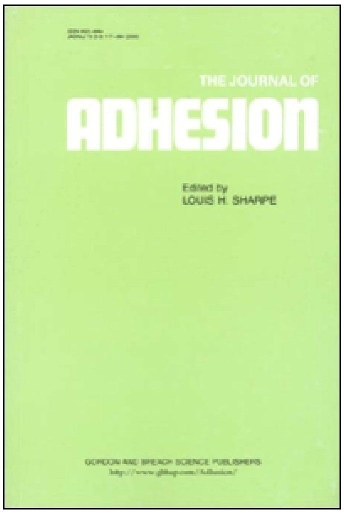

The Journal of Adhesion
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713453635

Rolling Motion of a Ball on Pressure Sensitive Adhesives

Hiroshi Mizumachi[a]; Tsugio Saito[b]
[a] Laboratory of Chemistry of Polymeric Materials, Department of Forest Products, Faculty of Agriculture, The University of Tokyo, Tokyo, Japan [b] Technical Department, Nichiban Co., Ltd., Iruma-gun, Saitama, Japan

To cite this Article Mizumachi, Hiroshi and Saito, Tsugio(1986) 'Rolling Motion of a Ball on Pressure Sensitive Adhesives', The Journal of Adhesion, 20: 2, 83 — 97
To link to this Article: DOI: 10.1080/00218468608074940
URL: http://dx.doi.org/10.1080/00218468608074940

J. Adhesion, 1986, Vol. 20, pp. 83–97
0021-8464/86/2002-0147 $18.50/0

Rolling Motion of a Ball on Pressure Sensitive Adhesives

HIROSHI MIZUMACHI

Laboratory of Chemistry of Polymeric Materials, Department of Forest Products, Faculty of Agriculture, The University of Tokyo, Bunkyo-ku, Tokyo-113, Japan

TSUGIO SAITO

Technical Department, Nichiban Co., Ltd., 100 Nishihara, Oyazawa, Hidaka-cho, Iruma-gun Saitama-350-12, Japan

(Received September 19, 1985; in final form February 25, 1986)

Rolling motion of a ball on pressure sensitive adhesives was carefully observed under well-controlled conditions. Rolling distance was measured as a function of time by means of stroboscopic photography, and rollout distance was measured as a function of initial height of a ball. Both rolling distances and rollout distances were analysed according to a unified theory, where rolling friction coefficient (f) of a pressure sensitive adhesive is involved. It is suggested that f depends on viscoelastic properties of the adhesives.

KEY WORDS Pressure sensitive adhesives; rolling ball; rolling friction coefficient; rolling process; tack; theory.

INTRODUCTION

Tack of pressure sensitive adhesives is sometimes estimated by means of some standardized tests, where rolling motion of a ball is concerned. In J. Dow method, for example, a sample of pressure sensitive adhesive is placed on an inclined surface and balls of various diameter are rolled on the surface with a leading distance of 10 cm, and diameter of the largest ball which stops within 10 cm in the adhesive zone is determined. If diameter of the ball is $(n/32)$ inch, then tack of the adhesive is "ball number n". The larger the ball number, the tackier the adhesive. In the case of PSTC-6 method, a ball of (14/32) inch diameter rolls down on an inclined path onto a horizontal surface of a pressure sensitive adhesive, and then rollout distance is measured. Here, reciprocal of rollout distance is believed to be proportional to tackiness of the adhesive. Johnston[1] described these methods, together with some other similar rolling ball tack tests in detail.

These ways of expressing tack might be useful among formulators and testers of pressure sensitive adhesives in practical cases, but physical meanings of the measured values are not always clear. It would be natural to think that rolling motion of a ball on a pressure sensitive adhesive reflects tackiness of the adhesive, because the motion must be closely related to both bonding and unbonding processes of a very short time-scale, which occur continuously around the surface of contact. However, we had better try to express tack in terms of physically well-defined quantities which depend on structures and properties of materials, and not on any trivial experimental conditions such as angle of inclination of a surface, leading distance, etc. We believe that rolling friction coefficient (f) of pressure sensitive adhesives is the most fundamental quantity to express rolling ball tack, because rolling motion of a ball is described by a set of equations of motion where f of the substrate material is involved, and f depends on the material, not on any of the above-mentioned trivial experimental conditions.

