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Influence of coating properties on paper-to-paper friction of coated paper

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Abstract Coated paper-to-coated paper friction properties were examined in relation to printing runnability difficulties like erroneous double feeding of paper sheets. Higher ratios of precipitated calcium carbonate (PCC) to clay in mixed pigment coatings resulted in higher static and kinetic coefficients of friction (COFs). Microroughness in the order of pigment particle size is considered to relate to COF, because cube-shaped particles of PCC resist sliding. Calendering decreased COF at larger amounts of PCC, but did not change COF of the sole clay formulation at all. Addition of ground calcium carbonate (GCC) decreased COF. The rate of decrease in kinetic COF with increasing number of sliding for the GCC-rich formulation was higher than that for the PCC-rich formulation, presumably because protruding parts, characteristic of the GCC-rich formulation, on the surface were selectively flattened. Addition of styrene–butadiene (SB)-latex up to 14 pph decreased COF, but static COF had the highest value at 18 pph. The antislip property (as a rubber) of SB-latex developed only in the static mode. Among lubricants formulated, the wax type decreased COF the most remarkably with more effect on kinetic COF than on static COF.

Key words Calcium carbonate · Coated paper · Friction · Surface roughness · Lubricant

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Introduction

Paper-to-paper and paper-to-other material frictions are related to many sorts of issues regarding printing runnability, print quality, and printing press design. High friction is desired in high-speed printing to maintain good register. Erroneous double or multiple feeding of sheets of paper is a serious difficulty that occurs in copiers and personal printers as well as in commercial printing presses and industrial optical character recognition (OCR). In every case, it is very important to keep paper friction properties constant and stable because modification of hardware requires much effort in adjusting printing systems. As far as erroneous double feeding is concerned, there are many possible factors involved: coefficient of friction between rubber roll and paper and between paper sheets, attraction occurring between paper sheets due to static electricity, and so on. On the other hand, demands for coated paper in the market are growing with the aim of high print quality. As the consumption of coated paper increases, it has more occasion to be processed through a variety of sheet feeders. This study focuses on the coefficient of friction (COF) between coated papers, so coated paper properties that are likely to influence the COF were chosen and examined.

As for uncoated paper, several properties influencing COF have been reported. For pulping and bleaching, kappa number did not affect friction properties despite differences in surface energy.[1] For papermaking and paper properties, beating does not significantly affect friction, but the author demonstrated that surface rigidity that was enhanced by beating increased COF slightly.[2] Rough/rough surfaces showed a lower static COF than smooth/smooth surfaces for paperboard handsheets, which indicates that the interlocking of surface asperities was not a factor.[3] For fillers, common fillers such as hydrous kaolin and talc decreased kinetic COF; calcined kaolin and, in particular, synthetic precipitated silicas and silicates increased it. Filler size and shape were considered to be dominant factors.[4] For surface chemistry, wood extractives like long-chain saturated fatty acids, fatty alcohols, and tristearin reduced COF most efficiently.[5]

Table 1. Coating color formulation of the series of pigment mixtures

Ingredient	Added amount (pph)												
Color	1	2	3	4	5	6	7	8	9	10	11	12	13
Clay	0	30	50	70	100	70	70	70	70	70	70	70	70
PCC	100	70	50	30	0	30	20	10	0	30	30	30	30
GCC	0	0	0	0	0	0	10	20	30	0	0	0	0
SB-latex	10	10	10	10	10	10	10	10	10	6	10	14	18
Starch	2	2	2	2	2	0	0	0	0	2	2	2	2
Dispersant	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1	1	1	1
Sodium hydroxide	0.01	0.01	0.01	0.01	0.01	0.1	0.1	0.1	0.1	0.01	0.01	0.01	0.01
Solids (%)	45	47.5	50	52.5	55	45	47.5	50	52.5	54.7	55	55	54.2

pph, parts per hundred; PCC, precipitated calcium carbonate; GCC, ground calcium carbonate; SB, styrene–butadiene

Experimental

Materials

Coating colors were prepared from following materials: clay (UltraWhite-90, Engelhard, USA), mean diameter of ca. 1.5 μm; precipitated calcium carbonate (PCC, Brilliant-15, Shiraishi Kogyo, Japan), mean diameter of ca. 0.4 μm; and ground calcium carbonate (GCC, Softon-1500, Shiraishi Kogyo), mean diameter of ca. 1.5 μm with a broad distribution. Figure 6 shows each type of carbonate particle present in the coating layer. Styrene–butadiene (SB)-latex (LX407G, Nippon Zeon, Japan) has a mean particle diameter of 100 nm and a glass transition temperature of 15°C. Starch (phosphoric ester type, P-140, Oji Corn Starch, Japan) as a cobinder, dispersant (polyacrylate T-40 Toagosei, Japan), and sodium hydroxide (special grade, Wako, Japan) were also used.

