

Friction of Linerboard Based on Recycled Fiber

NIKLAS GAROFF, NILS-OLOF NILVEBRANT, CHRISTER FELLERS

Swedish Pulp and Paper Research Institute, STFI, Box 5604, SE 114 86 Stockholm, Sweden

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ABSTRACT: The purpose of this investigation was to study the origin of the differences in paper-to-paper friction of linerboards based on old corrugated containers (OCC). The sheets were subjected to two extraction stages and analyzed with respect to, surface roughness, and their content of low-molecular-mass lipophilic compounds (LLC). Friction was measured using a friction tester based on the horizontal plane principle. The surface roughness was measured using a Perthometer profiler and the low molecular mass lipophilic constituent of the paper sheets was determined by gas chromatography-mass spectroscopy. The sheets were imaged using environmental scanning electron microscopy (ESEM), and the relative compositions of inorganic ions on the paper surfaces were determined by energy dispersive X-ray spectroscopy (EDS). The results showed that a high amount of LLC in the sheets lead to low friction, due to lubrication. It was also observed that large CaCO_3 particles on the surface had a friction-increasing effect, and that there was no relationship between the surface roughness and the friction. © 2002 Wiley Periodicals, Inc. *J Appl Polym Sci* 85: 1511–1520, 2002

Key words: fibers; surfaces; separation techniques; mass spectrometry; shear

INTRODUCTION

Friction is important during the manufacture and end-use of many paper grades. Specifically, linerboard used for the outer layers of corrugated board must have high friction to avoid slippage during transportation and storage.¹ It is a common experience in the paper industry that the friction of liners and in particular OCC (old corrugated containers) paper grades may vary significantly.

During papermaking fibres tend to be more oriented along the machine direction (MD) than the cross direction (CD). However, the sheet orientation has no effect on paper-to-paper friction.² The effect of surface roughness on paper friction

has been investigated in many studies, but contradictory conclusions are drawn in the reports. Broughton and Gregg³ report that rough paper surfaces have higher a friction than smooth paper surfaces, and conclude that paper friction is governed by the abrasion of surface asperities. On the other hand, Jones and Peel⁴ and Fellers et al.⁵ concluded that paper friction is independent of surface roughness. The results of several studies show that paper friction is strongly lowered by small amounts of certain low-molecular-mass lipophilic compounds occurring in wood, pulp and paper.^{1–3,6–9} For example long-chain saturated hydrocarbons with a hydrophilic head group have lubricating abilities, when added to the paper.^{3,9} Several authors propose lubrication mechanisms that have strong similarities to boundary lubrication.^{1,2,7–9} The effect of extractives and contaminants on the paper friction has in some investigations been partly attributed to the fact that they modify the surface free energy of the paper.^{1–3,7} In other studies no correlation was found between

Correspondence to: N. Garoff (niklas.garoff@stfi.se).

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paper-paper-friction of different paper grades and the surface energy characterised by contact angle measurements.^{5,10}

Low-molecular-mass lipophilic compounds (LLC) found in OCC are mainly a complex mixture of metal soaps, where different lipophilic acids are chemically bonded to predominantly calcium and sodium ions.¹¹ The metal soaps may incorporate other low-molecular-mass compounds.¹² The resulting mixture of compounds is insoluble in water, and is precipitated as a metal aggregate onto the fiber surfaces.^{13,14}

The purpose of this investigation was to study the origin of the differences in paper-to-paper friction between four different commercial linerboards based on old corrugated containers (OCC). Four different OCC-based papers with very different frictional characteristics were chosen for the investigation. The papers were characterized with respect to surface energy, surface roughness, and their content of LLC. The papers were imaged by environmental scanning electron microscopy (ESEM), and the relative compositions of inorganic ions on the paper surfaces were determined by energy dispersive X-ray spectroscopy (EDS).

