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Observation of a second bulk compressional wave in a porous medium at ultrasonic frequencies

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A second bulk compressional wave has been observed in a water-saturated porous solid composed of sintered glass spheres using an ultrasonic mode conversion technique. The speed of this second compressional wave was measured to be 1040 m/sec in a sample with 18.5% porosity. The theory of Biot, which predicts two bulk compressional waves in porous media, provides a qualitative explanation of the observations. To the author's knowledge, this type of bulk wave has not been observed at ultrasonic frequencies.

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It is the purpose of this letter to describe the experimental observation of a second bulk compressional wave which propagates at speeds approximately 25% of the speed of the normal bulk compressional wave in a fluid-saturated porous medium. This observation has been made using an ultrasonic immersion technique and a fluid-saturated porous medium consisting of water and sintered glass spheres. The excitation of the slow wave in the solid is shown to be consistent with the principles of mode conversion and refraction at plane liquid/solid interfaces. To the author's knowledge, this type of bulk wave has not been observed at ultrasonic frequencies. The existence of a similar low velocity compressional wave in an isotropic fluid-saturated porous media was predicted by Biot.[1]

An ultrasonic immersion technique was used to generate the bulk modes in a solid plate based on the concept of mode conversion and refraction at liquid-solid interfaces. Using this technique, which is similar to that of Smith[2] and Hartman and Jarzynski,[3] sound speeds of the normal compressional wave, the shear wave, and a slow compressional wave were determined. The geometry is depicted in Fig. 1. The pulsed ultrasonic system incorporated commercially available pulser/receiver electronics and nondestructive testing type broadband transducers. The transducers used included a pair of 28.6-mm-diam 500-kHz transducers, and a pair of 25.4-mm-diam 2.25-MHz transducers. Total acoustic path lengths between transmitter/receiver were typically 130 μsec in water. The velocities were determined from the measured arrival times of the appropriate pulses on an oscilloscope and a corresponding measurement of the angle of incidence. Uncertainty in the measured speeds was about 3%.

The solid samples used were water-saturated disks composed of sintered glass spheres. Aggregates of solid spheres of diameters between 0.21 and 0.29 mm were sintered at temperatures between 700 and 740 °C. Four samples of varying porosity (given in Table I) were fabricated by controlling the maximum oven temperature and the total time at that temperature. The samples were ground to achieve plane parallel faces, and water-saturated using a vacuum impregnation technique. Sample thickness varied between 14 and 21 mm and sample diameters between 90 and 100 mm. The anisotropy of the samples was tested by the measurement of the fast compressional speed in three perpendicular directions on one of the samples. The speeds were identical to within experimental uncertainty. The bulk glass had a density of 2.48 g/cm^3, compressional speed of 5.69 km/sec, and a shear speed of 3.46 km/sec as calculated from the manufacturer's modulus data.

The existence of a second bulk compressional wave in a porous solid can be demonstrated by studying Fig. 2. This shows the received pulses recorded after propagating through the water/porous solid/water system at four different angles of incidence. These results were obtained using sample 1 and 2.25 MHz broadband transmitting and receiving transducers. For the case of normal incidence, only compressional waves are generated in an isotropic solid. One anticipates, therefore, an echo pattern consisting of a direct, fast compressional, and then, equispaced in time, a set of multiple reflections. Pulses *A*, *C*, *E* and *G* in Fig. 2(a) are these arrivals. However, pulses *D* and *F* are additional arrivals not observed in nonporous solids. Pulse *D* represents an additional bulk wave traveling through the porous solid at a velocity much less than the normal compressional wave. Pulse *F* arrives later than pulse *D* by a time corresponding to the time difference between pulse *A* and *C*. Thus pulse *F*

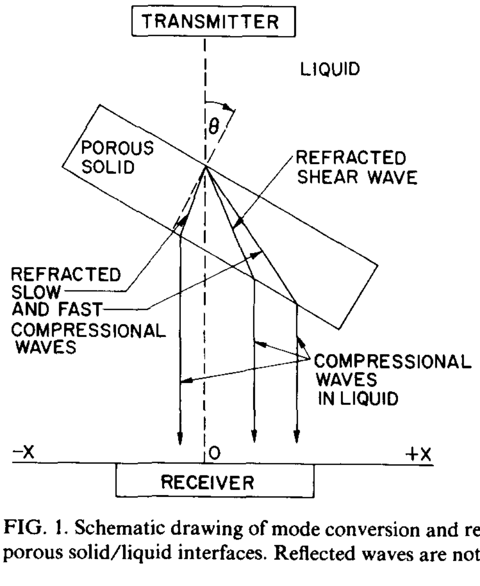

FIG. 1. Schematic drawing of mode conversion and refraction at liquid/porous solid/liquid interfaces. Reflected waves are not shown.

TABLE I. Measured sound speeds, porosities, and slow wave to fast wave amplitude ratio at normal incidence for water-saturated sintered glass samples.

Sample	Porosity (%)	Fast compressional speed (km/sec)	Shear speed (km/sec)	Slow compressional speed (km/sec)	Amplitude ratio ($\theta = 0$)
1	28.3	4.05	2.37	1.04	0.38
2	25.8	4.18	2.50	1.00	0.26
3	18.5	4.84	2.93	0.82	0.21
4	7.5	5.50	3.31	...	...

(which is also inverted with respect to pulse D) corresponds to a twice-reflected path in the solid where the arrival travels once through the solid at the slow speed and twice at the fast compressional speed. This is significant since it demonstrates that mode conversion between this additional bulk wave and the normal compressional wave occurs at the boundaries. Therefore, the existence of the first additional arrival, pulse D, and the mode converted arrival, pulse F, *both at normal incidence*, are evidence that this second bulk wave is primarily a compressional vibration.

