Paper friction—influence of measurement conditions

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ABSTRACT

An apparatus was constructed to study the factors influencing measurement of paper friction. The apparatus consists of a sled that slides on a horizontal table. Studies of paper friction using this apparatus revealed that:

- *The paper surfaces must not be touched by hand or otherwise contaminated.*
- *The hardness of the backing must be specified.*
- *The sled must be lowered into positon without any movement on the table surface.*
- *A guidance system is required to keep the orientation of the sled parallel to the table.*
- *Applied force must be built up slowly until the sled begins to slide. The sled should then slide at a constant speed without wobbling.*
- *Measurement of kinetic friction requires a rigid apparatus to avoid the stick-slip phenomenon.*

Applicaiton:

A preliminary study to identify test conditions for a future ISO standard method for measuring paper friction.

FRICTION HAS BEEN STUDIED EXTENsively for many materials, but little work has been reported for paper. Nevertheless, the friction properties of paper are important during converting and end-use operations.

Standard methods of measuring friction involve one of two fundamentally different techniques:

1. The horizontal-plane method, where a sled is pulled horizontally on a table by a line. By measuring the force F in the line, it is possible to calculate both the static (starting> and kinetic (sliding) coefficients of friction μ from the equation $\mu = F/N$, where N is the normal force.
2. The inclined-plane method, where a sled is placed on a flat surface and the surface is inclined gtadually with a constant angular velocity At a certain angle a, the sled begins to slide, and the static coefficient of friction μ is calculated from the equation $\mu = \tan a$.

This report focuses on the horizontal-plane method.

Table I lists some of the numerous "standard" methods that the paper industry uses to measure friction for paper products and plastics. All of these methods are based on the horizontal-plane principle. The problem we currently face is that the standards fail to specify all critical variables, leading to uncertainty in the results obtained.[1]

As seen in Table I, there is a wide variety in the test conditions for the various methods. The usual area of the sled is approximately 60 mm × 60 mm, while the surface pressure varies from 0.5 kPa up to 6.5 kPa. The sliding distance is usually one sled length, and the speed varies from 0.04 mm/s up to 2.5 mm/s. The static value is evaluated before either the first or the third slide. One of the standards (DIN 53375) stip ulates the need for a rigid connection between the sled and the pulling device to avoid stick-slip. (Avoidance of stick-slip is a condition for evaluating the kinetic friction.) The backing hardness also varies among the various test methods.

The present work has two aims:

1. To study and clarify the effect of the parameters that can influence measurement of paper friction
2. To recommend specifications for a future ISO standard method for measuring paper-to-paper friction.

MATERIALS AND METHODS

Test material

The following papers were used: copy paper (80 g/m^2), liner (180 g/m^2), newsprint (49 g/m^2), sack paper (80 g/m^2), and carton board (250 g/m^2).

Sheet direction of the samples

Paper can have different friction values in the machine direction (MD) and the cross-machine direction (CD). Since the intention of this work was to study the influence of test conditions on friction measurements, the investigation was limited to a study of the friction when the test pieces were arranged CD against CD with the same top or bottom sides facing each other.

