# MODULUS DISPERSION IN SANDSTONE AND LIMESTONE

**ABSTRACT:** The effects of frequency, strain amplitude, and saturation on Young's modulus were measured on specimens of Berea sandstone, Gypsy sandstone, Devine limestone, granite and welded tuff. Three techniques were employed at frequencies from $10^{-2}$ to $10^{6}$ Hz. The modulus of room dry samples remains relatively constant with frequency. Dispersion is observed in the saturated samples and is attributed to fluid flow. The moduli of sandstone, limestone, and granite decrease as strain increases.

## EXPERIMENTAL PROCEDURE

Young's modulus was determined as a function of frequency, strain amplitude, and water saturation for five rocks. Three techniques were used to cover frequencies ranging from $10^{-2}$ to $10^{6}$ Hz. The methods, corresponding frequency range, and

| Technique | Frequency Hz | Dimensions, mm | |
|---|---|---|---|
| | | Length | Diameter |
| **Cyclic loading** | **0.01 – 100** | **250** | **55** |
| **Resonant bar** | **1-200 k** | **201** | **13** |
| **Ultrasonic velocity** | **700 k** | **40** | **55** |

Samples were vacuum dried for 24 hours and then allowed to equilibrate to room conditions. The specimens were tested room dry, then saturated with water, and the measurement sequence repeated.

In order to compare the data collected with each technique, differences in strain amplitude must be considered. The ultrasonic velocity and resonant bar measurements are wave propagation techniques with peak strain amplitudes on the order of $10^{-8}$ to $10^{-6}$. These data are compared with cyclic loadings at strain amplitudes less than $5 \times 10^{-6}$.

The cyclic loading experiments were conducted in a servo-hydraulic load frame. A sinusoidal force of fixed frequency and amplitude was exerted on the specimen. Up to 200 cycles were collected at each frequency. The strain amplitude dependence was measured at a single frequency, 0.1 Hz, peak-to-peak strain spanned the range from $2 \times 10^{-6}$ to $10^{-4}$. The cyclic loading tests were completed first. The specimen was then subdivided for the wave propagation measurements.

## EXPERIMENTAL RESULTS

The effects of saturation and frequency on Young's modulus for Berea sandstone and Devine limestone are shown. The modulus for the dry condition is greater than the saturated modulus except at ultrasonic frequencies. For example, the modulus of limestone decreases from 30 to 10 GPa with saturation at frequencies between $10^{-2}$ and $10^{2}$ Hz. With increasing frequency, the modulus increases.

The effects observed on limestone and Berea sandstone are similar to those observed on the Gypsy sandstone, the Sierra White granite, and tuff. The greatest dispersion was observed on saturated Sierra White granite.

Strain amplitude affects the modulus for both the dry and saturated conditions. At strains greater and $5 \times 10^{-6}$, the modulus decreases. For example, the modulus of the limestone specimen decreased from 10.2 GPa at a strain of $4 \times 10^{-6}$ to 8.0 GPa at a strain of $9 \times 10^{-4}$. Similar effects were observed on the sandstones and granite. In contrast, the specimens of welded tuff, which is characterized predominantly by elliptical and spherical pores, exhibits no change in modulus over the range of $2 \times 10^{-6}$ to $10^{-4}$.

## DISCUSSION

Saturation reduces the modulus, particularly at frequencies below $10^{5}$ Hz. A small dispersion is observed in the saturated sandstone, limestone, and tuff. The granite, characterized by low aspect ratio cracks, exhibited the largest dispersion particularly at frequencies above 50 Hz. The frequency dependence can be attributed to fluid flow in the pores. When the cyclic loading rate exceeds the time constant for fluid diffusion within the pore space, the specimen begins to stiffen due to compression of the pore water. In turn, the effective modulus increases. The point at which relative stiffening occurs is related to the sample diameter, pore geometry, and boundary conditions for flow in the sample.

