A Bouncemeter for Measuring Resilience

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ABSTRACT: A device has been constructed which gives a convenient and reproducible measure of the resilience of elastic materials including thermoplastic elastomers as well as conventional crosslinked rubber. A steel ball strikes the surface of the firmly anchored sample at an angle of 45°. The horizontal distance traveled (the bounce distance), is recorded by having the ball make a mark in a shallow bed of fine gravel. In the common Lüpke and Bashore devices, the rebound of a metal element usually is estimated while the element is still in motion. It is shown that the bounce distance B is proportional to the square root of the Bashore or Lüpke rebound. All resilience tests are sensitive to the thickness of the sample used. However, tests with various rubbers and thermoplastic elastomers confirm that the square root relationship holds reasonably well for samples that are 1.27 cm thick over the range of 10 to 85% Bashore rebound. © 1997 John Wiley & Sons, Inc. J Appl Polym Sci **66:** 1787–1793, 1997

Key words: resilience; rebound; bouncemeter; Bashore; Lüpke

INTRODUCTION

The elastic properties of a polymeric material can be quantified in a variety of ways. Among the most familiar are

1. Conventional stress–strain measurements. For example, the ordinary tensile stress–strain curve can be carried to a point below failure and returned to zero stress. The area between the curves obtained on stretching and returning is the *hysteresis,* usually expressed as a percentage of the energy input during stretching.
2. Sinusoidal oscillations. When continuous forced oscillations (dynamic mechanical testing) of stress or strain are imposed on a sample in various geometries, the hysteresis in each cycle is additive and results in heat buildup. The phase angle between the stress and the strain also is a measure of hysteresis varying from zero for a purely elastic material to 90° for a purely viscous material. The inertial terms must be accounted for also. On the other hand, when a single input of energy is imposed and allowed to dissipate in, say a torsion pendulum, the energy lost per cycle is the *damping,* often expressed as the natural logarithm of successive strain amplitudes, A_a and A_{a+1}, that is,

$$\Delta = \text{log decrement} = \ln(A_a/A_{a+1}) \quad (1)$$

3. Tests which measure the ratio of returned energy to input energy for a single deformation. Rebound tests are simple, often inexpensive, and are useful for comparing materials, particularly rubbers and thermoplastic elastomers. The fraction of the vertical distance recovered after a rod or plunger has impacted a specimen is the *resilience* or *rebound.* It is in this last category that a new device is proposed which has several advantages over such widely used rebound tests as the Lüpke,[1] Bashore,[2] and Yerzley[3] tests.

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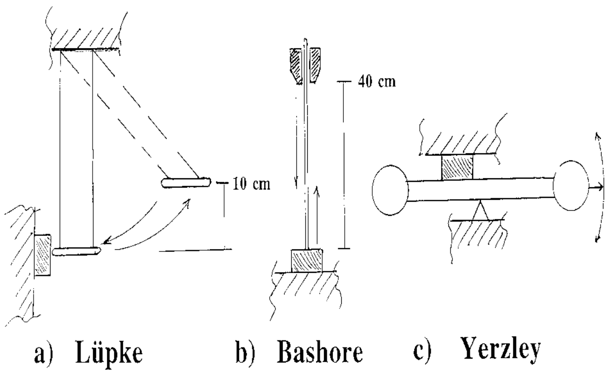

Figure 1 Standard resilience measuring devices, (a) Lüpke, (b) Bashore, and (c) Yerzley.

In the Lüpke test [Fig. 1(a)], a metal rod (350 g) suspended by four threads strikes a thick, vertically held rubber sample. The fraction of the vertical distance (initially 10 cm) recovered is measured, usually after some conditioning of the sample. The long horizontal path ($\sim$ 100 cm) taken by the rod amplifies the reading. A major drawback is the necessity of judging the rebound distance accurately by direct visual observation. Of course, a video camcorder can be used to get around this inconvenience, but the time and expense would be added.