In a previous report,[2] rolling motion of a ball on an inclined surface was studied and values of f of some pressure sensitive adhesive tapes were evaluated by analyzing rollout distances. In this report, we let a ball roll on a horizontal surface and tried to analyze both rolling processes and rollout distances by a unified theory in order to show that the motion can satisfactorily be described in terms of f of adhesives.

EXPERIMENTAL

Samples used in this study are commercially available pressure sensitive adhesive tapes, which are listed in Table I, where some of their characteristics are also given.

TABLE I
Pressure sensitive adhesive tapes

Sample	Backing	Use	Maker	Thickness of tape (mm)	Thickness of adhesive (mm)	Peel force (gf/12 mm)	Probe tack (gf/5 mm ϕ)
A	Coated fabrics	Packaging	Nichiban Co., Ltd.	0.38	0.14	670	420
B	Coated fabrics	Packaging	Sugawara Industrial Co., Ltd.	0.33	0.13	410	440
C	Coated fabrics	Packaging	Teraoka Seisakusho Co., Ltd.	0.37	0.15	480	490
D	Paper	Masking	Nichiban Co., Ltd	0.093	0.03	210	100
E	Paper	Masking	Nichiban Co., Ltd.	0.105	0.03	240	120
F	Paper	Packaging & masking	Kamoi Kakoshi Co., Ltd.	0.096	—	140	—
G	Cellophane	General	Nichiban Co., Ltd.	0.06	0.018	400	670
H	Coated	Surgical care	Nichiban Co., Ltd.	0.26	0.06	350	130

(A) Measurement of rolling distance of a ball as a function of time

A double-faced, pressure sensitive adhesive tape of the strong adhesion type was adhered on the surface of a steel plate with 4 mm thickness, upon which a tape sample was placed with the adhesive surface facing up. To ensure enough contact, the tape was pressed with a thin metal (a razor) except around the expected path of a ball. Then, the plate was set with careful adjustment in the horizontal part of the Nichiban tester, which is shown in Figure 1, so as to enable a ball to transfer smoothly from the leading path into the sample zone. A clean ball was placed on top of the tester and it was pushed softly by a jig until the ball began to roll down. Rolling distance was measured as a function of time (t), using stroboscopic photographs. A lamp was lit for 1/1000 second at every 1/100 second until a ball stopped. After a run is over, rollout distance was measured and the sample was taken away from the plate. A new specimen was set in the tester at every run. Examples of the photograph are shown in Figure 2.

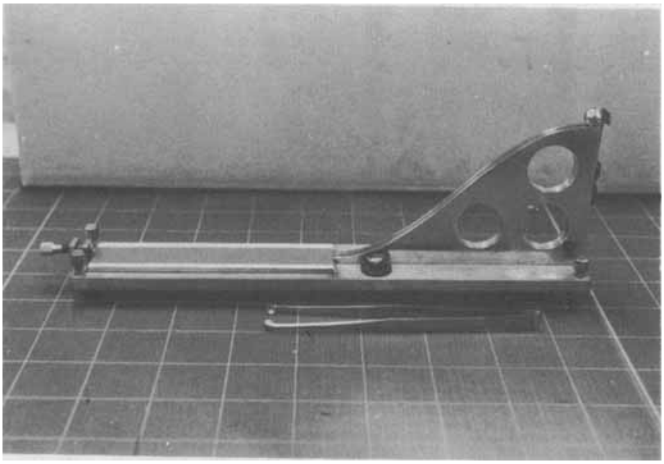

FIGURE 1 Nichiban ball tack tester, $H = 17.3$ cm.

