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DENTAL MATERIALS CHARACTERISATION FROM HERTZIAN CONTACT EXPERIMENTS

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Abstract
Hertzian circular contact between a ball made of dental material and a glass plate is investigated, measuring the contact radius, for quasistatic and static loading. Experimental contact radius was compared to the radius from Hertzian theory. The experimental contact radii were greater than the theoretical ones and hysteresis loop appeared. Under constant normal load, contact radius was slightly increasing in time, and variation with time of the relaxation modulus was traced. Therefore, the material of the balls behaves viscoelastic and contact experiments may be used in determining material properties of viscoelastic materials.

1. INTRODUCTION

Polymers, ceramics and composites are now frequently used in restorative dentistry, trying to fulfil specific requirements of biocompatibility, mechanical properties and aesthetics. The tribological characteristics of these materials used in biomedical applications can be revealed through contact mechanics theory and experiments, [1], [2], [3]. Hertzian contact can model the contact between teeth during mastication. Circular contact between a plane glass and a sphere made of dental material, loaded by a normal force, is used in quasi-static experimental tests aiming the determination of the contact area. For a circular Hertzian contact, loaded by the normal force *Q,* the contact radius has the expression, [1]:

$$a = \sqrt[3]{\frac{3Q\eta}{2k}}, \tag{1}$$

where, in the case of a sphere of *R* radius pressed onto a plane, the reduced curvature of the contact, *k*, takes the form:

$$k = 2/R. \tag{2}$$

The normal approach has the expression:

$$\delta = a^2/R \tag{3}$$

The contact stiffness is expressed by the relation:

$$\eta = \frac{1-\nu_g^2}{E_g} + \frac{1-\nu_{md}^2}{E_{md}}, \tag{4}$$

where ν_g and ν_{md} are the Poisson coefficients for glass and dental material respectively and E_g, E_{md} are the Young moduli for glass and the studied dental material.

Assuming a constant Poisson coefficient for the dental material, and using from theory of elasticity, the relation between elastic moduli and Poisson coefficient, the shear modulus for dental material G_{md} can be written:

$$G_{md} = \frac{1-\nu_{md}}{2\left(a^3\frac{4}{3RQ} - \frac{1-\nu_g^2}{E_g}\right)}. \tag{5}$$

From the above equation, it can be seen that under static loading, measuring the contact radius, the experimental shear modulus of the material can be found, [2].

2. EXPERIMENTAL TEST RIG

The circular contact between a ball, made of dental material and a glass plate, loaded normally, is investigated. The glass plate is thick, having the dimension order the same as the ball radius, so it can be assumed as a rigid half-space. The experimental device, presented in Figures 1 and 2, consists of a mechanical loading assembly, a ball conical hold, a glass plate case, a microscope (vertical adjusting for focusing the image) and a 2D co-ordinate moving table for bringing the contact area in the centre of the image.

During a test, there can be measured the following parameters: the normal force created by the spring (from a micrometer screw displacement); the contact radius, either directly from microscope's reticule on the ocular, Figure 2b, or by interfacing a camera with a computer, stocking the image and afterwards measuring by using images of etalon millimetre of the microscope.