Kluckow[4] lists a number of other pendulum tests, mostly based on commercially manufactured devices. As might be expected, workers in various countries have often developed their own variations. The Schob (Germany), Dunlop (Britain), and Goodyear–Healey (USA) machines all bear a superficial resemblance to each other. Scott[5] has described the use of a Tripsometer[6] which imparts much less energy to the sample than the Schob or the Lüpke. In each case, a rigid pendulum arm (or an off-center mass in the case of the Tripsometer) strikes a vertically mounted specimen and the rebound height is measured. The Lüpke has some advantages over these in that it is almost free of friction and it is quite inexpensive to build. A Lüpke device was constructed for the present work.

Adjusting the Lüpke indenter rod to give a perfectly perpendicular approach to the sample surface can be annoyingly time-consuming. The nylon fish lines used to suspend the rod were made adjustable in length by connecting the ends to a guitar peg board through a suitable arrangement of pulleys. Bell[7] has described the automation of both the Lüpke and Tripsometer devices.

In the Bashore test [Fig. 1(b)], a guided plunger (weighing $\sim$ 28 g) is dropped from a height of 40 cm onto a horizontal sample and the vertical rebound is measured. Possible friction between plunger and guide rod, especially during rebound, is a concern. For purposes of the present work, it was possible to construct a test device using the dimensions given in the ASTM procedure. It was found that reproducible results could be obtained after careful attention to sample clamping and centering. As with the Lüpke test, judging the actual rebound height by direct observation is difficult.

The Yerzley test [Fig. 1(c)] differs from the Lüpke and Bashore in several ways. The entire sample is in compression rather than being struck with an indenter. Also, the classical model uses a recording method which introduces substantial friction. However, the test can be used to establish the compressive modulus of a sample along with the resilience. The fact that the test mimics closely the action of an engine mounting unit has made it popular for tests of polychloroprene and butyl rubber compounds used in automotive applications. The sample thickness is not usually varied.

THE BOUNCEMETER

Kluckow[4] refers to older tests in which a steel ball is dropped vertically onto a rubber sample. The rebound height can be observed. In one modification, the sample surface is at 45° to the horizontal and the ball's horizontal travel can be measured. In either case the same problem of observing the motion of a fast-moving object is seen as with the Bashore. In the present device (Fig. 2), the sample surface is horizontal and a steel ball (3.43 g, 0.953 cm diameter), approaches the surface at an angle of $\sim$ 45°. The horizontal distance traveled by the ball from impact to the first landing is a measure of resilience. All of the balls used were chrome–steel ball bearings.

A major advantage of the present device is the ease with which the distance is recorded. The first impact of the ball after hitting the sample is on a thin layer of sand (actually pet bird gravel, Hartz Gravel'n Grit™) in which an indentation is left, rather like the mark left by an athlete in a broad jump competition. The sample is held in place on a vacuum chuck with the upper surface adjusted using a laboratory jack to the level of the sand bed. The ball is released from a height of 40.0 cm and rolls down through a glass tube before hitting the sample. A clamping device (Fig. 3) has been

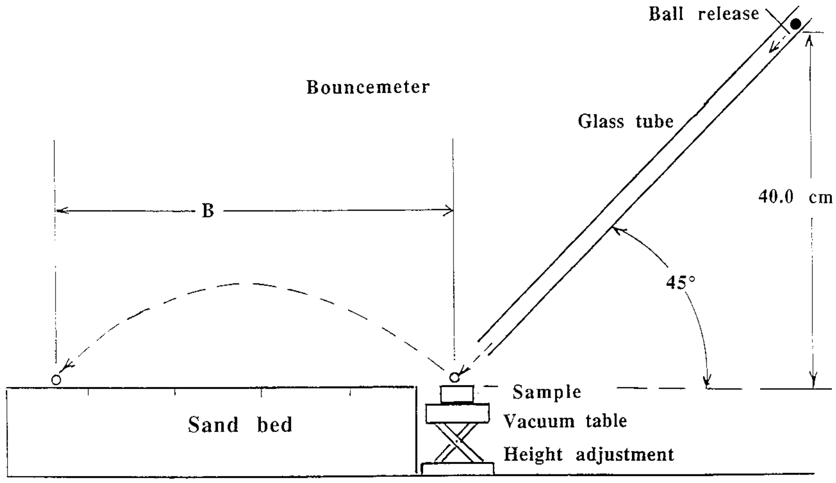

Figure 2 Schematic diagram of the bouncemeter.

found to give reproducible results when samples are plied to increase thickness.