The lubricants used were three types of dispersions. Stearate A (Nopcote C-104-HS, San Nopco, Japan) is a calcium salt of higher fatty acids. Stearate B (SN-Cote 231) is also a calcium salt of fatty acid, but with a shorter hydrocarbon chain. The wax type (SN-Cote 950) is a polyolefin. They were not originally developed to reduce COF, but to improve release from rolls, wet ink acceptance, and antidusting at supercalender rolls.

Coating colors and coated paper

Four series of coated paper were prepared. Table 1 shows the formulation of three series of pigment mixtures of the coating color. The first series (1–5) contained different ratios of clay and PCC. Coat weight ranged from 10 to 13 g/m^2. The second series (6–9) contained different ratios of PCC and GCC at a constant level of clay. Coat weight ranged from 18 to 24 g/m^2. The third series (10–13) contained different contents of SB-latex. Coat weight ranged from 10 to 13 g/m^2. Table 2 shows the series for different types of lubricants, all at 2 pph. All materials except SB-latex were dispersed with a centrifugal disperser (two combined rotations on the container and the disperser axes, hybrid mixer HM-500, Keyence, Japan) for 20–40 min in total at adequate intervals to prevent temperature rise. SB-latex, which tends to coher easily by hard dispersion, was added last and dispersed for 10 s.

Table 2. Coating color formulation of the series of lubricants

Ingredient	Added amount (pph)		
Clay	70	70	70
PCC	30	30	30
SB-latex	10	10	10
Starch	2	2	2
Lubricant			
Wax type	2	0	0
Calcium stearate A	0	2	0
Calcium stearate B	0	0	2
Dispersant	0.1	0.1	0.1
Sodium hydroxide	0.01	0.01	0.01
Solids (%)	55	55	55

All of the coating colors were applied to wood-free base paper of 63.7 g/m^2 basis weight with a wire bar no. 7 using a motor-driven draw-down coater (YOA-B, Yoshimitsu Seiki, Japan). The papers were then hot air-dried for 1 min. All of the coated paper, unless otherwise mentioned, were calendered with a laboratory calender (No. 2232, KRK, Japan) equipped with a pair of steel and neoprene rubber rolls at a linear pressure of 14.7 kN/m and a speed of 2.5 m/min. The surface temperature of the steel roll was ca. 60°C

Measurement

Surface roughness was determined as a centerline average roughness calculated from surface profiles measured by a confocal laser scanning microscope (CLSM) (VF-7500, Keyence) or by a stylus profilometer (SE-3, Kosaka Laboratory, Japan). Also, Bekk smoothness was measured using an Oken type tester (modified Bekk characterized by hydraulic pressure difference practically measured in place of time). Gloss was measured by a portable glossmeter (Multigloss-268, Minolta, Japan). Micrographs were taken with a scanning electron microscope (S-4000, Hitachi, Japan) and with the CLSM.

Friction tests were made using two types of apparatus. One was a friction sensitivity tester originally designed for

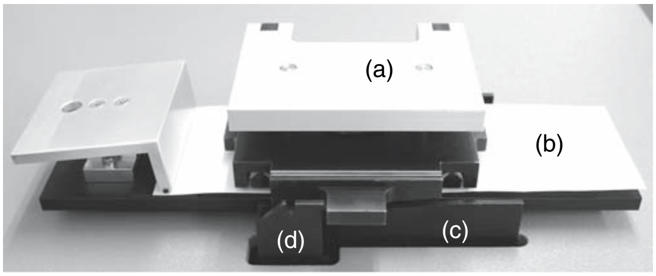


Fig. 1. Sled (*a*), table (*b*), elevator (*c*), and load detection arm (*d*) of the automatic friction coefficient testing machine

fabric texture (KES-SE, KatoTech, Japan). The dimensions of a test piece on the sled were 70 mm in length and 35 mm in width. The table was 40 mm in width. The sliding speed, the vertical pressure, and the sliding distance were 10 mm/s, 1.98 kPa, and 35 mm, respectively. The other apparatus was an automatic friction coefficient testing machine (Sagawa Manufacturing, Japan). This machine is designed in conformity with ISO 15359. All of the testing conditions for the measurements also followed the ISO standard. As results, the first and third static COF and the third kinetic COF, which are specified in the standard, are mainly shown. The sliding speed was 0.2 mm/s for the static COFs and 20 mm/s for the kinetic COF. Figure 1 shows the sled and the table of this machine. A step motor drives the table accurately and precisely. Setting of a test piece onto the sled was automated on the special clamping device (not shown) and could be performed easily without touching the test piece. Every friction test was performed under the standard conditions, of 23°C and 50% relative humidity.