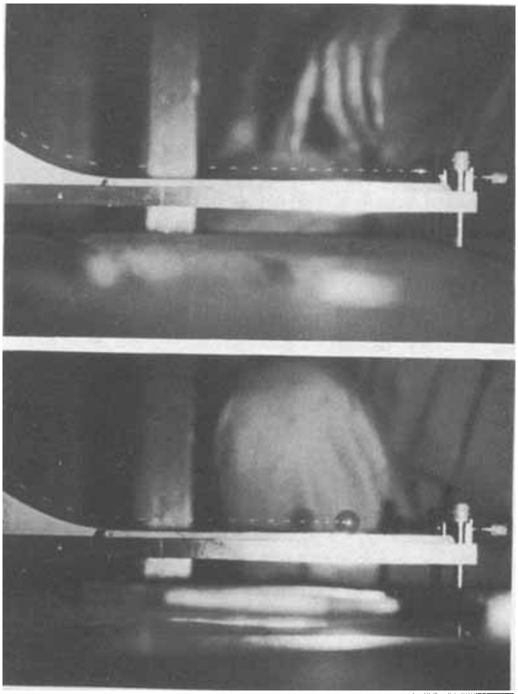

FIGURE 2 Stroboscopic photographs.

Hammond[3] stated that Gillespie had made an extensive study using stroboscopic photography to determine time/position of the ball, but results have not been published in any journal.

(B) Measurement of rollout distance of a ball as a function of initial height (*H*)

Similar testers with varying heights were used in the experiment. Temperature of measurement was 20° and 6°C for Tape G, 20° and 5.5°C for Tape A and 20°C for Tape H.

H was varied as follows:

$R = 0.96$ cm: $H = 6.0$, 11.5, 19.1 cm
$R = 0.80$ cm: $H = 5.8$, 11.5, 19.1 cm
$R = 0.64$ cm: $H = 5.6$, 11.5, 19.1 cm

Measurements were made ten times (10 runs) at every experimental condition, and a new specimen was set in the tester at every run.

RESULTS AND DISCUSSIONS

Equations of motion of a ball rolling on a pressure sensitive adhesive are as follows:[4,5]

$$M\ddot{x} = -F \tag{1}$$

$$M\ddot{y} = 0 = N - Mg \tag{2}$$

$$I\ddot{\Phi} = RF - fN \tag{3}$$

$$x = R\Phi + constant \tag{4}$$

where M, R, $I(=2MR^2/5)$ are mass, radius and moment of inertia of a ball, respectively, and F is static frictional force, N normal force, Φ angle of rotation of a ball, and f is rolling friction coefficient of a pressure sensitive adhesive.

From Eqs. (1)–(4), we get

$$\ddot{x} = -\frac{5gf}{7R} \tag{5}$$

Because f depends on the physical properties of the material, it must be expressed as a function of velocity (v) for viscoelastic

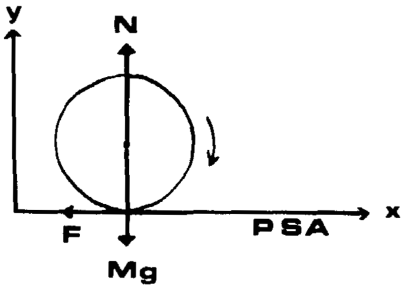

FIGURE 3 A ball rolling on a pressure sensitive adhesive.

materials. We proposed the following equation in the previous report[2]:

$$f = \phi_0 + \phi_1 v \tag{6}$$

Then, we get

$$v = v_0 \exp\left(-\frac{5g\phi_1}{7R}t\right) - \frac{\phi_0}{\phi_1}\left(1 - \exp\left(-\frac{5g\phi_1}{7R}t\right)\right) \tag{7}$$

$$(x - x_0) = \frac{7R}{5g\phi_1}\left(v_0 + \frac{\phi_0}{\phi_1}\right)\left(1 - \exp\left(-\frac{5g\phi_1}{7R}t\right)\right) - \frac{\phi_0}{\phi_1}t \tag{8}$$

$$(x - x_0)_{st} = \frac{7R}{5g\phi_1}\left\{v_0 - \frac{\phi_0}{\phi_1}\log\left(1 + \frac{\phi_1}{\phi_0}v_0\right)\right\} \tag{9}$$

where $(x - x_0)$ is rolling distance at time t and $(x - x_0)_{st}$ is $(x - x_0)$ at $v = 0$, namely rollout distance.