General Aspects of Friction and Lubrication

When two surfaces are brought to contact under the influence of a normal load, the area of real contact is generally much smaller than the geometric area. The reason is that all surfaces are rough, so that contact occurs only at discrete spots. The total friction force that develops upon tangential relative movement of the surfaces may be interpreted as the sum of the friction forces acting between the contacts. The value of the tangential force required to initiate relative motion is the static friction force. The tangential force required to maintain relative motion is the kinetic friction force. The coefficient of friction is the ratio between the friction force and the normal load. Providing that the material does not change during sliding, the static coefficient of friction is either larger than or equal to the kinetic coefficient of friction.¹⁵

In principal, lubrication can be achieved in two ways: by hydrodynamic lubrication or by boundary lubrication. If the rubbing surfaces are completely separated by a thick film of a fluid, they are hydrodynamically lubricated and the viscosity of the fluid determines the friction.¹⁶ Hydrodynamic lubrication requires that the film thick-

ness is greater than the height of the asperities on the surface, which means 1–10 μm in the case of paper.¹⁵ The amount of lubricant needed for such a thick film is much greater than that found in paper sheets. Hydrodynamic lubrication, therefore, does not seem to be a valid lubrication mechanism in the case of commercial paper.

When the surfaces are separated by the thinnest possible lubricant film, i.e., a monomolecular film on each surface, the surfaces are lubricated by boundary lubrication. In boundary lubrication, the adhesive forces and the shear forces between the monomolecular films determine the friction. The friction coefficients decrease to some value that is less than that for unlubricated surfaces but much higher than that in hydrodynamic lubrication. Boundary lubrication occurs between surfaces that are covered with stable films of surfactants, for example, fatty acids, which can resist the load at the contacts.¹⁷ The transition from boundary lubrication to hydrodynamic lubrication is determined by the thickness of the lubricant film.¹⁵

According to Garoff et al.,⁹ long-chain linear hydrocarbons with a polar head group, such as long-chain saturated fatty acids and long chain fatty alcohols with more than 15 carbon atoms in the carbon chain and sterols from wood, are efficient lubricants of paper surfaces because they can form ductile molecular films on the surfaces and thereby act as boundary lubricants. These authors also suggest that the reason for the poor lubricating efficiency of unsaturated fatty acids, resin acids, and alkanes depends on the fact that these compounds do not form stable molecular films.

MATERIALS AND METHODS

Samples

Four different commercial linerboards based on OCC were investigated. In all the measurements, the side of each board that was intended to face outwards in the corrugated board was analyzed. The linerboards were subjected to two different extraction stages, whereby new samples were generated. The frictional properties of the OCC-based papers were compared to those of Munktell's filter paper 00H, which is manufactured entirely from cotton cellulose and contains very low amounts of lipophilic material.⁹ In addition, the four sheets were calendered to enable the influ-

Table I The Origin of the Papers and the Sample Labeling Used in this Investigation

Paper	Origin	Sample Labeling			
		Before Extraction	After First Extr. Stage	After Second Extr. Stage	After Impregnation
A	OCC, pulp x	A0	A1	A2	—
B	OCC, pulp x, Surface-coated	B0	B1	B2	—
C	OCC, pulp y	C0	C1	C2	—
D	OCC, pulp z	D0	D1	D2	—
F	Munktell's Filter paper 00H	F0	—	—	FI

ence on friction of smoothing of the paper surface to be studied. Papers A and B were known to be manufactured from the same pulp. However, paper B was reported to have been surface-coated with CaCO_3 particles to increase friction, which was confirmed by ESEM and EDS. Samples A0–D0 were calendered at a line-load of 30 kN/m using a pilot calender. Prior to calendering, the steel rolls were cleansed thoroughly with acetone and ethanol to remove lipophilic contaminants. The surface roughness measurements were carried out using a Perthometer PRK profiler from Mahr GmbH (Germany). The surface roughness is given for different bandwidths as the root mean square (RMS), i.e., the square root of the arithmetic mean of the square of the vertical deviation from a reference line. The bandwidths analyzed

were 0.0625–0.125, 0.125–0.25, 0.25–0.5, 0.5–1, 1–2, 2–4, 4–8, and 8–16 mm. The origin of the samples and the sample labeling are described in detail in Table I.

The paper sheets were investigated in an ESEM model 2020 from Electroscan/Philips. Figure 1 shows ESEM images of samples A0 and B0. It can be seen that sample B0 contained large particles, which probable originated from the surface coating. The papers C and D were manufactured from different pulps than papers A and B. The ESEM images of the other samples were similar to that of sample A0. ESEM studies showed that samples B1 and B2 did not contain large particles. The particles were obviously removed in the extraction process.