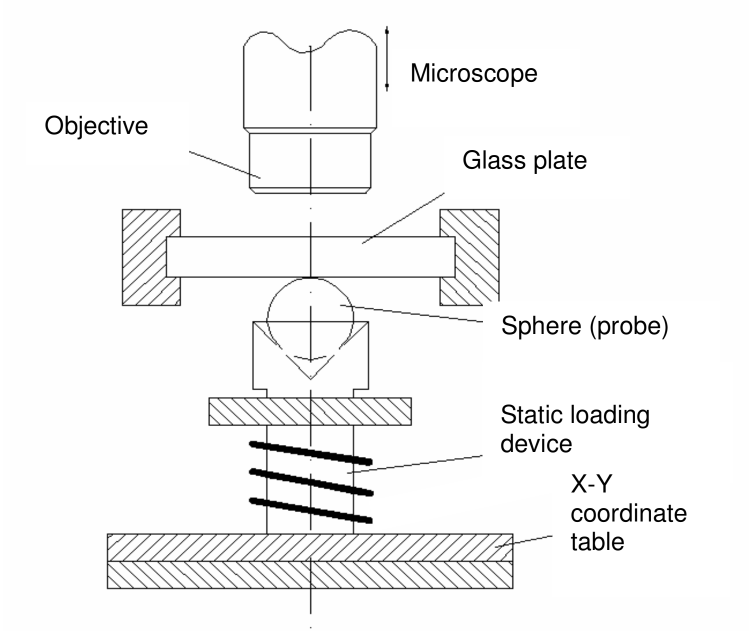

Figure 1. Scheme of experimental equipment

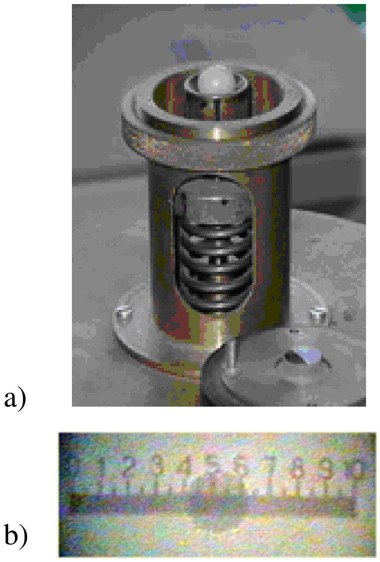

Figure 2. a)Normal loading device
b) Contact image

3. HERTZIAN CONTACT EXPERIMENTS

Experimental results were obtained for balls made of Royal dent. The material was assumed to behave elastically and the Hertzian theory is used in calculus. The shear and Young moduli were, $G_{em} = 8.966 \cdot 10^8$ N/m^2 and $E_{em} = 2.57 \cdot 10^9$ N/m^2 respectively, found from previous work. The Poisson coefficient, computed from theory of elasticity with the experimental values of G and E is $\nu = 0.394$. The mechanic characteristics of the glass plate are $\nu_g = 0.22$, $E_g = 6.35 \cdot 10^{10}$ Pa.

Two balls of dental material were loaded normally against the glass plate, and the contact radius was registered, for different loads. Figures 3 and 5 show the variation of the contact radius for increasing quasistatic load, decreasing load and theoretical curve, computed with relation (1). Cube of radius was plotted, since the Hertzian theory shows that the cube of the contact radius depends on the normal load, relation (1), so a linear relation is expected. Figures 4 and 6, present the cube of contact radius – experimental data approximated by numerically deduced curve and the theoretical results.

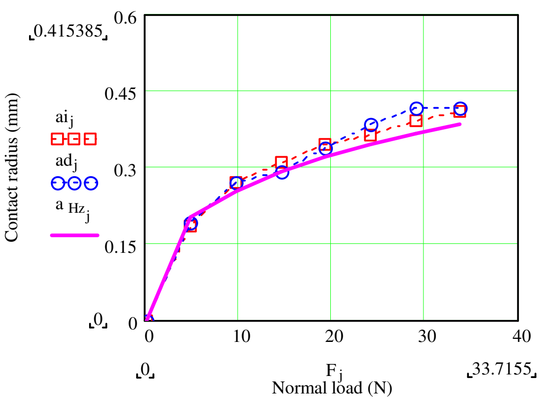

Figure 3. Variation of contact radius: ai - for increasing force; ad - decreasing force; a_{Hz}-according to Hertzian theory

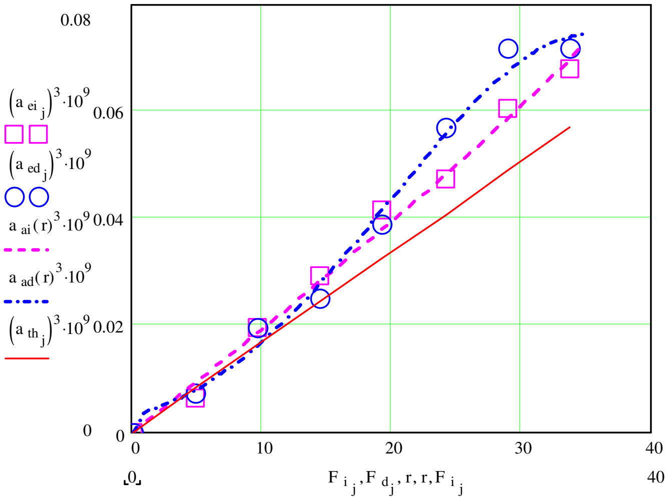

Figure 4. Numerical approximation of experimental data compared to theoretical estimation. Ball radius:R=12.7 mm

