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DETERMINATION OF THE FRICTION OF PAPER AND BOARD

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ABSTRACT

Three test methods for the determination of the coefficient of friction of paper have been investigated: inclined-plane, horizontal-plane and strip-on-drum. Significantly different friction values were obtained for the same paper samples by each of the tests and the reasons for some of these differences were studied. Aspects such as contact deformation, contact pressure, testing procedures both environmental and mechanical and the presence of extractives were found to influence the frictional properties of paper and board.

INTRODUCTION

The constantly changing sources of raw materials and ways in which paper is produced, processed and handled, requires a better understanding of how paper and board surfaces interact both with each other and with other materials during sliding.

There is evidence that the physical circumstances under which relative sliding takes place, whether in the friction of flat paper sheets in stacks, or in winding around rolls and capstans, as well as the ambient humidity and temperature conditions, are not only quite diverse but also influence the frictional behaviour of paper and board. The friction of paper against paper is thus of considerable importance in a range of handling, printing and conversion processes and is studied in the present work.

Paper-paper friction is influenced by both the physical nature and the chemical composition of the regions in contact. The wood species and the types of pulping and papermaking processes used determine the strengths of the inter-fibre bonds, the surface topography and the compressibility of the paper sheet as well as the amount of wood extractives present in the paper. During sliding motion only prominent features (asperities) on the uppermost fibre layers of the two sheets come into contact. However, the local contact forces will be influenced by the mechanical properties of the whole sheet thickness and as substances can readily migrate from within the paper structure to the surface and influence the contact area; the whole paper structure must therefore be considered in any discussion of paper friction.

The coefficient of friction (symbol μ) between two bodies is a dimensionless ratio between the tangential force, F, and the normal load, N, on the bodies during or at the point of sliding. In the former case, the value of μ is usually termed the coefficient of kinetic friction, μ_k, while the value when the system is just on the point of sliding under an increasing tangential force is called the coefficient of static friction, μ_S. The friction of a material such as paper, in which adhesive forces act locally at the contact points, and energy is also dissipated through fibre motion more deeply within the structure, can be treated as arising from two contributions: adhesion, μ_{ad} and hysteresis or deformation, μ_d :

$$\mu = F/N = \mu_{ad} + \mu_d \qquad (1)$$

This approach is also applicable to polymeric materials, and has been widely used by tribologists in that context. The adhesion term is associated with surface effects occurring to a depth of a few molecular layers on either surface. In paper it will originate in hydrogen bonds, van der Waals forces and other surface charge effects, while the deformation term is a bulk phenomenon (1-3). The effects of ploughing or grooving by the action of hard asperities can be treated as contributing to the hysteresis term (3).

Equation (1) has been used in some previous work on paper friction, by Bayer and Sirico (4), who treated the deformation component as arising predominantly from abrasion rather than from hysteresis. Back (5), however, considered the cohesion of the fibre network and the local deformation around the area of surface contact to control the frictional properties of paper, and dismissed suggestions that the surface energy (and hence interfacial adhesion) was the only significant influence on static friction for linerboard samples (6).

Borch (7), in contrast, maintained that interfacial adhesion controls friction. Gurnagul et al. (8) have suggested that the adhesion component of friction depends upon viscoelastic properties, with the sliding speed, temperature, and contact pressure between the sheets being important factors. It is thus clear that there is significant disagreement between previous investigators about the relative importance of the contributions from adhesion and deformation to paper-paper friction.

The influence of surface species present on the fibres has been studied by few authors. When wood extractives, a heterogeneous mixture of low molecular weight aliphatic substances such as fatty acids and sterols, are present on the paper surface they are found to reduce the surface energy and also the coefficient of friction (5). Higher molecular weight resin acids, steryl ethers and glycerides, however, appear to increase the friction despite producing low energy surfaces. It is possible that these apparently conflicting results may be associated with the boundary lubricating properties of the extractives when present on fibre surfaces (2, 3). Various solvents have been used to remove contaminants: in one reported investigation, linerboard samples were simply immersed in hexane for 30 minutes (6), while Back (5) carried out repeated extractions with chloroform followed by acetone in a Soxhlet extractor to ensure that not only the oleophilic materials but also the aluminium soaps were removed. Other investigators have extracted newsprint for four hours using high grade chloroform in a Soxhlet extractor (8).

Recycling has a significant influence on the static friction of papers made from chemical and mechanical pulps (5, 7). However, controlled laboratory recycling has shown that these changes in friction are only indirectly related to the physical and chemical changes that occur, and more directly related to the incorporation of contaminants into the recycled pulps (9).

The standard friction testing methods, as recommended by TAPPI, CPPA and ASTM etc., are the inclined-plane and the horizontal-plane methods, illustrated in Figure 1. Both methods use a fixed plane sheet sample, and a weighted sled to which the second sample is fixed. In the horizontal plane method, the tangential force needed to drag the sled along the plane at a fixed speed is measured with a calibrated load cell. In this way both static and kinetic friction can be determined. In the inclined plane test, the stationary sled is placed at one end of the sloping plane; its angle of inclination is then gradually and smoothly increased until the sled starts to slide. This method yields the coefficient of static friction only, from the value of the angle θ at which sliding starts:

$$\mu_s = \tan\theta \qquad (2)$$

Some standard methods for the determination of friction fail to specify critical details of the apparatus or test procedure, and the results can thus be both operator- and machine-dependant. In some standards the reported results are based on the average of replicated initial tests, each carried out with fresh samples, while others recommend the reporting of the value determined from the third sequential test with each pair of fresh samples; yet some authers have reported the average of five consecutive sliding tests (5, 8).

There are several problems of definition associated with the horizontal plane method related to the sledge weight and positioning, the softness of the material used to back up the paper sheet on the sled, the sliding speed and distance, as well as the number of repeated tests. Johansson et al. (10) have proposed a sledge weight of 915 grams, corresponding to a mean surface pressure of 2.5 kPa, as suitable for all types of paper. Based on their findings a revised horizontal plane testing apparatus and ISO test method have been proposed, in which the static coefficient of friction is derived from the results of the first sliding test (11). In this method the sledge, backed with soft foam rubber, exerts a pressure from 80 to 500% of that specified by the TAPPI methods for corrugated and solid fibreboard and for writing and printing paper respectively. It is claimed that the friction values determined by the ISO method are independent of the apparent surface pressure. The average result of the third sliding friction tests, over the 40 to 60 mm sliding distance, is used to calculate the coefficient of kinetic friction.

