Shear-wave propagation in rocks and other lossy media: An experimental study

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Ultrasonic shear-wave propagation studies have been carried out for the measurements of velocity and attenuation in some rocks, concrete and synthetic materials at room conditions. It has been found that 'pulse broadening', which occurs due to attenuation, can be measured quite accurately while carrying out shear-wave velocity measurements in them. The pulse broadening data could be used to determine the quality factor from which the shear-wave attenuation is computed using the standard relationships between velocity, attenuation and quality factor. The measurement technique is briefly described and the results obtained are presented and discussed.

ULTRASONIC pulse techniques are widely used for measuring the elastic and anelastic properties of both natural and synthetic materials for materials research and industrial applications. The choice of ultrasonics for the testing and evaluation of a whole gambit of materials arises due to the availability of different modes such as compressional, shear, Rayleigh, etc. and to work in a wide-frequency band (few kHz to few GHz) under a variety of experimental conditions. It thus provides a great advantage to characterize the material features over a wide range (from a fraction of mm to several cm), which will control the properties and performance of materials. With recent advances made in the development of focused-beam sensors, instrumentation, signal processing and imaging techniques, the ultrasonic techniques are being used for the evaluation of defects, microstructures and residual stresses as also in some high quality factor (high-Q) materials (materials in which the energy loss of ultrasonic waves is quite low).

Rocks and concrete occupy a unique place among the engineering materials. They are porous and contain several micro-structural disorders as a consequence of which the absorption of ultrasonic energy is relatively high in such imperfectly elastic materials. Nevertheless, a large number of tests have been carried out in several laboratories and at field sites using 'compressional waves', since it is easy to generate and propagate them in such materials under varied experimental conditions[1–4]. Several laboratory and field tests have clearly established that it is relatively easy to obtain attenuation data in rocks in terms of the quality factor (Q), the reciprocal of which is known as the dissipation factor or internal friction[1,2,5–10]. The attenuation data can provide more information than elastic wave velocities on lithology, physical state and fluid-saturation in rocks[2,6,8]. Furthermore, the laboratory experiments have contributed richly to understand and model the attenuation mechanisms in rocks, and to evaluate the influence of fluid saturation, signal frequency and other controlling factors such as confining pressure and temperature on the dissipation of elastic energy in rocks[8–14].

A large amount of data exist now on the compressional wave velocity (V_P) and attenuation in terms of quality factor (Q_P) of a variety of rocks[9–13,16–18]. But it has been recognized recently that the data on shear-wave velocity and attenuation in dry and water-saturated rocks and concrete are required for geotechnical evaluation of the ground and foundation structures[14,15]. The geophysical exploration studies for hydrocarbons and mineral resources require *in situ* shear-wave velocity and attenuation data to distinguish the acoustic impedance contrasts (bright spots) that are produced due to lithology and trapped fluids in rock, and to distinguish between gas, oil and water in the shallow parts of the earth's crust[2]. Investigations on precursory changes in shear-wave velocity and attenuation in earthquake-prone areas and in laboratory rock samples stressed to fracture are useful for earthquake prognostication, geothermal energy exploitation, etc.[2,14,15]. These particular needs have created a strong resurgence of interest and research concerning shear-wave velocity and attenuation studies in seismology and rock physics, as evidenced from recent publications[15–18]. Attempts to measure shear-wave attenuation in rocks at the laboratory scale have hitherto been confined to fine-grained and mono-mineralic rocks like sandstones and limestones using spectral ratio comparison method[15,16]. Using a commercially available high-energy ultrasonic pulser-receiver and a digital storage oscilloscope, we have carried out some tests using direct shear-wave transducers at room conditions for the determination of shear-wave velocity (V_S) and quality factor (Q_S) through pulse broadening measurements at 1.0 MHz frequency in some rocks, concrete and other lossy media such as ebonite, wood, teflon, etc. The attenuation value (α_S) has been computed from the measured values of Q_S and V_S of each sample. The technique is briefly outlined and the results obtained are presented and discussed here.

Generally, a broad-band pulse is used for exciting the transmitting piezoelectric transducer to generate elastic waves in laboratory samples for wave-propagation measurements. The 'first arrival', i.e. the leading signal of the elastic wave decays fast in highly absorbing materials such as rocks, concrete and polymers (rubber, plastic, etc.) leading to decrease in amplitude and spreading or lengthening in time with the increase in travel time or path length[6,7,10,19,20]. It is analogous to the change in shape of the seismic pulse due to absorption in the solid earth[5–7,19]. While the peak amplitude varies roughly as the inverse of the square of the travel distance (this inclu-