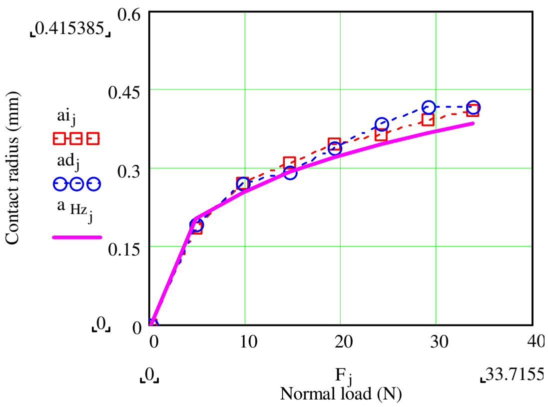

Figure 5. Variation of contact radius: ai - increasing force; ad - decreasing force; a_{Hz}-according to Hertzian theory

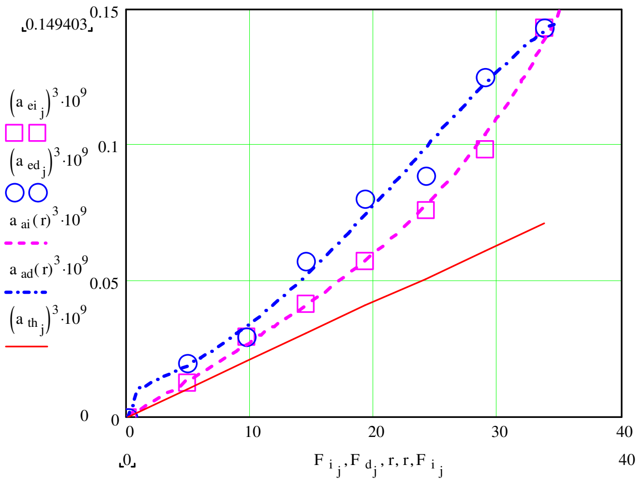

Figure 6. Experimental data for contact radius compared to theoretical estimation (Hertz theory). Ball radius:R=15.875mm

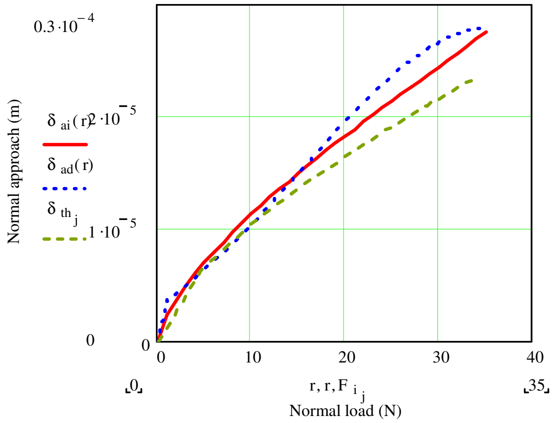

Figure 7. Normal approach versus load, R=12.7 mm; CH=4.63%

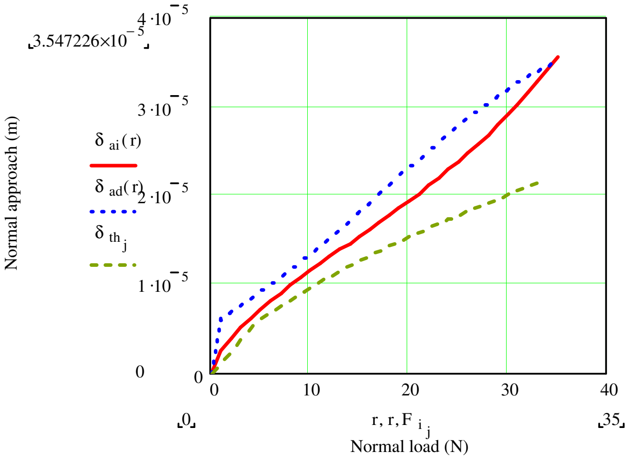

Figure 8. Normal approach versus load, R=15.875 mm; CH=14%

Hysteretic effects are revealed, since for all the performed test made for quasistatic increasing and decreasing loading, a difference was observed for the values of contact radius, showing greater values when unloading. This suggests either viscoelastic behaviour of the material or adhesion hysteresis. Computing the normal approach from contact radius with relation (3), the curves for normal approach versus force were traced and hysteresis loops were illustrated, as seen from Figures 7 and 8. The hysteresis coefficient CH was estimated.