If we neglect rolling friction of the solid material of the curved path, initial velocity of a ball in the pressure sensitive adhesive zone is expressed as a function of H.

$$v_0 = \left(\frac{10}{7}gH\right)^{1/2} \tag{10}$$

Then,

$$(x - x_0)_{st} = \frac{7R}{5g\phi_1}\left\{\left(\frac{10}{7}gH\right)^{1/2} - \frac{\phi_0}{\phi_1}\log\left(1 + \frac{\phi_1}{\phi_0}\left(\frac{10}{7}gH\right)^{1/2}\right)\right\} \tag{11}$$

We can analyze our data on rolling distance and those on rollout distance according to Eqs. (8) and (11), respectively.

(A) Rolling distance

Some of the typical data are shown in Figure 4. Not only rollout distance, but also the shape of a curve of $(x - x_0)$ vs t is different from specimen to specimen. Initial velocity of a ball must be the same for every case, regardless of R of a ball. From initial gradients of the curves in Figure 4, we get $v_0 = 150$ cm/sec, which is close to the calculated value.

Equation (8) was applied to these data and values of ϕ_0 and ϕ_1 were determined so as to minimize the sum of deviations of experimental data from the curve in every case. Value of ϕ_0 and ϕ_1 thus determined were substituted in Eqs. (7), (8) and (9), in order to obtain theoretical curves of velocity and rolling distance of a ball as a function of time, and rollout distance, which were compared with experimental ones. Some of the results of these analysis are given in Figure 5 and Figure 6, and they are summarized in Table

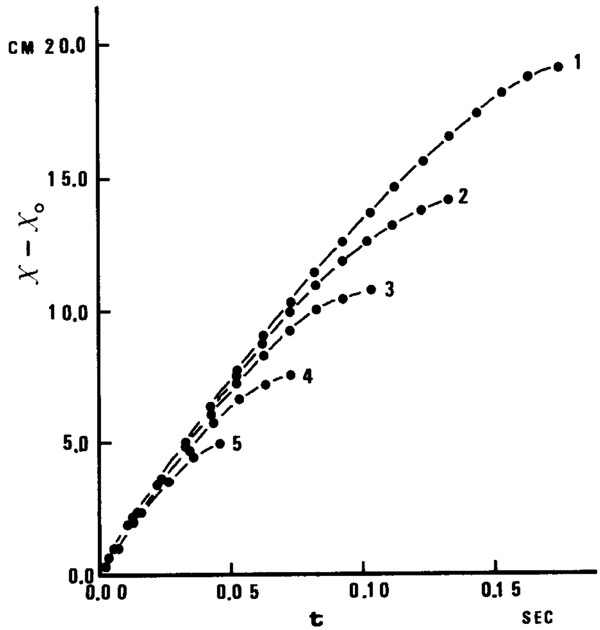

FIGURE 4 Some typical data of rolling distance of balls as a function of time. 1. Tape C, $R = 0.80$ cm, 2. Tape C, $R = 0.64$ cm, 3. Tape D, $R = 0.80$ cm, 4. Tape B, $R = 0.96$ cm, 5. Tape D, $R = 0.56$ cm.