EXPERIMENTAL

Rubber was compression-molded in a mold which yielded samples of four thicknesses. The polymers are styrene–butadiene copolymers (See Table I). The combinations of polymer, black, and oil were obtained by Banbury mixing the appropriate amounts of an SBR rubber (Duradene™ 706), a rubber-oil masterbatch (Duradene™ 750), and a rubber-oil-black masterbatch (Gentro™ 1848). Three other samples in addition to those of Table I were used. One is a styrene–butadiene triblock polymer (Kraton™ D3226) molded in the same way as the crosslinked rubbers. The other two are

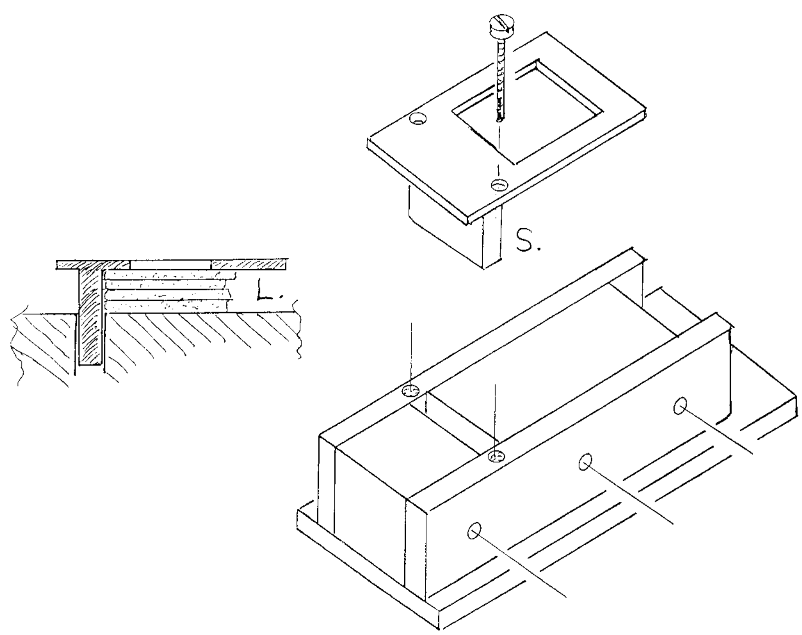

Figure 3 Clamping bracket for plied samples. Each layer (L) is butted against the vertical slider (S) in order to minimize "shuffling." The entire assembly is held in place on a vacuum chuck.

Table I Compounded Rubber Samples

Sample	Carbon Black (parts per hundred of rubber)
P	0
Q	10
R	20
S	30
T	40
Balance of Formulation	**Parts by Weight**
SBR rubber	100
Processing oil	30
ZnO	5
Sulfur	3
Mercaptobenzothiazole disulfide	3
Stearic acid	3
Butylated hydroxytoluene	3

Mixed on laboratory-scale Banbury mixer, compression-molded 20 min at 163°C.

balls, originally 1-inch in diameter, which have been machined to give two parallel flat surfaces with a sample thickness of 1.27 cm. One ball is a toy "superball," presumably polybutadiene, and the other is a "dead" ball with density of 1.14 g/cm^3, presumably a filled butyl rubber.

