INFLUENCE OF INCREMENTAL LINES UPON THE COMPRESSIVE STRENGTH OF SPERM WHALE DENTIN

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ABSTRACT

Compressive properties of sperm whale dentin were measured as a function of orientation of incremental lines. With respect to the general incremental lines' direction, three specimen orientations were selected: longitudinal, oblique (45°) radial and transverse radial. The machined cylindrical specimens were compressed in a mechanical testing machine. A load cell provided with the force values developed on the samples and a displacement transducer yielded the corresponding deformation values. The resulting stress-strain curves provided with values of proportional limits, ultimate compressive strengths and elastic moduli for each of the specimen orientation investigated. It was found that while the ultimate compressive strength values did not differ statistically with specimen orientation, proportional limits and elastic moduli showed some significant differences. Based on a possible functional adaptation, a theory has been formulated which correlates the results obtained with the growth patterns found in sperm whale dentin.

INTRODUCTION

Calcified tissues in vertebrates display a combination of structure and properties which reflect an adaption for their function in the living systems. Bones are designed to provide the adequate framework for sustentation of the body weight and muscular action. Teeth of ruminants display flat occlusal surfaces allowing grinding of grass and seeds whereas carnivorous animals have teeth which tear flesh and fracture bones. Some dentitions may only be used to shear and retain as in the case of some fish, aquatic reptiles and other sea going mammals.

Sperm whales' teeth are characterized by their conical shape, their continuous growth patterns and their funnel-shaped attachment to the jaw. They are not known to be used for chewing, however they can be utilized for snapping and retaining prey in the mouth. This investigation concerns itself with the influence that incremental line orientation in dentin have upon its resistance under compressive stresses. In light of the present findings, it is suggested that growth patterns and compressive stresses interact in the growing organ to explain the differences in the measured properties.

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MATERIALS AND METHODS

Sperm whale teeth were chosen because of their large dimensions and easy availability. The teeth were obtained through a marine life dealer and, as soon as received, they were inspected for any apparent defects. They were then placed in individually labelled plastic bags and stored in the freezing compartment of a refrigerator at $-18°C \pm 1°C$ until ready for machining. In this study a single tooth was selected as it provided enough specimens. It also was felt that this choice would restrict the variability inherent to the use of several teeth taken at random.

A sperm whale tooth is shown in figure 1. It has a short crown and a comparatively long root. The outer aspect of the tooth is covered by a thick layer of cementum (Ohsumi et al., 1963). Because of its regular texture and amplitude, the dentin in the cervical area, shown in figure 2(A), was chosen to prepare the various types of specimens used. This region of the tooth was divided in several horizontal sections. Each section was used to machine three specimens in different orientations. With respect to the incremental lines, the specimen orientation was as follows: longitudinal, oblique (45°) radial and transverse radial as shown in figure 2(B). A total of 6 specimens in each group was produced in this manner.

The dentin specimens were turned with a jeweler's lathe at low speed. Each cutting pass was made small to avoid any mechanical damage to the material. The specimens were moistened with a drip of Krebs-Ringer phosphate buffer solution during this procedure. This precaution was taken to avoid overheating and also provided proper lubrication for the cutting of the dentin. The specimens' end faces were ground flat at right angle to their principal axis. This procedure was carried out by inserting the samples in holes of slightly greater diameter made in a flat

Fig. 1. Bucco-lingual view of a sperm whale tooth.

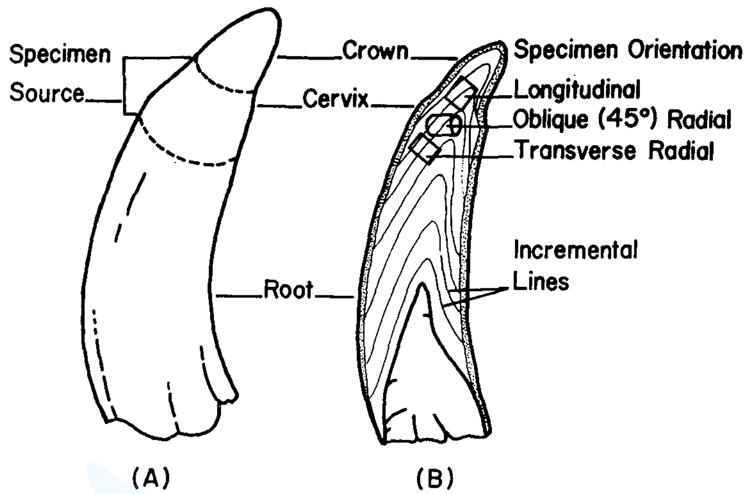

Fig. 2. Sperm whale tooth: (A) Specimen source and (B) Specimen orientation with respect to the incremental line direction.

hardened steel slab of a given thickness. The finished specimens were of the following dimension: diameter=0.085 in., length=0.158 in. Before the actual tests, the specimens were placed in labelled jars filled with Krebs-Ringer phosphate buffer solution and stored in a refrigerator at a temperature of about 3°C.

