Model for Thickness Effect with Impact Testing of Viscoelastic Materials

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ABSTRACT: Thickness effect on impact parameters is studied and a model is developed for flat-ended drop weight impact testing of viscoelastic materials. The model represents a relationship of specimen thickness with impact force/stress and impact energy. A polymeric material, ethylene vinyl acetate (EVA), was used for experimental verification. Experimental results for a thickness range of 1–9 mm at impact energy levels of 0.42, 0.96, and 1.54 J have been found to be in reasonable agreement with predictions based on the model with some approximated parameters. © 2001 John Wiley & Sons, Inc. J Appl Polym Sci 81: 1762–1767, 2001

Key words: impact; viscoelasticity; thickness; protection; mouthguard

INTRODUCTION

Applications of protective materials may include mouthguards,[1] knee pads, a cushion for the football goalpost, helmets, bullet proof vests, car bumpers, and other gear. The means of protection depends on material properties, material geometry, and its applications. When one object collides with another, two stages of protection in the level of energy are involved. The first stage involves transformation between kinetic energy and strain energy. The second stage involves transformation that creates damage such as permanent deformation, cracks, delamination, and holes. There are various applications of these protection stages. Some materials, such as those for mouthguards, are used mainly for the first stage protection. Other materials, such as those for car bumpers, are used for protection, including the second stage.[2–5] This article is concerned with the first stage, rather than the second stage, and therefore one of typical materials for mouthguards was selected as a model material for the present study.

Polymers are major materials being used for the mouthguards. Mechanical properties of polymers are time dependent because of their viscoelasticity, causing the size effect of specimen.[6–8] Such time-dependent properties make polymers difficult not only in predicting their behavior but also in establishing compatibility of test results, other unless the tests are conducted under the same conditions. For the size effect, specimen diameter and specimen thickness have been considered by some researchers for disk-shaped specimens. Recently, Kim and Stojcevski[6,8] modeled the diameter variation in relation to impact energy and impact force/stress. Park et al.[9] investigated empirically the thickness effect on impact force/stress using a ball drop test.

This article focuses on specimens of circular plate and flat-ended impactor to produce uniform strain and to minimize complex stress distribution. The main purpose of this article is to rationalize the relationship of viscoelastic materials

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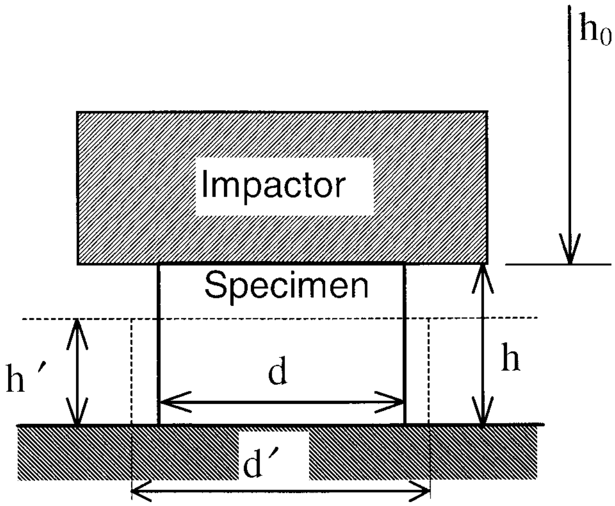

Figure 1 Impact specimen deformation underneath a flat-ended impactor.

among impact force, impact energy, and specimen thickness.

DEVELOPMENT OF A MODEL FOR A RELATIONSHIP OF THICKNESS WITH IMPACT FORCE/STRESS AND IMPACT ENERGY

A similar approach to that used for diameter effect[6,8] may be employed. When a flat-ended impactor collides with a specimen, the specimen shape changes from diameter d to d' and from thickness h to h', to store the applied impact energy as shown in Figure 1. The magnitude of deformation depends on the size of specimen. For instance, the magnitude of deformation of a specimen of large thickness is greater than that of small thickness.

