International Journal of Engineering Science 111 (2017) 52–60

Contents lists available at ScienceDirect

International Journal of Engineering Science

journal homepage: www.elsevier.com/locate/ijengsci

Fraction-exponential representation of the viscoelastic properties of dentin

Seyedali Seyedkavoosi[a], Dmitry Zaytsev[b], Borys Drach[a], Peter Panfilov[b], Mikhail Yu. Gutkin[c,d,e], Igor Sevostianov[a,*]

[a] Department of Mechanical and Aerospace Engineering, New Mexico State University, Las Cruces, NM, 88003, USA
[b] Department of Physics, Institute of Natural Sciences, Ural Federal University, Ekaterinburg, 620000, Russia
[c] Institute of Problems of Mechanical Engineering, Russian Academy of Sciences, St. Petersburg, 199178, Russia
[d] Department of Mechanics and Control Processes, Peter the Great St. Petersburg Polytechnic University, St. Petersburg, 195251, Russia
[e] ITMO University, St. Petersburg, 197101, Russia

ARTICLE INFO

Article history:
Received 15 September 2016
Accepted 1 November 2016

Keywords:
Dentin
Viscoelasticity
Fraction-exponential operator
Molar
Incisor

ABSTRACT

We propose the fraction-exponential description of the viscoelastic properties of dentin. Creep tests are performed on specimens cut from the molar coronal part. Four parameters determining instantaneous and long term Young's moduli as well as the relaxation time are extracted from the experimental data. The same procedure is repeated using the experimental measurements of Jantarat, Palamara, Linder, and Messer (2002) for the specimens cut from the root part of incisor. Physical meaning of the parameters and the difference between them for different sets of specimens are discussed.

1. Introduction

In the present paper we develop a fraction-exponential model for viscoelastic properties of dentin. Dentin represents the main part of tooth mineralized tissue with a rather complex hierarchical microstructure. The latter can change due to various diseases like caries or sclerosis, or/and due to aging and thus lead to changes in the mechanical performance of dentin. As mentioned by Kinney, Marshall, and Marshall (2003), knowledge of dentin properties is also important for understanding the effects of the wide variety of restorative dental procedures in clinical dentistry: properties of restorative materials should be similar to those of the living tissue.

Chemically, dentin consists of approximately 70 wt.% inorganic material, 18 wt.% organic matrix and 12 wt.% water (Halgaš, Dusza, Kaiferova, Kovacsova, & Markovska, 2013). Mechanical properties of dentin, as of any other material, are governed by its microstructure which has multiscale hierarchical character. It is characterized by the presence of tubules (~1.5 μm in diameter) that run from the dentin-enamel junction towards the pulp. The tubules are surrounded by highly mineralized cylinders of peritubular dentin, roughly 0.5–1 μm in thickness, composed largely of apatite. These tubules are separated by intertubular dentin that consists of a hydrated matrix of type I collagen which is reinforced with a nanocrystallites of carbonated apatite (Brauer, Hilton, Marshall, & Marshall, 2011). The structural and compositional dissimilarities

---

[*] Corresponding author. Fax: +1 575 646 6111.
E-mail address: igor@nmsu.edu (I. Sevostianov).

http://dx.doi.org/10.1016/j.ijengsci.2016.11.005
0020-7225/

between the enamel and dentin induce significant differences in their mechanical behavior (Shahmoradi, Bertassoni, Elfallah, & Swain, 2014). Quantitative understanding of the relationship between microstructure and mechanical properties of human dentin allows identification of the microstructural parameters governing the properties and leads to new methodologies in development of tissue equivalent materials.

To the best of our knowledge, the first systematic experimental study of mechanical properties of dentin under compression was performed by Black (1895) who, in particular, showed that location and orientation of the tubules of the test specimens do not significantly affect the overall properties. This result was later argued in works of Peyton, Mahler, and Hershenov (1952) and Stanford, Paffenbarger, Kumpula, and Sweeney (1958). In the latter work, it was also shown that the dentin demonstrates anisotropic (transversely-isotropic) properties. Viidik (1968) gave a review of the mechanical properties of collagenous tissue (including dentin) and their relation to morphology. Balooch et al. (1998) used an atomic force microscope to measure the mechanical properties of demineralized human dentin under three conditions: in water, in air after desiccation, and in water after rehydration. The experiments showed that contribution of collagen fibers into elastic stiffness of dentin is negligible, although collagen is a significant contributor to dentin strength and toughness. Bo, Quanshui, Qing, and Jiade (2000) studied elastic behavior of dentin and reported results of tensile experiments on the small dentin specimens either parallel or perpendicular to the dentin tubules. The determined effective Young's modulus and Poisson's ratio of dentin matrix were 29.5 GPa and 0.44, respectively. Kinney et al. (2003) provided a detailed review of the experimental results on the mechanical properties of human dentin obtained in the second half of XX century. The authors briefly discussed the composition and microstructure of dentin and then summarized results on its elastic properties, hardness, strength, fracture toughness, and fatigue. Viscoelastic properties were also discussed but not many results were mentioned.