The dentinal tubules' main direction in the various specimens studied are

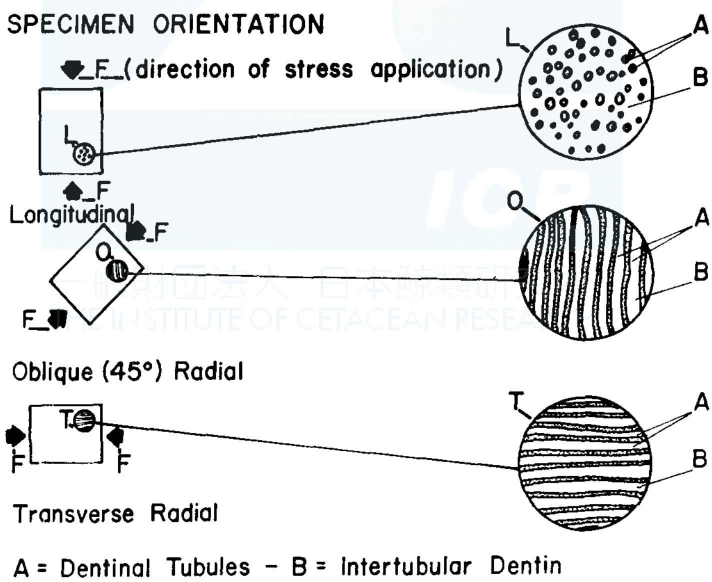

Fig. 3. Dentinal tubule alignment in three types of specimen orientation.

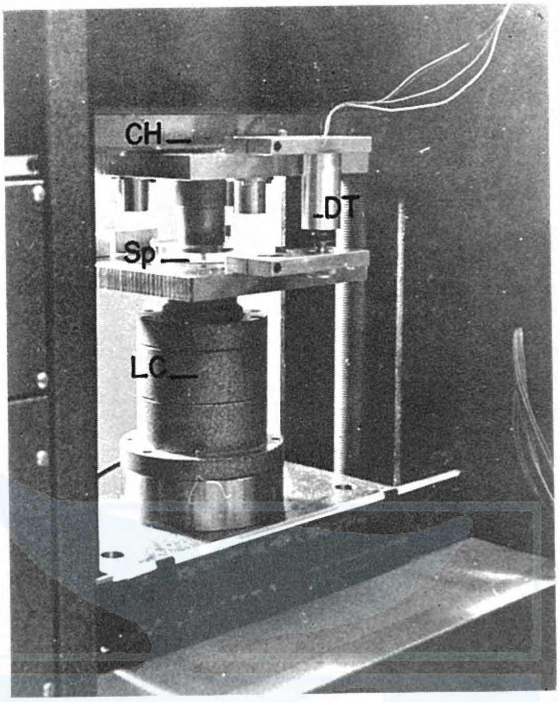

Fig. 4. Photograph of the compression apparatus: (SP) Specimen, (LC) Load cell, (DT) Displacement transducer, (CH) Crosshead.

represented in figure 3. This result was obtained by making a series of longitudinal sections in each specimen after completion of testing and examining the thin ground sections under standard and polarized light microscopy. Essentially, it was observed that the dentinal tubules were directed at right angle with respect to the general orientation of the incremental lines. The orientation of the incremental lines in each type of specimen was assessed by direct inspection.

Deformation and fracture of the specimens was performed in an Instron mechanical testing machine (Fig. 4). The load signals were taken from the testing

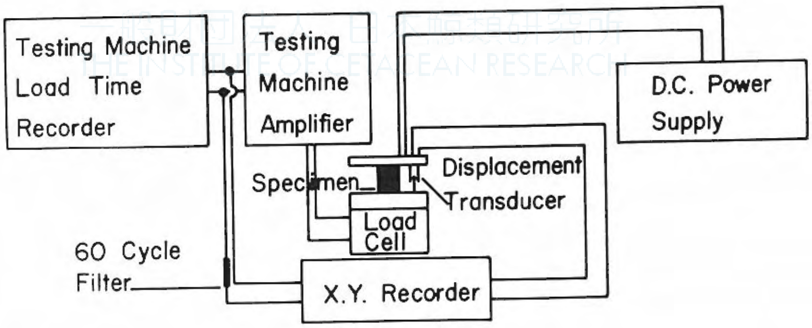

Fig. 5. Block diagram of the circuitry used in the compression tests.