To investigate the degree of permanent damage, such as ploughing tracks, induced by the

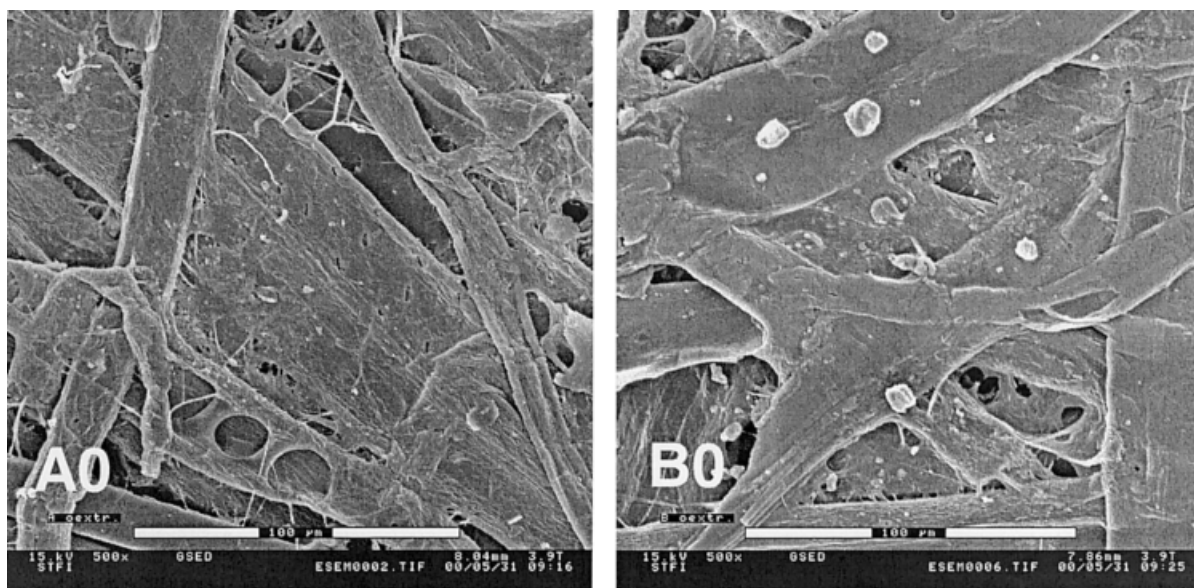


Figure 1 ESEM images of the samples A0 and B0. Sample B0 contained large CaCO_3 particles. The ESEM images of the samples C0 and D0 were similar to that of samples A0.

CaCO₃ particles during sliding, sample B0 was subjected to 30 slidings using the friction tester and imaged by ESEM.

The attachment for energy dispersive X-ray spectroscopy (EDS) of the ESEM was used to characterize the samples A0–D0 with respect to the composition of inorganic atoms on the paper surfaces. A description of the method is given elsewhere.¹⁸

Extraction of Paper

The low-molecular-mass material was removed from the linerboards by solvent extraction. Two different extraction devices, a SoxTec™ and a Soxhlet extractor, were employed. These devices are both based on the regeneration of fresh solvent by reflux. The SoxTec apparatus used was a SoxTec™ System 2 HT2 extractor from Foss (Denmark). This apparatus has two working modes, where the extraction is carried out by keeping the sample, that is placed in a porous cellulose socket, immersed in boiling solvent. Rinsing of the sample is achieved in the other mode, where the extraction socket is lifted above the level of extract and drops of condensed solvent roll through the socket.¹⁹ The extraction of a sample in a Soxhlet apparatus is achieved in cold condensed solvent. The sample is rinsed in batches by means of a siphon mechanism.²⁰

In general, extraction with a nonpolar solvent is employed to remove the low-molecular-mass constituent of paper. In a pretrial, the sheets were extracted with acetone in the SoxTec™ extractor after acidification with acetic acid according to the standard procedure used in the Scandinavian pulp and paper industry.²¹ This procedure was originally developed for the extraction of pulps, but it is also applied for the extraction of paper sheets.