In order to provide a better simulation of the contact conditions in some papermaking and converting operations, in which paper webs are held under tension during sliding contact around mandrels or rolls, a new strip-on-drum apparatus has been devised which differs significantly from the horizontal- and inclined-plane tests. The method, also illustrated in Figure 1, involves measurement of the tension at the fixed end of a paper strip hanging round a rotating drum which carries the second paper strip. The method is also used in the rubber and textile industries (12, 13). Detailed consideration of the mechanics of the test shows that the tension in the strip, and the mean pressure between the strips, both vary around the contact arc (14). The mean coefficient of friction between the strips is simply derived from the tensions T_1 and T_2, and the arc of wrap (in this case 90°) by the well-known 'capstan equation':

$$\mu = \frac{2}{\pi} \ln\left(\frac{T_2}{T_1}\right) \qquad (3)$$

By imposing a slow rotation on the drum and continuously measuring the tension in the strip, both static and kinetic friction can be determined. The method is currently under consideration as a general ASTM standard for the determination of friction between a web material and a drum (15).

MATERIALS AND EXPERIMENTAL METHOD

Ten different paper products were used during this investigation: a non-recycled and a recycled Kraft board (designated L1 and L2); a non-recycled newsprint and two newsprint samples with 50% and 80% recycled content (NP1, NP2 and NP3); three samples of writing paper containing different levels of mineral pigments and cotton fibres (WP1, WP2 and WP3); and two cotton linter samples, one made of lightly beaten and the other of well-beaten fibres (C1 and C2). These samples were chosen to investigate the influence on friction of extractives, the fibre structure and composition of mechanical and chemical pulps, the presence of contaminants from recycling and the degree of interfibre bonding. The sample were all well characterised by a variety of methods, and are more fully described in Table 1.

SAMPLE	CHARACTERISTICS
L 1	100% non recycled, >90% SW KP, 0.05% ash, 200 g/m^2
L 2	100% recycled, mixture of SW and some HW, 21% ash, 220.5 g/m^2
NP 1	100% non-recycled, >90% TMP, HW+SW mix, 0.25% ash, 45.3 g/m^2
NP 2	50% DIP, 80% TMP + 20% KP, HW+SW mix, 4.1% ash, 45.0 g/m^2
NP 3	80% DIP, 60% TMP + 40% KP, HW+SW mix, 3.4% ash, 43.0 g/m^2
WP 1	mainly HW, trace SW, 20% cotton fibres, 15% chalk, retention aid, 83.6 g/m^2
WP 2	mainly HW, trace SW, 15% cotton fibres, 7% chalk, retention aid, 80.5 g/m^2
WP 3	mainly HW, some SW, 7% cotton, 3% chalk, retention aid, 80.9g/ m^2
C 1	100% cotton linters, lightly refined, 0.007% ash, 85.9 g/m^2
C 2	100% cotton linters, highly refined, 0.007% ash, 100.0 g/m^2

L = linerboard; NP = newsprint; WP = filled writing paper and C = cotton linters.
SW = softwood; HW = hardwood; KP = Kraft pulp; TMP = thermo mechanical pulp; DIP = de-inked pulp

Table 1 - List of the samples used and some of their characteristics.

The effects of surface contaminants and wood extractives were studied by removing them from the samples, by extracting the specimens in a Soxhlet extractor with chloroform for two hours followed by high purity acetone for one hour.

Three different test methods were used to explore the frictional behaviour, as explained in the previous section: the inclined-plane, horizontal-plane and strip-on-drum methods (Figure 1).The coefficient of friction was determined under standard testing conditions (temperature 23 ± 1°C and relative humidity 50 ± 2%; samples were conditioned for >24 hours before testing), except where otherwise specified.

The inclined and horizontal plane tests were generally performed according to standard procedures defined by TAPPI T815 om-95 for the inclined-plane method and T816 om-92 for the horizontal-plane method. For the inclined-plane method the angle of inclination was increased at a smooth rate of 1.5 ± 0.5° per second and the sledge exerted a pressure of 2.45 kPa at $\theta=0°$. For the horizontal plane method the sledge exerted a pressure of 0.86 kPa and was moved at 2.5 mm/s for a distance of 80 mm over the fixed sample. In both tests the sledges were rubber-backed. In the inclined- and horizontal-plane methods, both the method of placement of the sledge and the time at rest before sliding were found to influence the measured coefficient of friction. Backward sliding of the sledge and/or its misplacement (i.e. non-parallel to the axis of the lower sample) resulted in lower values of μ_S, while leaving the sledge at rest for significantly more than 20 s gave a consistent small increase in μ_S. While these changes in friction were small, they were clearly potential sources of error, and standardised procedures were therefore introduced in this work which involved mechanically placing the sledge to prevent backsliding or misalignment, and ensuring that the time at rest was constant at 20 seconds.

The strip-on-drum test was performed with the apparatus described by Sato *et. al.* (14); the stationary strip was 30 mm wide and the strip on the moving drum was 60 mm wide. The angle of wrap was 90° around a drum of diameter 110 mm, as illustrated in Figure 1. The tensile load applied to the free end of strip T_1 was between 2.9 and 10.8 N. This load was chosen to be within the elastic deformation regime, as determined for each sample from ten tensile stress-strain curves.

The influence on friction of sample orientation and sliding direction was examined and in all cases care was taken to orient the samples during the friction measurements in a well-characterised manner. Experiments were performed with the sliding in the machine direction (MD), and were made parallel to the manufacturing direction (MD+) and in some cases antiparallel (MD-); other tests were made with sliding in the cross-machine direction (CD) and in some intermediate orientations. Most tests were performed with the felt side (FS) of one sample sheet in contact with the wire side (WS) of its counterpart, in order to simulate practical winding and sheet stacking operations.

Five frictional tests were performed with each pair of specimens by each method, but only the results of the initial sliding tests were used to calculate the coefficient of static friction; the subsequent tests were used to explore the trends in μ with repeated sliding. Each experiment was replicated five times with different samples.

Scanning electron microscopy (SEM) and in some cases atomic force microscopy (AFM) were used to characterise the surface changes caused by sliding. Non-contact profilometry was also used to examine some of the paper surfaces before and after sliding.