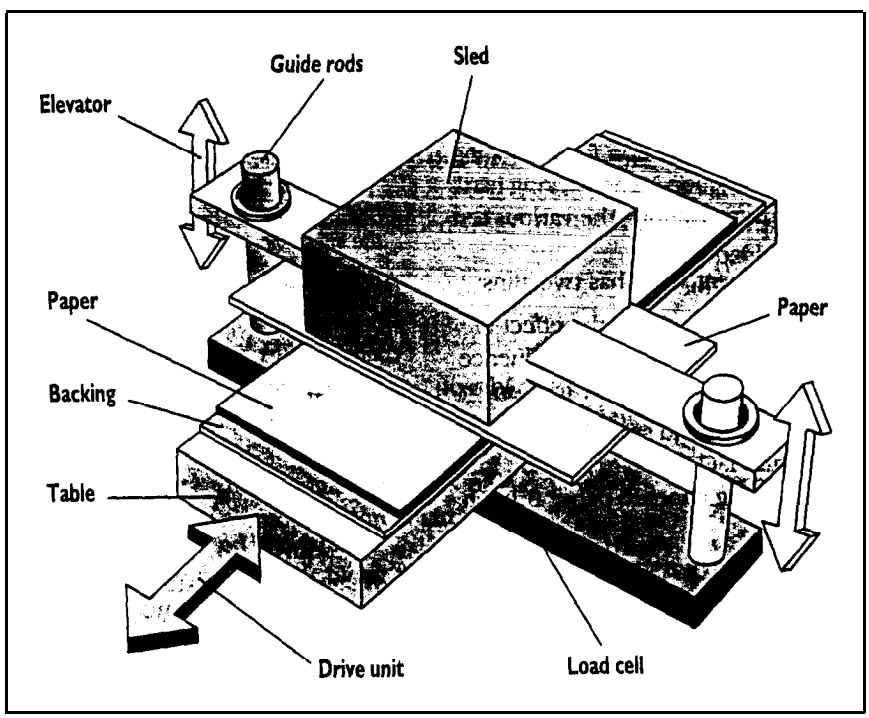
Cutting and handling of test sheets

To avoid any contact with the test surfaces before measurement, a cutting template, with an opening in the middle, was constructed. The size of the cut sheets was 102 mm × 60 mm. Two sheets were cut for each test, one to fix to the sled and one to the table.

The sheets were cut with the test surface upwards to avoid contact with the underlying surface. The test sheets were then handled with tweezers and placed test surface against test surface in a rack. They were conditioned at 23°C 50% RH and tested in the same climate. Each value in the report is an average of 10 replicates, with 95% confidence limits shown.

[1] Back, E.L. TAPPI 1991 International Paper Physics Conference Proceedings, TAPPI PRESS, Atlanta, pp. 49-65.

Method	Material	SLED'S APPARENT CONTACT AREA, mm²		mm × mm	Surface pressure, kPa	Backing	sliding distance, mm	Pulling rate, mm/s	SLIDINGS Number	SLIDINGS Static or kinetic
ASTM 3247	corrugated and solid fiberboard	2000	or	62.5 × 62.5	3.44	hard	62.5	2.54	3	Only the 3rd, static value is evaluated
ANSI/ASTM D 1894-78	plastic film and sheeting	...		63.5 × 63.5	0.49	soft	130	2.5	1	Static and kinetic
DIN 6729	punched tapes	...		15 × 75	6.54	soft	0	0.04	1	Static only
DIN 53375	plastic film	4000	or	63 × 63	0.49	soft	60	1.67	1	Static and kinetic
ISO 8295	plastic film	4000	or	63 × 63	0.49	soft	60	1.67	1	Static and kinetic
T 816 pm-92	corrugated and solid fiberboard	2000	or	63.5 × 63.5	3.5	hard	63.5	2.5	3	Only the 3rd static value is evaluated
T 549 pm-90	writing and printing papers	...		63.5 × 63.5	0.48	soft	130	2.5	1	Static and kinetic



1. Apparatus for measuring paper friction

Apparatus

Description, STFI, in collaboration with FPL, has constructed an apparatus to measure friction. The apparatus was designed so that test conditions could be easily varied to investigate their influence on friction measurements. Moreover, the apparatus is completely automatic, thus eliminating human error. Figure 1 shows the apparatus, which has the following features:

