# Load-deformation characteristics of human teeth

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## ABSTRACT

The susceptibility of the human teeth to changes such as caries, abrasion, attrition, erosion, malocclusion, trauma and restorative procedures has necessitated the need to investigate the load-deformation characteristics of the human teeth. This study investigated the creep characteristics of dentine under compressive loading comparable to occlusal stresses. Dentine specimens of cylindrical morphology were prepared from recently extracted non-carious lower molar teeth. Slices of mid-coronal dentine sectioned with a slow-speed diamond saw were cut into cylindrical discs, after which they were stored (aq) at 4 °C for 24h to re-stabilize their water content. The load-deformation behaviour of the dentine was then measured in water for 2h during loading and then 2h of recovery at two stresses (10 & 18 MPa) and at temperatures of 37 & 60 °C. The creep variables evaluated included the maximum strain, permanent strain, strain recovery and an initial modulus of compression. Maximum strain and the modulus of compression were higher at increased stress and temperature while such changes did not affect the permanent and recovery strains. Dentine exhibited flow response under 'clinical' compression with a maximum strain ~ 1% and high recoverability. It did show a permanent strain of 0.3 %. This establishes a performance standard for the stability of restorative biomaterials replacing human dentine.

**KEY WORDS:** Creep, compressive stress, dentine, strain, occlusal

## INTRODUCTION

The need for the control of translational and rotational motions of the teeth under varied occlusal forces and the assessment of stresses generated by a loaded tooth gave rise to the study the load-deformation behaviour of the human teeth. The biomechanical nature of the tooth tissue is inherently complex; as such the mechanical properties of dentine and enamel involve stress-strain relations due to tension, compression, bending and shear modes. The difficulty therefore, in understanding thoroughly the mechanical properties of dentine arises from the existence of two phases of the natural tooth tissue with very different properties. Some theoretical models were proposed to predict the mechanical behaviour of hard tissues like bone, enamel and dentine. These included the Hashin spherical particle model and the Voigt, Reuss and Hashin-Shtrikman models[1]. Modification of the models has helped in the conceptual understanding of response pattern of a tooth tissue when subjected to load application[2]. Comparison made between these models and with experimental data has demonstrated that the stress response of human dentine is consistent with such models [3].

Earliest systematic studies that investigated the compressive behaviour of dentine dates from 1895 [4]. Such studies reported that neither the location nor the orientation of the dentinal tubules made any difference in the deformation characteristics of teeth. Recent investigations have used methods such as Atomic Force Microscopy (AFM)-based indentation techniques to study the rheological properties of demineralized human dentine in an aqueous medium [5]; and the hardness and elasticity of peritubular and intertubular dentine [6,7,8]. The creep behaviour of dentine has been attributed to the high proportion of organic material. water, and the collageous tissues[9] present in it.

This work is aimed at assessing and evaluating creep of human dentine under the action of compressive stresses comparable to normal occlusal forces, at clinically low temperatures (37 °C) and 60 °C (representing temperature of hot beverages). Data obtained from such a study are particularly important

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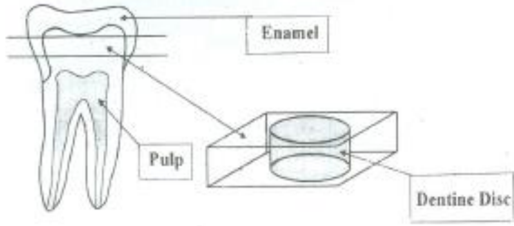

**Figure 1:** Crown dentine (tooth tissue) from which dentine specimens were sectioned and disc-shaped dentine specimen that was fabricated.