Jantarat, Palamara, Linder, and Messer (2002) studied the creep, stress relaxation and strain rate behavior of human root dentin and showed that the viscoelastic behavior is linear. Pashley et al. (2003) analyzed stress–relaxation curves in tension and came to the opposite conclusion – the dentin matrix exhibits viscoelastic properties, but it is not linearly viscoelastic. Duncanson and Korostoff (1975) used stress relaxation measurements to show that the relaxation modulus of dentin exhibits a linear dependence on the logarithm of time during a period of about four decades and that the distribution of relaxation times is constant to a high degree during this interval for the orientation investigated. Cui, Wang, Zhang, and He (2010) suggested to use a poro-viscoelastic mechanical model to describe dentine with no cracks. The model is able to predict creep strain, stress relaxation and instant elastic response with anisotropic constitutive relation for porous cylindrical composite materials. Zaytsev, Grigoriev, and Panfilov (2012) provided in vitro experimental results on elastic behavior of human dentin under compression including shape, size, and strain rate effects. Halgaš et al. (2013) characterized the hardness, elastic modulus, the load size effect on hardness, load rate effect on deformation and indentation creep of human enamel and dentin using instrumented indentation methods. They showed that the indentation load rate had only a minor influence on the penetration depth/energy loss of enamel. The creep behavior of enamel at applied loads of 10, 50, 100 and 400 mN exhibits a relatively short primary creep region and a pronounced secondary region with a stress exponent of $n = 1.8$.

Recently, Singh, Misra, Parthasarathy, Ye, and Spencer (2015) and Singh (Master thesis, 2009) developed a linear viscoelastic model for collagen–adhesive composite and dentin adhesives and demonstrated the applicability of the model by predicting stress relaxation behavior, frequency-dependent storage and loss moduli, and rate-dependent elastic modulus. Jafarzadeh, Erfan, and Watts (2004) experimentally determined the viscoelastic characteristics of human dentin under the action of a uniaxial static compressive stress and showed that dentin exhibited a linear viscoelastic response under 'clinical' compressive stress levels with a maximum strain ~1% and high recoverability: permanent set $< 0.3\%$. Chuang et al. (2015) proposed a quantitative approach to characterize the viscoelastic properties of dentin after demineralization, and to examine the elastic properties using a nano-indentation creep test. Petrovic, Spasic, and Atanackovic (2008) used Mittag–Leffler function to model viscoelastic properties of dentin given by Jantarat et al. (2002). The analysis provided in the mentioned work, however, is formally mathematical and does not provide any physical guidance regarding the choice of particular values of the model parameters.

To the best of our knowledge the micromechanical model for viscoelastic properties of dentin has never been proposed in literature. This process is complicated by the lack of solid information on mechanical behavior of dentin, in general, and its creep-relaxation behavior, in particular. Generally, the approach to find analytical solution of the homogenization problem for a heterogeneous material with viscoelastic constituents is based on elasticity-viscoelasticity correspondence principle. The problem is formulated in the Fourier or Laplace domain, treated as the elastic one, and then, inverse transform gives the desired viscoelastic solution. The main challenge appearing in this approach is to obtain analytical formulas for the inverse transform. It can be done only in some simplistic cases represented as combinations of dashpots and springs. Unfortunately, these models are not sufficiently flexible to match experimental data for real materials. An alternative approach has been proposed by Scott Blair and Coppen (1939, 1943) (based on experimental observations) and by Rabotnov (1948) (theoretically) (hereafter –SBR model). They suggested to use fraction-exponential operators that, on one hand can describe experimental data of real materials with sufficient accuracy and, on the other hand, allow the inverse Laplace transforms in an explicit analytical form. Detailed description of the approach is given, for example, in the books of Rabotnov (1977) and Gorenflo, Kilbas, Mainardi, and Rogosin (2014). Methodology of application of fraction-exponential operators to heterogeneous materials has been recently developed by Sevostianov and Levin (2016) who introduced creep and relaxation contribution tensors that allow description of the effect of inhomogeneities on the overall viscoelastic properties in a unified way and thus, extend any of known micromechanical schemes from elastic materials to viscoelastic ones. The approach