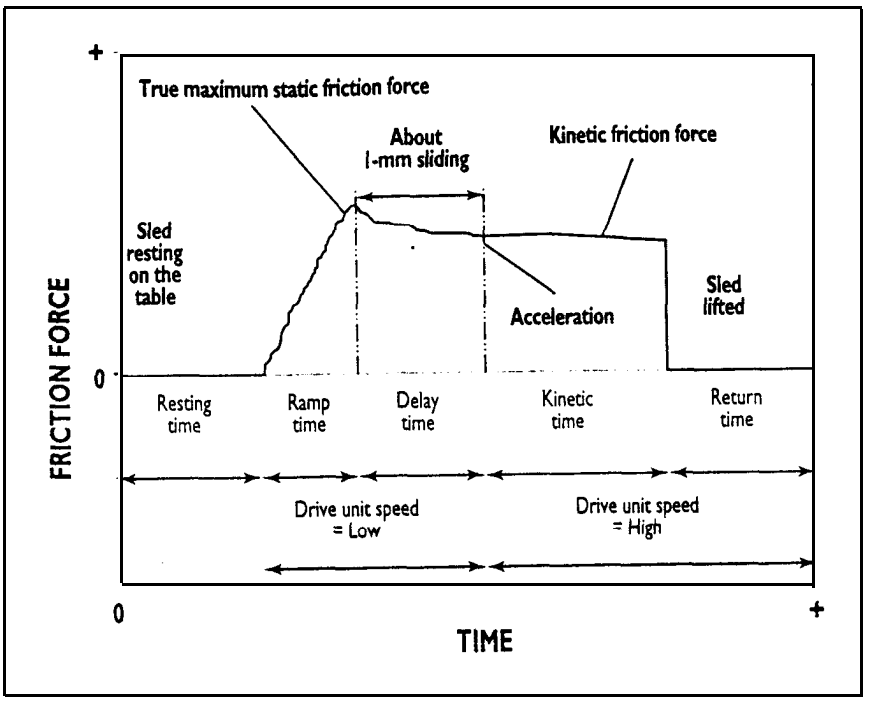
- The paper can rest on a backing both on the table and on the sled.
- The speed of the drive unit can be changed several orders of magnitude to increase the friction force slowly or to rapidly slide the sled during the sliding phase.
- The sled is steered by guide rods, which prevent wobbling in the plane of the test piece.
- The apparatus is very rigid, with no significant elastic parts other than the load cell itself.
- The apparatus is completely automatic, which makes it possible to repeat sequences in a reliable way, thus avoiding human error when lowering the sled into position.
- A computer controls and records the force and the sequences.

Measurement cycle. **Figure 2** illustrates one measurement cycle. The sled is lowered and allowed to rest on the table for a certain resting time. Thereafter, the drive unit moves the table at a low speed for a certain time; the ramp time, which causes the force to increase smoothly. When the static friction force reaches maximum, the drive unit continues to move the table, and the surfaces begin to slide slowly relative to each other during the delay time (corresponding to about 1 mm of sliding). This delay time is necessary to define the true maximum at which the static friction coefficient is determined At the end

of the delay time, the sled accelerates immediately to a constant speed during the kinetic phase, where the kinetic friction force is measured. The sled lifts and then returns to the starting position during the return time. This cycle can be repeated.

The maximum value during the first ramp time and delay time is defined as the static friction force, from which the first static coefficient of friction, S_1, is evaluated. The corresponding kinetic coefficient of friction, K_1, is evaluated from the mean force during the kinetic time. Corresponding coefficients of friction during the proceeding slidings are denoted, S_2, K_2, S_3, K_3, etc.

The apparatus was run using two test schemes with regard to the sliding direction. In the S-test, the sled slides in the same direction during each cycle. In the R-test, the sliding direction is reversed after each cycle.



2. Friction force as a function of time during one measurement cycle

RESULTS

Several variables that can influence the measurement of friction were studied. Some of these variables were related to the design of the apparatus, others to the flexibility and possibilities of variation when the apparatus is used. The influence of different paper grades was also considered.

Table II shows the reference measurement conditions, which were cho sen based on the existing standard methods for measuring the friction of paper and plastics. Deviations from these nominal conditions are reported where applicable.

Parameter	Reference measurement condition
Sled contact area with the paper	60 mm × 60 mm
Sled height	20 mm
Sled weight	985 g
Apparent surface pressure	2.7 kPa
Backing on the table	2 mm closed-cell neoprene cellular rubber (foam rubber)
Surface on the sled	hard metal surface
Resting time	1 s
Ramp time	1–2 s
Sliding speed	5 mm/s
Sliding distance for each sliding	30 mm
Coefficient of friction	S_1, the static coefficient of friction during the first sliding
Test scheme	S-test scheme: sled is lowered, starts and performs one sliding, stops, is lifted, and returns to starting position
Location (x) of force application on the sled*	zero