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## MATERIALS AND METHODS

Discs of dentine specimens were prepared from the crowns of extracted lower molar teeth (Figure 1). This was done in such a way as to obtain a maximum volume and an axial orientation of the tubules within the dentine discs. Slices of mid-coronal dentine (~ 2 mm) were prepared using a slow-speed micro-slicing machine with a water-cooled diamond saw. The prepared dentine slices were then rubbed flat to obtain the appropriate thickness using wet 600 grit silicon carbide papers. Dentine discs were fabricated from the slices by cutting with a straight No. 731 M fissure bur with a high-speed hand piece and copious water spray. The discs, after fabrication, measured 3.0 mm in diameter and were 1.8 mm thick. They were then stored in distilled water at 4 °C for 24 hours prior to the tests, to restabilize the water content and thus avoid any changes in their physical properties.

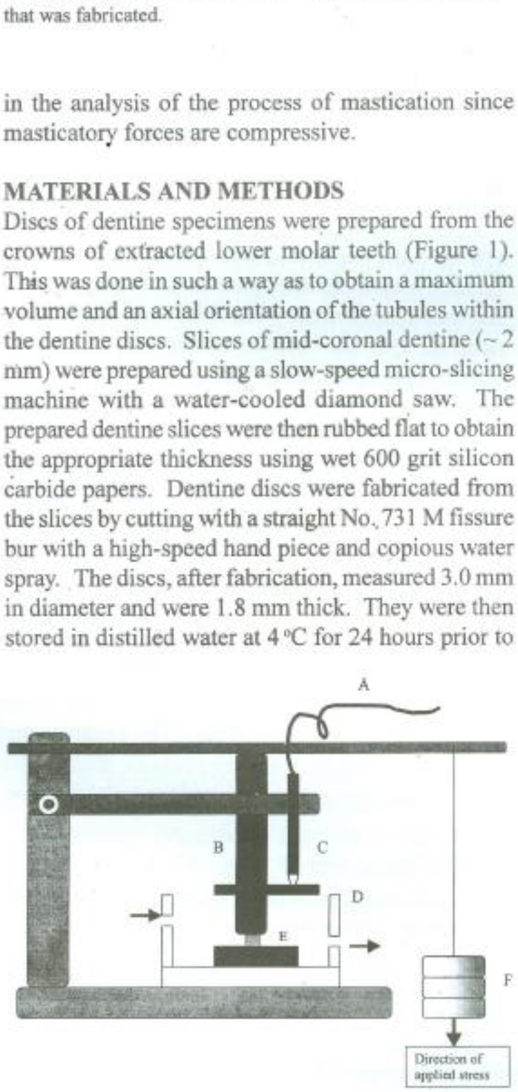

**Fig. 2:** Schematic diagram of the Load-deformation measurement apparatus; (A) LVDT extension that links up the data logging system to the pc via an ADC; (B) Loading pin; (C) LVDT that recorded the micro displacements; (D) Water bath made from acrylic; (E) Dentine disc position; (F) Applied compressive stress

The experiment involved application of a constant uniaxial compressive stress, recording of strain of the dentine for 2 hours and releasing the stress for 2 hours strain recovery. Two compressive stresses, 10 and 18 MPa, were applied to the specimens. This was done at two temperatures 37 °C and 60 °C. Five sets of six dentine discs were each subjected to the stress and stress-recovery regimes. The apparatus (Figure 2) used comprised 1 cm diameter loading pin (B) and a lever that ensured a linear displacement of the pin. The discs were mounted on a platform uniaxial to the compressive loading pin surrounded by a temperature-regulated water-bath (D) that ensured temperature equilibration during measurements. Data obtained was further analysed statistically, using a 2-way ANOVA and Scheffe's 0.5 significant level tests.

## RESULTS

The *Superposition Principle* was formulated for the analysis of some creep characteristics of solids [1]. The principle postulates that the effects of either stress or strain increments on viscoelastic materials (including dentine) are additive. The vast majority of solids studied at small strains conformed to this principle, or at least there was a critical strain below, which the principle was valid. The load-deformation variables evaluated in this study were obtained from the creep-time characteristic profiles of dentine (Figure 3 & 4) which included: Maximum compressive Strain, $\mathbf{Y}_m$, Permanent strain, $\mathbf{E}_s$, Relative strain recovery, $\mathbf{Y}_R$ and the Initial modulus of compression denoted by $\bar{\mathbf{E}}$. These parameters were evaluated from the data obtained on the creep measurements of the dentine specimens (Table 1).