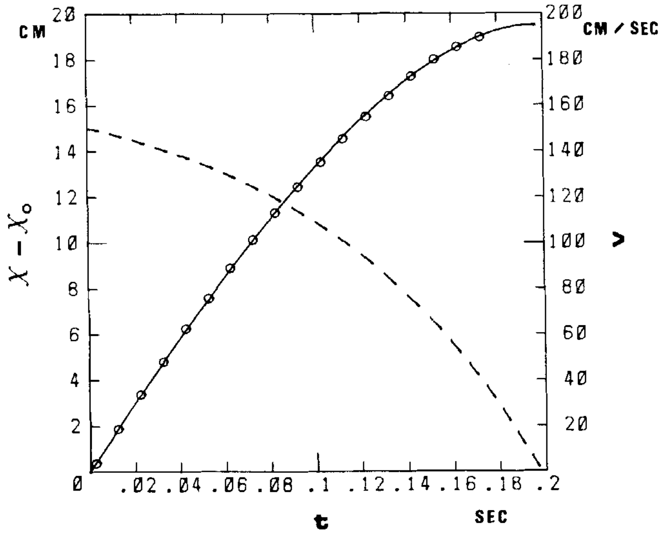

FIGURE 5 Comparison between experimental points (O) and a theoretical curve (——) of rolling distance. Velocity is also shown by a broken line (-----). Tape B, $R = 0.80$ cm, $\phi_0 = 2.01$, $\phi_1 = -0.0116$.

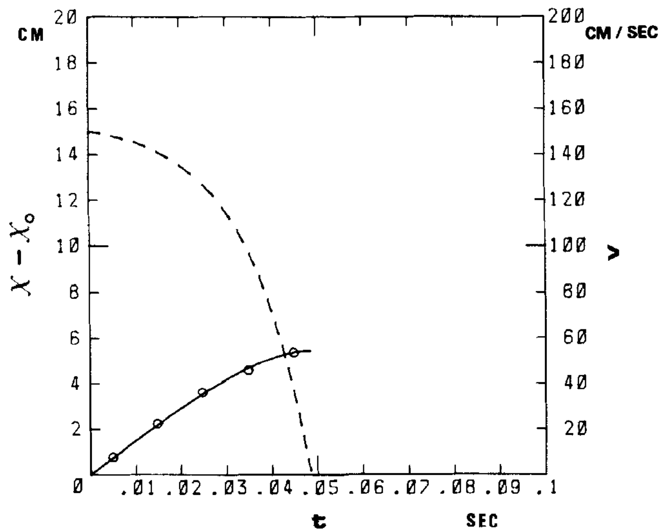

FIGURE 6 Comparison between experimental points (O) and a theoretical curve (——) of rolling distance. Velocity is also shown by a broken line (-----). Tape D, $R = 0.56$ cm, $\phi_0 = 8.95$, $\phi_1 = -0.0579$.

TABLE II
Results of analysis of rolling distances

Sample	R (cm)	ϕ_0 (cm)	ϕ_1 (sec)	DEV[a] (cm^2)	$DIST_{cal}$[b] (cm)	$DIST_{obs}$ (cm)
B	0.96	6.74	−0.0396	5.90×10^{-2}	7.37	7.68
B	0.96	4.10	−0.0150	1.30×10^{-2}	6.35	6.51
C	0.96	2.38	−0.0137	2.88×10^{-1}	19.45	19.74
C	0.80	2.01	−0.0116	6.62×10^{-2}	19.49	19.22
C	0.64	2.72	−0.0166	1.46×10^{-1}	13.90	14.23
C	0.64	2.62	−0.0159	7.63×10^{-2}	14.42	14.67
D	0.80	3.48	−0.0195	8.57×10^{-2}	10.48	10.79
D	0.80	4.26	−0.0257	8.01×10^{-2}	10.61	10.98
D	0.56	6.00	−0.0356	1.19×10^{-2}	4.99	5.33
D	0.56	8.95	−0.0579	2.14×10^{-2}	5.44	5.87
E	0.80	1.47	−0.0066	2.25×10^{-1}	17.32	17.62
E	0.80	1.32	−0.0053	2.59×10^{-1}	17.22	17.46
F	0.80	2.18	−0.0075	1.96×10^{-1}	9.29	9.49
F	0.80	2.37	−0.0086	1.31×10^{-1}	8.84	9.13
F	0.80	2.26	−0.0073	1.09×10^{-1}	8.64	8.93
G	0.80	3.44	−0.0212	1.12×10^{-1}	14.55	14.90

[a] $DEV = \Sigma (y - y_i)^2$
[b] $DIST = (x - x_0)_{st}$

II, where data of Tape A are lacking, because we could not determine time/position of the ball on the tape by photography.