Static test were also carried out under constant normal load and, as shown in Figure 9, the contact radius was slightly increasing in time, so variation with time of the relaxation modulus was therefore traced, Figure 10, using relation (5). The dependence of mechanical characteristics of time is typical for viscoelastic material, so, added to the hysteresis loops previously observed, it can be concluded that the material of the balls behaves viscoelastic rather than elastic, as initially was assumed.

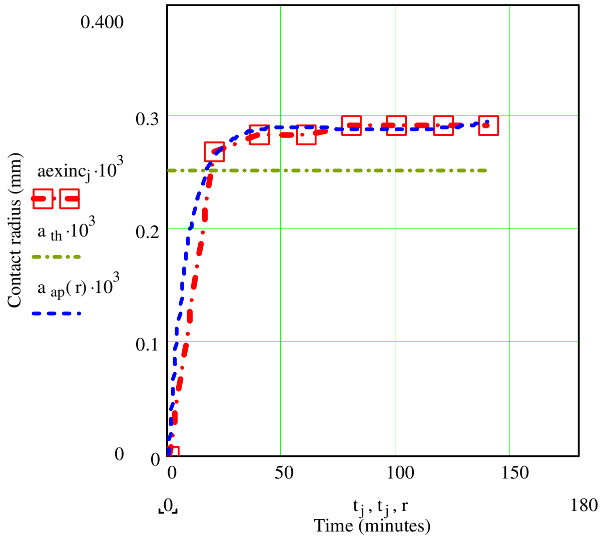

Figure 9. Variation of contact radius (a_{exinc}-experimental, a_{th} - theoretical Hertzian and a_{ap} - approximated curve) for constant normal load, R=12.7 mm

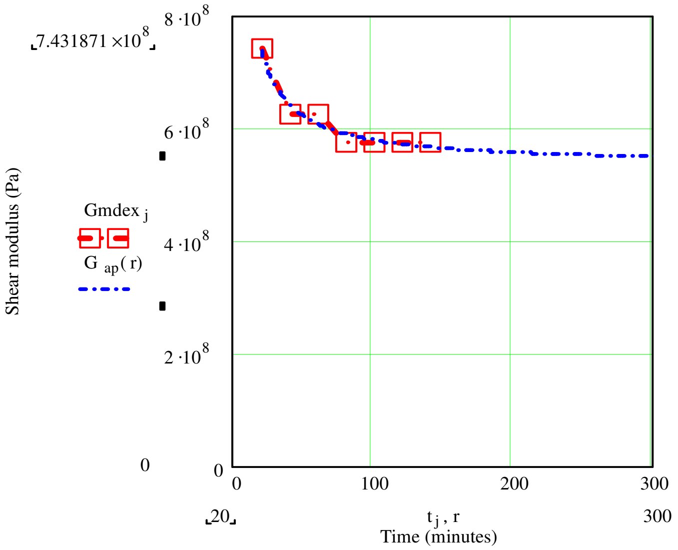

Figure 10. Variation of shear modulus, from contact tests: G_{mdex}-experimental data, and G_{ap}-approximated trace

Simple viscoelastic models can be considered in polymer description, [5]. For a Maxwell model, consisting from a spring in series with a dashpot, the relaxation modulus has the expression, [4]:

$$\psi_M(t) = G_0 \exp\left(-\frac{t}{\tau_M}\right) \tag{6}$$

where G_0 represents the instantaneous modulus. With $G_0 = G_{em}$ (found from previous tests), it can be seen that there is no concord between experimental data and the Maxwell model, Figure 11.