The compressive elastic modulus (E_c) for viscoelastic materials is a function of strain rate[10]:

$$E_c = f(d\varepsilon/dt) \tag{1}$$

where ϵ is the strain and t is the time.

The strain based on the volume constancy for the specimen is given by

$$\varepsilon = \ln(e+1) = \ln\left(\frac{-\Delta h}{h}+1\right) = \ln\frac{h'}{h} \tag{2}$$

where e is the nominal strain and $\Delta h = |\, h\text{-}h' \,|$ so that

$$\varepsilon = f(h) \tag{3}$$

for a given diameter.

The velocity of the impactor from the moment of collision with the specimen would depend on the specimen thickness when $h_0 \gg h$, where h_0 is the impactor drop height. It is assumed that the average contact time of the impactor with the specimen up to the maximum peak force is proportional to the thickness of specimen. Thus,

$$t = Ah \tag{4}$$

where A is a constant.

Accordingly, equation (1) becomes

$$E_c = f(h) \tag{5}$$

The time-dependent elastic modulus for polymers is often based on an empirical power equation because of their theoretical complexity[8,11–13] and practicality:

$$E_c = E_0' t^{-n'} \tag{6}$$

where E_0' *is a constant and* $-n' = \dfrac{d(\ln E_c)}{d(\ln t)}$

Substituting equation (4) into equation (6) yields

$$E_c = E_0 h^{-n'} \tag{7}$$

where E_0 is a constant and $-n' = \dfrac{d(\ln E_c)}{d(\ln h)}$

For a circular plate, impact force according to the energy conservation principle is given by[14]:

$$F = d\sqrt{\frac{\pi E_c \Lambda}{2h}} \tag{8}$$

where d is the diameter, F is the impact force, and Λ is the elastic strain energy ($\approx$ impact energy). Combining equations (7) and (8) yields

$$F = h^n c\sqrt{\Lambda} \tag{9}$$

and

$$\sigma = h^n c'\sqrt{\Lambda} \tag{10}$$

where $n = \frac{-(n' + 1)}{2}$, σ is the stress and (c', c) are constants.

EXPERIMENTAL

Materials

The material used for the test is ethylene vinyl acetate (EVA) copolymer in a sheet form, with a nominal thickness of 4 mm, supplied by a commercial mouthguard manufacturer. The material was analyzed using nuclear magnetic resonance (NMR) spectra. It was found to consist of 26% vinyl acetate.

Test Sample Preparation

Circular test specimens of various diameters were punched out of EVA sheets of ≤4-mm thickness of, received from the manufacturer. The thickness of test specimens of > 4 mm or <4 mm was controlled using the heat of boiling water. To produce specimens of >4-mm thickness, two individual specimens with the same diameters were laminated by pressing for about 1 min in boiling water. The laminated specimens were left in the boiling water for another three minutes for visual inspection to ensure that there was no delamination and that no water was trapped. To produce specimens of <4-mm thickness, each specimen was pressed between two platens to a desired thickness after being heated up in the boiling water and was repunched to control the diameter. The samples were conditioned before testing by leaving them wrapped in paper towels in a dry environment at about 23°C for several days.