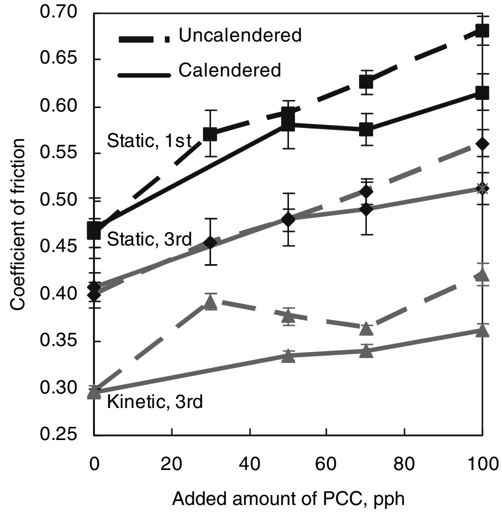


Fig. 2. Influence of PCC/clay ratio on coefficient of friction. *PCC*, precipitated calcium carbonate. *Bars* indicate 95% confidence interval

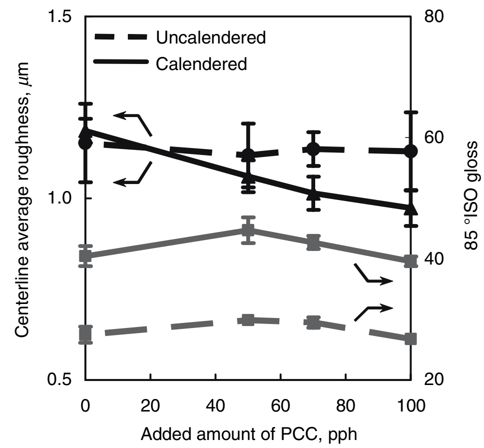


Fig. 3. Roughness and gloss of coated papers with different PCC/clay ratios. *Arrows* show relevant axes

Results and discussion

Ratio of clay, PCC, and GCC

Figure 2 shows that the static and kinetic COFs increased with increasing amount of PCC, for both the calendered and the uncalendered samples; 1–5. Figure 3 shows roughness measured by the CLSM and 85° ISO gloss. From the standpoint of roughness alone, there seems to be a trend that rougher surfaces provided lower COF for the calendered samples. However, calendering not only smoothened the surface, but also partially compressed the surface structure. Note that high density and rigidity resulting from the compression might be a more dominant factor. Another possible factor is pigment particle shape. Cube-shaped particles of the rhombohedral PCC might have resisted sliding. Practically, larger oscillations, namely, more remarkable stick–slick behavior was observed in the friction change during sliding, characteristic of PCC-rich samples. To paraphrase it, roughness in the particle size range called microroughness is closely related to COF. With regard to calendering effect, calendering decreased COF more remarkably at larger amounts of PCC, but no effect was observed with the sole clay formulation. Importance of microstructure has been stated previously.[6] Rättö et al.[6] found that the use of clay particles with different average diameters had no marked effect on the friction properties; however, a great difference was noted between papers coated with kaolin and those coated with $CaCO_3$. Significant differences were also detected when using calcium carbonate particles of different shapes. It concluded that it was the particle shape and its influence on the surface microstructure that was of importance.

Figure 4 shows the effect of GCC on COF. The automatic friction coefficient testing machine was used to measure COF only for this series of coated paper; 6–9. Measured COF values are fairly comparable between this machine and the friction sensitivity tester under identical measurement conditions. However, the static COF was much lower than those shown for the other series of coated

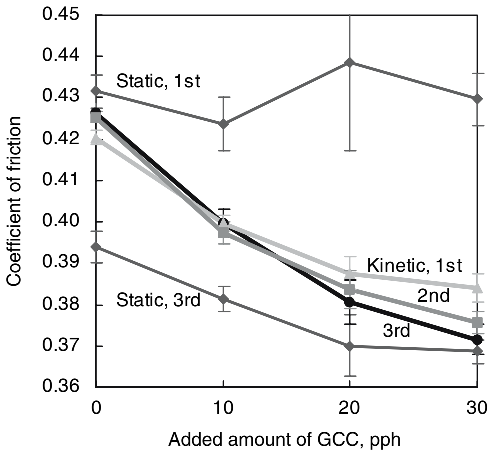


Fig. 4. Influence of GCC/PCC ratio on coefficient of friction. Total carbonate amount is 30 pph in addition to 70 pph clay. *GCC*, ground calcium carbonate

