Static friction properties of linerboard

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The surface free energy of the linerboard is the predominant factor controlling static friction.

Many converting and handling operations require linerboard with a high friction coefficient. Manufacturers of corrugated board are expressing concern about the increased use of recycled linerboard, which is more slippery than virgin linerboard.

Several reports on the friction properties of fine paper (*1-4*), newsprint (*5*), and linerboard (*6-11*) have been published. These studies attempted to relate friction properties to sheet surface profile and to various operating conditions. Unfortunately, the conclusions drawn are often contradictory. For example, Broughton (*1*) reported that calendering lowers the coefficient of friction for paper, while Jones (*3*) came to the opposite conclusion.

When two smooth surfaces of a polymeric material are in contact, the static friction is affected by the polymer's surface free energy (*12*). For a cellulosic material such as paper, it is conceivable that the force of friction is affected by the surface free energy of the sheet as well as its surface profile. In fact, it is possible that inconsistencies in the previous studies of paper friction were caused by neglecting the effect of surface free energy.

We studied the effects of surface free energy and surface profile on the static friction coefficient of linerboard. The effects of moisture content, antiskid treatment, and surface contamination were also considered.

Experimental procedure

Slide-angle tester

All static friction tests were done using the slide-angle tester according to TAPPI Test Method T 815. We used a TMI model no. 32-25 for these tests. In this test, one sample is attached to a plane, and a second sample is attached to a sled, which is then placed on top of the plane. The plane is tilted until the sled begins to slide. The angle at which sliding occurs is called the "slide angle," and the coefficient of friction is equal to the tangent of this slide angle. The results throughout this report are given as slide-angle values (linerboard-linerboard interface). Tests were carried out at 50% RH and 23°C, and all samples were handled with clean surgical gloves to prevent contamination.

TAPPI Test Method T 815 recommends taking the third reading of the slide angle as the measure of static friction because of the large variability of the initial slide values. In our case, measurements were repeated up to 25 times on the same sample to ensure that a stable reading of the slide angle was obtained. The results reported here are equilibrium slide-angle values, typically achieved after five repetitions on the same sample.

Various surface combinations were tested [i.e., machine direction (MD) vs. MD, cross-machine direction (CD) vs. CD, and MD vs. CD]. Similar results were obtained for each combination. The slide-angle values presented here are MD vs. MD. Results for each linerboard were obtained by testing three separate samples.

Paperboard samples

Thirteen Canadian commercial linerboards were tested, ranging from unbleached kraft liners to bleached recycled liners. The physical properties of the linerboard samples are listed in **Table I**. One of the recycled linerboards also was treated with an antiskid colloidal silica.

In addition to the commercial linerboards, paperboard handsheets (200 g/m^2) were made from dried, unbleached kraft pulp for experiments investigating the effects of surface roughness and sizing. Handsheets were sized by dipping them in a 1% solution of Aquapel No. 356 (Hercules) in hexane for 30 s and then heating them in a high-humidity oven at 100°C. The sized handsheets were completely water repellent, while the unsized handsheets absorbed water instantaneously. The samples were conditioned at least 24 h before testing.

"Contamination" of handsheets

Bleached kraft handsheets (200 g/m^2) were used to investigate the effect of contaminants on friction properties. Handsheets were immersed in solutions of glycerol trioleate in chloroform of various concentrations ranging from 0.5% to 10% by weight (*13, 14*). After a brief treatment, the sheets were removed, aerated, and conditioned for 24 h prior to testing.

Solvent extraction of recycled linerboard

A commercial recycled linerboard was immersed in hexane for 30 min to remove solubles from the board. The

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I. Summary of commercial linerboard properties

Sample number	Sample type*	Basis weight, g/m²	Moisture content, %	Caliper, μm	Bulk, cm³/g	Slide angle, degrees	Surface free energy, mN/m
1	UBK	190	7.7	332	1.71	24	38.9
2	UBK	232	7.6	343	1.44	30	51.0
3	UBK	192	8.2	305	1.59	31	40.2
4	UBK	315	8.2	511	1.62	30	37.5
5	UBK	171	7.3	260	1.48	25	45.5
6	UBK	119	7.7	195	1.55	30	47.8
7	UBK	123	8.3	209	1.70	30	35.0
8	UBR	300	7.6	300	1.70	11	22.7
9	UBR	196	7.8	355	1.74	12	26.8
10	UBR	122	7.8	206	1.64	12	24.1
11	BK	193	7.6	289	1.46	27	49.4
12	BR	174	6.9	242	1.37	13	39.9
13	UBR-T	196	7.8	355	1.74	25	39.8