RESULTS AND DISCUSSION

Effects of Sample Thickness and Ball Diameter

It is observed that data can be linearized by plotting the bounce distance, B, versus the inverse thickness for all the samples tested (Fig. 4). The amount of energy that can be absorbed by a given specimen should reach a limit at infinite thickness. The influence of a hard, but not very resilient support (typically steel) might be expected to diminish inversely with distance from the striking surface. Of course, the distance that the striker penetrates into the material will vary with the hardness of the material and with the amount of energy imparted to the sample by the striker. Another factor could be the area over which the energy is applied. According to Scott,[5] variations in thickness can be compensated for in the Tripsometer by making the falling height of the pendulum proportional to the square of the thickness. In another approach, a German standard mentioned by Scott uses a correction of $11/(w + 5)$ times the resilience for samples, with thickness w between 5 and 7 mm.

Kluckow's results using the Schob test on a rubber sample of modest resilience yield a relatively straight line (Fig. 5). There have been other attempts to compare the resilience values obtained from one test to another using the impact energy or the time of contact as criteria.[5] The amount of energy imparted in several test methods used in the present work is summarized in Table II. When three of the methods of resilience measurement are compared (Fig. 6), the advantage of a low energy test becomes apparent. The Lüpke has the highest dependence and the Bouncemeter the least.

The Yerzley result (Fig. 6) seems to be out of place if impact energy is the only criterion. How-

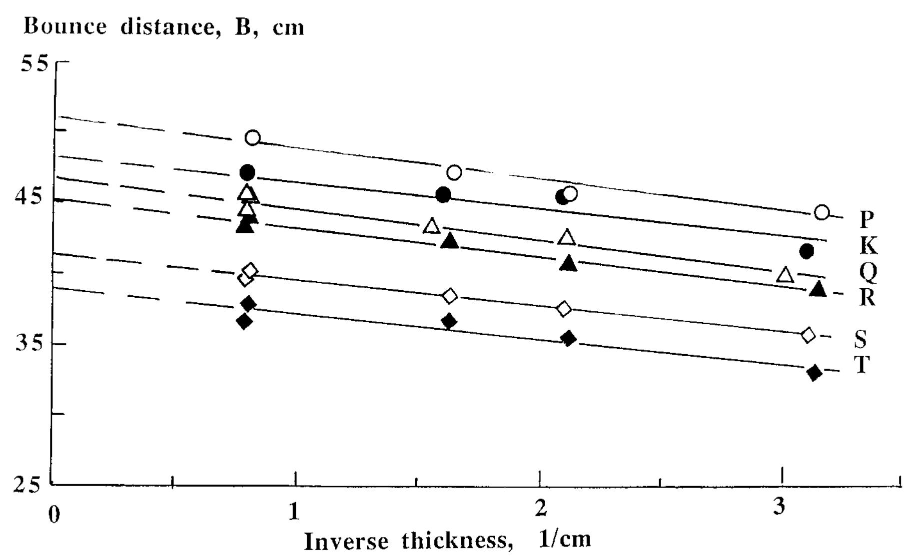

Figure 4 Bounce distances for the samples described in Table I using the 0.953-cm diameter ball.

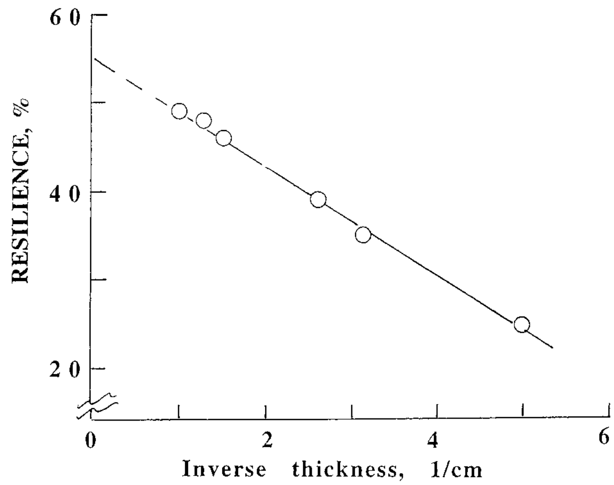

Figure 5 Schob device data of Kluckow[4] plotted according to the current recommendation.

ever, it must be remembered that, in the Yerzley test, the energy is distributed over a much wider area ($\sim$ 2.9 cm^2) and the sample is kept in compression. For sample Q, the compressive modulus is 930 kPa and the resilience was measured at an average compression of 22%.