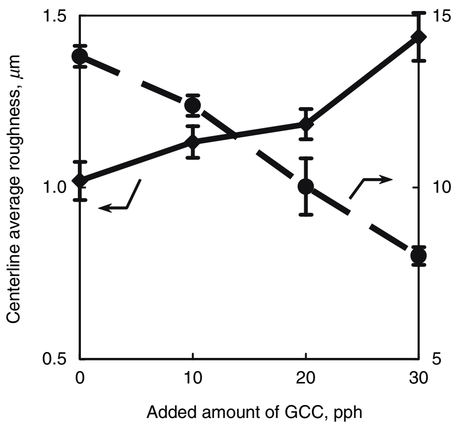


Fig. 5. Roughness and gloss of GCC-containing coated papers. *Arrows* show relevant axes

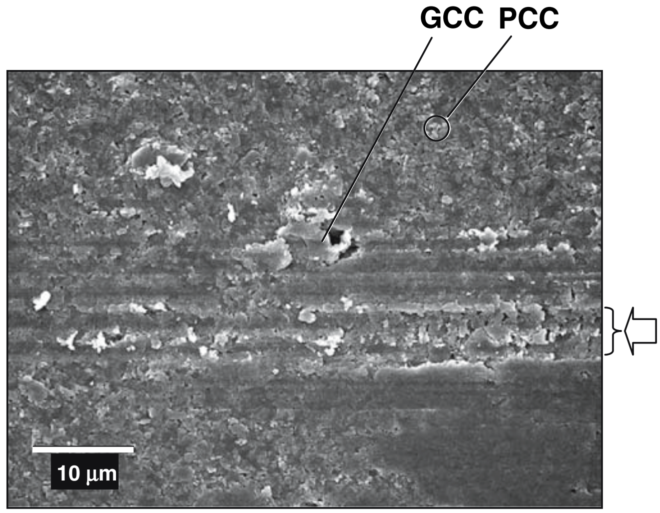


Fig. 6. Scanning electron micrograph of surface of on-table test piece of coated paper (GCC/PCC/Clay = 20/10/70 pph) subjected to three times of sliding. *Large arrow*, scarification probably caused by large particles on counter test piece

paper, because the sliding speed was as low as 0.2 mm/s for this series compared with 10 mm/s for the rest. Addition of GCC decreased the third static COF and the kinetic COFs, although it did not affect the first static COF significantly. The first to the third kinetic COFs indicate that kinetic COF decreased with increasing number of slides for the GCC-rich formulation, but, in contrast, it was unchanged or rather surprisingly increased for the PCC-rich formulation. GCC contains large particles and one might predict that these large particles would obstruct smooth sliding. Figure 5, in practice, shows that the centerline average roughness increased and gloss decreased with increasing amount of GCC, but unexpectedly, GCC addition facilitated sliding. Concerning roughness, there are some articles that state that it decreases COF;[3] and there are others that state it increases COF. With uncoated sandpaper-molded handsheets prepared so that all of the properties other than roughness are equal, roughness increased COF with the exception of the very rough sheets.[2] More discussion must be made after serious consideration of contact area between the two facing sheets of paper tested, plastic and elastic deformability of surfaces, adsorption of water molecules on surfaces, and so on. For coated paper, plastic deformability of surfaces seems to be very important as the micrographs of the surfaces imply.

Figure 6 is a scanning electron micrograph showing a surface of the coated paper (GCC/PCC/Clay = 20/10/70 pph) after friction measurement. The test piece was set on the table and subjected to three slides, as one measurement of sequence. Some scratches due to sliding are observed to run in the horizontal direction, namely, the sliding direction. The center of the surface indicated by an arrow seems to have been scarified probably by large particles on the counter test piece set on the sled. Scarification is likely to occur more often with coated surfaces when more GCC is added. However, more commonly, scratched and deformed parts had flatter surfaces like in the dark area in the lower right corner of Fig. 6, suggesting that it would permit smooth sliding afterward. Practically, Bekk smoothness increased after friction measurement for all these coated paper samples.