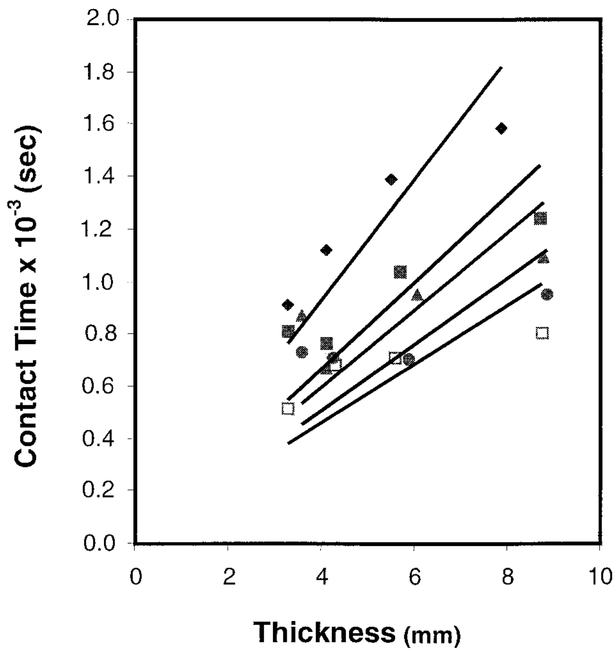

Figure 3 Contact time to peak force as a function of thickness at a constant impact energy of 1.54 J, but various specimen diameters (mm): ◆, 6.0–6.3; ■, 9.1–9.5; ▲, 12.5–12.9; ●, 15.3–15.9; and □, 17.2–19.0. Solid lines represent the best fit to data with forced intercepts at zero.

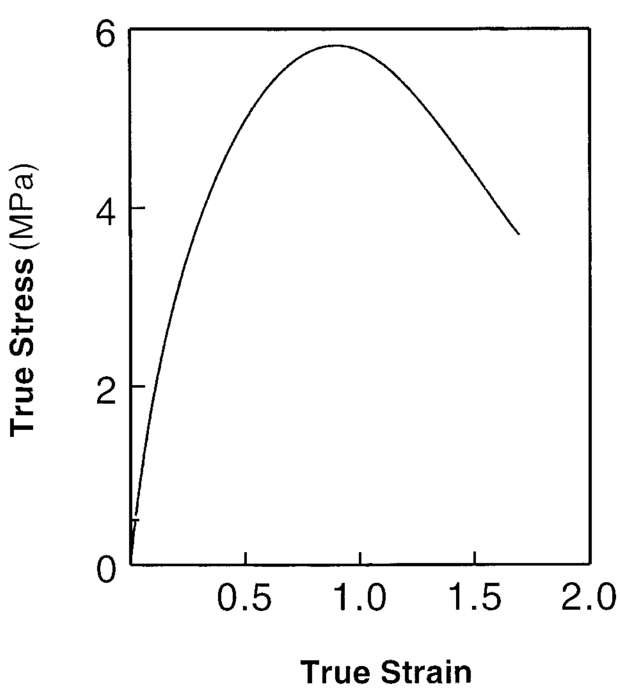

Figure 2 True stress–strain curve of ethylene vinyl acetate (EVA) of a specimen of 8-mm diameter and 4-mm thickness.

Mechanical Testing

As part of the characterization, a compression test for a specimen with 4 mm thick and 8 mm in diameter was conducted on a universal testing machine (Shimadzu DSS 5000) at a cross-head speed of 5 mm/min and 23°C. Shell Retinax A was used for lubrication between specimen and compression platen. The true stress strain curve shown in Figure 2 was obtained using the instantaneous contact area between specimen and platen, calculated on the basis of volume constancy of the specimen assuming noncompressibility because the cylindrical surface of the specimen is not restrained and its compressibility may be reduced.

A hardness test was conducted in accordance with ASTM D2240-91 at 20°C, using a model 409 Durometer Type D. The average value obtained was 33 ± 0.5. The time duration for firm contact was 1 s for all tests.

Drop-Weight Impact Test

The impact test set-up consisted of a flat-ended impactor, an electromagnet for the impactor release mechanism, a load cell with a capacity of 10 kN and a computer with software for data logging (Wave View for DOS, Eagle Appliance Pty Ltd). Two sets of drop-weight impact tests were conducted for thickness effect : the first one was at 21–22°C for a constant impact energy of 1.54 J, but for various specimen diameters; the second one was at 23°C for a constant diameter of ~12.5 mm, but for various impact energy levels. Times to reach the peak force were measured with a resolution of 4E-05 second. Deformation of specimens was mostly elastic but in a few of them was plastic, undergone up to 5% thickness change at the highest energy level of 1.54 J.