*See Fig. 7

II. Reference measurement conditions

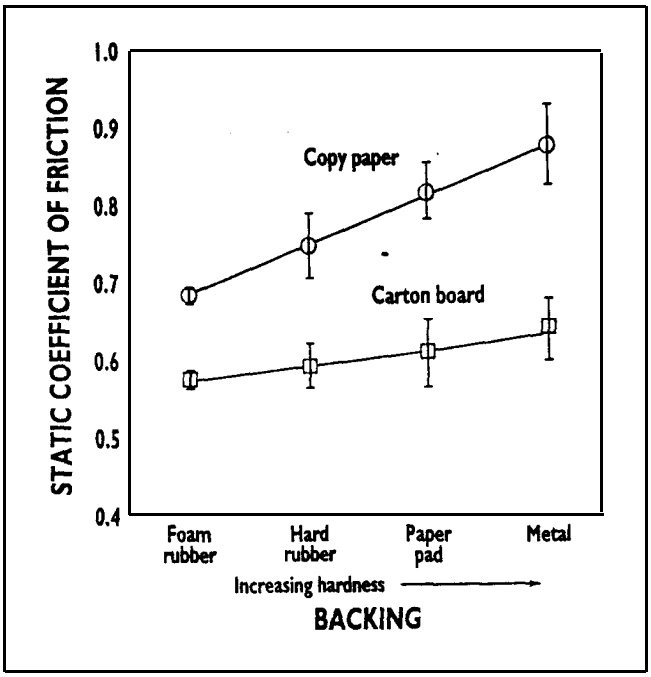
Resting time and time to reach maximum static force

Tests were carried out to investigate whether the resting time and ramp time influenced the measured friction. Two different drive-unit speeds were used to yield ramp times of 1 s and 3 s. Resting times of 1 s and 20 s were investigated. The three paper grades tested–copy, liner, and newsprint–showed similiar results. Within the interval investigated, neither the resting time nor the ramp time had any influence on the static-friction results.

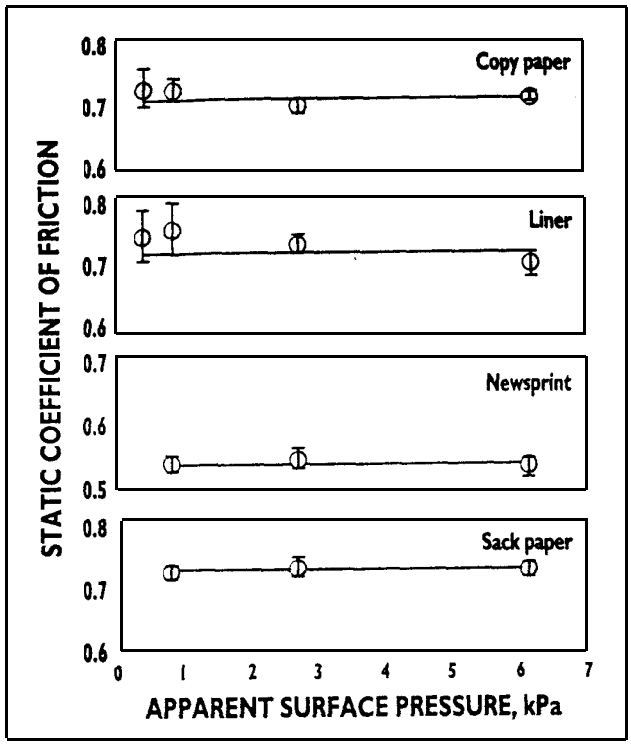
Backing

The sled backing was a hard metal surface. The influence of the hardness of the table backing was investigated by testing four different backing materials:

