DOE/ER/13749-4

OBJECTIVES

During the next year of this proposed work we plan to continue our investigation of ultrasonic wave propagation in fluid-saturated porous materials. Our main objectives are to further develop the (i) slow surface wave inspection and (ii) air-saturation techniques for ultrasonic evaluation of porous formations and to adapt these novel techniques to the inspection of highly permeable natural rocks (above 100 mD). This research effort should find applications in the geophysical evaluations of fluid-bearing porous rocks, where parameters such as tortuosity, shape factor, permeability, saturation level, and internal impurity are difficult to measure by conventional techniques using low-frequency acoustic or other methods.

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PREVIOUS RESULTS

1. Slow Surface Wave Technique

During the last year we have continued our investigation of ultrasonic wave propagation in fluid-filled porous materials. Previously, we studied the feasibility of using different surface modes to characterize both synthetic and natural rocks. We introduced a novel experimental technique based on the direct generation of surface waves by edge excitation. At first, we used two low-frequency (100-500 kHz) shear transducers in pitch-catch mode to launch and receive the ultrasonic surface wave.[1-3] The contact transducers were coupled to the opposite edges of the porous specimens with normal polarization relative to the surface. The same technique was successfully used to generate Rayleigh-type surface modes on the free surface of both dry and water-saturated specimens, as well as Stoneley-type interface modes on the fluid-loaded surfaces of immersed samples. Recently, we developed a special interferometric technique for non-contact detection of ultrasonic vibrations on diffusely reflecting rough surfaces.[4] This method was found to be more suitable for surface wave inspection of porous ceramics and natural rocks than the previously used contact techniques.

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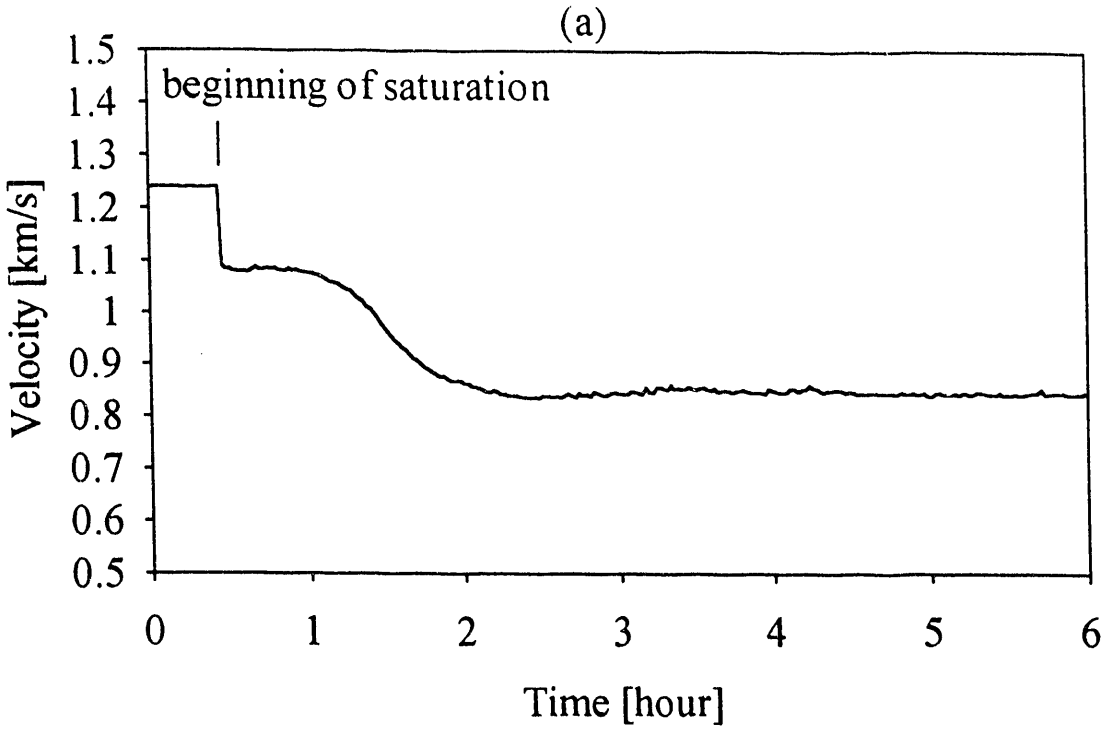
Almost ten years ago, Feng and Johnson predicted the presence of a new surface mode on a fluid/fluid-saturated porous solid interface with closed surface pores.[5,6] We found that, due to surface tension, practically closed-pore boundary conditions can prevail at an interface between a non-wetting fluid (e. g., air) and a porous solid saturated with a wetting fluid (e. g., water or alcohol).[7] At first, in order to study the propagation of the new surface mode under the most favorable experimental conditions, experiments were made on alcohol-saturated porous sintered glass specimens at 100 KHz. As an example, Figure 1 shows the surface wave velocity and attenuation coefficient as functions of saturation time for a sintered glass bead sample (Grade 55, Eaton Products). Owing to the low viscosity of methyl alcohol, more or less complete saturation is reached within a few seconds after the bottom of the 1"-thick sample is soaked. As a result, the velocity quickly drops from 1,240 to 1,090 m/s and the attenuation increases by almost a factor of two. At this point, the slow wave propagation is still very weak since some of the pores are clogged by trapped air bubbles. At room temperature and atmospheric pressure, it takes approximately one hour for the alcohol to dissolve the remanent air saturation thereby opening the blocked pore channels. During this period, the surface wave velocity drops to 840 m/s and the attenuation coefficient increases to 1.1 dB/mm. These results are in good agreement with analytical predictions based on Feng and Johnson's theoretical approach.

