Motion of Low Viscosity Liquids in Cortical Bone Subjected to Cylic Loading

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Abstract

The viscoelastic properties of cortical beef bone were determined by measuring the strain-time relationship of bone under a constant stress of 2 kgm/mm^2. From the strain-time diagrams, numerical expressions for the creep compliance and complex compliance of bone were derived. It is postulated that when bone is subjected to a cyclic stress that in each cycle energy is expended in moving low viscosity liquids in bone. It is proposed that this motion of low viscosity liquids is of prime importance in supplying nutrients to the living bone cells.

Introduction

Many references have been made to the effects of stresses and strains on bone as a living tissue. For example, it has been shown that the removal of mechanical stresses such as occurs when an experimental animal is immobolized in a plaster cast or when man is subjected to the weightlessness of outer space, causes the ultimate strength and the density of bone to decrease (Kazarian and Gierke, 1969). One is led to ask, "What is the mechanism by which mechanical stresses influence bone as a living tissue?" Bassett (1965) suggested that there is a piezoelectric mechanism present but Anderson and Eriksson (1968) have disputed this theory. In the present paper, a mechanism is proposed that manifests itself in the viscoelastic properties of bone.

Literature and Experimental Procedure

Several investigators [Smith and Walmsley (1959), McElhaney (1965), Sedlin (1965), Smith and Keiper (1965) and Bonfield and Li (1967,1968)] have studied the viscoelastic properties of bone. However, very little emphasis has been placed on the fact that, since bone is a viscoelastic material, energy will be absorbed by bone when it is subjected to cylcic stresses (Ferry, 1961) and Flügge, 1968). This energy is supplied by an external source and is dissipated as heat generated by the motion of the viscous liquids in bone. The amount of energy absorbed is temperature dependent. When temperature is held constant the energy absorbed per unit volume per cycle of applied stress is given by:

$$W = - \pi \sigma_o^2 G_2 (\omega)$$

$G_2(\omega)$ is the loss compliance of the material, σ_o^2 is the amplitude of the applied stress, and ω is the frequency of the applied stress in radians per second.

Twenty-two compression specimens of fresh cortical bone were machined from the mid-shaft of a beef femur under a jet of water. Eight specimens were tested in a fresh, wet condition, eight were air dried for 48 hours (losing an average of 3.8% by wt) then tested, and six were furnace dried for 12 hours at 105°C(losing an average of 12.2% by wt). Creep curves were obtained for all specimens using a stress of 2.05 ± 0.05 Kgcm/mm^2. It took approximately 0.1 seconds to apply the load and for the recorder to respond to the resulting strain.

Results

Figure 1 shows typical creep curves obtained for the fresh, wet, air dried and furnace dried specimens.

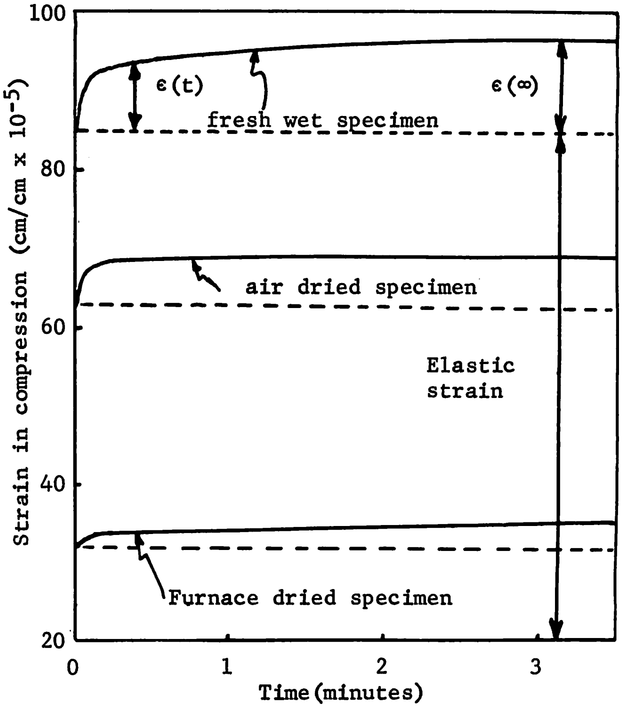

Fig. 1: Strain time diagrams for fresh wet, air dried and furnace dried cortical beef bone subjected to a constant stress of 2.0 kgm/mm