* UBK = unbleached kraft liner
UBR = unbleached recycled liner
BK = bleached kraft liner
BR = bleached recycled liner
UBR-T = unbleached recycled liner, (sample 9) treated with antiskid colloidal silica

procedure was repeated three times using fresh hexane each time. The board was then dried and conditioned for testing.

Determination of surface free energy

Surface free energy of the linerboard was evaluated by the contact-angle method using a goniometer (*15, 16*). For hydrophilic and porous surfaces where a liquid could be absorbed, the capillary-rise method (*17*) was used.

Results and discussion

The initial slide-angle values for samples of the same board varied substantially. However, the equilibrium slide-angle values were constant. The variability in the initial slide angle is not well understood, but we speculate that it may be due to the structural and chemical heterogeneity of the interfacial region between the two surfaces. **Figure 1** shows the change in slide angle for successive measurements on typical unbleached kraft and unbleached recycled liners. The initial slide angle for unbleached kraft liner is generally higher than that of unbleached recycled liner. As seen in Fig. 1, slide angle for the kraft liner tends to increase with successive measurements, while the recycled liner shows the opposite trend. The results presented in this report are based on equilibrium values for slide angle.

It is generally believed that friction between two rough surfaces is caused by the interlocking of surface asperities. However, Tabor's adhesion theory (*18*) suggests that the friction between two surfaces can result from molecular-level adhesion forces at the interface. If this is the case, then two smooth surfaces could have a higher friction coefficient than two rough surfaces, since the greater

II. Effect of sizing* on friction for unbleached kraft handsheets (200 g/m²)

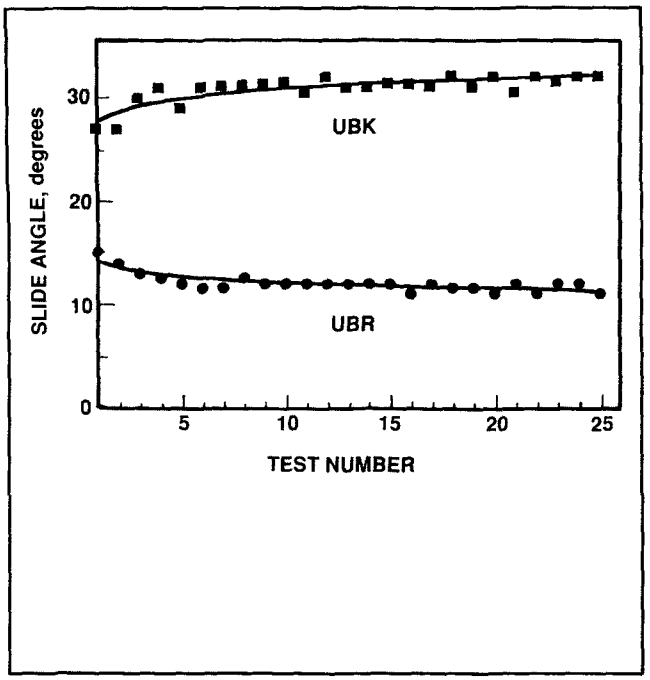
	Slide angle, degrees	Surface free energy, mN/m
Unsized	28	46.3
Sized	14	25.0

*Alkyl ketene dimer.