RESULTS

Influence of the test method and sample orientation

The strip-on-drum apparatus allowed the friction force to be measured continuously during relative displacement of the paper samples. Figure 2 shows typical records, for a Kraft linerboard sample (L1), plotted in terms of the coefficient of friction (derived from the measured and applied tensions T_2 and T_1 through equation (3). Two curves are shown: for the first and third tests on the same, initially fresh, pair of specimens. The form of the first curve is typical of that seen in the initial sliding contact of all the fresh paper samples and indicates a coefficient of static friction (represented by the peak friction reached after a certain amount of displacement) which is typically greater than the kinetic value applicable once sliding was established. Subsequent sliding of the same specimens led in all cases to a reduction in the value of peak friction (i.e. μ_s), but to little or no change in the plateau value (μ_k), so that after some four or five repeated sliding contacts the values of μ_s and μ_k were effectively the same.

Strip samples cut at different orientations to the MD were used in the strip-on-drum apparatus to explore the variations of friction with direction of sliding relative to the paper structure. Experiments were performed in which sliding occurred parallel to the machine direction (MD+) on the felt side of one sheet and the sliding direction on the WS of the counter-sample was changed progressively from MD+ to CD. Tests were also performed with sliding in the CD on the WS of one sample, in contact with the FS of the counter-sample with its sliding direction varied between MD+ and CD. Typical results of these tests, for the L2 linerboard sample, are shown in Figure 3. For this sample, as in the cases of all the other machine made papers, significant variations in friction occurred; the highest friction was observed for sliding in the cross machine direction, with the paper structure parallel (i.e. MD+ parallel to MD+), while the lowest friction was found for sliding along the machine direction, again with the structure parallel.

Tests were also performed to examine whether friction was influenced by the sense of sliding, for samples sliding parallel to the machine direction in both sheets. Sliding pairs were distinguished in which the machine directions of the two sheets were parallel (designated MD+/MD+) and antiparallel (MD+/MD-), and the two possible directions of sliding were explored in each case. Figure 4 shows the results from experiments on the 100% non-recycled pulp linerboard (L1) with these two pairings. The two possible directions of sliding in each case gave similar friction coefficients, but there were significant differences between the pairings, whether contact was WS versus FS, WS versus WS or FS versus FS. For no other paper sample were such effects observed. Examination of the surface of the L1 linerboard revealed that it possessed a pronounced topographic texture, shown clearly by illumination with a low-angle light source, with ridges ca. 1-3 μm high (higher on the WS than on the FS) aligned at an angle of ~15° to the machine direction (Fig. 5). The other samples showed no such modification of the surface.

The effects on friction of repeated sliding were examined in detail by removing the load on the samples in each case, returning the samples to their starting positions, reloading, and repeating the friction measurement on the same sample contact area. The data in Figures 2 and 4 were gathered in this way. Figure 6 shows more comprehensive results from the repeated sliding tests, and also illustrates the similarities between the static friction measured by the three test methods, for all ten paper samples. In each case the value of μ_s fell with repeated sliding and tended towards a value close to the value of μ_k measured by the same test method (where possible), which remained essentially constant over the number of cycles examined. For initial sliding on virgin samples, the static friction measured by the horizontal-plane method was typically 15-20% lower than that measured by the inclined-plane test and some 25-30% lower than that derived from the strip-on-drum method.

Effects of contact pressure

The influence of the normal contact pressure between the two surfaces during sliding was studied by increasing the weight of the sled used in the inclined-plane tests and by increasing the dead weight load attached to the free end of the paper samples in the strip-on-drum test (Fig. 1). The static friction measured by the inclined-plane method showed little or no change with increased contact pressure (Fig. 7a), while values determined from the strip-on-drum method in some cases decreased significantly with increasing contact pressure (Fig. 7b). This decrease was not, however, the same for all samples.

Effects of contaminants

The behaviour of the solvent-extracted samples was compared with that of the as-received, conditioned materials. In each case, whether solvent-extracted or not, the samples were conditioned for at least 24 hours under standard conditions before testing. For the extracted samples the static friction was consistently and significantly higher than for the as-received samples. The smallest increase occurred with the 100% cotton linters (Fig. 8a), followed by the writing papers and the linerboards (in increasing order), while the mechanical pulp newsprints, made from non-recycled and recycled TMP (Fig. 8b) showed the most significant increase in static friction. All three friction test methods were used for these studies and led to qualitatively similar conclusions.

Scanning electron microscopy and atomic force microscopy

Scanning electron microscopy before and after sliding showed that each sliding contact was associated with progressive disruption of the surface fibres. In the poorly-bonded sheets (C1 and the newsprint samples), this disruption consisted in the breakage of fibrils bridging fibres on the top surface layers after only one sliding contact (Fig. 9a). The paper structure became increasingly disrupted when three or more sliding tests had been carried out, associated with fibre debonding and the formation of a fine layer of fibre debris between the sliding surfaces (Fig. 9b). In well-bonded sheets (linerboard sample L1) burnished areas and some fibre debonding were present, as seen in Figure 10. The ploughing effects of large mineral particles present on the surface of the recycled linerboard (L2) were evident after the first sliding contact (Fig. 11). And higher resolution images of the sizing layer of the same sample (L2) showed that this very thin layer was disrupted by the first sliding contact and suggested that during subsequent contacts the surfaces became separated by a fine layer of debris (Fig. 12).The calcium carbonate-filled writing papers showed a small increase in static friction with sliding contact, during the inclined and horizontal plane tests, believed to be associated with a redistribution of the mineral filler present on the surface (Fig. 13a), caused in part by the disruption of the retention aid. Further contacts led to significant debonding of the fibres and to the comminution of the filler particles, which formed a fine, loose powdery layer between the sliding surfaces (Fig. 13b).

Atomic force microscopy, at the nanometre scale, indicated that the prominent areas of the two surfaces that come into contact during sliding were burnished even after a single test at minimal contact pressure (Fig. 14a). For filled papers, redistribution and grinding of the filler particles was observed on the surface of the top fibre layer (Fig. 14b). These results were also observed during non-contact profilometric studies of the same samples of linerboard (Fig. 15a) and writing paper (Fig. 15b).

DISCUSSION

The results presented above have illustrated that values of coefficient of friction for paper sliding against paper can vary over a wide range, from below 0.2 to almost 0.9 in this work, between different paper samples and, importantly, under different conditions of measurement. The coefficient of friction is thus not an intrinsic property of the material. The presence of extractives can have a major influence on friction, but it is clear that other aspects of the paper structure (such as fibre properties, sheet structure, the presence of binders, fillers, and contaminants etc.) also have major effects on the frictional behaviour.