The solvent used in this study consisted of 98% chloroform and 2% formic acid. The papers were examined in two test series. In the first test series, the papers were characterized by friction tests, ESEM imaging, EDS, GC-MS analysis of the extracts and surface roughness measurements. The extract from sample A0 was also used for an impregnation experiment. The work scheme used in the first test series is shown in Figure 2, exemplified by paper A. In the second test series, fresh paper samples were used and they were characterized by friction tests, extraction and GC-MS analysis of the extracts. The purpose of the second test series was to yield new

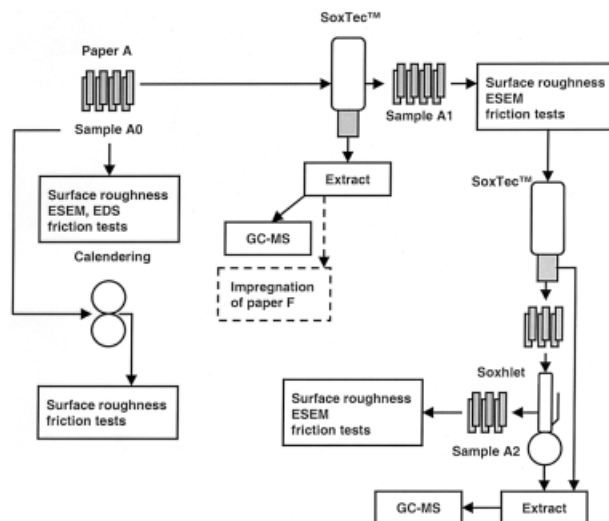


Figure 2 The work scheme used in the first test series. In this series, the papers, exemplified by paper A, were characterized by friction tests, ESEM-imaging, EDS, extraction, GC-MS analysis of the extracts, and surface roughness measurements. Additionally, extract from sample A0 was also used for an impregnation experiment.

samples to estimate the reproducibility of the friction tests and of the quantification by GC-MS.

In the first test series, unextracted sheets were characterized by friction tests, ESEM imaging, EDS, and surface roughness measurements. To investigate the influence of smoothing of the surface on friction, new sheets of each sample were calendered, after which they were subjected to surface roughness measurements and friction tests. The samples prior to extraction were labeled A0, B0, C0, and D0, respectively. Before extraction, sheets of each paper were cut to eight friction test pieces, extracted with in the SoxTec™ extractor for 1 h at reflux, and rinsed for 2 h. The extract from this extraction was quantitatively analyzed by GC-MS. After the first extraction stage, two pieces were withdrawn for ESEM imaging and surface roughness measurements, and the remaining six pieces were subjected to friction testing. These samples were labeled A1, B1, C1, and D1, respectively. After friction testing of the six pieces, they were further extracted in a second extraction stage. This second extraction stage was divided into two steps. In the first step, the pieces were extracted with fresh solvent in the SoxTec™ extractor in the same manner as in the first extraction stage. In the second step, the pieces were extracted in a Soxhlet extractor under reflux for 24 h. During

this period, the test pieces in the Soxhlet extractor were rinsed in batches about 250 times. The extracts from the two steps of the second extraction stage were combined and analyzed by GC-MS. After the second extraction stage, two pieces were withdrawn for surface roughness measurements and the remaining four pieces were subjected to friction testing. These paper samples were labeled A2, B2, C2, and D2, respectively.

GC-MS Analysis

The bulk amount of LLC in the papers was quantified by analyzing the extracts by GC-MS. The extracts were further worked up to isolate the low-molecular-mass lipophilic constituent by pH adjusting the extracts with dilute sulfuric acid to pH 2–3 and subsequent extraction with petroleum ether (boiling range 40–60°C) after addition of acetone and methanol.²² The petroleum ether phases containing the LLC were completely evaporated under a stream of nitrogen gas. The extracts were then redissolved in dichloromethane after addition of the internal standard, iso-palmitic acid. The extracts were silylated with *N,N*-Bis(trimethylsilyl)-trifluoroacetamide in pyridine at 70°C. A Hewlett Packard 5989 B mass spectrometer interfaced with a Hewlett Packard 5890 Series II gas chromatograph was used. The gas chromatograph was equipped with a low bleed/MS CP-Sil 8 CB column, 25 meters long, with an inner diameter of 0.25 mm and a phase thickness of 0.4 μm . The results from the quantification by GC-MS were based on duplicates. The deviation from the average was not greater 10%.