However, since the extrapolation to infinite thickness is time-consuming, it was decided that 1.27 cm (0.500 inch) could also be used as a reference thickness since it is a standard used in various tests such as the Lüpke, Bashore, and Yerzley. In point of fact, the Bouncemeter distance is actually within a few percent of the distance extrapolated to infinite thickness (Fig. 4).

For the Bouncemeter, the selection of a standard ball diameter is a compromise between having a mass which is sufficient to overcome aerodynamic drag and yet small enough to allow reproducible results from samples varying in thickness. The advantage of a small ball is seen in Figure 7 where a ball diameter of 0.56 cm ($\frac{7}{32}$ inch) gives almost identical bounce distances for samples varying in thickness down as far as 0.33 cm ($\frac{1}{8}$ inch). However, the diameter chosen as a standard, 0.953 cm ($\frac{3}{8}$ inch) often gives the longest bounce distance for the samples tested here.

Table II Typical Amounts of Energy Imposed on Sample

Test Method	Impacting Conditions: Mass (g)	Initial Height (cm)	Energy (J)
Yerzley	5,000	5	2.5
Lüpke	350	10	0.3
Bashore	28	40	0.1
Bouncemeter	3.4	40	0.01

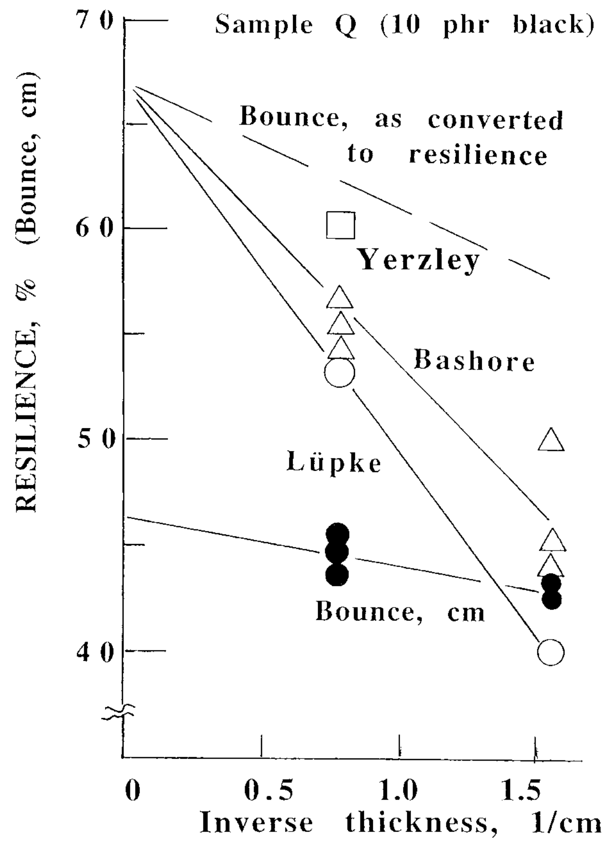

Figure 6 Resilience for sample Q extrapolated to infinite thickness is virtually the same using three methods. The Yerzley test was run at only one thickness.

Relationship to Bashore Resilience

The relationship between bounce distance, B, and resilience (or rebound) R, as it may be measured in the Lüpke or Bashore devices, can be derived by a simple physical exercise.