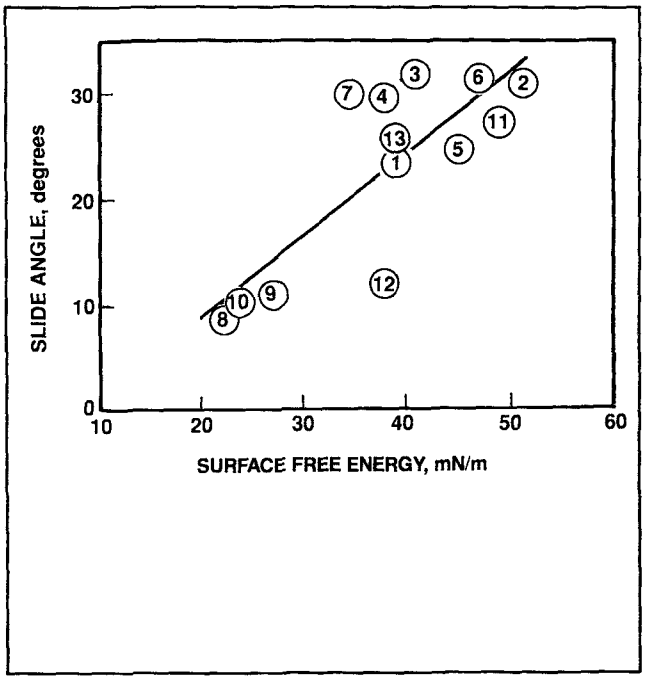
III. Effect of relative humidity on friction

	Slide angle, degrees	
	50% RH	90% RH
UBK (Sample 2)	30	35
UBR (Sample 9)	12	20

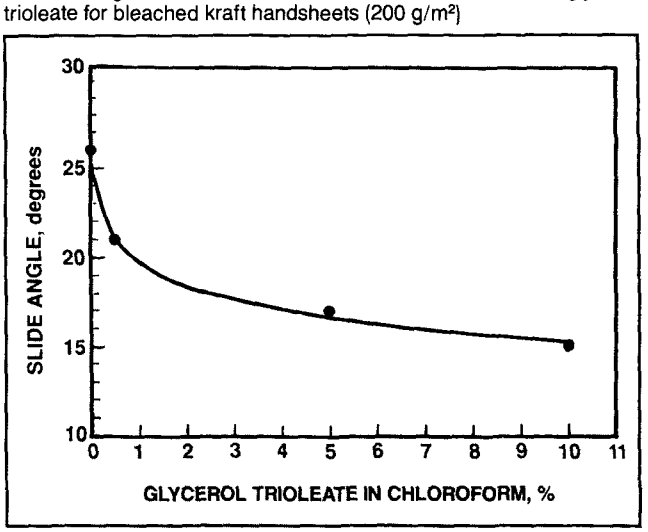
1. Slide angle as measured in 25 successive tests for typical unbleached kraft and unbleached recycled liners



2. Slide angle as a function of surface free energy for 13 commercial linerboards of comparable surface roughness (Parker Print-Surf value greater than 7.0 μm). Circled numbers correspond to the sample numbers in Table I.



3. Slide angle as a function of surface contamination with glycerol trioleate for bleached kraft handsheets (200 g/m²)



contact area between the smooth surfaces would bring more of these intermolecular forces into play.

Adhesion forces at the interface between two materials are generally controlled by the surface free energies of the materials. In this article, we first examine the effect of surface free energy on static friction and then go on to assess the effects of surface contamination, roughness, relative humidity, and antiskid treatment.

Effect of surface free energy

Figure 2 is a plot of static friction (expressed as slide angle) vs. surface free energy for the commercial linerboards listed in Table I. The linerboards were of comparable surface roughness but differing sheet structure. As seen in Fig. 2, slide angle generally increases with surface free energy.

Recycled linerboard (samples 8, 9, 10) had the lowest surface free energies and the lowest slide angles. These linerboards were made from old corrugated cartons containing a variety of hydrophobic materials such as waxes, hot-melt adhesives, and sizing agents, any of which could reduce both surface free energy and friction. Removing such materials through solvent extraction should improve the friction properties. This was confirmed by extracting an unbleached recycled liner (sample 10) with hexane. The resulting increase in surface free energy from 24.0 mN/m to 35.2 mN/m was accompanied by an increase in slide angle from 12° to 20°, while roughness was unchanged.