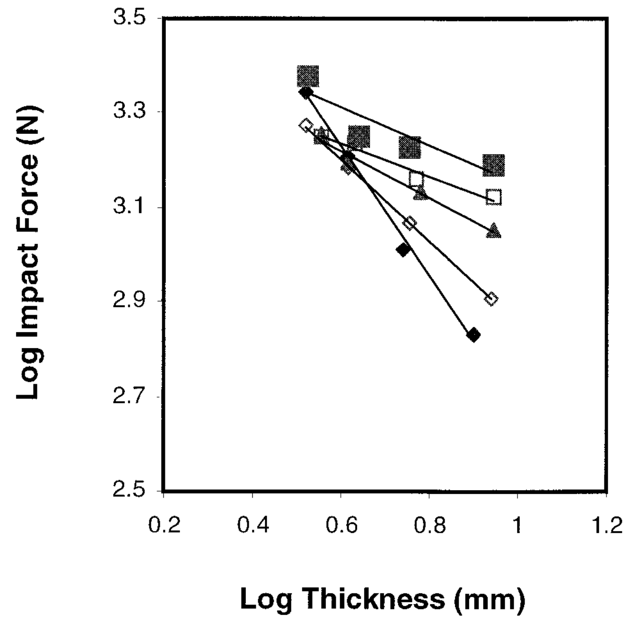

Figure 5 Log impact force as a function of log specimen thickness at various specimen diameters. Symbols for specimen diameters (mm): ◆, 6.0–6.3; ◇, 9.1–9.5; ▲, 12.5–12.9; □, 15.3–15.9; and ■, 17.2–19.0.

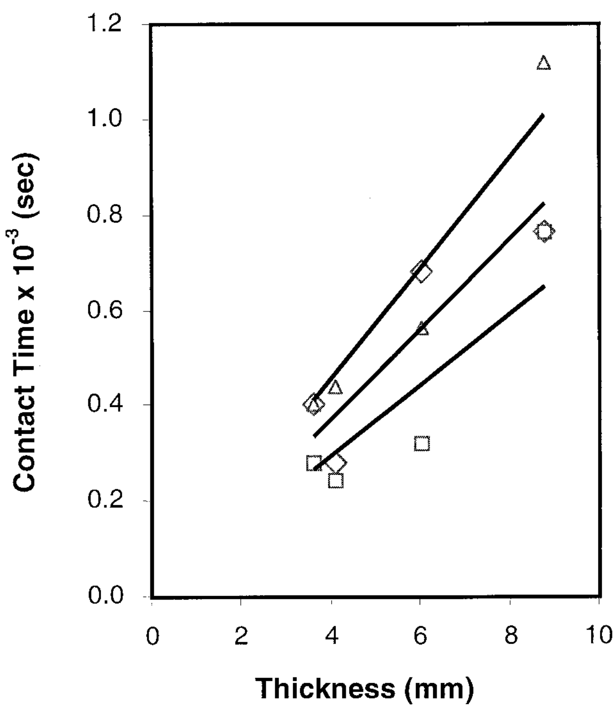

Figure 4 Contact time to peak force as a function of thickness at a constant specimen diameter of ~12.5, but different impact energy levels: △, 1.54 J; ◇, 0.96 J; and □ 0.42 J. Solid lines represent the best fit to data with forced intercepts at zero.

RESULTS AND DISCUSSION

For verification of the assumption made in equation (4), the contact time to peak impact force for contact period between impactor and specimen was measured and are shown in Figure 3 for various specimen diameters ranging from 6 to 19

Table I Constants in $F = h^n c\sqrt{\Lambda}$ at an Impact Energy of 1.54 J for Various Diameters Used in Figure 5

Data	Diameter (mm)	Correlation Coefficient	n	Log c
1	6.0–6.3	−0.9971	−1.37	4.055
2	9.1–9.5	−0.9996	−0.86	3.725
3	12.5–12.9	−0.9856	−0.49	3.518
4	15.3–15.9	−0.9803	−0.35	3.454
5	17.2–19.0	−0.8834	−0.40	3.556

