Slow wave propagation in air-filled porous materials and natural rocks

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Slow compressional waves in fluid-saturated porous solids offer a unique acoustical means to study certain material properties, such as tortuosity and permeability. We present a novel experimental technique based on the transmission of airborne ultrasound through air-filled porous samples. The suggested method can be used to measure the velocity and attenuation of the slow compressional wave in a wide frequency range from 30 to 500 kHz. More important, the technique is so sensitive that it provides irrefutable evidence of slow wave propagation in air-saturated natural rocks and lends itself quite easily to tortuosity measurements in such materials, too.

The existence of a slow compressional wave in an isotropic and macroscopically homogeneous fluid-saturated porous medium was predicted by Biot in 1956.1,2 The main feature of this mode is that its velocity is always lower than both compressional wave velocities in the fluid and solid frame. Below a critical frequency, depending on the pore size in the frame and the kinematic viscosity of the fluid, the slow compressional wave is highly dispersive and strongly attenuated over a single wavelength. Above this critical frequency, it becomes a dispersion-free propagating wave with increasing but fairly low attenuation.

Since 1980, when Plona was able to observe slow wave propagation in artificial rocks made of sintered glass beads,3 the question of why slow waves cannot be detected in real rocks has been one of the major issues in the acoustics of fluid-saturated materials. Recently, Klimenatos and McCann showed that this lack of perceivable slow wave propagation is probably due to inherent internal impurities, such as submicron clay particles, found in all types of natural rocks.4 These clay particles, deposited both within the pore throats and on the surfaces of the rock grains, greatly increase viscous drag between the fluid and solid frame, which results in excessive attenuation and usually complete disappearance of the slow wave. One way to reduce the excessive attenuation of slow waves in porous materials is to use special fluids of very low viscosity to saturate the specimen. For instance, superfluid 4He below 1.1 K has been shown to work very well in fused glass bead samples,5 superleak materials consisting of compacted powders,6-8 as well as in sandstones,9 but the technique is obviously very cumbersome.

The question of whether or not excessive attenuation renders the detection of slow waves impossible arises. Not necessarily! Even a very weak slow wave attenuated by as much as 50-60 dB could be easily detected but for the presence of much stronger background “noise” caused by the direct arrivals and scattered components of the fast compressional and/or shear waves. If we could generate slow wave only and nothing else, it would be much easier to detect it in spite of the substantial attenuation.

Compared to the solid frame, liquid fluids like water usually have a lower, but still comparable density $\rho_f$ and bulk modulus $B_f$. Although their viscosity $\eta$ is also relatively high, which makes saturation of the porous sample somewhat troublesome, their kinematic viscosity $\eta_l = \eta/\rho_f$ is fairly low. On the other hand, gaseous fluids like air have very low density, bulk modulus, and viscosity as well, while their kinematic viscosity is usually rather high. Therefore, it is very simple to saturate a porous sample by air, but the slow wave is expected to be highly dispersive and strongly attenuated. In spite of these adverse effects, slow waves can be readily observed when an air-filled porous sample is ionized by airborne ultrasonic waves. Because of the tremendous acoustical mismatch between the incident compressional wave and the porous solid, all energy is either reflected or transmitted via the slow wave without generating appreciable fast compressional or shear transmitted waves.

In spite of the excellent coupling between the incident compressional wave and the transmitted slow wave and the obvious advantage of saturating the specimen with low-viscosity air rather than high-viscosity water, slow wave propagation in air-filled porous samples has never been extensively studied in natural rocks. It should be mentioned that considerable work has been done on air-filled granular absorbers, such as unconsolidated leaden balls, sand grains, and fibrous materials, at relatively low frequencies between 50 Hz and 2 kHz.10-12 The apparent lack of interest is probably due to unusual technical difficulties associated with the generation and detection of airborne ultrasound and to the fact that slow waves are not expected to propagate in air-saturated porous samples as easily as in water-saturated ones.13 Since the kinematic viscosity of air is so large and the velocity of sound in air is so small, there is but a very narrow frequency window where the attenuation coefficient is sufficiently low to observe a dispersion-free slow wave. This “window” is set by the conditions that the viscous skin depth $\delta = (2\eta/\rho_0\omega)^{1/2}$ be less than the pore size $a_p$, and, simultaneously, the wavelength $\lambda$ be larger than the grain size $a_g$. Table I summarizes the relevant physical parameters of water and air as well as $f_{min}$ and $f_{max}$, i.e., the limits of the frequency window where slow wave propagation is expected. $a_p = 200 \, \mu m$ grain diameter and $\phi = 30\%$ porosity was assumed in the calculations. The slow wave velocity at high frequencies can be easily calculated by assuming a perfectly stiff frame as $c = c_f/\epsilon^{1/2}$, while the tortuosity $\epsilon$ can be esti-
TABLE I. Physical parameters of water and air at 20 ºC.

\[
\begin{array}{cccccc}
\text{Parameter} & \rho_s & c_s & \eta_s & f_{\text{min}} & f_{\text{max}} \\
\text{(kg/m}^3\text{)} & (\text{m/s}) & (\text{mm/s}) & (\text{kHz}) & (\text{kHz}) \\
\hline
\text{Water} & 1000 & 1480 & 1 & 5 & 810 \\
\text{Air} & 1.3 & 332 & 15 & 75 & 180 \\
\end{array}
\]

mated from the porosity \(\phi\) as \(\alpha = 1/2(\phi^{-1} + 1)^{14}\) As for determining \(f_{\text{min}}\) and \(f_{\text{max}}\), we assumed that the pore size is approximately 15% of the grain size and at least four times higher than the viscous skin depth to account for smaller cross sections at the crucial pore throats:

\[
f_{\text{min}} = \frac{\eta_s}{\pi(0.04a_g)^2}
\]

and

\[
f_{\text{max}} = c/2\pi a_g.
\]

Table I clearly demonstrates the greatly reduced frequency window where dispersion-free and (more or less) attenuation-free slow wave propagation can be expected in air-filled samples of approximately 200 \(\mu m\) grain size. On the other hand, these results do not exclude slow wave propagation over a much larger frequency range. They simply mean that the slow wave becomes increasingly dispersive below 100 kHz and very strong attenuation can be expected above 200 kHz.