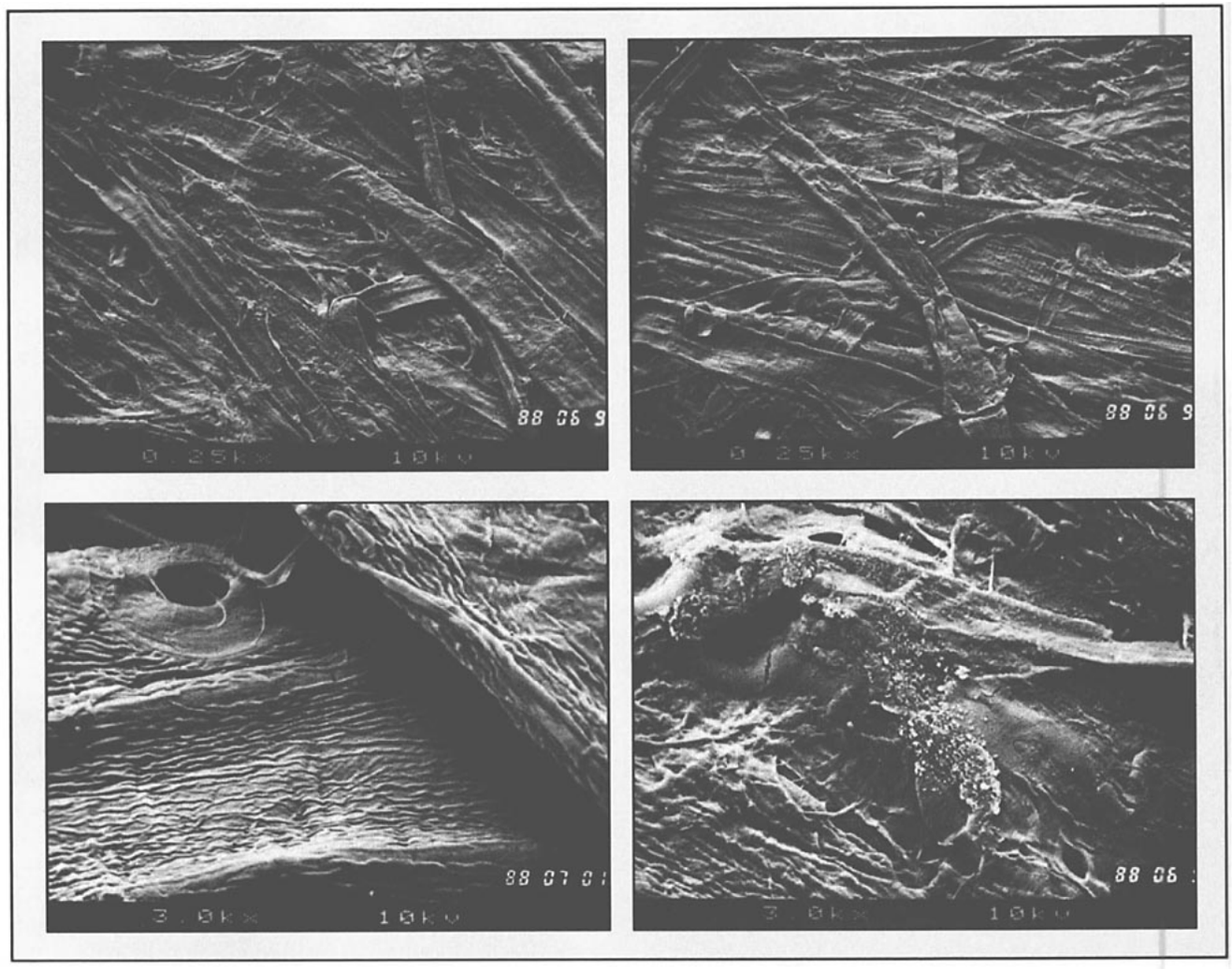
Sizing also can significantly affect the surface free energy of a linerboard. **Table II** shows results for an unbleached kraft handsheet sized with alkyl ketene dimer. The significant decrease in surface free energy was accompanied by a drop in the slide angle even though surface roughness remained constant.

These results clearly indicate that the surface free energy of the linerboard should be considered as one of the predominant factors controlling static friction.

Effect of surface contaminants

Surface contamination of paper samples can adversely affect friction properties (*13, 14*). Therefore, paperboard samples must be carefully handled during testing to avoid contamination. Glycerol trioleate, an oily substance similar in chemical structure to some wood extractives, was used as a contaminant. **Figure 3** shows that treatment of bleached kraft paperboard handsheets with glycerol

4. SEM photomicrographs of unbleached recycled linerboard. Top: low magnification. Bottom: high magnification. Left: untreated surface. Right: surface treated with colloidal silica.



trioleate resulted in a large drop in static friction, even at low levels of contamination. This may partially explain the differences in slide angle for similar products from different mills.

