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The relationship between Shore hardness of elastomeric dental materials and Young's modulus

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ABSTRACT

Objectives. Hardness of elastomers can be directly related to Young's modulus, a relationship that was investigated in detail by Gent in a paper in 1958. The aim of this study was to test this relationship for 13 dental elastomers (12 silicone and 1 polyether) using the equation derived by Gent and one from BS 903 (1950) that accounts for departures at low values.
Methods. The dental elastomers were subjected to tensile testing and Shore A scale hardness measurements. Young's moduli were calculated from the hardness values using the Gent equation and the BS 903 equation. These calculated values were then compared with values derived experimentally from the tensile tests.
Results. Hardness values were in the range 30.2 (±0.5)–62.9 (±0.8) with the corresponding calculated modulus values in the range 1.1–4.1 MPa and 0.9–4.3 MPa for the Gent and modified equations, respectively. Young's modulus values derived from the tensile data were in the range 0.8 (±0.3)–4.1 (±0.3) MPa, showing good agreement with those calculated from the hardness values. Providing viscoelastic creep is minimal during the duration of the test, there is a reasonably well-defined relationship between Shore hardness and Young's modulus in the hardness range studied.
Significance. Simple, non-destructive hardness measurements can be used to determine Young's modulus values. Such values are needed in any calculations of stress distributions in soft lining materials, e.g. by FEA.

1. Introduction

Hardness measurements offer a rapid and easily performed method of testing solids, and have their origins in the testing of metals. Such tests are convenient for quality control and specification purposes, as for example in the various grades of gold alloys [1]. Hardness measurements abound in the literature on composite filling materials [2–4].

A variety of tests are available [5] (Knoop, Brinell, Rockwell, Barcol), defined by the geometry and dimensions of the indenter, and the load applied. In the case of metals, and other solids such as glassy polymers, composites, and calcified tissues, the indenter on application of a load produces a permanent indentation, and the hardness number is usually the load per unit surface area of the indentation. The underlying physics of such indentation measurements was described in detail by Tabor [6], where it was shown that hardness is related to yield stress in compression. This relationship has also been shown to apply to dental amalgam, and dentine [7,8].

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Hardness testing is also carried out on elastomeric materials, for example the Shore hardness and ISO tests. Again, it is a convenient quality control, easily and rapidly carried out. Some manufacturers of impression materials use it to characterize the stiffness of set impression materials. However, the character of what is being measured is completely different to the tests described above. The indentation in the case of elastomers is predominantly elastic in nature, i.e. is recoverable. Depending on the type of test, the indenter is either flat-ended (Shore), or spherical (ISO). For a flat-ended indenter, the appropriate equation is [9]:

$$F = \frac{2aEw}{1-\nu^2} \tag{1}$$

where F = force, a = the radius of the indenter, E = Young's modulus, w = the depth of indentation, and ν = Poisson's ratio.

This, and the succeeding equations derived from it are for a semi-infinite solid. In practice this means the dimensions of an actual test piece need to be sufficient that the stress field caused by the indentation has sensibly decayed to zero at the bounding surfaces.

Since elastomers are sensibly incompressible [10], $\nu = 0.5$, and Eq. (1) becomes:

$$F = \frac{8}{3aEw} \tag{2}$$

In the case of a sphere the corresponding equation is [7]:

$$F = \frac{4Ea^{1/2}w^{3/2}}{3(1-\nu^2)} \tag{3}$$

and with $\nu = 0.5$ for rubber-like material [11], becomes:

$$F = \frac{9}{16Eaw^{3/2}} \tag{4}$$

Eqs. (1) and (3) were originally derived by Hertz [12].

In both cases, the degree of indentation (w) against a constant force (F) is a direct function of E. Hence *a priori*, there should be a direct relationship between Shore or ISO hardness and Young's modulus (E), and indeed Shear (rigidity) modulus (G), as for elastomers at small strains $E = 3G$.

The relationship between Shore and ISO hardness and Young's modulus was investigated in detail by Gent [13], who derived the following semi-empirical equation:

$$E(\mathrm{MPa}) = \frac{0.0981(56 + 7.66s)}{0.137505(254 - 2.54s)} \tag{5}$$

where s = the Shore hardness.

Ideally, the hardness scale should convert a modulus range of 0–∞ to a hardness scale of 0–100. Clearly Eq. (5) fulfills this for $s = 100$ but not for $s = 0$, and there are small departures from the master curve at s values below 40 given in Gent's paper, based on BS 903(1950). Eq. (6), [14] however, does meet the above criterion:

$$H = 100\,\mathrm{erf}(kE^{1/2}) \tag{6}$$

where $k = 3.186 \times 10^{-4}\ \mathrm{Pa}^{-1/2}$.

In this study, both of these two equations have been tested for a range of dental silicone elastomers and one polyether impression material.

2. Materials and methods

The dental elastomers included in the study are listed in Table 1 all of which cure at room temperature and all the silicones included are addition cure. The polyether used was Impregum PS (3M ESPE).

2.1. *Sample preparation*

All specimens were prepared using the following procedure. Sheets of materials (2 mm thick for tensile testing and 6.5 mm thick for hardness testing) were prepared in metal moulds lined with acetate sheets. The materials were all mixed/dispensed according to the manufacturers' instructions. Material was packed into the appropriate metal mould which was placed in a hand-operated hydraulic press (Quayle Dental, Sussex, UK) under 100 bar pressure. The sample was then left for at least 2 h to ensure complete cure.

Table 1 – Materials.

Material	Manufacturer	Application
Tokuyama soft	Tokuyama Corp., Tokyo, Japan	Soft lining material
Tokuyama medium soft	Tokuyama Corp., Tokyo, Japan	Soft lining material
GC soft	GC Corp., Tokyo, Japan	Soft lining material
GC extra soft	GC Corp., Tokyo, Japan	Soft lining material
Odontosil	Dreve-Dentamid Gmbh, Germany	Orthodontics
Episil-E	Dreve-Dentamid Gmbh, Germany	Maxillo facial
Epiform flex	Dreve-Dentamid Gmbh, Germany	Maxillo facial
Zerosil soft	Dreve-Dentamid Gmbh, Germany	Impression material
Zerosil super soft	Dreve-Dentamid Gmbh, Germany	Impression material
Zerosil light	Dreve-Dentamid Gmbh, Germany	Impression material
Zerosil mono	Dreve-Dentamid Gmbh, Germany	Impression material
Extrude	Kerr Corp., Michigan, USA	Impression material
Impregum PS	3M ESPE, Loughborough, UK	Impression material