The identified LLC were divided into the following groups:

1. Long-chain saturated fatty acids, with a carbon chain of 15 carbon atoms or more
2. Fatty alcohols
3. Sterols
4. Short-chain saturated fatty acids with a carbon chain of less than 15 carbon atoms
5. Unsaturated fatty acids
6. Alkanes
7. Betulinol
8. Resin acids

A description of these compounds is given elsewhere.^{9,23} The first three groups represent compounds that may act as boundary lubricants (BL) on paper surfaces. The amount of LLC in the prolonged extracted samples A2–D2 was set to

zero in the tables and figures, because no significant amounts were obtained when the samples were extracted further.

Impregnation of the Filter Paper

To study the influence of LLC on the friction of a clean filter paper, an experiment was carried out where a filter paper was impregnated with the extract obtained from the first extraction stage of paper A. Paper A was chosen as the source of LLC because it had the lowest friction, so that it was expected that the extract from this paper would have the largest effect.

Prior to impregnation, the LLC was isolated from the extract according to the same method used for GC-MS analysis and redissolved in 100 mL chloroform. Filter paper sheets were cut to eight friction test pieces and impregnated with 2/3 of the extract solution. This amount was calculated by dividing the dry weight of the filter paper pieces by that of the pieces of sample A0, which were 8 g and 12 g, respectively. In this way, the concentration of LLC in the impregnated filter paper roughly equaled that of sample A0. Sheets were impregnated by putting them into a large glass basin, so that the bottom of the basin was completely covered by the pieces, and the extract was then poured into the basin. After about 12 h, the solvent had completely evaporated and the filter paper pieces had adsorbed the extractives.

Friction Tests

The friction testing was carried out according to ISO 15359²⁴ using the Amontons II from Mu measurements (USA), which is based on the horizontal-plane principle.²⁵ According to this standard, three coefficients of friction are defined: the static coefficient of friction obtained from the first sliding, the static coefficient obtained from the third sliding over the same track and the kinetic coefficient of friction obtained from the third sliding over the same track.

In this investigation it was decided to use the data obtained from the third sliding. The given friction values were obtained from measurements where the sliding direction corresponded to the crossdirection of the paper. The values for the friction coefficients and the corresponding 95% confidence limits were based on the average of six to eight measurements. The confidence limits obtained varied between 0.01 and 0.03.

RESULTS

In pretrials, the paper sheets were extracted with acetone in the SoxTec™ extractor according to the standard procedure used in the pulp and paper industry.²¹ To our surprise, we observed that the extraction had no effect on paper-to-paper friction, indicating that the extraction did not efficiently remove the LLC from the papers. It was therefore decided to employ a more extensive extraction procedure.

Table II summarizes the results of the friction trials, the surface energy analysis, and of the GC-MS analysis. Here, the third static (S3) and the third kinetic (K3) coefficients of friction and the amounts of low-molecular-mass compounds, as quantified by GC-MS, are shown.

The compounds found in the extracts were fatty acids, fatty alcohols, alkanes, sterols, betulinol, and resin acids. The compounds were divided into eight groups, as shown in Table II. The long-chain saturated fatty acids consisted mainly of palmitic acid (16 carbon atoms) and stearic acid (18 carbon atoms). The short-chain saturated fatty acids were dodecanoic acid and tetradecanoic acid. The fatty alcohols were octadecanol, icosanol (20 carbon atoms) and docosanol (22 carbon atoms), i.e., long-chain saturated fatty alcohols. The unsaturated fatty acids were oleic acid and linoleic acid. The alkanes were saturated n-alkanes with chain lengths between 18 and 35 carbon atoms. The sterols were sitosterol and sitostanol. The resin acids were abietic acid, dehydroabietic acid, and isopimaric acid.

Table II shows that the lipophilic acids constituted about 75% of the LLC and that the rest was mainly alkanes. The fatty alcohols, the sterols, and betulinol were minor components of the LLC.

The Effect of Extraction on Friction

Originally, the four linerboards had very different friction values. Figure 3 shows the third static and the third kinetic coefficient of friction of the investigated samples. Before extraction, the order among the papers with increasing friction was A, C, B, and D, and there was no significant difference between the static and kinetic coefficients of friction. After the first extraction stage, the coefficients of friction dramatically increased. It was noted that they increased to the same level, despite the different values before extraction. After the second extraction stage, the coefficients of

friction increased further, at least to the level of the filter paper. However, after the second extraction stage, the differences in friction between the papers were larger than those after the first extraction stage. Figure 3 shows that the coefficients of friction of the filter paper (sample F0) decreased after impregnation (sample FI) with the extract of sample A0 and roughly to the level of sample A0.