Because deviations are very small in all the runs, and calculated values of rollout distance are almost the same as the observed ones, we believe that rolling motion of a ball can satisfactorily be described by these equations. However, ϕ_0 and ϕ_1 are not necessarily the same for two runs of the same condition. For example, in the case a ball of radius 0.56 cm rolling on Tape D, (ϕ_0, ϕ_1) is (8.95, −0.0579) at the first run, and (6.00, −0.0356) at the second, in spite of the fact that deviations for individual runs are very small.

The reason is not known exactly. A specimen of a pressure sensitive adhesive tape is prepared by unwinding a roll and cutting it, and then it is a set on a tester by apparently the same procedure. But there could be some differences in the fine states of specimens which we usually do not recognize. There is always a scatter of points in this kind of experiment, but it is a very interesting fact that any individual run can be described at full length according to a very simple mechanical principle. If we want to obtain data on rolling friction coefficient which can significantly be correlated with physical properties of adhesives, we have to make many runs for the same sample and take the means.

(B) Rollout distance

Data of rollout distance $(x-x_0)_{st}$ as a function of height (H) are shown in Figures 7–9. Each curve contain 20–30 experimental points. Values of ϕ_0 and ϕ_1 were determined by fitting Eq. (11) to all the experimental points by applying the least squares method. Then, these values were substituted in Eq. (11) to obtain theoretical curves, which are also shown in the figures. ϕ_0 is always positive, but ϕ_1 can be negative, zero or positive. The shape of the curve is influenced by the sign of ϕ_1; it is concave when $\phi_1<0$, and convex when $\phi_1>0$. And when $\phi_1=0$, f is independent of v, and then a straight line must be obtained.

Results of the analysis are summarized in Table III. Because these are determined from data of many runs, the sum of deviations are greater than those for an individual run. However, the theoretical curves are in good agreement with experimental points. Here, it is interesting to note that ϕ_1 of Tape A changes its sign from negative to positive as the temperature is raised from 5.5° to 20°C, and on the other hand that of Tape G is always negative in the temperature range of 6–20°C.

Detailed analysis cannot be done because chemical components and physical properties of the adhesives are not known, but the following interpretations might be possible.

It is reasonable to expect that if we plot f of a viscoelastic material against log v over a very wide range at a constant temperature, a curve having a peak or peaks will be obtained and that the curve will shift toward the higher velocity side when the temperature is raised. These situations can be explained according to a model theory on tack of pressure sensitive adhesives.[6] Velocity of a ball on a pressure sensitive adhesive decreases from v_0 ($\log v = 2$) to absolutely zero ($\log v = -\infty$), but f of very low v does not affect these experiments. In other words, we are interested in f of a relatively narrow range of velocity in logarithmic scale. Then, in case of Tape A, we measured f of both sides of the peak, which is schematically shown in Figure 10. f is decreasing at 5.5°C and

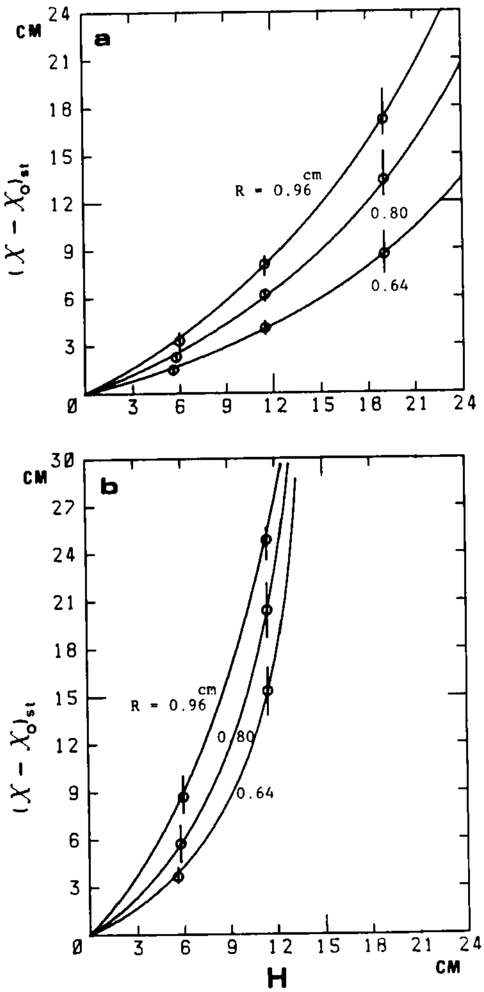

FIGURE 7 Comparison between experimental points (ϕ) and theoretical curves (——) of rollout distance as a function of initial height of a ball. Sample is Tape G and temperature is 20°C (a) and 6°C (b). 10 runs were made at every height and all the data were used in the least squares procedure.