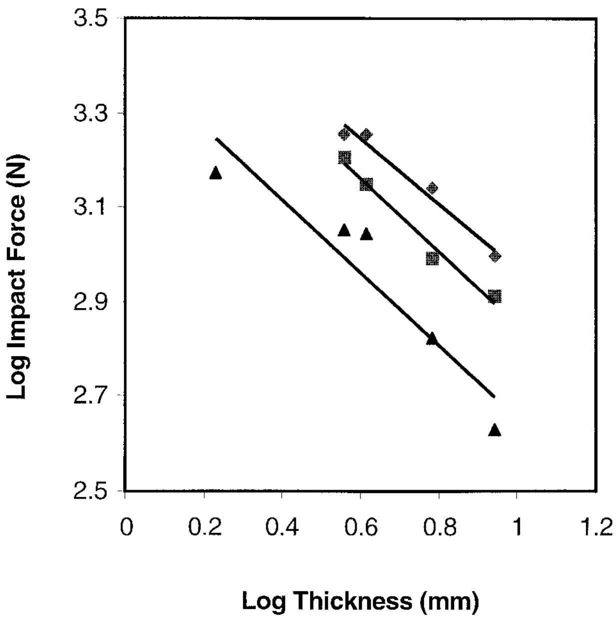

Figure 6 Log force as a function of log specimen thickness at various impact energy levels for a specimen diameter of ~12.5 mm: ◆, 1.54 J; ■, 0.96 J; and ▲, 0.42 J. Solid lines represent least-square lines and dashed lines predictions by equation (9).

mm. The specimen diameters are given in ranges because of difficulty in obtaining exact dimensions. Solids lines represent the best fit to data with forced intercepts at zero. However, the data have a tendency to cross over the best-fit lines. Nonetheless, for the purpose of approximation, it may be reasonable to regard the contact time as being proportional to thickness for various diameters. Also, a trend is seen such that the slope decreases with increasing diameter. Further, the time to peak impact force was measured as a function of thickness at different impact energy levels as shown in Figure 4. It is again seen that the data tend to cross over the best fit lines of forced intercepts at zero, slopes of which were found to be 1×10^{-5}, 0.9×10^{-5}, and 0.7×10^{-5} for impact energy levels of 1.54, 0.96, and 0.42 J, respectively. Also, the effect of impact energy variation on the contact time appears to be significant—the contact time increases with increasing impact energy.

Figure 5 shows impact force measured as a function specimen thickness for various specimen diameters ranging from 6 to 19 mm at an impact energy of 1.54 J. The impact force appears to decrease with increasing thickness and with decreasing diameter. As listed in Table I, high values of correlation coefficients were obtained particularly for small diameters, supporting the validity of equation (9) for diameters between 6 and 16 mm.

Figure 6 shows the impact force measured, in comparison with predictions made by equation (9), as a function of specimen thickness at various impact energy levels (0.42–1.54 J) for an approximately constant diameter of ~12.5 mm. The solid lines represent predictions. The agreement between measurements and predictions appears to be good at 1.54 and 0.96 J, but not particularly at 0.42 J. Correlation coefficient for each energy level and other values of parameters are given in Table II. Also, corresponding impact stress, in comparison with predictions from equation (10), is given in Figure 7 as a function of specimen thickness at various impact energy levels. Similar levels of agreement with those shown in Figure 6 between measurements and predictions are seen. In general, it is possible that some poor predictions are due mainly to the weak proportionality between the contact time and specimen thickness.