Dentine exhibited a maximum strain of 1.08 % at the elevated temperature of 60 °C under 10 MPa compression and 1.58 % at the same temperature under 18 MPa compressive stresses. Statistical analysis of Maximum strain data indicated significant differences ($p < 0.01$) between data obtained at the two stress levels and at the two clinical temperatures, although the interaction term for temperature and stress was not significantly different ($p = 0.08$). The percentage of permanently strained dentine tissue was 0.41%, under 18 MPa stress at 60 °C, and at 37 °C, 0.24 % of tissue was permanently strained under 10 MPa compression. Differences in $E_s$ values at the

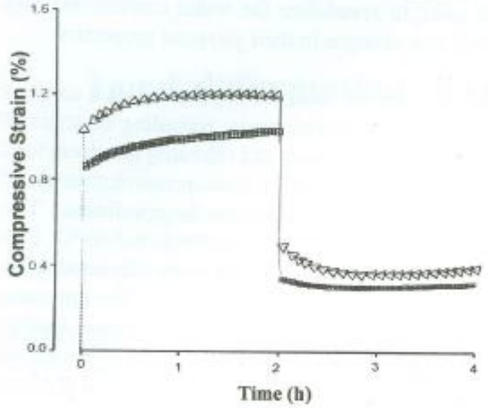

**Figure 3:** Creep strain-time dependence of dentine at 37 °C under the action of 10 MPa (□)and 18 MPa (△)compressive stresses;

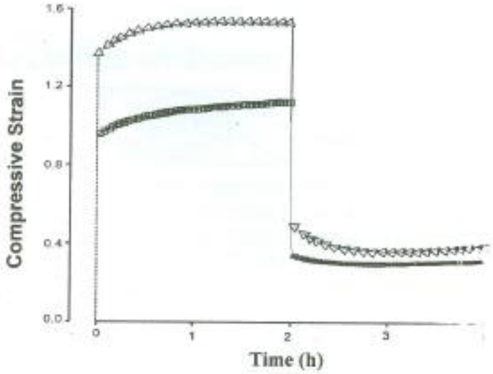

**Figure 4:** Creep Strain -time dependence of dentine at 60 °C under the action of 10 MPa (□) and 18 MPa (△) compressive stresses.

two temperatures (37 and 60 °C) were significant ($p < 0.01$). Relative recovery strains exhibited by the dentine under the temperature and stress regimes ranged between 70 % and 80%. Strain recovery data did not show significant differences ($p = 0.85$; $p = 1.84$) when compared under both temperature and stress regimes. The initial modulus of compression was evaluated from the time-dependent flow characteristics of the dentine measured. These were calculated as ratios of applied stress and strain and they ranged between 12 and 18 Giga Newton/square metre (GN/m$^2$), as indicated in Table 1. The differences in Compressive moduli compared at both clinical stresses and temperature were significant ($p < 0.01$).

## DISCUSSION

Human dentine in this study has shown creep characteristics under the action of low uniaxial static compressions of 10 and 18 MPa at 37 and 60 °C. Owing to the importance and orientation of dentinal tubules when considering mechanical properties of the tissue, specimens were fabricated from crown dentine. This was because morphology of the tooth placed some restriction on the fabrication of dentine specimens from other portions of the tooth without interfering with the pulpal horn and chamber. A typical time-dependent load-deformation (creep) profile of the dentine tissue was characterised by an initial rapid deformation, an elastic behaviour, followed by a creep stage. After releasing the stress, there was an initial rapid recovery phase and then an irreversible viscous phase, giving rise to some permanent strain in the tissue. The profile of the creep recovery curves after stress release, showed an instantaneous drop in strain and slower strain decay to non-zero strain value. The instantaneous drop represented the recovery of elastic strain, while the delayed recovery represented the inelastic strain.