Our experimental results provide clear evidence of the propagation of the new slow surface mode on the free surface of a fluid-saturated porous solid when the pores are closed at the surface by capillary forces. While the shear velocity drops a meager 2-5% upon saturating the specimen, the corresponding drop in the true surface wave velocity is a disproportional 20-50% depending on the tortuosity of the specimen and the sound velocity in the saturating fluid. The resulting large difference between the shear and surface wave velocities is a unique feature of permeable solids. For ordinary solids, the surface wave velocity is always between 86% and 96% of the shear velocity. On the free surface of a fluid-saturated porous solid, the slow surface wave velocity can be as low as 60% of the shear velocity. One of the main advantages of the slow surface mode, in comparison with the slow bulk mode, is that it can be observed in water-saturated natural rocks, too. Although, similarly to its bulk counterpart, the slow surface mode is greatly attenuated by viscous losses in natural rocks, its detectability is still much better. This is because both competing surface modes, i. e., the Rayleigh and Stoneley modes, are strongly leaky into the very lossy slow bulk mode and are decaying much faster than the slow surface mode. With no other modes propagating on the surface, the slow surface



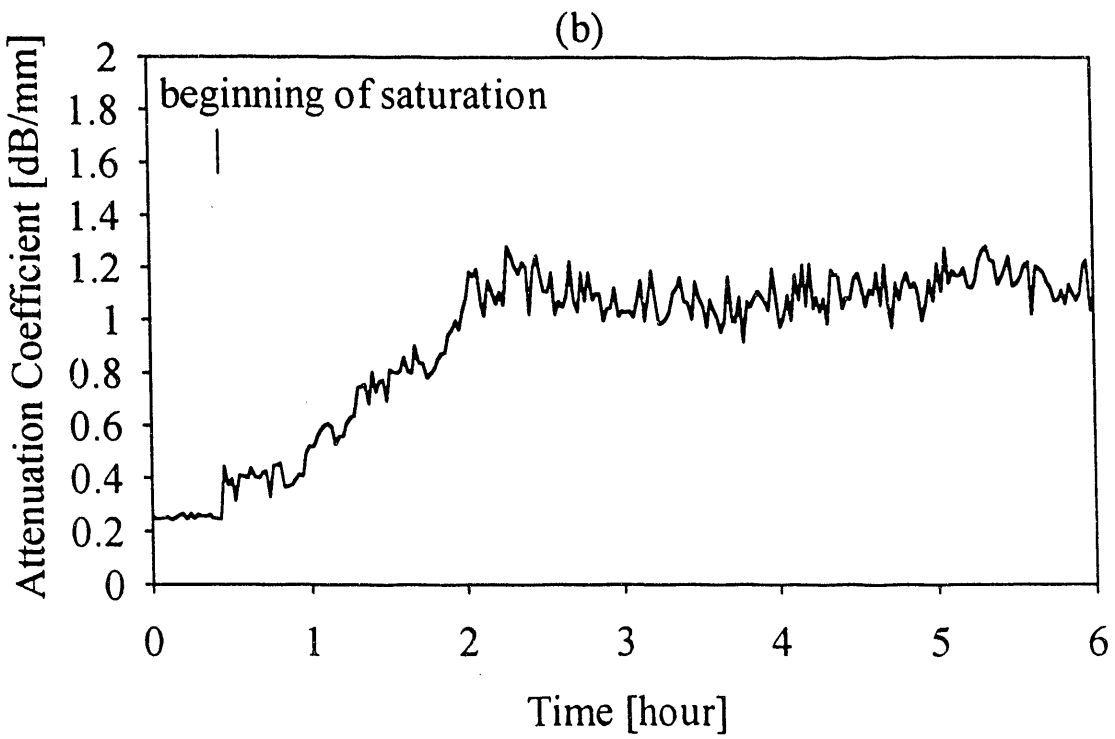


Figure 1 Surface wave velocity (a) and attenuation coefficient (b) versus saturation time for methyl alcohol on a porous glass specimen (G55) at 100 KHz.

mode can be easily recovered from the dominating electrical noise by extensive averaging in the time domain. Figure 2 shows the measured surface wave velocity in water-saturated Massillon and Berea sandstones between 100 and 600 mD. In natural rocks, as long as two-to-five days are necessary to achieve full saturation with water at room temperature. The shear velocity is basically unaffected by water saturation, although it drops 2-3% as a result of the added inertia of the liquid. In comparison, in the most permeable rocks, the surface wave velocity drops as much as 40 % due to the presence of the slow surface mode. In low-permeability samples, below approximately 200 mD, the fluid is essentially immobilized in the pores by viscous forces. Such rocks behave like ordinary solids; the surface wave velocity is only a few percent lower than the shear velocity regardless whether the sample is saturated or not. Of course, both the velocity and the attenuation of the slow surface mode are sensitive to the dynamic permeability of the porous formation rather than to the static one. Consequently, quantitative assessment of the "static" permeability requires that the measurement be carried out at a sufficiently low frequency.