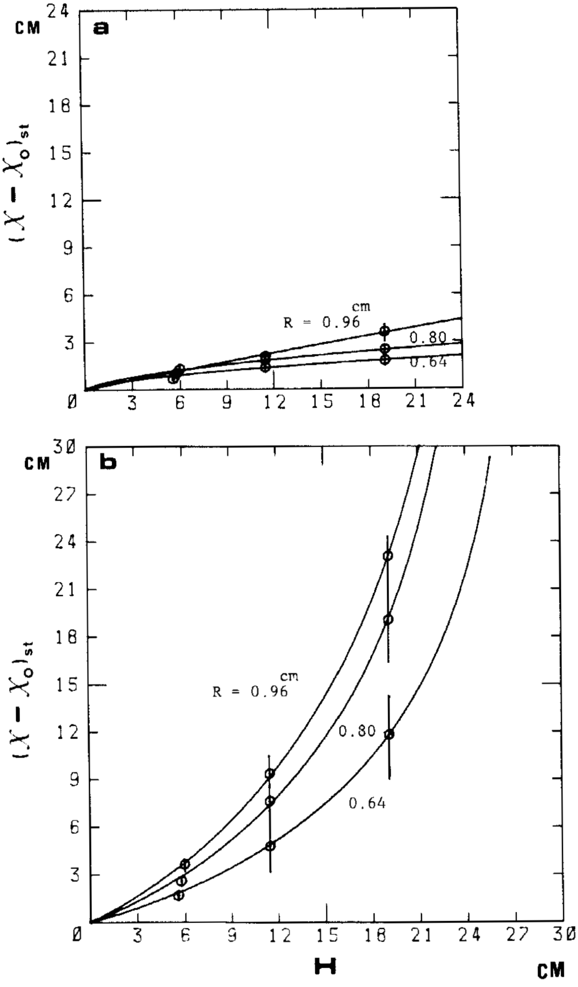

FIGURE 8 Comparison between experimental points (ϕ) and theoretical curves (——) of rollout distance. Sample is Tape A and temperature is 20°C (a) and 5.5°C (b).

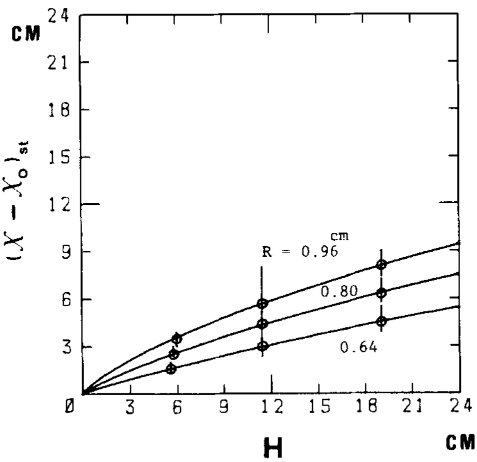

FIGURE 9 Comparison between experimental points (ϕ) and theoretical curves (——) of rollout distance. Sample is Tape H and temperature is 20°C.