The three test methods used in this work all gave reproducible values for the coefficient of friction, but there were consistent differences between the values determined by the different methods. Several factors can be identified which underlie these differences. It has been shown in earlier work (5, 14) that the friction of paper against paper does not obey Amontons' Laws perfectly: the coefficient of friction is not independent of contact pressure. In this respect, the behaviour of paper is no different from that of organic polymers, in which load-dependence of friction arises from the elastic nature of the contact deformation (3). This effect provides one important and direct explanation for the differences in friction measurements from the different methods; it is worth noting that the mean contact pressure itself varies with the level of the frictional force in both the inclined-plane and the strip-on-drum methods. The strip-on-drum method differs significantly from the other two in that one of the paper strips is under substantial tension during the test, which may tend to modify both the sheet structure and its response to compressive loading. Although it would in principle be possible to perform the horizontal-plane and inclined-plane tests with the fixed sample under tension, this is not normally done.

A further, more subtle, reason for the differences observed between the test methods may lie in the distribution of contact pressure over the nominal contact area in each case. The normal pressure varies round the arc of contact in the strip-on-drum test in a well-defined way (14). In the other tests it will also vary, although in a less-readily analysed manner which depends on the detailed geometry of the sled, the point of application of the tensile load in the horizontal-plane test, and on the compliance of the backing material. For a material such as paper in which the coefficient of friction varies with the contact pressure, these effects will lead to apparent variations in the measured coefficient of friction.

This work has also illustrated the importance of several aspects of the testing procedure in achieving reproducible and meaningful measurements of friction. Sample orientation and sliding direction must be defined and controlled; apart from the more gross effects of the paper surface (wire side or felt side) and sliding direction relative to the machine direction, the precise sense of sliding (whether parallel or antiparallel to the machine direction, for example) can also be important in the case of some papers with significant structural or surface directionality. Studies of the effects of repeated contacts (as shown in Figure 6) have highlighted the large changes in static friction which can occur in some papers on repeated sliding over the same area, which are associated with detectable morphological changes; values of kinetic friction, in contrast, show much less change. Such effects raise the question of the wisdom of quoting, say, the mean friction derived from a sequence of measurements on the same pair of samples, rather than the mean of a series of replicated tests on fresh samples.

Friction measurements on samples with and without solvent extraction have confirmed earlier work (5, 6, 8) which showed the importance of extractives in the friction of some papers. For the samples with high levels of extractives (the newsprints) the effect was very marked, while for those with a lower level (the cotton linters) the effect, although still detectable, was not so great. In all cases extraction led to an increase in friction, suggesting that the extractives have a lubricating effect.

The effect of extractives on friction cannot readily be explained by a change in the level of viscoelastic energy dissipation within the fibre array, but is more consistent with modification of the adhesive forces acting between the surfaces of the fibres in contact. The increase in static friction observed with prolonged static contact times is also consistent with an increase in the strength of inter-fibre adhesive forces. However, the clear evidence of a dependence of friction on contact pressure, as seen in the strip-on-drum results, as well as the structural damage associated with repeated sliding contacts, suggest that there must be at least some contribution to friction from subsurface deformation. It would seem to oversimplify the problem to ascribe the friction of paper to either adhesion or deformation alone.

CONCLUSIONS

Frictional properties vary markedly between different papers, but although they are influenced by a diversity of morphological and chemical factors intrinsic to the paper sample, they also depend on the mechanical and environmental conditions under which the tests are performed.

Significantly different values of coefficient of friction are determined by the three test methods investigated: inclined-plane, horizontal-plane and strip-on-drum. Some reasons for these differences are now clear, and must be appreciated in interpreting test results and in devising standard test procedures. In conducting friction tests, stringent control must be placed on sample orientation and sliding direction, as well as on contact pressure. Large changes in friction may occur on repeated sliding over the same area, which can cause significant damage to the paper surface, and these effects must be recognised in test procedures.

The strong influence on friction of the presence of extractives suggests that surface forces play a role in the friction of paper, but the mechanism almost certainly also involves dissipative processes more deeply within the sheet; the friction of paper, as of many other materials, must be ascribed to a combination of surface adhesive forces and deformation processes occurring within the bulk.

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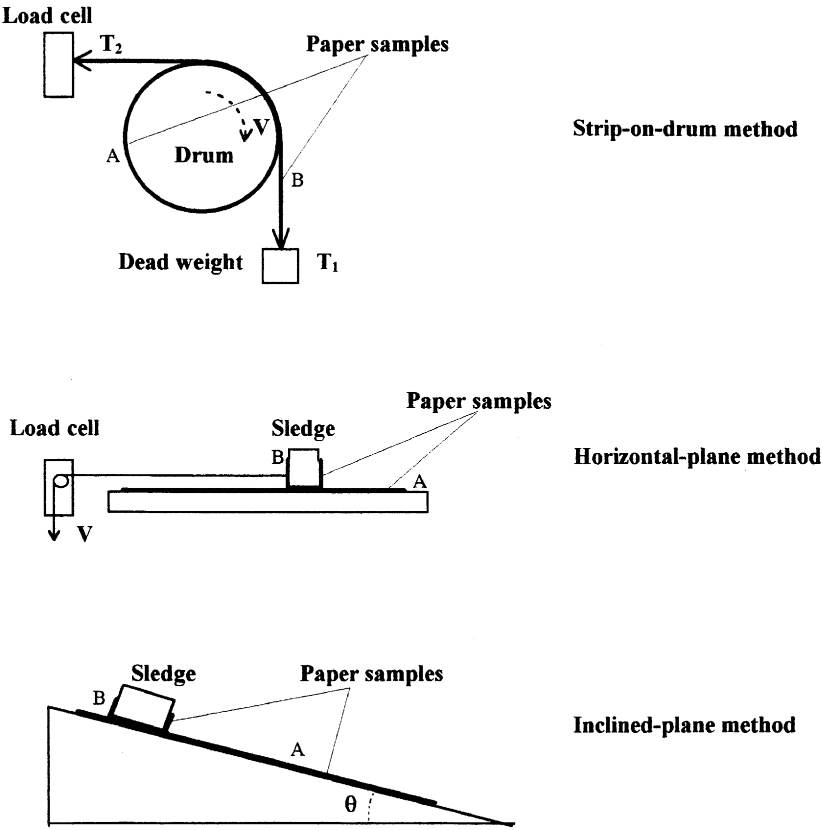


Fig.1 - Schematic representation of the three testing methods used to determine the μ_s. The first two methods were also used to determine the μ_k. The surface in contact on paper sample B stays constant while the area in contact for sample A is continuously changing during sliding contact during all three tests.

