. This is a common characteristic of viscoelastic materials, in that increasing the frequency is equivalent to lowering the

temperature. The attenuation is also observed to increase with increasing frequency and, in this case, an approximately linear relationship with frequency exists for both the attenuation and the velocity. Attenuation and velocity measurements beyond 4.0 Mc./sec. were not possible with the present technique because of the rapidly increasing attenuation.

Figure 7 shows the variation of attenuation and velocity with density for the unloaded samples at the frequencies of 0.667 and 1.5 Mc./sec. The velocity is observed to be an approximately linear function of the density. Similar effects have been observed in density studies of polyethylene[9] and, although the results there are due to an intermolecular effect, i.e., degree of crystallinity, both results illustrate how the effective stiffness manifests itself in the velocity of propagation of ultrasonic waves. The attenuation in this material decreases approximately linearly with increasing density over the same range of density at 25°C.

Interpretation of Results

In general, four viscoelastic constants are necessary to characterize a viscoelastic material, since there are shear and compressional viscosities in addition to the shear and compressional moduli characteristic of elastic materials. To determine all four of these constants, measurements on both the longitudinal and the shear wave velocities and attenuations are needed. In the present experiments, measurements of shear waves were attempted by using samples approximately 1 mm. thick and bonding the samples to the aluminum with water glass (sodium silicate and calcium carbonate mixture), wax, and the silicone grease. However, at room temperature, the attenuation of shear waves in this material was so great that none of the above techniques yielded shear wave data.

Assuming that the viscous forces are proportional to the time rate of change of the strain as in the Voigt model,[8b] the one-dimensional wave equation becomes

$$\rho(\partial^2 u/\partial t^2) = (\lambda + 2\mu)(\partial^2 u/\partial x^2) + (\lambda' + 2\mu')(\partial^3 u/\partial x^2 \partial t) \qquad (3)$$

where λ and μ are the Lamé constants and λ' and μ' are viscous constants which relate the stress to the rate of change of the strain. In the absence of shear wave data, an approximate three-constant theory can be obtained by making Stokes' assumption that there is no viscosity associated with a hydrostatic compression. Measurements of viscous losses in polymeric liquids and viscoelastic solids indicate that this assumption is not true in general and that a compressional viscosity as well as a shear viscosity must be postulated to explain the losses associated with longitudinal wave transmission. In some materials, such as Buna-N rubber[5] and polyiso-butylene liquids,[10] the viscosity associated with the λ Lamé constant is negligible in comparison to the viscosity associated with the μ Lamé constant for longitudinal waves, so that the above assumption is valid. However, if the assumption is invalid, the shear viscosities computed in this way become upper limits rather than true value. With Stokes'

assumption, the effective viscosity may be shown to be $4\mu'/3$.[11] The one-dimensional wave equation then becomes

$$(K + 4\mu/3)(\partial^2 u/\partial x^2) + 4\mu'/3(\partial^3 u/\partial x^2 \partial t) = \rho(\partial^2 u/\partial t^2) \qquad (4)$$

where K is the bulk modulus, u is the displacement in the x direction, and μ is the shear modulus. Assuming a harmonic time dependence, the solution of the amplitude equation gives for the effective modulus:

$$\lambda + 2\mu = K + 4\mu/3 = \rho c^2(1 - r^2)/(1 + r^2)^2 \qquad (5)$$

and for the viscosity:

$$4\mu'\omega/3 = \rho c^2 2r/(1 + r^2)^2 \qquad (6)$$

where $r = \alpha c/8.68\omega$, α is the attenuation in db./cm., ω is the angular frequency, c is the wave velocity, and μ' is the coefficient of shear viscosity. It is to be emphasized that the shear viscosities calculated in this way represent upper limits, unless the material behaves as a Stokes' solid. To separate the effective modulus, $K + 4\mu/3$, and the effective bulk wave viscosity into their compressional and shear constituents would require separate measurements on the shear wave velocity and attenuation.