machine amplifier and fed to the y axis of an x-y recorder. The deformation values were measured by a displacement transducer and its output fed to the x axis of the x-y recorder (Fig. 5). Both loads and corresponding deformation values were simultaneously plotted on the recorder and later converted into engineering stress and strain values by using the formulae: P/A_o and $\Delta L/L_o$ respectively, where P=load, A_o=original cross sectional area, ΔL=change in length and L_o=original specimen length. Because of the comparative character of the study, data analysis, according to a true stress-true strain relationship, was not felt to be relevant and therefore was not performed.

Before the tests, the refrigerated dentin specimens were allowed to warm up and come to equilibrium with the ambient temperature. Once again their dimensions were checked. The deformation to failure was conducted at a constant cross-head speed. This portion of the experiment was carried out with the specimen immersed in Krebs-Ringer phosphate buffer solution to avoid the possibility of specimen moisture loss during the test. The water and inorganic content of the specimens were obtained by desiccation and ashing respectively, as shown in Table 1.

TABLE 1. COMPOSITION OF SPERM WHALE DENTIN

Oven Dried (105°C)	Ashing (1100°C. for 24 hours)	
Water % of wet weight	Organic Matter % of dry weight	Inorganic Matter % of dry weight
14.72	28.55	71.45

RESULTS

The results listed in Table 1 represent the composition of sperm whale dentin. The water content is representive of the hydration water as well as the water found in the dentinal tubules. It is however recognized that some chemically absorbed water still remained in the material and was not displaced at the selected drying temperature (Eastoe, 1967). A more detailed analysis showed that the inorganic matter was mostly composed of calcium and phosphorus, whereas the organic phase was found to be proteinic in nature.

In Table 2 the results for the elastic modulus, proportional limit and ultimate strength of various specimen orientations are given along with the strain rate at which each group of experiments was carried out.

TABLE 2. MECHANICAL PROPERTIES OF SPERM WHALE DENTIN SPECIMENS UNDER COMPRESSION

Specimen Orientation:	Longitudinal	Oblique (45°) Radial	Transverse Radial
Ultimate Strength (psi)	29300*±4400**	28000±4500	26000±1500
Proportional Limit (psi)	4400±1500	3700±700	3700±600
Elastic Modulus (psi)	$(7.8\pm1.3)\times10^5$	$(4.3\pm1.4)\times10^5$	$(2.9\pm1.5)\times10^5$
Strain Rate (sec^{-1})	$(64.6\pm1.0)\times10^{-5}$	$(55.9\pm6.6)\times10^{-5}$	$(64.6\pm8.1)\times10^{-5}$

* Mean ** Standard Deviation

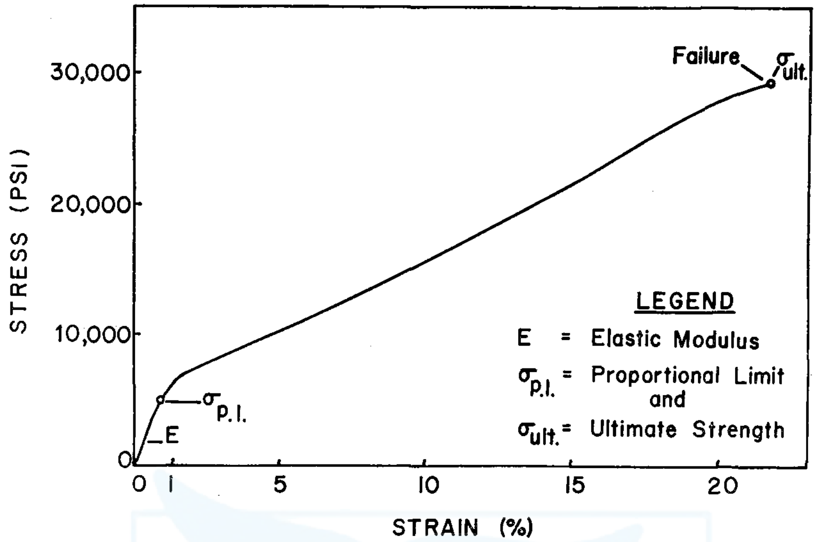

Fig. 6. Typical stress-strain curve with salient features and representative values obtained with various specimen orientations.

A general view of the stress-strain curve is given in figure 6. Its salient features and stress values result from graphing several curves obtained by testing various specimens in the different orientations. The linear portion of the curve is representative of the elastic modulus, the proportional limit was measured at the onset of a plastic strain of about 3×10^{-1}, and the ultimate strength, which here is also the stress at failure, was obtained at maximum plastic strain.