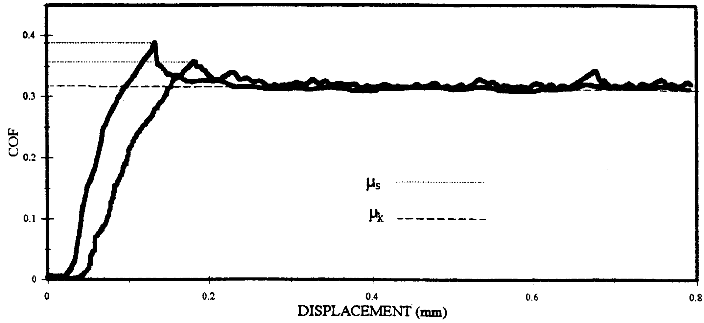


Figure 2 - The first and third continuous coefficient of friction (COF) displacements plots obtained with the strip-on-drum apparatus for linerboard L1. The maximum value corresponds to μ_s and it decreases with each sliding contact so that after four or five frictional contacts, with the same pair of paper samples, μ_s and μ_k are essentially the same.

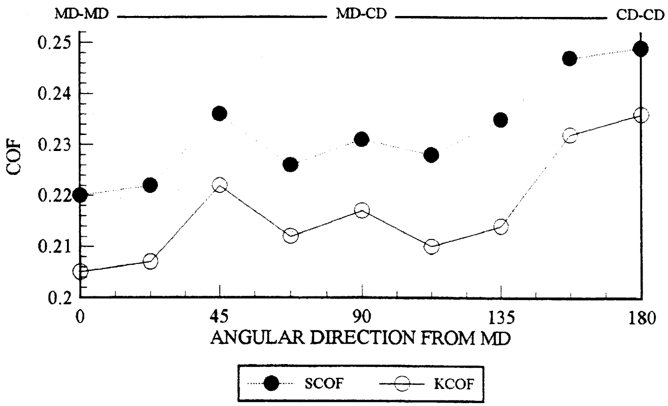


Figure 3 - Effects of sliding direction, as described in the text, determined for samples of linerboard L2 by the strip-on-drum method. Tests with CD-CD produced the highest coefficient of friction results while those with MD-MD gave the lowest, for all three testing methods.

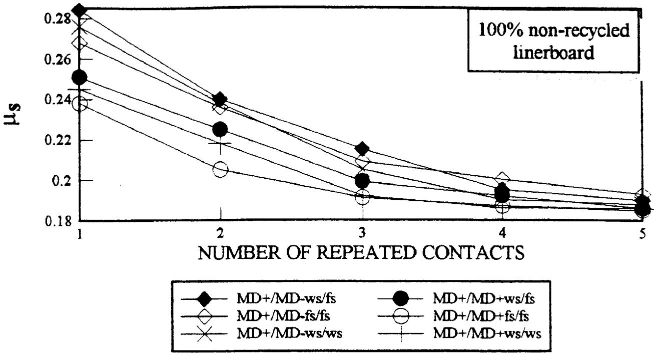


Figure 4 - Effects of relative sheet orientation and number of sliding passes, determined in the strip-on-drum test for linerboard L1, for sliding parallel to the machine direction. The orientation of the paper sheet during testing has implications for μ_s only in the cases where the paper surface has been modified, as in this linerboard.

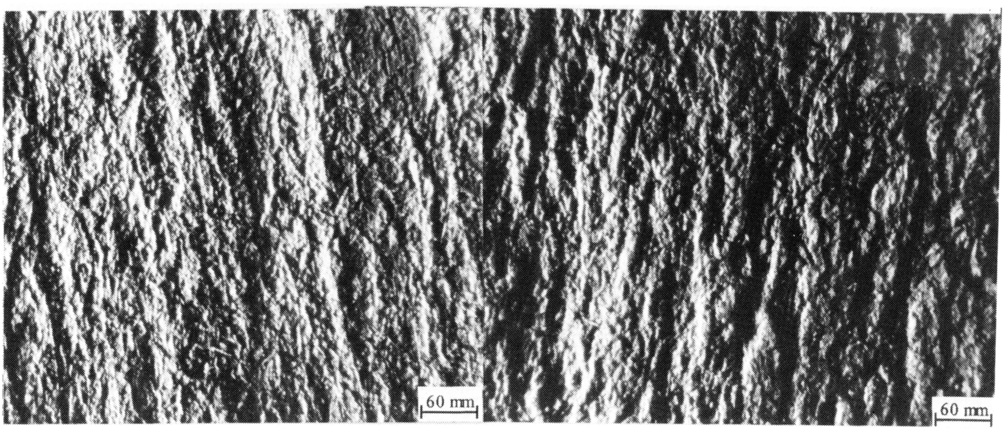


Figure 5 - Optical micrographs of linerboard L1 taken with reflected light incident at a ~10° angle to the paper surface; (a) felt side, showing a pattern of ridges at a 10-15° angle to MD with a valley depth of ca 1.5μm, spaced ca 1.0 mm apart; (b) wire side showing a pronounced but ill-defined ridging at a similar angle to MD with a valley depth >3μm.

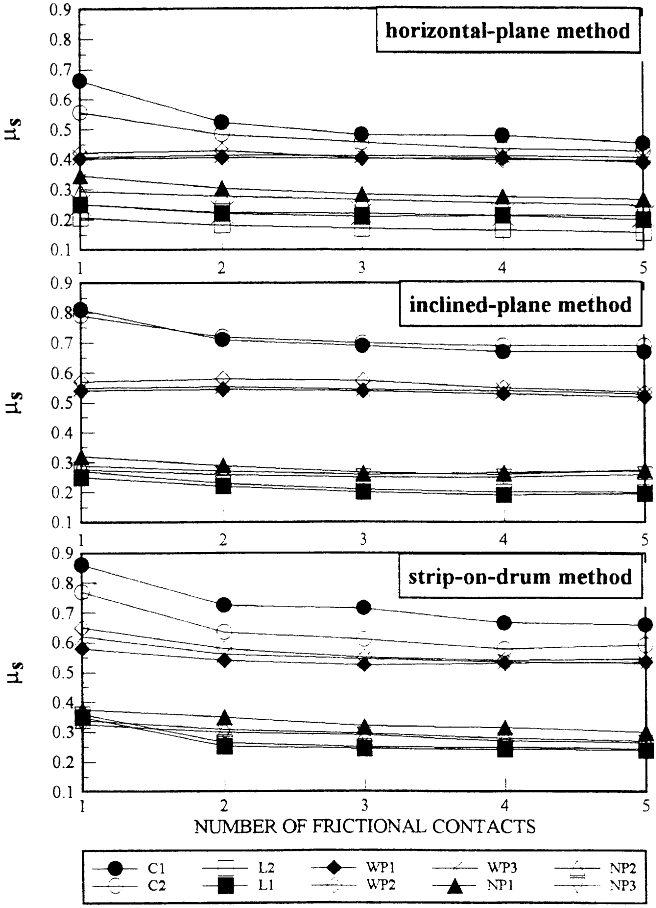


Figure 6 - The effects of repeated sliding contacts on μ_s. All three methods indicate that there is a decrease to a plateau value that is equivalent to μ_k.