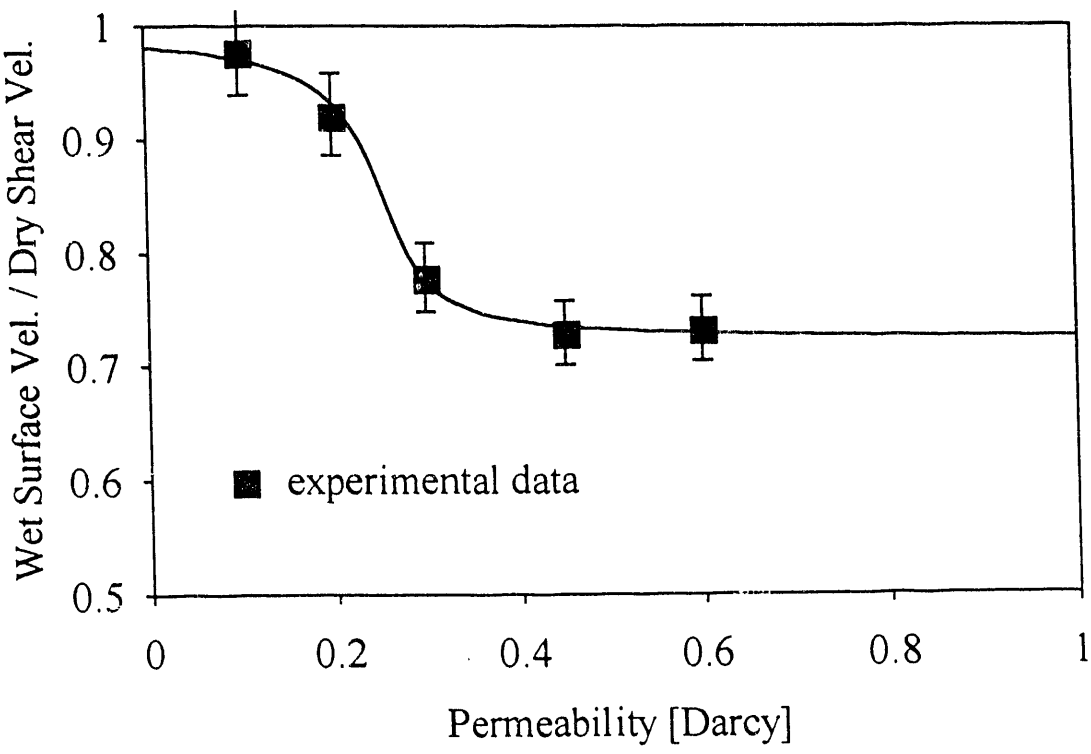


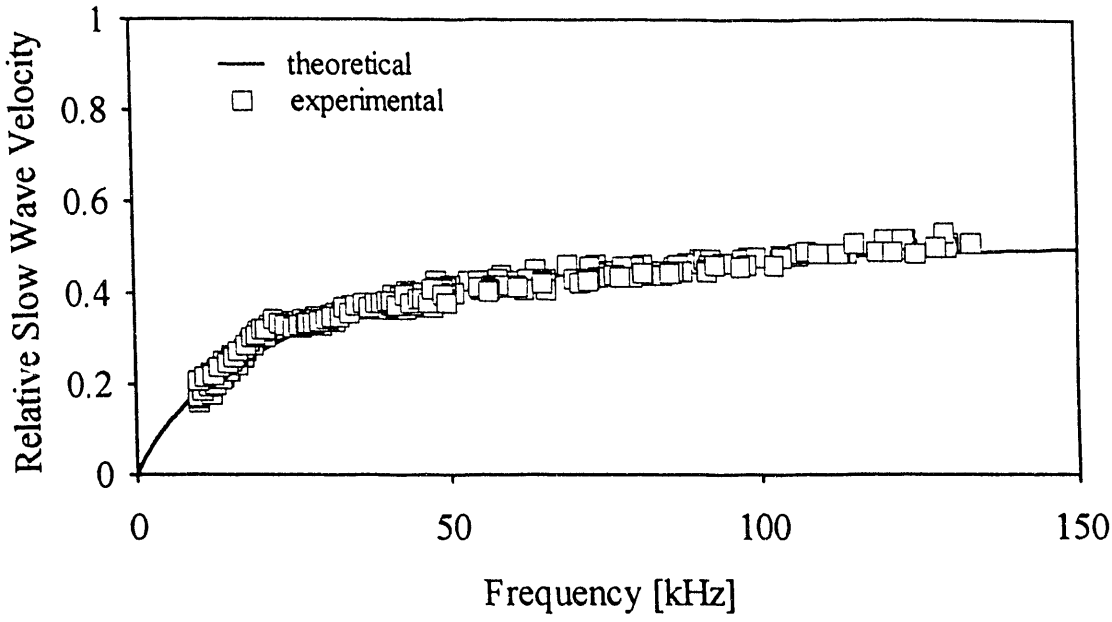
Figure 2 Normalized surface wave velocity versus permeability in Massillon and Berea sandstones.

2. Air-Saturation Technique

Beside investigating guided acoustic waves in water-saturated porous materials, we also studied bulk wave propagation in air-saturated specimens. We further developed our experimental technique which is based on the transmission of airborne ultrasonic waves through air-filled porous plates.[8] This method can be readily used to study the frequency-dependent propagation properties of slow compressional waves in different porous materials including natural rocks. By simple technical improvements, we extended the measuring range so that we could continuously cover both low-frequency (diffuse) and high-frequency (propagating) regimes of slow wave propagation.[9] In the diffuse region, which is usually below 100 kHz, both the velocity and the attenuation coefficient are primarily determined by the static permeability of the material. In the propagating region, the velocity depends on the tortuosity only while the attenuation coefficient depends also on the pore size and shape.