TABLE III
Results of analysis of rollout distances

Sample	Temperature (°C)	R (cm)	ϕ_0 (cm)	ϕ_1 (sec)	DEV[a] (cm^2)
A	20	0.64	0.76	0.0665	7.15×10^{-1}
A	20	0.80	0.87	0.0590	6.46×10^{-1}
A	20	0.96	4.55	0.0060	1.39×10^{0}
A	5.5	0.64	2.85	−0.0145	3.13×10^{1}
A	5.5	0.80	2.45	−0.0130	2.93×10^{1}
A	5.5	0.96	2.35	−0.0123	1.81×10^{1}
G	20	0.64	3.10	−0.0140	8.62×10^{0}
G	20	0.80	2.62	−0.0120	9.68×10^{0}
G	20	0.96	2.32	−0.0104	1.01×10^{1}
G	6	0.64	1.71	−0.0122	1.17×10^{1}
G	6	0.80	1.51	−0.0106	1.15×10^{1}
G	6	0.96	1.10	−0.0069	9.05×10^{0}
H	20	0.64	1.73	0.0095	4.22×10^{0}
H	20	0.80	1.11	0.0130	4.81×10^{0}
H	20	0.96	0.73	0.0160	1.22×10^{1}

[a] $\mathrm{DEV} = \sum (y - y_i)^2$

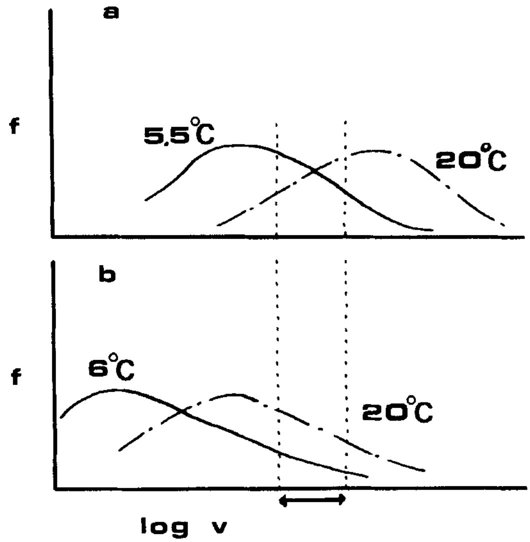

FIGURE 10 Schematic representation of f as a function of velocity. Effective velocity range for this experiment is shown by ⟷. (See text.) Samples are Tape A (a) and Tape G (b).

increasing at 20°C as velocity increases within the range of our experiment. On the other hand, the peak of f of Tape G is located at very low velocity, and it does not come in the velcoity range of our interest. Therefore, f is a decreasing function of v at 6° and 20°C. If temperature of experiment is raised further, there can be conditions where we find f of Tape G as an increasing function of v. This is indicating the fact that the glass transition temperature (T_g) of the pressure sensitive adhesive of Tape G is much lower than that of Tape A.

CONCLUSIONS

Rolling motions of a ball on pressure sensitive adhesives were measured in well-controlled conditions and the results could successfully be described by a simple mechanical theory, where rolling friction coefficient f of the material is expressed in terms of two parameters ϕ_0 and ϕ_1.

Hammond[3] stated that Gillespie tried to analyze his data, assuming that a ball loses its energy in proportion to distance in one case or in proportion to time in another, but that he was unable to summarize his data by a unified theory. However, as far as our data are concerned, rolling processes of a ball could be analyzed by our unified theory over the whole range of velocity in this experiment and, at the same time, rollout distance could also be analyzed by the same theory. It is suggested that f is closely related to physical properties of adhesives.

If we could accumulate data on f, using well-characterized pressure sensitive adhesives, there will be much progress in our understanding on tack.

Acknowledgement

Part of the work was supported by a Grant-in-Aid for Co-operative Research of The Ministry of Education, Science and Culture of Japan.

References

1. J. Johnston, *Adhesives Age* **26,** 34 (1983).
2. F. Urushizaki, H. Yamaguchi and H. Mizumachi, *J. Adhesion Soc. Japan* **20,** 295 (1984).
3. F. H. Hammond, Jr., in *Handbook of Pressure-Sensitive Adhesive Technology,* D. Satas, Ed. (Van Nostrand Reinhold Co., NY, 1982).
4. *Mechanics,* T. Inui, *et al.*, Eds (Press of The University of Tokyo, 1960).
5. H. Mizumachi, *Material Technology* (Japan) **2,** 6 (1984).
6. H. Mizumachi, *J. Appl. Polym. Sci.* **30,** 2675 (1985).