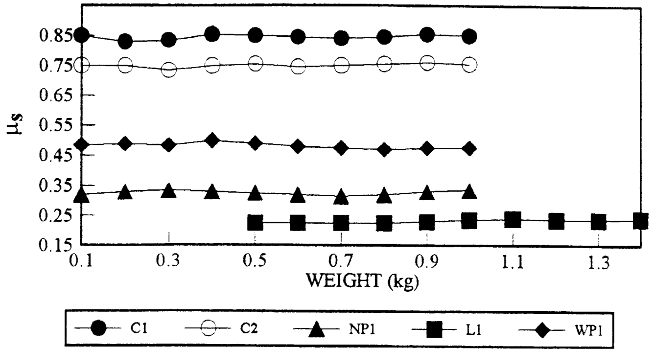


Figure 7a - Static friction determined by the inclined-plane method for different sled weights. Increasing the contact pressure had little or no effect on μ_s.

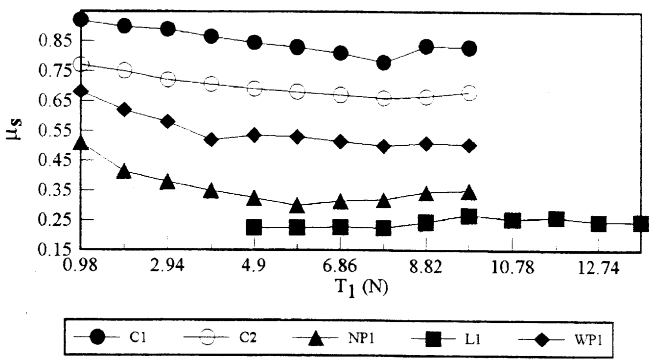
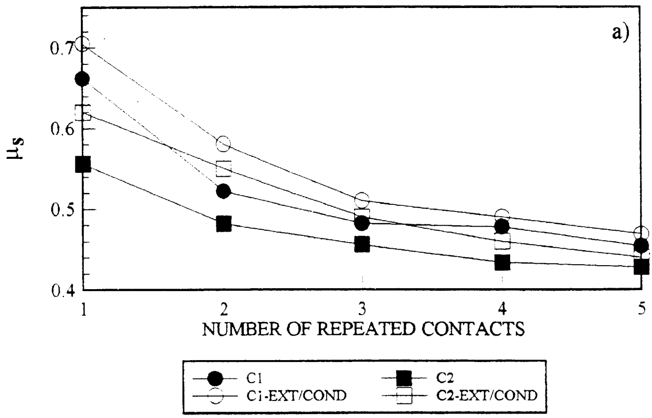


Figure 7b - Static friction determined by the strip-on-drum method for different strip tensions, controlled by the dead weight load T_1. In some cases μ_s decreased significantly as T_1 was increased.



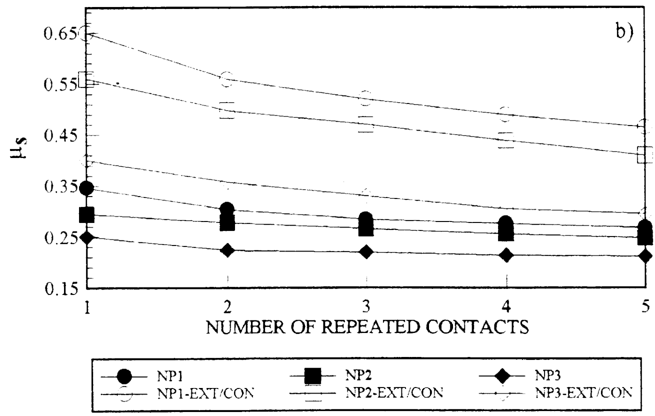


Figure 8 - Effects of wood extractives removal, followed by environmental conditioning, on static friction determined by the horizontal-plane method: (a) cotton linters samples with a low extractives content: (b) newsprint samples with a high extractives content.

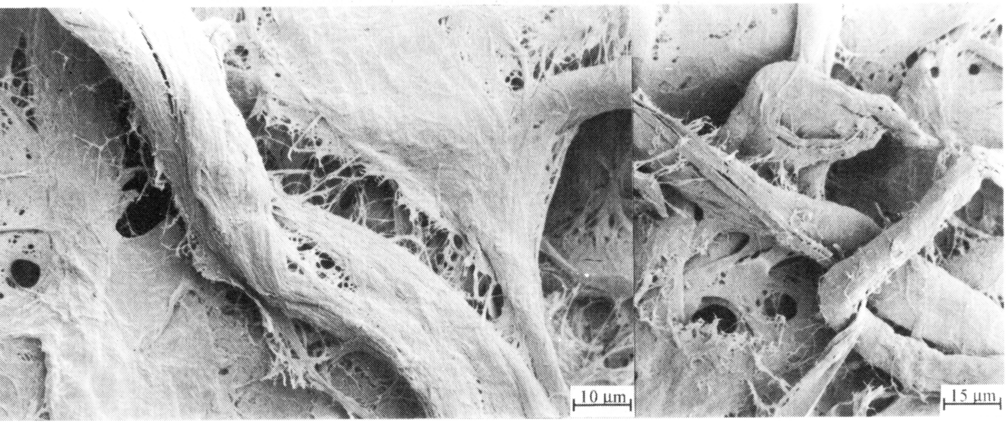


Figure 9 - SEM micrographs of the surface of a poorly bonded cotton linter sample (C1); (a) the effects of a single frictional contact which has caused fibrils bridging fibres on the top fibre layer to break; (b) the effects of five repeated contacts which have led to extensive disruption of the top few fibre layers and the formation of fibre debris between the sliding surfaces.