The propagation of slow compressional waves in air-saturated permeable solids was studied by experimental means between 10 kHz and 500 kHz. The velocity and attenuation coefficient were measured as functions of frequency from the insertion delay and loss of airborne ultrasonic waves transmitted through thin slabs of 1 - 5 mm in thickness. Porous ceramics of 2 - 70 D and natural rocks of 200 - 700 mD permeability were tested. In the low-frequency (diffuse) regime, the experimental results are in good agreement with theoretical predictions; the phase velocity and attenuation coefficient are essentially determined by the permeability of the specimen and both increase proportionally to the square-root of frequency. In the high-frequency (propagating) regime, the experimental results agree with the theoretical predictions for the phase velocity but not for the attenuation coefficient. The phase velocity asymptotically approaches a maximum value determined by the tortuosity of the specimen while the attenuation coefficient becomes linearly proportional to frequency instead of the expected square-root relationship. As an example, Figure 3 shows the normalized slow wave velocity and attenuation coefficient in a 2.4-mm-thick Cavallo Buff Massillon Sandstone specimen of 700 mD static permeability. It is suggested that the observed discrepancy in the high-frequency behavior of the slow wave attenuation coefficient is due to the irregular pore geometry which significantly reduces the high-frequency dynamic permeability of the specimens via excess viscous drag as well as elastic scattering. This phenomenon will be further investigated in the second year of our current research project.

a)



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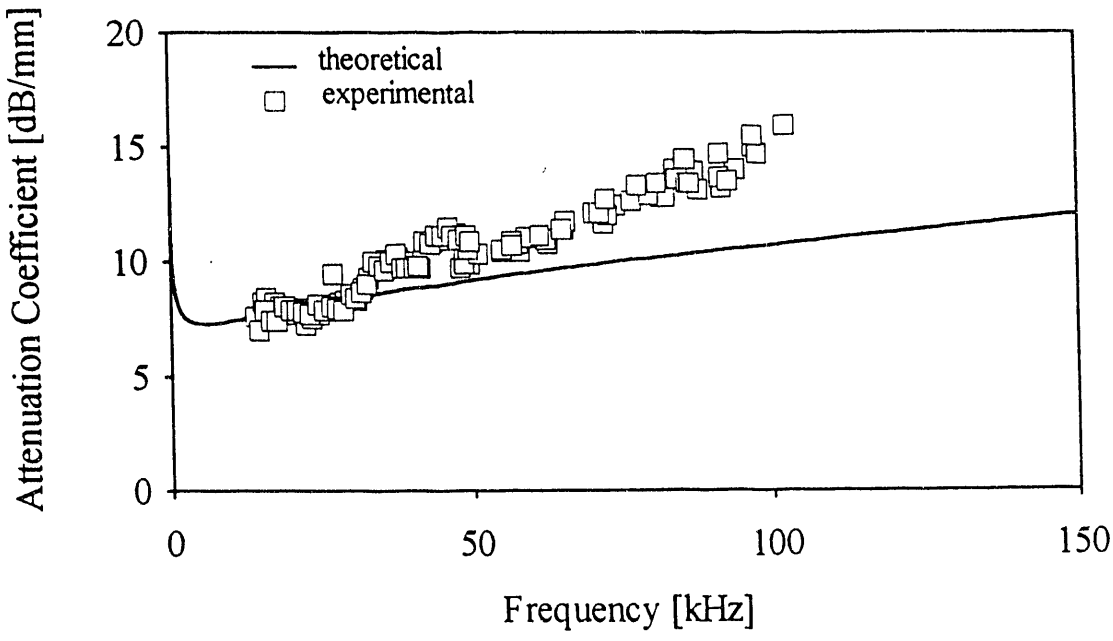

Figure 9 Normalized slow wave velocity and attenuation coefficient in a 2.4-mm-thick Cavallo Buff Massillon Sandstone specimen.

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