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des an inverse first power of distance due to geometrical spreading), the spreading of waveform varies linearly with the travel distance[5–7,10,19]. The spreading of pulse manifests itself as a simple broadening on both positive and negative sides, without developing any zero-crossings in its wave shape[5–7]. It can be measured in terms of either width or rise time, and the changes occurring in either of them in the test signal with respect to a reference signal represent the energy loss or attenuation in the material under test[5–7,10,19]. The change that occurs in the width of the first arrival (or leading signal) of the shear-wave with respect to the reference shear-wave is shown schematically in Figure 1. The reference signal is usually the ultrasonic signal received either by direct contact between the driving and receiving transducers, or through any standard material such as aluminium (Figure 1). It shows a weak forerunner of compressional wave (*P*-wave) followed by a prominent shear-wave train which is commonly observed during the measurements of shear-wave propagation in materials. These features can be seen in Figure 2 which shows the hard copies of the shear-waveforms that are stored and saved in the oscilloscope during shear-wave propagation measurements in an aluminium sample and a rhyolite rock sample. In general, the broadening of first prominent arrival (Figure 1) is a measure of the attenuation (α) of the elastic wave, and the following equations show the relationships among them[5,6,10].

$$1/Q = V.\Delta t/L, \qquad (1)$$

$$1/Q = V\alpha/\Pi f, \qquad (2)$$

$$\alpha = \Pi f \Delta t/L \quad \text{(in nepers/cm)}, \qquad (3)$$

$$\alpha = 8.686\,(\Pi f \Delta t)/L \quad \text{(in decibels/cm)}, \qquad (4)$$

where V is the elastic wave velocity in cm/s, Δt is the change in pulse width (half-wave period) in microseconds of the first arrival (i.e. leading signal in the obtained wave-train) in the test sample with respect to that of reference signal, L is the pathlength (i.e. length of the test sample) in cm, f is the signal frequency in Hz and α is the attenuation parameter.

We used a high-energy ultrasonic pulser-receiver (model no. Ultran HE 900) on the driving side and a Hewlett Packard digital storage oscilloscope (model no. 54645 A) on the receiving side, which is equipped with cursor facilities. Measurements of pulse broadening have been carried out with an accuracy of ± 0.01 µs, as described earlier[10,13,20]. A pair of hard-faced, direct-contact, shear-wave transducers of 1.0 MHz resonant frequency has been used for carrying out the wave propagation measurements. The test samples have been prepared in the form of right circular cylinders (30 mm diameter and 60 mm length) by core-drilling in rock blocks and concrete, and by machining the synthetic material rods to the required size. The two end-faces of each test sample were ground flat and parallel to within ± 0.01 mm. The wave period between the first-downward and first-upward pulse $(T_2' - T_1')$ of the received wave-train constitutes the major measurement parameter (Figure 1). The time-of-flight (i.e. travel time) measurement $(T_0' - T_0)$ is carried out with respect to the onset of the first received shear-wave pulse for determining the *S*-wave velocity. Measurements have been carried out in test samples of different lengths prepared from each rock block and material rods of perspex, ebonite, etc. The results obtained have confirmed a linear relationship between L and $V_S \cdot \Delta t$ (Figure 3). The slope of each curve is the quality factor from which α_S and Q_S^{-1} of the respective test material can be deduced using eqs (2)–(4).

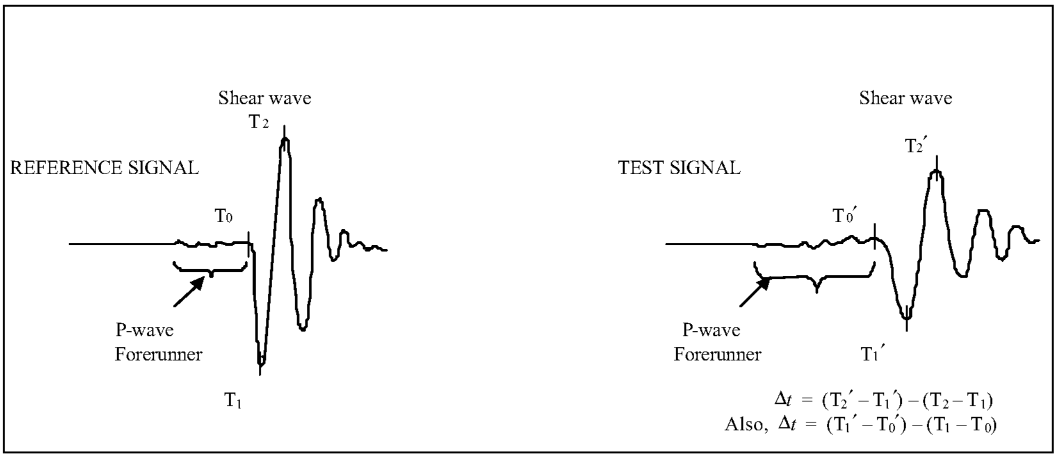

Figure 1. Schematic diagram of the waveforms of reference and test signals for the measurement of Δt using ultrasonic shear-wave transducers. Notice the increase in half-width (i.e. pulse broadening) and decrease in amplitude of the leading signal of shear-wave on propagation through the material.