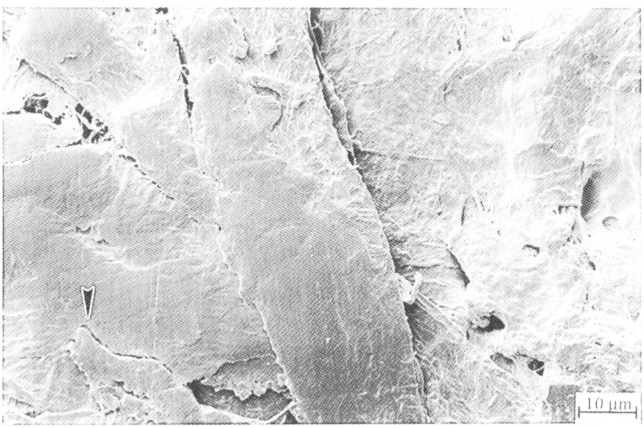


Figure 10 - SEM micrograph of a well-bonded linerboard sample (L1), showing the development of burnished areas and some fibre debonding which is indicated by the arrow.

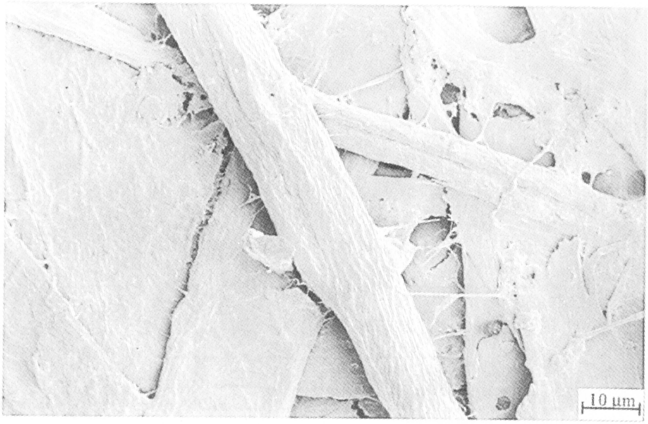


Figure 11 - SEM micrograph of the surface of a linerboard made from 100% recycled pulp (L2), showing the ploughing effects of hard mineral particles, fibril breakage and fibre debonding after one sliding contact.

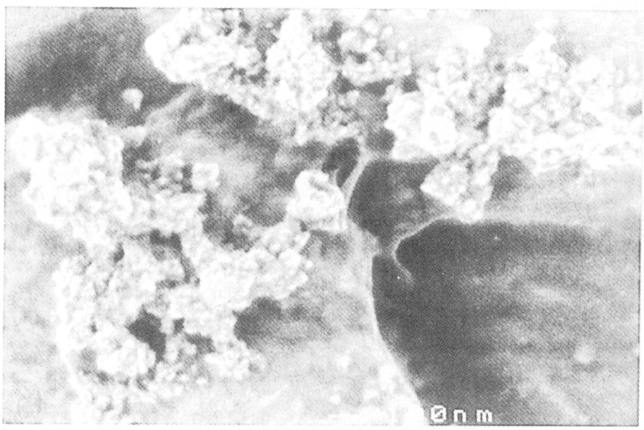


Figure 12 - High magnification FEGSEM micrograph of the 100% recycled linerboard (L2) surface showing the disruption caused by a single sliding contact to the sizing layer.

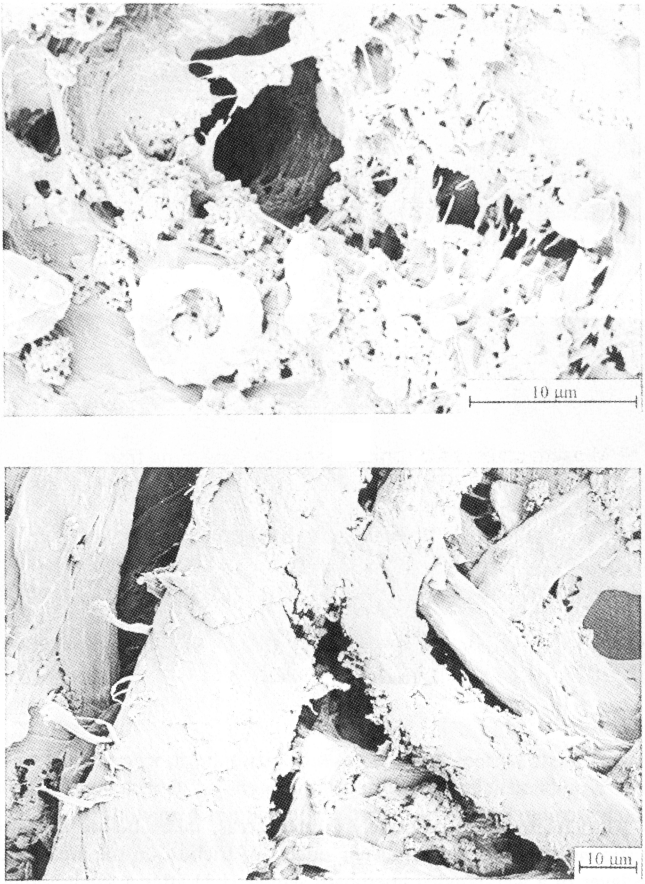


Figure 13 - SEM micrographs of the surface of writing paper (WP1): (a) disruption of the mineral filler distribution resulting from a single sliding contact; (b) extensive debonding and the comminution of mineral fillers as a consequence of further contacts.

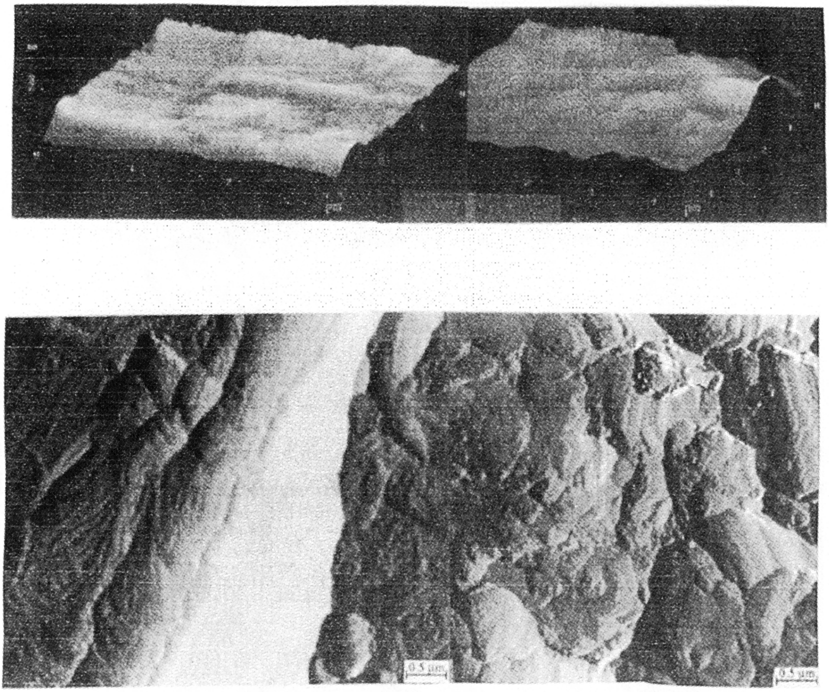


Figure 14 - AFM micrographs of closely located areas, taken before and after sliding contact: (a) showing micro-scale burnishing effects of friction on the areas in contact in the top fibre layer of a well-bonded linerboard sample (L1) after a single sliding contact; (b) showing extensive redistribution and comminution of the mineral filler particles on the surface of a writing paper (WP1) after three sliding contacts.