Effect of surface roughness

The effect of surface roughness on the static friction of linerboard was investigated using paperboard handsheets of similar surface free energy and bulk. Handsheets were prepared by wet pressing one side of the sheet against a smooth chrome plate and the other side against a felt. Slide angle was measured on smooth against smooth sides and on rough against rough sides. A slide angle of 28° was observed for the smooth/smooth combination (Parker Print-Surf 4.5 μm), while a slide angle of 22° was observed for the rough/rough combination (Parker Print-Surf 8.5 μm). This indicates that the interlocking of surface asperities is not a factor in increasing friction on the rough side of linerboard. The predominant mechanism of friction seems to be that of adhesion, which is enhanced by the larger contact area achieved with smooth surfaces.

Effect of relative humidity

Moisture plasticizes cellulosic fibers, making them more conformable. One would thus expect moisture content to have a significant effect on friction properties of the linerboard. An unbleached recycled liner and a kraft liner were conditioned at 90% RH and 23°C for 24 h and then tested at 90% RH. Moisture contents of the unbleached recycled and the unbleached kraft liners at 90% RH were 17.5% and 19.0%, respectively. **Table III** shows that the equilibrium slide angle increased significantly with humidity for both linerboards. We speculate that the increase in static friction could be due to either (a) fiber softening, (b) an increase in surface free energy (*19*), or even (c) an increase in segmental diffusion of hemicellulose chains because of a reduction in the glass transition temperature (*20, 21*).

Antiskid treatment

Surface treatment with colloidal silica increases the static friction of linerboard (*6–11*). After treating one side of an unbleached recycled linerboard with colloidal silica, we measured slide angle on treated-against-treated sides and untreated-against-untreated sides. The treated side showed a significant increase in slide angle, from 11° to 25°. This increase in slide angle was accompanied by an increase in surface energy from 26.8 mN/m to 39.8 mN/

m. We could not distinguish any differences in the surface structures of the treated and untreated sides based on Parker Print-Surf measurements. **Figure 4** shows that the treated and untreated sides were indistinguishable at low-magnification scanning electron microscopy (SEM). Some silica deposits on the fiber surface were apparent under high magnification.

Previous workers have attributed the improved friction properties of colloidal-silica-treated board to a fiber-stiffening effect (*8*). However, we believe that the major contribution to the increase in friction comes from the increase in surface free energy in the treated linerboard. This suggests that surface contamination may be the reason why the advantage of colloidal silica treatment is sometimes lost in the mill environment.

Effect of sheet properties

Figure 2 shows that there is some scatter in the points around the least-squares fit of the data. This indicates that static friction at the linerboard-linerboard interface is controlled by factors other than surface free energy. The data in Table I were examined using multiple linear regression analysis. The following relationship between slide angle (static friction), surface free energy, and moisture content was found:

$$\text{Slide angle} = -113.6 + 13.9\ (\%\ \text{moisture}) + 0.763\ (\text{surface free energy})$$

The fit, as expressed by r^2, was 0.96, and the standard error of the estimated slide-angle value was 1.82°. The regression coefficients for percent moisture and surface free energy were highly significant below the 1% level. The *t*-values for the regression coefficients indicated that surface free energy was the predominant factor, with moisture content having a smaller effect. Overall, the relationship indicates that 96% of variation in slide-angle (static friction) data in this particular experiment can be attributed to surface free energy and moisture content.

Conclusions

Static friction of linerboard is affected by several factors. Surface free energy had a significant influence on the static friction of the linerboard samples, indicating that adhesion at the linerboard-linerboard interface is the predominant factor controlling friction. Friction also increased with increasing moisture content. Improvements in friction properties of linerboard (i.e., increased friction) were obtained through antiskid treatment with colloidal silica and through solvent extraction of surface contaminants.

Interlab comparisons of friction results are commonly contradictory and confusing. This may in part be explained by the fact that surface chemistry of the samples is not considered. The results presented here show that surface contamination has a significant effect on friction properties. Extreme care must be taken to ensure that there is no contamination during sample handling and testing.

While this report is based on equilibrium slide-angle values, the initial slide angle may be more important in practical cases. Clearly, the static friction properties of linerboard involve complex mechanisms that require further research.□

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