**Table 1:**

Table shows the mean values of the creep variables evaluated. Measurements were taken on the six specimens of dentin geometry under each condition of testing. Standard deviations are indicated in parenthesis. Same symbols indicate non-significant differences between values (2-way ANOVA statistical analysis).

| **Compressive Stress (MPa)** | 10 | | 18 | |
|---|---|---|---|---|
| **Temperature (°C)** | 37 | 60 | 37 | 60 |
| **Creep Parameters** | | | | |
| Maximum Strain, **Ym**, (%) | 0.90 (0.15), | 1.08 (0.20), | 1.18 (0.04), | 1.58 (0.28) |
| Permanent Strain, **E$_s$**, (%) | 0.24 (0.04)* | 0.33 (0.09)* | 0.28 (0.04)** | 0.41 (0.09)** |
| Relative Strain Recovery, **Y$_R$**, (%) | 72.4 (2.35)$^{@}$ | 69.32(2.26)$^{\&+}$ | 76.64 (2.95)$^{@+}$ | 73.41(2.21)$^{\&+}$ |
| Compressive Modulus, **E**, (GN/m$^2$) | 12.54 (1.15) | 12.21 (0.73) | 17.64 (1.68) | 14.71 (1.84) |

The low magnitudes of strain recovery and compressive modulus of dentine obtained at 60 °C, is comparable to observations made in evaluating the elastic moduli of the dentin in a temperature range of 21 - 60 °C [6]. The modulus of compression evaluated did show the effect of stress and temperature variations on the strength of dentine. Moderate stresses of 10 and 18 MPa loaded on the dentine in this investigation were high enough to deform the tooth tissue beyond its proportional limit resulting in low permanent strains up to 0.5 %. The load-deformation behaviour of dentine has been influenced by the magnitude of the applied stress cycles and temperature variations. In this study, an increase from 3 % to 17 % of the initial compressive modulus at 10 MPa and 18 MPa is shown at 37 °C and 60 °C. The composite-structural properties of the dentine tissue are worth considering in order to appreciate the flow (creep) behaviour of dentine, which is basically a binary composite comprising collagen and hydroxyapatite crystals (HAP). HAP is chemically stable even below 40 °C [9,10] and that possibly accounts for the small change in compressive modulus at 37 °C, under 18 MPa compression. The temperature-dependence of the load-deformation characteristics of dentine is attributed to its collagen content and the volume fraction of water in the tissue. These have been described as having a cumulative effect on the modulus of elasticity, proportional limit and compressive strength [11,12,13,14]. As a result of the relative chemical stability of the composite structure of dentine within a wide range of temperature, moderate temperatures at which this study was done caused minimum structural changes in the tissue.

Maximum strains observed could be due to the increase in the creep processes at a higher temperature of 60 °C. The low moduli of compression and the strain recovery magnitudes reported in this study, (between 12 - 18 GPa) at 60 °C, may be attributed to a possible weakening in the bonding between collagen and HAP microcrystals. The load-deformation characteristics may also be due to the collapse of the dentinal tubules as a result of stress concentrations during initial loading of the dentine specimens. Consequently, fluid exchanges induced by application of stresses gave rise to a time-dependent deformational response. Notwithstanding, the plasticizing effect of the water content of the tissue may also account for the small values of residual strains.

## CONCLUSION

The dentine structure is complex at several levels. However, this work has shown that its load-deformation characteristics are evident upon the application of occlusal loads, according to principles of creep theory. The investigation also suggests that low compressions generated small permanent changes in the dentine tissue due probably to the collapse of the dentinal tubules. The maximum strain, a high recoverability and a very low permanent strain that were realized for dentine, have a propensity to establish a performance standard for the creep stability of restorative biomaterials in replacing human dentine.

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