Editors note : A colour version appears on page 1326 immediately preceding this paper

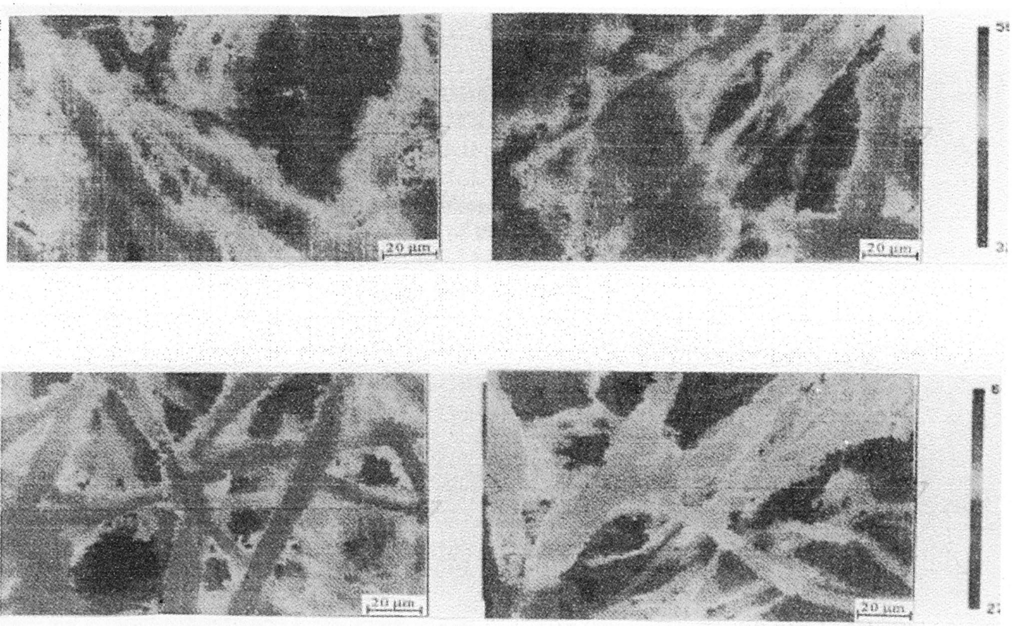


Figure 15 - Non-contact profilometry studies of closely located areas taken before and after three sliding contacts: (a) showing the burnishing and debonding effects of sliding friction on Li; (b) showing disruption of the paper surface and redistribution of the mineral particles on the surface of WP 1.

Editors note :A colour version appears on page 1327 immediately preceding this paper

Transcription of Discussion

Determination of the Friction of Paper and Board

Glynis de Silveira, Consultant, Cambridge University, UK

Christer Fellers, Senior Research Scientist, STFI, Sweden

While I agree with most things you have said, I don't agree with what you said about kinetic friction being equal to static if you do sufficiently many slidings. At STFI we have tested tonnes of paper with our friction tester and we don't find that. In some cases this is true but in some it is not. You seemed to propose that this is a general law.

Glynis de Silveira

Yes, I found this to be true with most of the samples tested in the strip-on-drum method. The number of repeated slidings necessary for the static and kinetic frictions to be similar depended on the speed of the sledge in the horizontal-plane method. But in the strip-on-drum method this was consistently so, independent of the rotational speed of the drum. I think that the Coefficient of Friction vs Displacement traces I showed attest to this fact.

Christer Fellers

Is the speed of sliding slow?

Glynis de Silveira

Yes, it was as low as 500 µm per second.

Christer Fellers

Yes, well then I understand the result, and we have found approximately the same results for very low sliding speeds.

Professor Jean-Claude Roux, EFPG, France

Have you tried to do your test measurements with applying the same pressure on the paper samples?

Glynis de Silveira

Yes.

Jean-Claude Roux

And do you find a different co-efficient of friction.

Glynis de Silveira

Yes.

Jean-Claude Roux

Isn't it surprising to get different co-efficients because it's a physical property of both surfaces?

Glynis de Silveira

The coefficient of friction depends partly on the deformation of the paper. When different types of paper were subjected to the same load the amounts of deformation obtained were different. And this may account for the differences in the coefficient of friction. The same was believed to occur when a tensile load was attached to the top paper strip in the strip-on-drum test but in this case the deformation took place along the whole paper strip and not only locally as was the case for the other two tests.

Ilka Kartovaara, R&D Vice President, Enso Group, Finland

You state that the friction co-efficient is composed of two parts, the adhesive and the deformation component. In fact in practically all cases in your experimental results, the friction co-efficient decreases as you increase load. How do you reconcile this with your theoretical aspect?

Glynis de Silveira

These tests were always performed on a set of fresh paper samples. The coefficient of friction results obtained with the inclined and horizontal plane methods seem to be independent of the loads applied. However, when tensile loads were applied in the strip-on-drum method of the coefficient of friction decreased. I believe this results from the increased deformation of the sheet structure. Hard contaminant particles and/or fillers pigments modified the deformation mechanism of paper and as a consequence the coefficient of friction changed.

Mark T Kortschot, Associate Professor, University of Toronto, Canada

My guess is that friction is rather complicated to measure and when we find material properties like this, often we choose to simulate the end use condition as closely as possible.

Glynis de Silveira

Yes.

Mark Kortschot

Can you give me an idea of how closely the pressures and tensions and so on in the friction tests that you are doing simulate conditions of end use.

Glynis de Silveira

I tried to simulate these parameters taking into account the paper tube making process which was of special interest to this project. I was also trying to simulate the tensile forces to which paper is subjected during some other processes. One of the main conclusions of this work is the need to specify which test method was used and not state only the coefficient of friction value determined. And the test method used should simulate the end-use of that particular paper sample. This is a result of the different values of coefficient of friction determined by the three test methods investigated.