Figure 3 shows that K3 generally behaved in a manner similar to S3 upon extraction. For this reason, K3 has been omitted from the following plots.

Low-Molecular-Mass Lipophilic Compounds and Friction

Figure 4 shows two curves, where the third static coefficient of friction, S3, is plotted against the amount of the LLC and the amount of boundary lubricants (BL, i.e., the long-chain saturated fatty acids, fatty alcohols, and sterols) expressed as milligram per gram dry paper. It is evident in this figure that the coefficients of friction of the papers followed a very general trend, where the friction was low when the amounts of LLC and BL in the paper were high. Figure 4 also shows that although sample B0 had about the same amount of LLC as sample A0 it had a significantly higher friction. The deviation from the general trend was attributed to the ploughing effect of the large CaCO₃ particles, which were identified by ESEM (Fig. 1). Paper B, nevertheless, followed the general trend after it had been extracted. It was observed that the coefficients of friction of sample B0 had not changed after 30 slidings. ESEM images showed no ploughing tracks on the surface of sample B0 after the slidings.

Inorganic Atoms on the Paper Surfaces

The atoms on the paper surfaces detected by EDS were calcium, silicon, aluminium, oxygen, potassium, chlorine, and sulfur. The compositions of atoms in the samples A0, C0, and D0 were essentially the same on the two sides. It was, however, observed that sample B0 contained about 5% more Ca on the side that was friction tested than on the opposite side. This calcium can be assumed to originate from the CaCO₃ particles.

Surface Roughness and Friction

In Figure 5, the third static coefficient of friction of the linerboards samples is plotted against the

Table II. The Third Static (S3) and the Third Kinetic (K3) Coefficient of Friction and the Low-Molecular-Mass Lipophilic Compounds (LLC), as Quantified by GC-MS, of the Investigated Papers

Sample	Low-Molecular-Mass Lipophilic Compounds (LLC) by GC-MS (mg/g)										
	Boundary Lubricants (BL)										
	S3	K3	Long-Chain Saturated Fatty Acids	Fatty Alcohols	Sterols	Short-Chain Saturated Fatty Acids	Unsaturated Fatty Acids	Alkanes	Betulinol	Resin Acids	Total LLC
A0	0.23	0.21	0.60	0.04	0.03	0.09	0.49	0.33	0.02	0.55	2.15
A1	0.65	0.58	0.09	0.02	0.00	0.03	0.05	0.07	0.00	0.01	0.27
A2	0.82	0.70	≈0	≈0	0.00	≈0	≈0	≈0	0.00	≈0	0
B0	0.43	0.44	0.53	0.03	0.03	0.04	0.53	0.32	0.02	0.56	2.06
B1	0.61	0.55	0.08	0.01	0.00	0.02	0.07	0.04	0.00	0.03	0.25
B2	0.76	0.75	≈0	≈0	0.00	≈0	≈0	≈0	0.00	≈0	0
C0	0.37	0.41	0.42	0.06	0.04	0.03	0.21	0.49	0.04	0.53	1.82
C1	0.62	0.54	0.06	0.01	0.00	0.01	0.03	0.05	0.00	0.03	0.19
C2	0.74	0.69	≈0	≈0	0.00	≈0	≈0	≈0	0.00	≈0	0
D0	0.52	0.52	0.39	0.03	0.04	0.07	0.24	0.42	0.02	0.36	1.57
D1	0.64	0.58	0.10	0.00	0.00	0.04	0.10	0.03	0.00	0.02	0.29
D2	0.82	0.71	≈0	≈0	0.00	≈0	≈0	≈0	0.00	≈0	0
F0	0.77	0.66									
F1	0.29	0.21									

The final column shows the total amount of low-molecular-mass lipophilic compounds. The amounts are shown as milligram per gram dry paper.