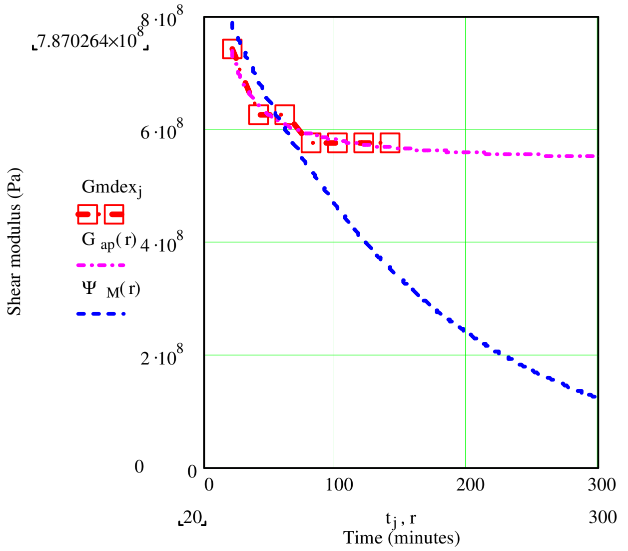

Figure 11. Experimental relaxation modulus (G_{mdex}), numerically approximated trace (G_{ap}) and relaxation modulus for a Maxwell model, (Ψ_M)

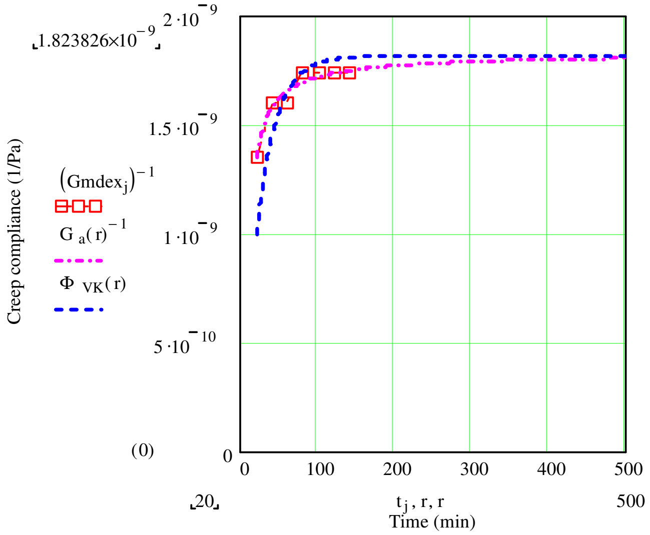

Figure 12. Compliance from experimental modulus and creep compliance for a Voigt-Kelvin model

The second mechanical model considered, known as approximating viscoelastic polymers, is the Voigt-Kelvin model, containing a spring in parallel with a dashpot, [5]. The creep function for Voigt-Kelvin model is expressed by the relation, [4]:

$$\Phi_{VK}(t) = \frac{1}{G_\infty}\left(1 - \exp\left(-\frac{t}{\tau_V}\right)\right) \tag{7}$$

where the equilibrium shear modulus is $G_\infty = 5.5 \cdot 10^8$ Pa, as determined from experimental tests. Figure 12 shows a good agreement between theoretical curve of the creep function and the experimental data, therefore we can conclude that for the tested dental material, a Voigt-Kelvin model is a good approximation.

4. CONCLUSIONS

Using a test rig designed for static normal loading of a Hertzian contact, the contact between a sphere made of dental material and a glass plate was investigated. The contact radius was visualised and measured using a microscope.

Two types of test were carried out: quasistatic loading and unloading, and static loading. First, the elastic behaviour of the material was assumed and the experimental contact radii were compared to the values computed from Hertzian theory. The experimental contact radii were greater than the theoretical ones. A slight difference between loading and unloading was also observed, the unloading radius being retarded from the loading one. Therefore, a hysteresis curve appeared, for both dimensions of balls.

From tests made under constant normal load, another feature occurred: contact radius was slightly increasing in time, so variation with time of the relaxation modulus was therefore traced. This is characteristic for viscoelastic material, so, added to the hysteresis loops previously observed, it can be concluded that the material of the balls behaves viscoelastic rather than elastic, as initially was assumed.

From experimental data, attempts to model the dental material with simple models were made. The Maxwell model did not suit the experimental relaxation modulus but the creep function of Voigt-Kelvin model was in good agreement with experimental tests. Accordingly, contact experiments may be used in determining material properties of viscoelastic materials.

There are advantages when using circular Herztian contact testing as an alternative to standard uniaxial tests in order to determine the properties of a viscoelastic material. Using small samples of material, the material properties can be determined. When prescribing constant normal applied load, from variation of contact radius, the creep function of the material can be found.

Further tests can be made concerning dynamic loading, as radial fretting often occurs in real dental contacts during mastication, and the equipment used for the present work is appropriate for such investigations.

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