Let fractional resilience (R_f) equal the ratio of the rebound height, h_2, to the initial height, h_1 [Fig. 8(a)]. Assume that a ball bouncing from height h_1 also has a constant horizontal velocity $u' = dx/dt$ [Fig. 8(b)]. The time of fall due to gravity (g = 981 cm/s^2) from a vertical distance $y = h_2$ is

$$d^2y/dt^2 = g \quad dy/dt = gt \quad y = gt^2/2 = h_2 \quad (2)$$

Then the total time, Δt, for the rise and fall of

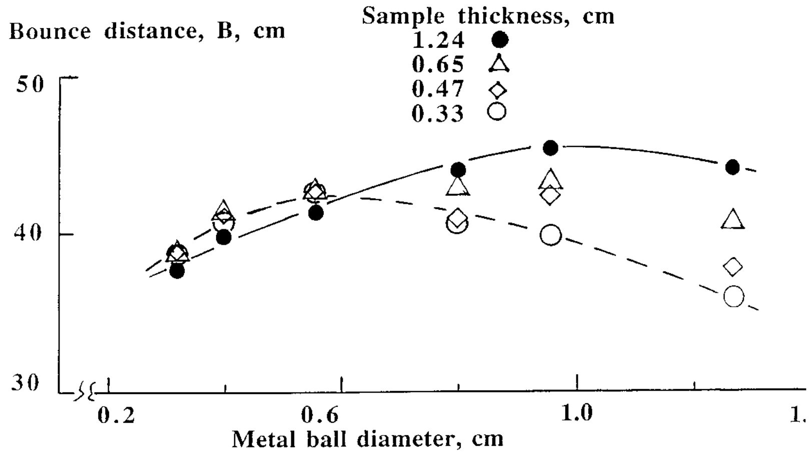

Figure 7 A relatively soft rubber, sample Q, is used to illustrate the influence of ball size on bounce distance as a function of sample thickness.

the ball (the "hang time") corresponding to height h_2 is

$$\Delta t = 2t = 2(2h_2/g)^{1/2} \qquad (3)$$

Also, the horizontal velocity, u', is the horizontal distance, B, traveled in time Δt:

$$u' = dx/dt = B/\Delta t = B(8h_2/g)^{-1/2}$$

$$\text{and } h_2 = R_f h_1 \qquad (4)$$

The quantities u' and h_1 are relatively constant in the Bouncemeter and can be lumped together with g in k''.

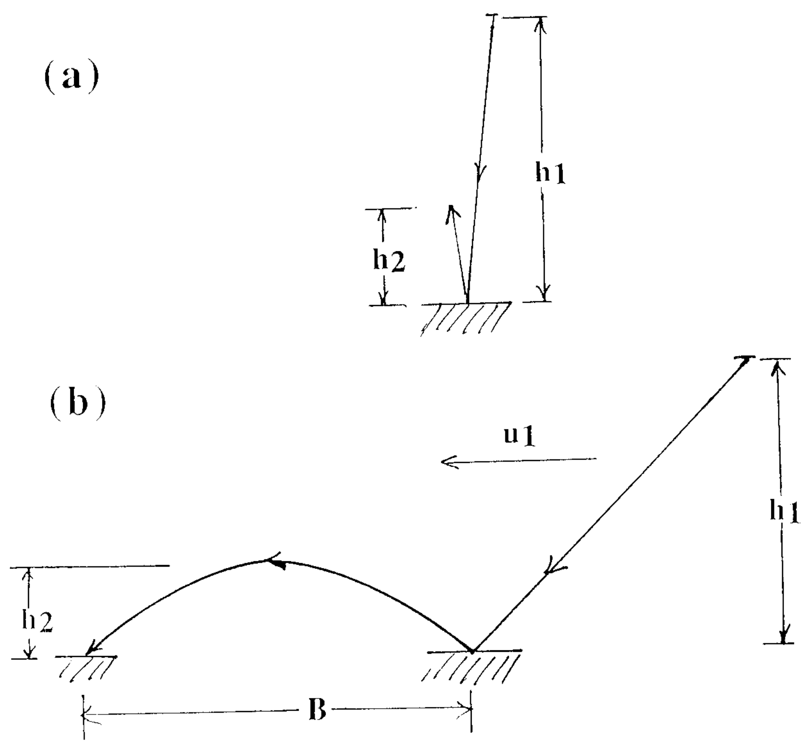

Figure 8 (a) In rebound tests like the Lüpke and Bashore, resilience is measured directly as the recovery of potential energy (vertical distance). (b) In the bouncemeter, the horizontal distance is a function of the vertical recovery and the relatively constant horizontal velocity.