As the angle of incidence θ is increased from zero to some finite value less than the longitudinal critical angle, i.e., $\theta_c^* =$ arcsin (speed in water/fast compressional speed in solid), only three pulses are received [Fig. 2(b)]. Pulse A is the usual compressional wave, pulse B is the mode-converted shear wave, and pulse D is the slow speed compressional wave. The fast compressional arrival has shifted toward a shorter arrival time, while the slow arrival has shifted toward a longer time. Based on refraction principles, these time shifts are indicative of the fast and slow compressional wave speeds being faster and slower than the speed in water, respectively. [A similar time shifting result is observed also in Figs. 2(c) and 2(d).]

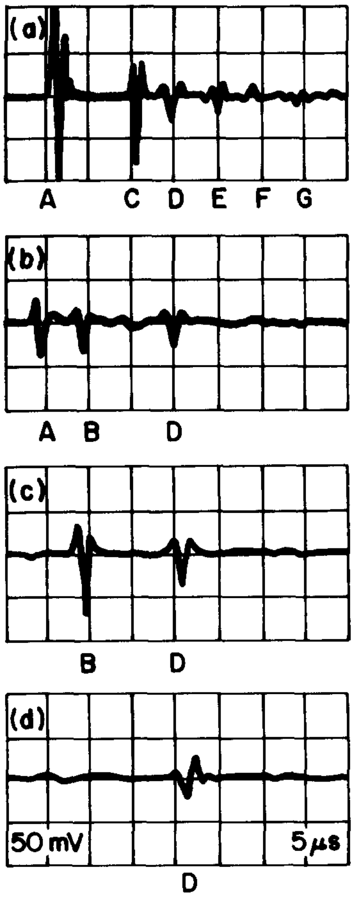

FIG. 2. Received pulses after propagation through water/porous solid/water system at various angles of incidence θ. (a) $\theta = 0°$, (b) $0 < \theta < \theta_c^*$, (c) $\theta_c^* < \theta < \theta_s^*$, (d) $\theta_s^* < \theta < 90°$.

As the angle of incidence is increased beyond θ_c^* but less than the shear critical angle, i.e., $\theta_s^* =$ arcsin (speed in water/shear speed in solid), only the shear arrival (pulse B) and the slow compressional (pulse D) are observed [Fig. 2(c)]. The fast compressional wave has been critically refracted and no longer propagates through the disk. In this configuration the spatial separation of the ray paths due to refraction as shown in Fig. 1 is most clearly evident. As the receiver was translated in the $+x$ direction, it was observed that the amplitude of the shear arrival increased to a maximum relative to the slow wave amplitude. Conversely, as the receiver was translated in the $-x$ direction, the slow wave amplitude was observed to increase to a maximum relative to the shear. This beam shift to the negative side of the transmitter-receiver axis is further indication that the speed of the slow wave is less than that of water.

Finally, the received signal when $\theta > \theta_s^*$ is shown in Fig. 2(d). In this case only the slow compressional arrival is observed since the fast compressional and shear wave have both been critically refracted. A critical angle for the slow wave was neither observed nor expected.

Velocity measurements were made using the 500 kHz transducer pair. At the lower frequencies, dispersion and attenuation were less severe and pulse distortion was minimal. Measured sound speeds averaged from data taken at several different angles of incidence are given in Table I. Also included is the ratio of the direct slow wave peak amplitude to the direct fast wave peak amplitude at normal incidence.

In these experiments, the observed "extra" arrival reflects and refracts in a manner consistent with a low-speed compressional wave in the porous solid. The identification of this observed "extra" arrival as a bulk wave and not a miscellaneous echo or scattering path was made by systematically perturbing (via translations) all combinations of the source, receiver, and sample relative positions and using short time pulses. If the "extra" arrival was not a bulk wave, its timing relationship to the known shear and compressional bulk waves would have to be dependent on such source, receiver, or sample translation. This type of dependency was never observed. In addition, this type of "extra" arrival was never observed in samples of similar dimensions made from such nonporous materials as aluminum, stainless steel, or Plexiglas.

The data in Table I indicate that both the fast compressional and shear speed increase with decreasing porosity while the slow wave speed decreases. The slow wave speed at a porosity of 7.5%, however, was not measured since the appropriate pulse was too small to uniquely identify. The amplitude ratio data is consistent with this fact since as porosity decreases, the slow wave amplitude also decreases. Thus, the largest slow wave amplitude was observed at the largest porosity (i.e., sample 1, porosity = 28.3%).

A complete identification of the mechanism responsible for this observed slow compressional wave is still under investigation. The Biot porous media theory which predicts the existence of a similar slow compressional wave seems to provide the most reasonable explanation. However, a more thorough comparison of the relationship between Biot's theory and the properties of this observed slow compressional wave is necessary. Currently, measurements of wave speeds and attenuations for all three waves are being made on a larger suite of samples.

If one assumes a Biot model, then the conditions that favor a large amplitude second compressional wave are those of high acoustic frequency and a large fluid permeability in the sample. These conditions are met in this investigation where the ultrasonic frequencies are in the low MHz range, and the fluid permeability is approximately 1 μm^2. This work has applications in wave propagation studies in various types of porous media such as marine sediments[4] and porous rocks.[5]

In summary, a second bulk compressional wave in a water-saturated sintered glass porous media has been observed using a mode conversion technique. This slow compressional wave, which to the author's knowledge has not been directly observed before, has a velocity less than that of the usually compressional and shear wave in the solid and also less than that of water. This observed wave can be tentatively identified with the slow speed compressional wave predicted by Biot.

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