The velocity decrease shown in the curves of Figures 2–4 indicates that a relaxation mechanism is present in the effective modulus. However, as previously noted, the effect is reversible to about 110°C., i.e., the velocity is reproducible at room temperature if the sample is not exposed to a temperature higher than 110°C. At higher temperatures, the velocity at room temperature is lower, depending on the density and temperature to which the sample was exposed.

A differential thermal analysis (DTA) was performed on the 0.325 g./cc. sample, and thermograms were obtained to approximately 400°C. It was found that a glass transition state occurs at 145.8°C. with decomposition beginning at approximately 200°C. and complete decomposition resulting at 408°C. Of particular interest is the existence of a small curing exotherm in the region of 50–145°C., which disappeared on repeated heating. The material is a thermosetting resin and, as such, crosslinking increases with increasing temperature. The resultant effect is probably such that structural changes occur with increasing cure, resulting in a permanent decrease in either the shear or the compressional modulus and consequently in a decrease of the longitudinal velocity. Again, to attribute these effects to shear or compressional behavior would require shear wave measurements.

It is of interest to compare the dynamic moduli with moduli under static conditions. As previously mentioned, the densities of these foam materials are varied by changing the amount of blowing agent to obtain the desired ratio of void to epoxy in the matrix of the resin. When the density is increased fourfold, the compressive, flexural, and tensile strengths and moduli, obtained statically for the unloaded samples, are increased by approximately an order of magnitude.[3] The effective modulus for bulk

wave propagation [eq. (5), Figs. 2 and 3] shows similar behavior, increasing by almost an order of magnitude over the same density range.

Most of the internal strains in the aluminum-loaded samples were removed by annealing at 250°C. for long periods, during which time the samples shrank and leveled off to a dimensionally stable structure.[3] This is consistent with the experimental observation that an inflection point in the velocity did not occur and that the velocity and density at room temperature were reproducible when these samples were cycled to temperatures near 250°C. Since the effective modulus for aluminum decreases slowly and linearly to temperatures of at least 125°C.,[12] one could make the assumption that the effective modulus, and consequently the velocity, of the aluminum-loaded foams should approach the behavior characteristic of aluminum as the percentage of aluminum is increased. However, to determine the controlling factor in the effective modulus, this effect must be compared with that produced by the combined properties of the epoxy and the density. As shown in Figure 4, the curve corresponding to the material loaded with 8% aluminum by weight (lower curve) shows more temperature variation than the material loaded with 4% aluminum by weight (upper curve). Since the slope of the velocity curve for the 8% loaded sample is roughly equal to that for the unloaded samples, the assumption that the percentage of aluminum is the controlling factor in the temperature dependence of velocity is apparently invalid. However, without knowledge of the velocity–temperature variation in pure epoxy for the particular resin used here, the shape of the curve corresponding to the 4% loaded material cannot be definitely attributed to either density or resin characteristics.

References

1. Arnold, N. D., and A. H. Guenther, *J. Appl. Polymer Sci.*, **10**, 731 (1966).
2. Dorr, A. T., and A. H. Guenther, *J. Appl. Polymer Sci.*, **10**, 745 (1966).
3. Mead, M., D&R Pilot Plants, Inc., Hazardville, Conn., private communication.
4. McSkimin, H. J., and P. Andreatch, *J. Acoust. Soc. Am.*, **34**, 609 (1962).
5. Nolle, A. W., and P. W. Sieck, *J. Appl. Phys.*, **23**, 888 (1952).
6. Pears, C. D., W. T. Engelke, and J. D. Thornburgh, Technical Documentary Report No. ML-DTDR 64-87, II, AF Materials Lab., 1964, p. 56.
7. Howse, P. T., C. D. Pears, and S. Oglesby, TR 60-657, Wright Air Development Division, Wright-Patterson AFB, Ohio, 1960, p. 57.
8. Kolsky, H., *Stress Waves in Solids*, Dover, New York, 1963, (a) p. 120; (b) p. 117.
9. Davidse, P. D., H. I. Waterman, and J. B. Westerdijk, *J. Polymer Sci.*, **59**, 389 (1962).
10. Mason, W. P., W. P. Baker, H. J. McSkimin, and J. H. Heiss, *Phys. Rev.*, **75**, 936 (1949).
11. Mason, W. P., *Electromechanical Transducers and Wave Filters*, Van Nostrand, New York, 1964, p. 304.
12. Dorr, A. J., Air Force Institute of Technology, Wright-Patterson AFB, Ohio, private communication.