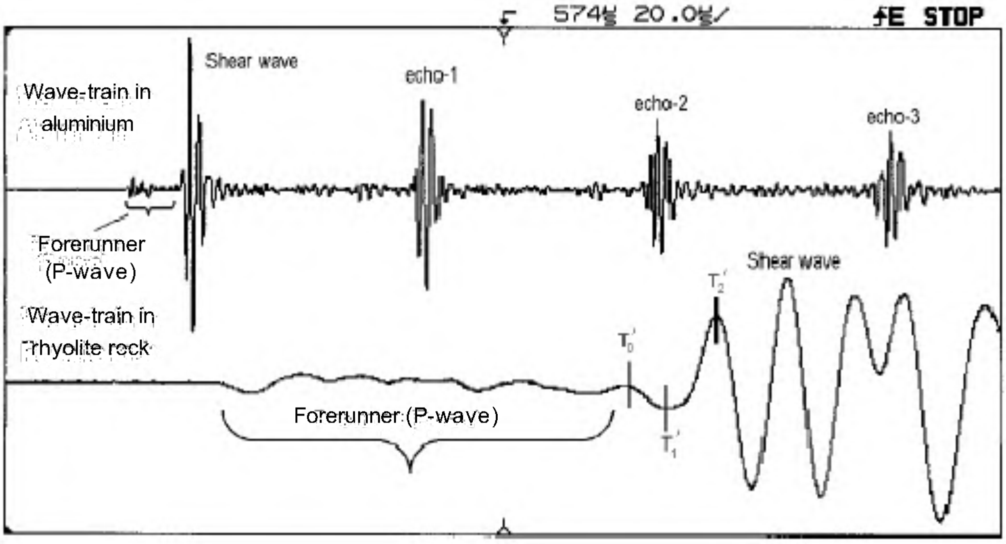

Figure 2. Hard copies of the wave-trains obtained from shear-wave measurements in an aluminium test sample (top trace, 20 µs/cm sweep speed) and a rhyolite rock sample (bottom trace, 2 µs/cm sweep speed). Tests were carried out using direct shear-wave transducers of 1.0 MHz resonant frequency. Both the traces show a weak forerunner of *P*-wave. The $(T_2' - T_1')$ represents the pulse width for carrying out pulse broadening measurements with respect to the reference signal (see text for details).

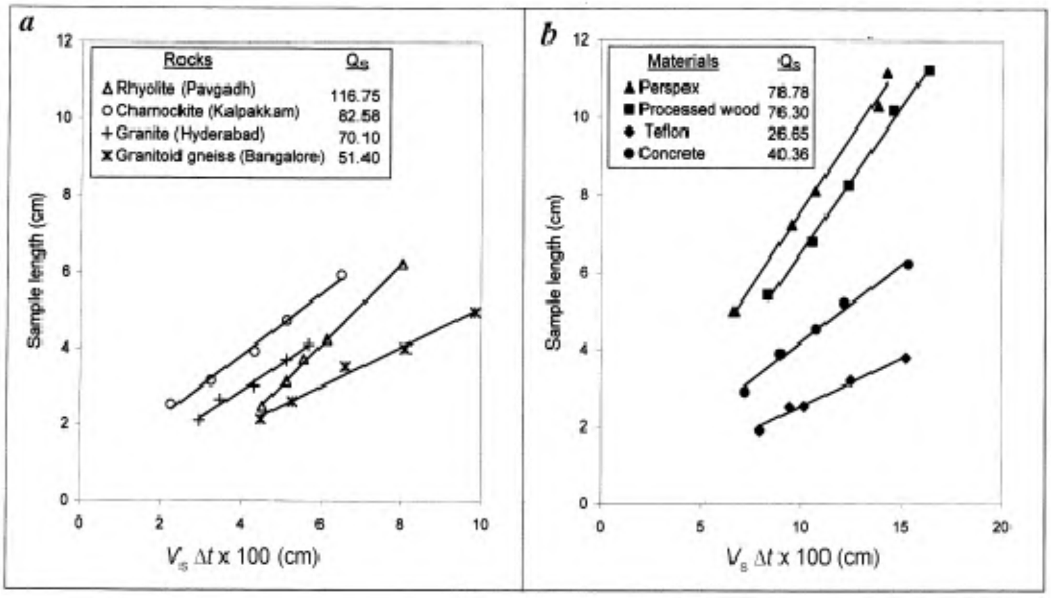

Figure 3. Plot showing experimental data and least-square best-fits confirming the linear relationship between sample length and $V_S.\Delta t$ in (***a***) rock samples and (***b***) synthetic materials. (Inset) Computed values of Q_S (slopes of the lines).