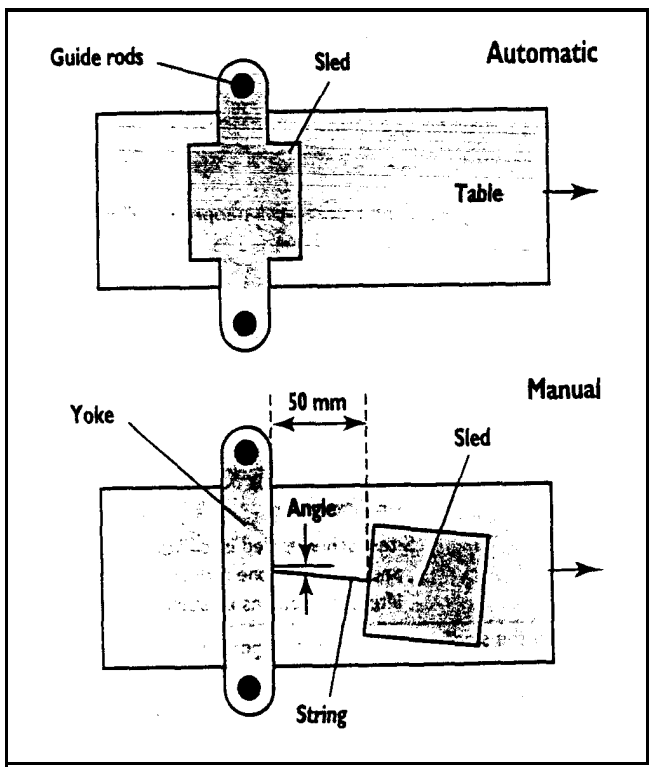
- 2-mm-thick foam rubber
- 2-mm-thick hard rubber sheet
- A pad of the paper being tested (30 sheets of copy paper or 10



3. Static coefficient of friction as a function of the backing material for copy paper and carton board



4. Static coefficient of friction as a function of the apparent surface pressure for four papers



5. Positioning of the sled automatically (top figure) and manually at an angle of either zero or 10° to the direction of movement (bottom figure)

sheets of carton board)

- The hard metal surface of the table.

The backings were fastened to the table with double-sided tape, and the test sheets were then raped onto the backing

The *x*-axis of **Fig. 3** shows increasing hardness from foam rubber to hard rubber to paper pad to metal. The results indicate that harder backings yield higher friction and also give greater scatter than the soft foam-rubber backing

Variations in backing on sled and table

In a separate experiment, the position of the foam-rubber backing was investigated. Three different placements were used:

1. Table only
2. Sled only
3. Table and sled.

The measured friction was not affected by where the soft backing was placed.

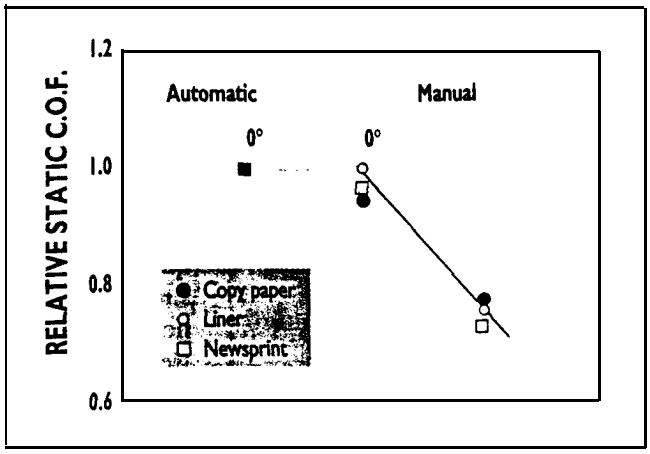
Apparent surface pressure

The influence of pressure on friction measurement was investigated by varying the weight of the sled while holding measurement area constant. The results in **Fig. 4** show that contrary to expectations,[2] the applied pressure had no influence on the friction within the range tested.

Manual or automatic positioning of the sled

The automatic positioning of the sled was compared with manual positioning. The test configurations are depicted in **Fig. 5.** The manual positionings involved fastening a string onto the sled and fastening the other end to a yoke that was fastened to the guide rods. The sled was placed either at an angle of zero or 10° relative to the sliding direction.

[2] Benabdallah, S. M. H. and Yelle, H. J. Matl. Sci. 26: 2445(1991).



6. Influence of manual positioning of the sled on the static coefficient of friction for three papers. (All values are relative to the coefficient of friction for the automatic positioning procedure.)