Figure 7 shows surfaces of the coated paper (10 pph of GCC) after friction measurement. The test piece had been set on the sled. Image A was acquired with a conventional charge coupled device (CCD) camera. A considerable number of scratches due to abrasive sliding can be observed at the upper left near the center of the image and some abrasion can also be seen at the upper right. Image B captured by the CLSM shows a contour map of the same location of the sample. In this image, whiter areas represent higher elevations. The two images confirmed that the location of scratches agreed well with that of zones at high elevations. Actual contact generating friction in sliding occurs with higher or protruding parts of each test piece, while the remainder is not contacted or is loosely contacted.

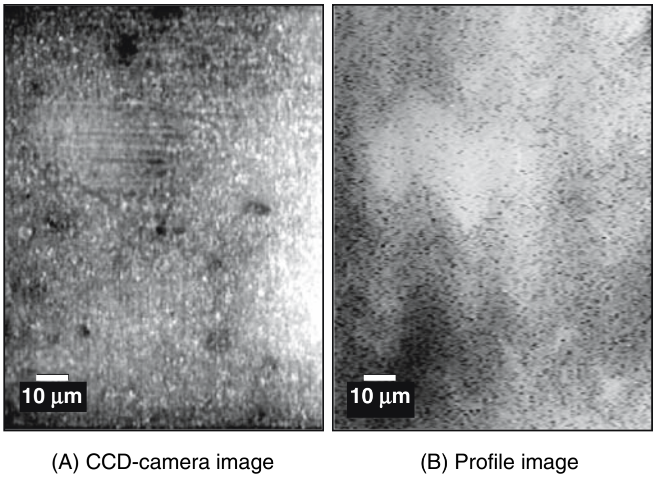


Fig. 7A,B. Surface of on-sled test piece of coated paper (GCC/PCC/Clay = 10/20/70 pph) subjected to three times of sliding. **A** CCD camera image, **B** profile image. Images (**A**) and (**B**) are of the same location

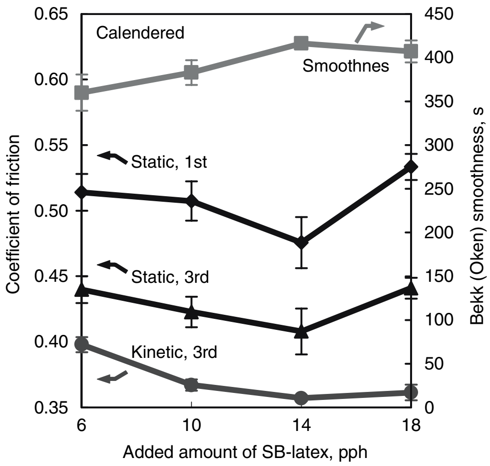


Fig. 8. Influence of styrene–butadiene (SB)-latex content on coefficient of friction. *Arrows* show relevant axes

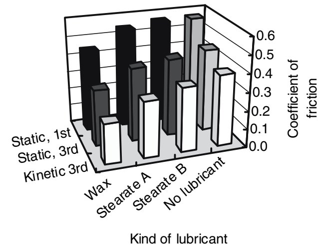
Content of SB-latex

SB-latex is a kind of rubber, so addition of SB-latex was likely to increase COF. Figure 8, however, shows that addition of SB-latex up to 14 pph decreased COF for the series 10–13. The static COFs had the highest COF at 18 pph. The property as a rubber appeared only in the static mode. Regarding roughness shown as Bekk smoothness, the third kinetic COF, in particular, correlated well with smoothness. This result reversed the relationship of the previous series of GCC-containing coated paper. To discuss roughness effects on COF further will require more data and consideration.

Lubricant effects

Figure 9 shows lubricant effects on COF. The wax type reduced COF the most of the three. When compared between static and kinetic COFs, the lubricants reduced kinetic COF more effectively. In particular, the wax type reduced it by 44%. The effects of lubricants are well explained and discussed in past research.[5]

Fig. 9. Influence of lubricants on coefficient of friction



Conclusions

Coated paper-to-coated paper friction properties were examined. High PCC to clay ratio in mixed pigment coatings resulted in high static and kinetic COFs. Microroughness in the order of pigment particle size is considered to relate to it, because cube-shaped particles of PCC resist sliding. Calendering decreased COF at large amounts of PCC, but did not change COF of the sole clay formulation at all. Addition of GCC decreased COF. The rate of decrease in kinetic COF with increasing number of slidings for the GCC-rich formulation was higher than that for the PCC-rich formulation, presumably because protruding parts, characteristic of the GCC-rich formulation, in the surface were selectively flattened. Addition of SB-latex up to 14 pph decreased COF, but static COF had the highest value at 18 pph. The antislip property (as a rubber) of SB-latex developed only in the static mode. Among lubricants formulated, the wax type decreased COF the most remarkably with more effect on kinetic COF than on static COF.

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