A dozen samples have been tested in this study. All the samples were oven-dried prior to the tests, for removal of moisture. A viscous fluid such as honey or grease was used as acoustic couplant for the tests. The samples tested include six rocks, one concrete and four commonly available synthetic materials, and an aluminium specimen which is used as a reference material for velocity and attenuation measurements. With the exception of aluminium, all the specimens tested showed pulse broadening of the first arrival (i.e. leading signal) of the shear-wave, which helped us obtain the values of Q_S and α_S in them. The value of Q_S in aluminium is quite high (17000–19000), even at frequencies of 3.0–7.0 MHz[6,21]. Hence the aluminium specimen did not show any broadening of either the first arrival or its echoes (i.e. successive reflections at the ends of the test piece) unlike rhyolite, which

Table 1. Density, shear-wave velocity, quality factor and attenuation determined in samples of rocks and synthetic materials

Test sample	Density (g/cc)	V_S (m/s)	Q_S	α_S (dB/cm)
Rock samples				
Rhyolite	2.471	2994	116.75	0.7806
Granite (Hyderabad)	2.676	3345	70.10	1.1637
Granite (Kudankulam)	2.692	3173	56.32	1.5269
Granitoid gneiss	2.718	2992	51.40	1.7743
Hypersthene granite	2.724	3385	66.27	1.2164
Charnockite	2.863	3662	82.58	0.9023
Synthetic materials				
Processed wood	0.695	1582	76.30	2.2605
Perspex	1.202	1382	78.78	2.5062
Ebonite	1.444	1555	74.43	2.3576
Teflon	2.121	441	26.65	23.2171
Concrete	2.200	2365	40.36	2.8586

is a rock (Figure 2). The two traces shown in Figure 2, have been obtained at different sweep speeds to show distinctly the shear-wave echoes in aluminium sample and broadening of the pulse in rock. All the rock samples of the present study are poly-mineralic and granitic in composition, with density ranging from 2.471 to 2.863 g/cc (Table 1). The charnockite sample has a higher density owing to the presence of pyroxene (a mafic mineral) in it and consequently, it has the highest shear-wave velocity among all the samples tested (Table 1). Concrete and other synthetic materials have lower densities (0.695–2.200 g/cc) and lower shear-wave velocities (441–2365 m/s) according to the present study (Table 1). Consequently, shear-wave attenuation in all the synthetic materials is relatively high. The Q_S of rock samples tested ranged from 51 to 117, while the velocity ranged from 2992 to 3662 m/s. Among the rocks, rhyolite is found to be exceptionally good as far as the elastic-wave propagation is concerned, by virtue of the presence of large silica (glass) as groundmass in it. Rhyolites have relatively low density and low attenuation (i.e. higher Q) among the samples that we have tested. Both Q_P and Q_S are relatively high in them and they are found to increase with increase in volume percentage of groundmass in rhyolites. Some of the synthetic materials like processed wood, perspex and ebonite have shown Q_S values which are comparable to some of the rocks. Interestingly, teflon and concrete, which have many industrial applications, show lower Q_S and higher α_S than the other synthetic materials (Table 1). Since the composition, texture and microstructure of the materials tested are widely varying, no systematic correlations among their density, shear-wave velocity and quality factor or α_S could be found. The dependence of Q_P on mineral composition and porosity in rhyolite was found to be quite regular and positive[18]. The shear-wave data (Q_S and V_S) showed some scatter, which indicates that the shear-wave energy loss due to friction and scattering at grain boundaries and pre-existing microcracks in rhyolites is not only high, but also non-uniform. A detailed petrographic examination of the rhyolites samples is required. Synthetic materials require detailed study of microstructure and ultrasonic tests on frequency dependence of Q_S to investigate the attenuation mechanisms in them. These preliminary experiments have provided the initial database, and also a wide scope for detailed investigations on the quality factor and attenuation of shear-waves for the characterization of lossy media such as poly-mineralic rocks and synthetic materials.

It is concluded that the determination of Q_S from pulse-broadening measurements of the first arrival (i.e. leading signal of the S-wave) is not only simple, but also gives fairly accurate results to characterize the material. It requires a high-energy pulser on the driving side for exciting the shear-wave transducer. If measurements are carried out using orthogonally polarized shear-wave transducers, the velocity anisotropy and Q-anisotropy can also be investigated in rocks and other lossy materials using pulse-broadening measurements. Work on such lines will be taken up soon.

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