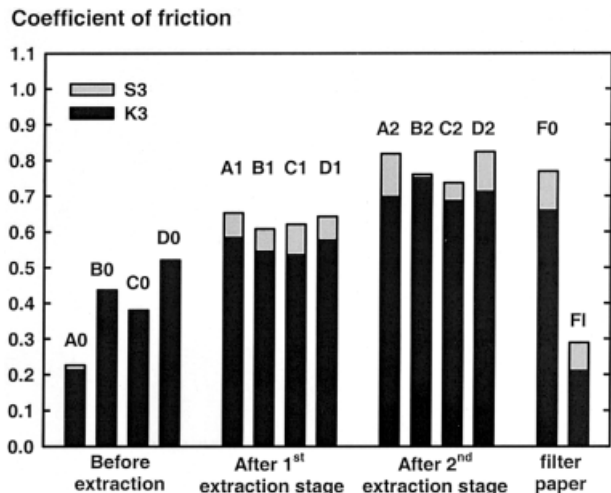


Figure 3 The third static (S3) and the third kinetic coefficient of friction (K3) of the investigated papers before and after the extraction stages. For comparison, the friction coefficients of clean filter paper and of the filter paper impregnated with the extract from sample A0 are also shown.

corresponding RMS surface roughness of the band 1–2 mm, which was arbitrarily chosen to show the effect of calendering. The choice of bandwidth for the comparison was not critical because similar trends were observed when the static coefficient of friction was plotted against the corre-

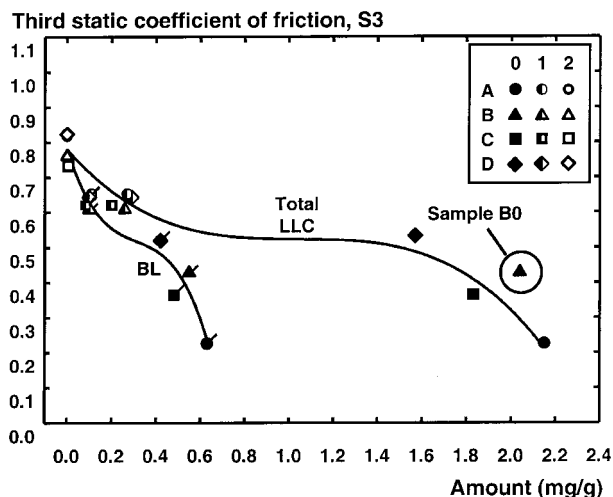


Figure 4 The third static coefficient of friction plotted against the total amount of low-molecular-mass compounds (total LLC) and boundary lubricants (BL) expressed as milligram per gram dry paper. The symbols representing the amount of boundary lubricants are marked with a flag.

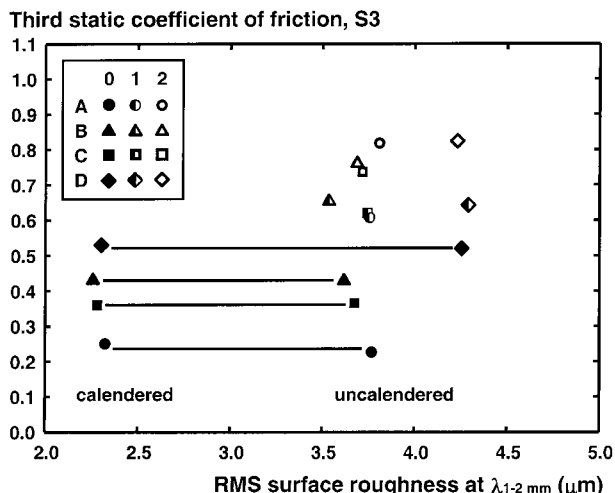


Figure 5 The third static coefficient of friction of the linerboard samples plotted against the RMS surface roughness for the band of 1–2 mm. Also shown are the values for the samples A0–D0 after calendering.

sponding RMS roughnesses of the other bands. From Figure 5 it is evident that all the uncalendered linerboard samples had a surface roughness of about 4 μm, but very different coefficients of friction. Calendering of the samples A0–D0 decreased the surface roughness of the samples to about 50% of its original value, but left the coefficient of friction unchanged.

DISCUSSION

The purpose of this investigation was to study the origin of the differences in paper-to-paper friction of linerboards based on old corrugated containers (OCC). The difference in friction between the samples A0 and B0 shown in Figures 3 to 4 show that the paper-to-paper friction of OCC-based linerboard was affected by the ploughing effect of large CaCO₃ particles. Papers with low friction may be surface treated by applying such particles onto the surface. However, this does not solve the problem of the origin of the low friction. We approached this problem by carefully characterizing the linerboards by chemical analysis and physical testing.