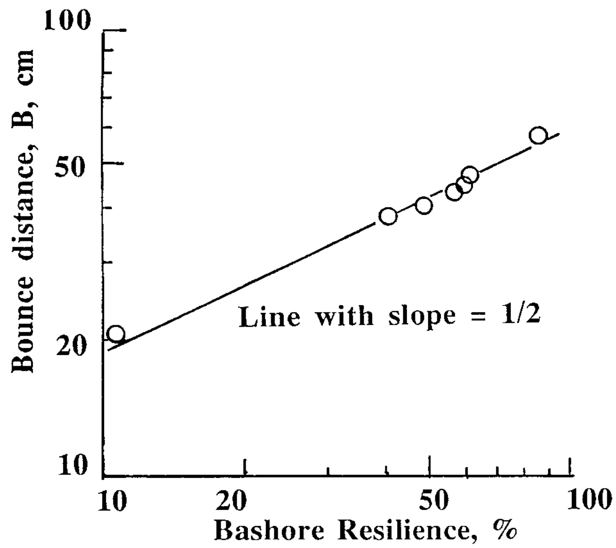

Figure 9 The predicted dependence of bounce distance on the square root of resilience is very nearly achieved using 1.27-cm thick samples. The 0.953-cm ball was used.

$$B = k''(R_f)^{1/2} \tag{5}$$

Thus, the bounce distance, B, should be proportional to the square root of the resilience as measured by devices like the Lüpke or Bashore resiliometers. When the distances B from the Bouncemeter are compared with the Bashore resilience, a slope of 1/2 comes near to fitting the data despite the fact that the actual values are used for 1.27-cm thick specimens rather than an extrapolation to infinite thickness (Fig. 9).

The actual horizontal velocity to be expected can be estimated from geometry also. It should be independent of the mass of the ball. The ball starts at $h_1 = 40.0$ cm and rolls down a glass tube. An energy balance for a ball of unit mass equates the initial potential energy, gh_2, with the kinetic energy of motion, $(u'')^2/2$ and the rotational energy of the ball around its own axis[8] which amounts to $(u'')^2/5$.

$$gh_2 = (0.5 + 0.2)(u'')^2 \tag{6}$$

With $h_1 = 40.0$ cm and $g = 981$ cm s^2, $u'' = 237$ cm s^{-1}. Since the ball hits at an angle of 45°, the horizontal component u' is going to be

$$u' = 237 \sin 45° = 237 \times 0.7071 = 168 \text{ cm s}^{-1} \tag{7}$$

In order to test this estimate, a measurement of velocity was carried out using rotating sector photography. For a sample which gave a bounce distance of $B = 46.0$ cm, h_2 was 10.7 cm. Equation 3 gives $\Delta t = 0.296$ s. Equation 4 gives $u' = 155$ cm s^{-1}, which is very close to the prediction of eq. (7). The ball images were separated by a horizontal distance of 8.1 cm when the time between sector flashes was 0.053 s, yielding a second estimate of $u' = 154$ cm s^{-1}. The difference between the 168 and 155 cm s^{-1} is due mainly to energy dissipation in the sample, but it also includes aerodynamic friction.

CONCLUSIONS

The salient advantages of the Bouncemeter over the other devices examined in this work are (1) the resilience (bounce distance) is easy to read; (2) the device is simple to operate and maintain; (3) the apparatus is inexpensive and easily constructed; (4) the accuracy obtained is comparable to the others; (5) results are less dependent on sample thickness; and (6) since there are no bearings, there is almost no friction.

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