Figure 1 shows the block diagram of the experimental arrangement used in this preliminary study to investigate slow wave propagation in air-filled porous specimens. Standard ultrasonic NDE equipment was used without any particular effort to obtain high generation or detection sensitivity. The rather poor coupling between the applied contact transducers and air resulted in a low, but fairly constant sensitivity over a wide frequency range of 30–500 kHz. In order to assure an acceptable signal-to-noise ratio, extensive signal averaging was used up to \(10^3\) samples.

Figure 2 shows the reference (without the sample) and transmitted (with the sample at normal incidence) ultrasonic signals for different porous samples at 150 kHz. One of the main advantages of air saturation over the more conventional technique of water saturation is that slow waves can be observed without any interference from other bulk modes. As a result, in spite of the inherently higher attenuation, the detection threshold is usually much lower and slow wave propagation can be readily observed in natural rocks as well. This is a unique feature of the air-saturation technique since slow wave propagation has never been observed in water-saturated natural rocks. The principal geometrical and acoustical parameters of the porous samples used in our experiments are summarized in Table II. The slow wave velocity and attenuation were measured at 150 kHz and the tortuosity was calculated as \(c = c_f/c^2\). Great attention was paid to verifying that the sole mechanism of ultrasonic transmission was the slow compression mode in the porous sample. We found that the easiest way to do this was to wet the specimen with a few drops of water, which completely killed the transmitted signal in each case. In a few minutes the water usually evaporated and the slow wave reappeared, testifying to the ease of saturating most samples by air. The slow wave velocity in the sample can be calculated from the thickness \(d\) and the additional time delay \(T\) observed upon inserting the specimen between the transducers as \(c = 1/(1/c_f + T/d)\).

Besides observing slow wave propagation in highly attenuating natural rocks, the superior sensitivity of the suggested technique offers a unique opportunity to study the behavior of the slow wave in a very wide frequency range, too. Figure 3 shows the slow wave velocity as a function of frequency in a sintered glass bead sample of 120 \(\mu m\) grain diameter. At lower frequencies below 100 kHz, the slow

FIG. 1. Block diagram of the experimental arrangement to study slow wave propagation in air-filled porous materials.

FIG. 2. Reference and transmitted signals through different air-filled porous materials at 150kHz (a) reference, (b) glass bead, (c) Massillon sandstone, and (d) gray Berea sandstone.
TABLE II. Physical parameters of different porous samples.

<table>
<thead>
<tr>
<th></th>
<th>Sintered glass bead</th>
<th>Massillon sandstone</th>
<th>Gray Berea sandstone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (mm)</td>
<td>1.73</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Grain size (μm)</td>
<td>120</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>30</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>Permeability (mdarcy)</td>
<td>6000</td>
<td>600</td>
<td>400</td>
</tr>
<tr>
<td>Slow wave velocity (m/s)</td>
<td>215</td>
<td>190</td>
<td>164</td>
</tr>
<tr>
<td>Tortuosity</td>
<td>2.3</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>Attenuation (dB)</td>
<td>22</td>
<td>46</td>
<td>52</td>
</tr>
</tbody>
</table>

The wave exhibits strong dispersion with decreasing velocity, which is in good agreement with the predictions of Biot. At higher frequencies there is no apparent dispersion and the slow wave velocity approaches 220 m/s, also in good agreement with the $c_s/\alpha^{1/2} = 225$ m/s asymptotic value calculated for $\alpha = 2.17$ tortuosity. Figure 3 also shows the insertion loss (total attenuation) of the transmitted signal as a function of frequency in the same sintered glass bead sample. The measured attenuation seems to be a fairly linear function of frequency over the very wide frequency range of 30–500 kHz. Similar behavior was previously observed in air-filled absorbents and water-saturated porous samples as well (see lines B and C in Fig. 4 of Ref. 15). It is even more interesting that the viscous losses dominate the total attenuation in the higher part of the frequency range, too. At 500 kHz, the $a_vk$ product is already 1.7, but there is no sign of sharply increasing attenuation due to scattering. This seems to be partly due to the very high kinematic viscosity of air, which makes the viscous losses dominate over the scattering effect, even at relatively high frequencies. Another contribution can be the greatly reduced scattering of the slow compressional mode in air-filled samples where the rigid frame acts like a waveguide. Since there is no appreciable coupling to any other modes of wave propagation, the sound energy cannot help following the tortuous path allowed by the frame and the scattering induced attenuation must be fairly low.

![Fig. 3. Slow wave velocity and insertion loss as a function of frequency in a sintered glass bead sample of 120 μm grain size and 1.73 mm thickness.](image)

FIG. 3. Slow wave velocity and insertion loss as a function of frequency in a sintered glass bead sample of 120 μm grain size and 1.73 mm thickness.

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