CONCLUSIONS

A model has been developed for thickness effect of specimen on impact force/stress for various impact energy levels. Experimental results have been found to be in reasonable agreement with

Table II Constants in $F = h^n c\sqrt{\Lambda}$ and $\sigma = h^n c'\sqrt{\Lambda}$ at a Diameter of > 12.5

Data	Impact Energy (J)	Correlation Coefficient With Force	Correlation Coefficient With Stress	n	Log c	Log c'
1	0.42	−0.942	−0.947	−0.765	3.711	1.616
2	0.96	−0.990	−0.987	−0.764	3.727	1.630
3	1.54	−0.985	−0.989	−0.688	3.664	1.567

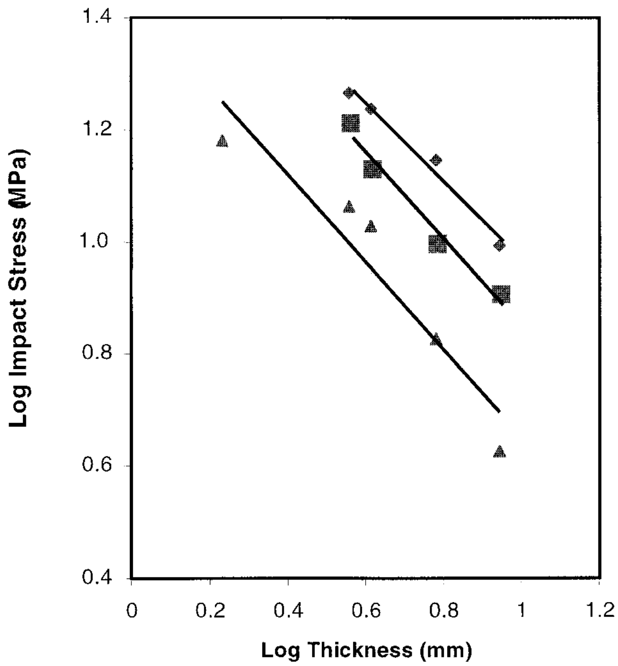

Figure 7 Log impact stress as a function of log specimen thickness at various impact energy levels for a specimen diameter of ~12.5 mm: ◆, 1.54 J; ■, 0.96 J; and ▲, 0.42 J. Solid lines represent least-square lines, and dotted lines predictions by equation (10).

predictions based on the model with an approximated proportionality between the contact time and specimen thickness.

REFERENCES

1. Kim, H. S.; Mathieu, K. J Mater Sci: Mater Med 1998, 9, 457.
2. Cantwell, W. J.; Morton, J. Composites 1991, 22, 347.
3. Abbot, T. A. Presented at the 38th International SAMPE Symposium, May 10–13, 1993; p 2083.
4. Richrdson, M. O. W.; Wisheart, M. J. Composites Part A, 1996, 27A, 1123.
5. Yuan, Q.; Kerth, S.; Karger-Kocsis, J.; Friedrich, K. J Mater Sci Lett 1997, 16, 1793.
6. Kim, H. S.; Stojcevski, S. Presented at the 56th Annual Technical Conference of the Society of Plastics Engineers, ANTEC 1998, April 26–May 1, 1998, Atlanta, GA; Vol 3, Part 3, p 2738.
7. Kim, H. S. Presented at the CD Proceedings of ICTACEM98, International Conference on Theoretical, Applied, Computational and Experimental Mechanics, December 1–5, 1998; Indian Institute of Technology: Kharagpur, India; paper no J07.
8. Kim, H. S.; Stojcevski, S. J. Reinforced Plast Composites 1999, 18, 539.
9. Park, J. B.; Shaull, K. L.; Overton, B.; Donly, K. J., J Prosthet Dent 1994, 72, 373.
10. Dieter, G. E. Mechanical Metallurgy; McGraw-Hill: New York, 1976; p 350.
11. Nutting, P. G. Proc Am Soc Test Mater 1921, 21, 1162.
12. Kim, H. S.; Wang, X. M. J Mater Sci 1994, 29, 3209.
13. Van Krevelen, D. W. Properties of Polymers; Elsevier: Amsterdam, 1990; p 394.
14. Beer, F. P. Mechanics of Materials; McGraw-Hill: Toronto, 1985; p 492.