Lubrication of OCC-Based Linerboard

Figure 3 shows that the coefficient of friction dramatically increased to the level of clean filter paper after removal of LLC from the papers. Con-

versely, the friction of clean filter paper decreased to about the same low level of sample A0 after impregnation with LLC from that paper. Figure 4 shows a quantitative relationship between S3 and the content of LLC and BL in the papers. We conclude that the paper-to-paper friction of the linerboards was quantitatively governed by the degree of lubrication by LLC.

Table II shows that the amount of BL was fairly proportional to the amount of LLC. The decrease in friction with increasing amount of LLC in the papers may, therefore, be due to the increase in the amount of BL.

The Effect of Large CaCO₃ Particles on Friction

The presence of hard particles on the surface of a softer material such as paper gives rise to higher friction than is experienced on the same material without the particles. This is because a larger tangential force must be applied to initiate and to maintain sliding due to the greater energy losses from mechanical deformation, such as ploughing.

The coefficients of friction of sample B0, which contained large CaCO₃ particles, did not change with repeated slidings. ESEM-images showed no sign of permanent damage generated after sliding, such as ploughing tracks or grooves. This indicated that the mechanical deformation was elastic during the sliding of sample B0.

The Choice of Extraction Procedure

Acidic extraction with acetone in a SoxTec™ extractor according to the standard procedure²¹ did not change the paper-to-paper friction of the sheets. Therefore, we decided to extract the sheets with a more efficient solvent than acetone. We chose chloroform for the solvent, because of its excellent abilities to dissolve lipophilic compounds and its ability to dissolve lipophilic metal aggregates.¹⁹ Further, we noted that it was necessary to extract under acidic conditions because protonization of the lipophilic acids facilitated the dissolution of the metal aggregates. Formic acid was chosen for the proton donor, because it has a pKa value below that of the lipophilic acids, and because it is volatile and soluble in nonpolar solvents. We found that considerable amounts of LLC were removed from the sheets in the second extraction stage, even though they had already been extracted in the SoxTec™ device, which showed that the first extraction stage was insufficient. We suggest that the extraction per se is

more efficient in the SoxTec™ system, because the sample is extracted in boiling solvent. However, the rinsing step, seems to us less efficient, as has also been pointed out in a previous investigation.¹⁹ Therefore, we combined the efficient extraction in the SoxTec™ system with the efficient rinsing step of the Soxhlet system to remove as much LLC as possible from the sheets.

Changes in the Composition of the LLC in the Papers Due to Extraction

Table II shows that the relative amounts of the low molecular mass compounds changed after the first extraction stage. The relative amounts of the long-chain saturated fatty acids and fatty alcohols increased in the papers, which indicated that these substances were the most difficult to remove from the papers. This means that the first extraction stage was less efficient in removing the boundary lubricants than the other low molecular mass lipophilic compounds from the papers.

Friction Was Independent of Surface Roughness

Figure 5 shows that friction was independent of the surface roughness of the paper samples, which is in accordance with the results obtained from other investigations.^{4,5} Thus, in agreement with these investigations it can be concluded that paper-to-paper friction of the OCC-based linerboard was not governed by the interlocking of surface asperities. An explanation for this observation may be that the pressure acting on the asperities at the contact regions under the influence of a normal load is so high that it deforms the asperities on the paper surface. According to the adhesive friction model of Bowden and Tabor,²⁶ the coefficient of friction is dependent on only two mechanical properties, the shear strength of the contacts and the plastic yield stress of the material, which implies an independence of surface roughness.

CONCLUSIONS

1. There was a quantitative relationship between the level of paper-to-paper friction of OCC-based linerboard and the amount of low-molecular-mass compounds and especially boundary lubricants, such as long-chain saturated fatty acids, long-chain fatty alcohols, and sterols.

2. Severe extraction procedures were necessary to remove long-chain saturated fatty acids, which were present as metal aggregates, from OCC-based linerboard.
3. Paper-to-paper friction of OCC-based linerboard was independent of the surface roughness.
4. Paper-to-paper friction can be increased by the presence of large CaCO₃ particles on the paper surface. This is because a larger tangential force must be applied to obtain sliding due to greater energy losses from mechanical deformation.

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