From a graph of $\ln \left[\frac{\varepsilon(\infty) - \varepsilon(t)}{\varepsilon(\infty)} \right]$ vs. time in seconds, equations (2) and (3) were determined for the creep compliance of fresh wet bone and air dried bone respectively.

$$J(t) = [4.5 - (.15e^{-t/91} + .23e^{-t/3.4} + .20e^{-t/.37})]10^{-11} \frac{\text{cm}^2}{\text{dyne}} \qquad (2)$$

$$J(t) = [3.27 - (.11e^{-t/46} - .10e^{-t/1.8})]10^{-11} \frac{\text{cm}^2}{\text{dyne}} \qquad (3)$$

There was so very little retarded strain with the furance dried specimens that it was not possible to determine an equation for their creep compliance.

The complex compliance $G(\omega) = G_1(\omega) + i\,G_2(\omega)$ was derived from the creep compliance. The loss modulus, $G_2(\omega)$, for the fresh wet and air dried specimens are given by equations (4) and (5) respectively.

$$G_2(\omega) = -\left[\frac{\omega \mathrm{x} 10^{-13}}{6.35\mathrm{x}10^{-4}+6.1\omega^2} + \frac{\omega \mathrm{~x~} 10^{12}}{.12 + 1.5\omega^2} + \frac{\omega \mathrm{~x~} 10^{-11}}{13.3 + 1.8\omega^2} \right] \frac{\mathrm{cm}^2}{\mathrm{dyne}} \qquad (4)$$

$$G_2(\omega) = -\left[\frac{\omega \mathrm{~x~} 10^{-13}}{20\mathrm{x}10^{-4}+4.2\,\omega^2} + \frac{\omega \mathrm{~x~} 10^{-12}}{.57 + 1.8\,\omega^2} \right] \frac{\mathrm{cm}^2}{\mathrm{dyne}} \qquad (5)$$

The energy absorption by fresh wet and air dried bone was calculated using equations (4) and (5) in equation (1). The results are shown graphically in Figure 2.

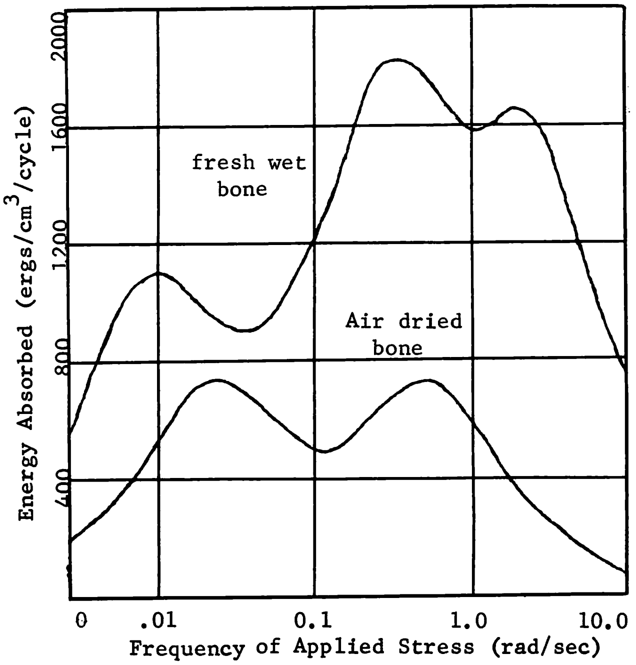

Fig. 2: Energy absorption in fresh wet cortical beef bone and air dried cortical beef bone subjected to a cyclic stress of frequency ω(radians/second), amplitude 2.0 kgm/mm^2 at room temperature

Discussion

The fact that there is much more energy absorbed by the fresh wet bone than by the air dried bone when they are subjected to cyclic stresses suggests that low viscosity liquids play an important role in energy absorption by bone. Indeed if one gently tightens a vice on a piece of fresh wet cortical bone, it is readily observed that liquids are squeezed from the bone. It requires energy to move these liquids through the fine vascular network of bone.

When in vivo bone is subjected to a compressive stress, some of the liquids in the lacunae, canaliculi, and other finer porosities of bone will be squeezed into the capillaries of the blood supply in bone. When the stress is removed, liquids will flow from the capillaries back into the lacunae, canaliculi and other finer porosities. This represents an effective mechanism whereby mechanical stressing can influence the transport of nutrients and waste products between the blood system and the living cells within bone. The energy required to make the mechanism operative comes through the everyday habits of walking, lifting, etc. When these mechanical stresses are removed, such as occurs in outer space, the mechanism is no longer operative.

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