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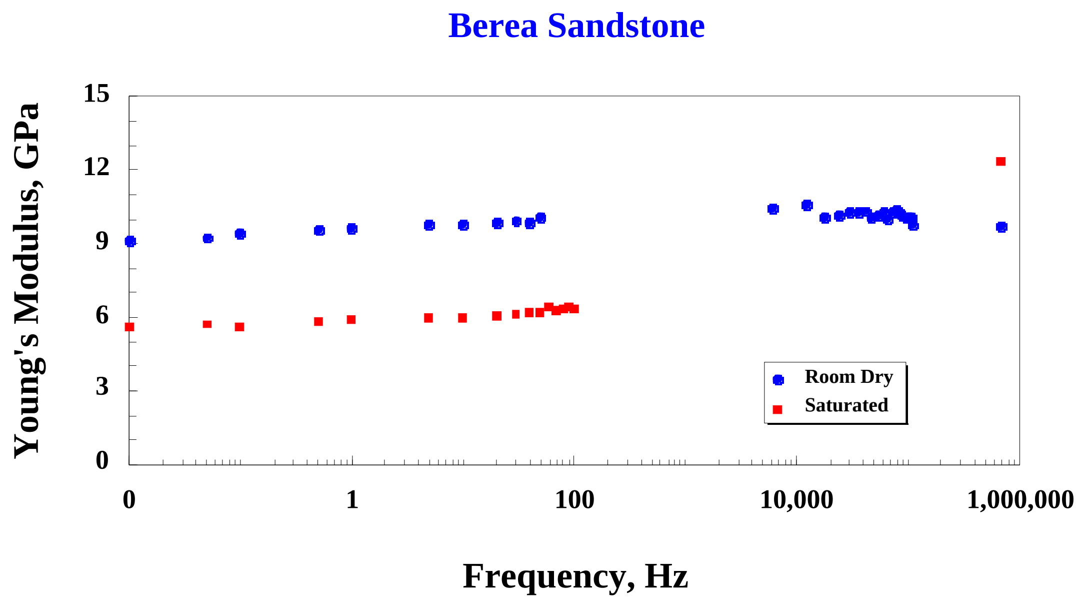
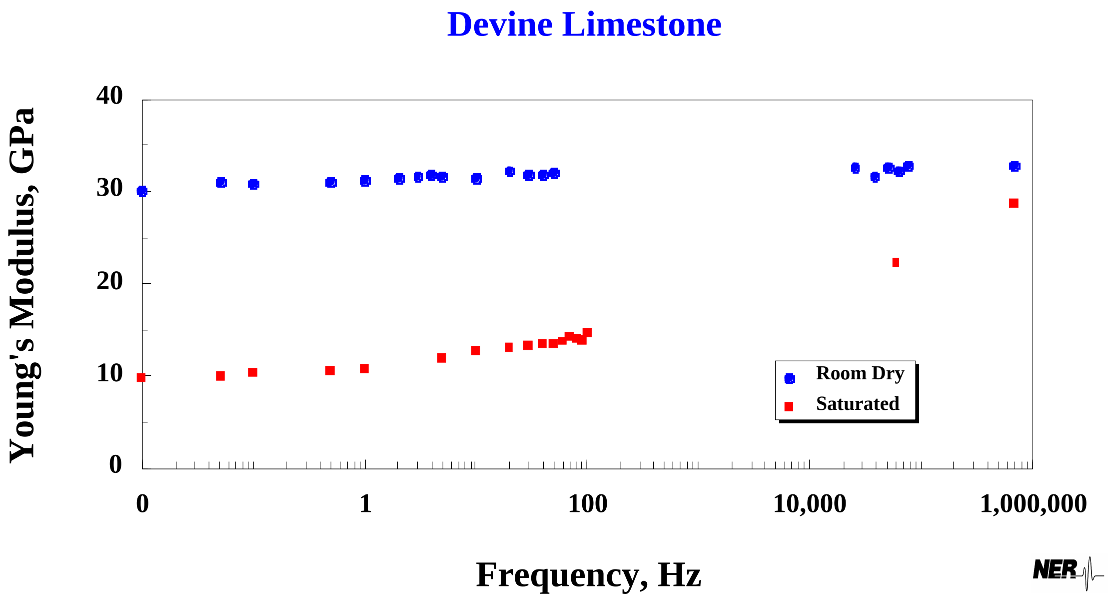

Berea Sandstone


Devine Limestone

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