Résumé

La vitesse et l'atténuation d'ondes de choc longitudinales dans une mousse époxy solide sont mesurées par la technique d'impulsion acoustique dans le domaine de fréquences de 0.667 à 4.0 mégacycles par seconde et dans le domaine de températures depuis la température ambiante jusqu'à 150°C. Les mesures sont rapportées à la densité de la résine époxy solide et avec une charge à base d'aluminium comme paramètres. Sur les domaines de températures et fréquences indiqués une atténuation complète et des mesures de vitesse ont été rapportées pour une mousse correspondant à une densité de 0.325 g/cc. Dans le domaine des densités de 0.088 g/cc jusque 0.325 g/cc pour des mousses non chargées, une atténuation est rapportée à température ordinaire. On observe que la vitesse longitudinale à toutes les densités décroît avec la température d'environ 40% sur un espace de 100°C et qu'il existe une relation approximativement linéaire avec la température. Les vitesses au sein de ces mousses chargées avec des faibles pourcentages d'aluminium et traitées à la chaleur à 250° manifestent un comportement thermique qui est dépendant des effets combinés de la charge, des variations de densité, et des propriétés des époxy. Pour la mousse chargée avec la densité la plus élevée (1.068 g/cc), la vitesse est rapportée pour une température jusque 250°C. Les vitesses pour tous les échantillons de densité variable, à l'exception des mousses chargées, montrent des inflexions à des températures d'environ 110°C. Les mesures atténuation-température sur l'échantillon de 0.325 g/cc montrent un comportement similaire à cette température sauf que l'effet est beaucoup plus prononcé que l'inflection de vitesse, d'où une indication meilleure de la zône de transition. La précision de la mesure est d'environ 2% pour les vitesses longitudinales relatives et d'environ 20% pour les mesures d'atténuation.

Zusammenfassung

Geschwindigkeit und Dämpfung longitudinaler Wellen in einem festen Epoxyschaumstoff wurden durch ein akustisches Pulsverfahren in Frequenzbereich von 0,667 bis 4,0 Mhz und im Temperaturbereich von Raumtemperatur bis 150°C gemessen. Die Messungen werden mit der Dichte des festen Epoxyharzes und mit der Füllung durch Aluminiumverunreinigungen als Parameter dargestellt. Im angegebenen Temperatur- und Frequenzbereich werden vollständige Dämpfungs- und Geschwindigkeitsmessungen für einen Schaumstoff mit einer Dichte von 0,325 g/cc mitgeteilt. Im Dichtebereich von 0,088 bis 0,325 g/cc für die ungefüllten Schaumstoffe wird die Dämpfung bei Raumtemperatur mitgeteilt. Die Longitudinalgeschwindigkeit nimmt für alle Dichten mit der Temperatur um etwa 40% über 100°C ab, es besteht eine lineare Abhängigkeit von der Temperatur. Die Geschwindigkeiten in den mit einem kleinen Prozentsatz an Aluminium gefüllten und bei 250°C hitzebehandelten Schaumstoffen zeigte ein von den kombinierten Einflüssen der Füllung, der Dichteänderung und der Epoxydeigenschaften abhängiges Temperaturverhalten. Fur den gefüllten Schaumstoff mit der höchsten Dichte (1,068 g/cc) werden Geschwindigkeitsangaben bis zu einer Temperatur von etwa 110°C gemacht. Die Dämpfungs- und Temperaturmessungen an der 0,325 g/cc-Probe zeigen bei dieser Temperatur ein ähnliches Verhalten ausser dass der Effekt viel stärker hervortritt als der Geschwindigkeitswendepunkt und daher ein besseres Merkmal für die Umwandlung bildet. Die Genauigkeit der Messungen beträgt etwa 2% für die relativen Longitudinalgeschwindigkeiten und etwa 20% für die Dämpfung.