DISCUSSION

It was felt that the determination of the chemical composition of sperm whale dentin (Table 1) would be of help in explaining, in part, some of its properties and provide a base of comparison with other calcified tissues which have been more extensively studied. Although some resemblance was found with bovine cortical bone (Lugassy, 1968), major similarities between the properties exhibited by these two materials were not readily apparent. This left the possibility of other factors such as structural arrangements of the various phases in the material to be of significant influence upon the properties observed. This suggestion will be further developed in the discussion.

In Table 2 a trend towards increasing values seems to exist when comparing the results obtained for the elastic moduli, proportional limits and ultimate strengths of the transverse radial, oblique (45°) radial and longitudinal specimens, respectively. However, when statistically analyzed the above data showed that except for the following: elastic modulus values of the longitudinal and transverse radial, longitudinal and oblique (45°) radial specimens, and proportional limit values of the longitudinal and transverse radial, and oblique (45°) radial and transverse radial specimens, there was no difference at the 5% significance level between the average stress values of the various group compared. No apparent reason could be found, including the effect of lower strain rate values obtained with the oblique (45°) radial specimens or the possible misalignment of the incremental lines in the samples for the lack of significant difference existing between the elastic modulus of the oblique (45°) radial and transverse radial specimens, and the proportional limit of the longitudinal and oblique (45°) radial specimens. Further study on these particular points is contemplated in the near future.

Microstuctural organization has been found to significantly influence the type of mechanical response observed with calcified tissue (Ascenzi et al., 1966; Evans et al., 1966; Lugassy, 1968). It has also been recognized that during formation, the types of mechanical stimuli exerted on developing bone will condition its resulting structure.

In the case of sperm whale dentin, it is felt that the vertical forces applied on the teeth during their growth have some influence over the dentin formed. These forces transmitted to the pulp would be resolved as shear stresses at the level of the odontoblastic layers. In the present case, it is suggested that the shear stress lines are, in effect, conditioning the formation and orientation of the incremental lines through their angulation with respect to the main axis of the tooth. To some extent, they could constitute the mechanical stimuli. With respect to the rate of deposition, nature and composition of dentin in the incremental lines, it would appear that they are related to the mode of life and feeding cycles of these mammals (Ohsumi et al., 1963).

The difference between the mechanical response of the longitudinal and transverse radial specimens could be explained as follows: When deformed at right angle with respect to the growth patterns, the weaker areas where calcification has been poor or incomplete would influence the overall response of the sample tested. However, in the case of a longitudinal specimen, because of their regularity and uniformity, the incremental lines seem to act as a nest of reinforcing lines tending to increase the resistance of the structure to the effects of vertical stress application. Mechanically this response would be best related to the straight line portion of the stress-strain curve found under the proportional limit in figure 6.

When sperm whale dentin is subjected to large deformations, corresponding to the stress-strain curve section above the proportional limit in figure 6, it is felt that the structural changes in the material produced by slippage and flow are of such magnitude that the influence of the incremental lines become of insignificant effect as revealed by the relatively similar ultimate strength values of the various specimen groups tested. The above mechanism points to the viscoelastic character of the response of sperm whale dentin (Lugassy, 1968; Lugassy et al., 1969), and its strain rate dependency. These reasons explain the strain rate values given in Table 2.

Low strain rate fractures of other calcified tissues, such as those occurring in bovine cortical bone, have been characterized by shear surfaces oriented at a 45° angle with respect to the axis of stress application. In sperm whale dentin comparable fracture surfaces have been observed and appear to have not been influenced by the orientation of the incremental lines or the relatively large strains occurring at failure.

CONCLUSION

The influence of incremental lines upon the mechanical properties of sperm whale dentin has been studied and representative values given. It was found that except for a difference between the elastic moduli of the longitudinal and transverse radial, and longitudinal and oblique (45°) radial specimens, and the proportional limit of the longitudinal and transverse radial, and oblique (45°) radial and transverse radial specimens, there was no statistical difference at the 5% significance level for the other properties studied including: ultimate strengths, proportional limits and elastic moduli of these and other groups of specimens. Although it is recognized that other factors may strongly influence the structural anisotropy of calcified tissues, it is felt that in the case studied, for small deformations, the presence of incremental lines offer the means of optimal resistance of sperm whale teeth to stresses applied on them vertically and also explains their growth patterns and the mechanical properties measured. Within these limits, sperm whale teeth seem to have been structurally adapted for their functions in their selective environment.

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