The three paper grades tested-copy paper, liner, newsprint-showed similar results for static coefficient of friction (COF), as seen in **Fig. 6.** No difference was observed between the automatic and the manual positioning at an angle of zero degrees. When the sled was positioned at an angle, however, the static coefficient of friction decreased.

Force application point

The location where force is applied was investigated because some believe that the tipping moment might influence the results. The location of force application, *x*, was varied from zero to 10 mm, half the height of the sled, as seen in **Fig. 7.** Within the investigated interval, the location *x* had no influence on the friction.

Handling of test pieces

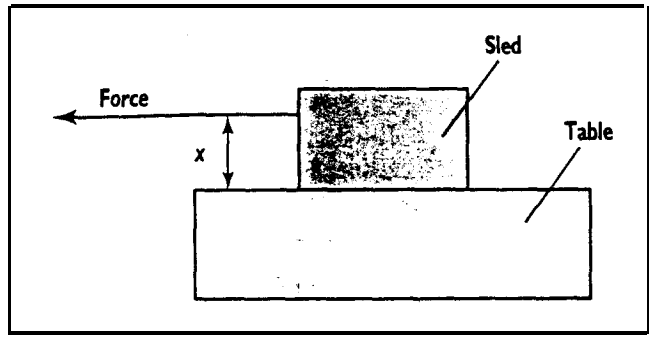
Contact-free handling of the test sheets is an important consideration in friction measurement. This was demonstrated by comparing results for contact-free test surfaces with surfaces that had been touched with the thumb and the hand. The results in **Fig. 8** show that the friction decreased considerably when the surfaces were touched before measurement.

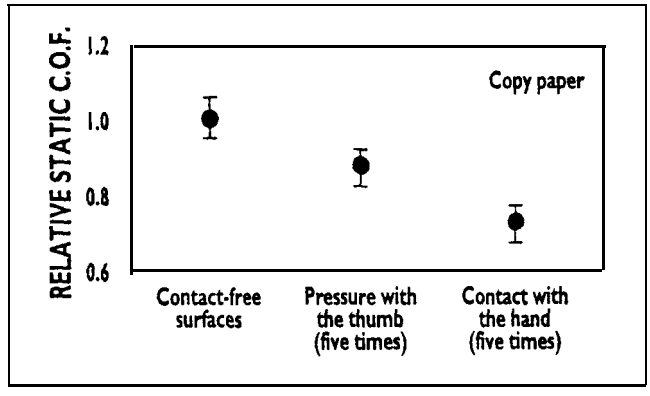
Influence of sliding distance

Fig. 9 shows the change in static friction with the sliding distance in the same direction (S-test) for copy paper Five slidings were carried out for each of four sliding distances. For copy paper, it is clear that longer sliding distances decrease the static friction during repeated sliding. However, no significant change in friction was observed for sliding distances of 30 mm and 6O mm.

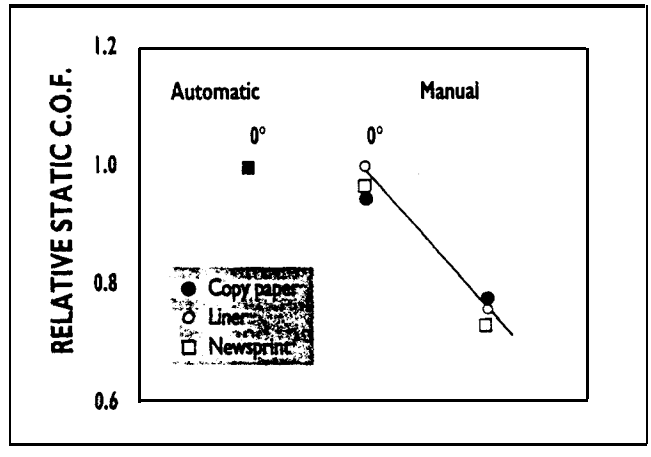
Comparison of S-test and R-test schemes

Figure 10 shows the result of a comparison between the S-test (sled slides in the same direction in each cycle) and the R-test (sliding direction is reversed after each cycle). When repeated slidings were in the same direction, the static friction for copy paper and liner decreased with repeated slidings. Newsprint behaved differently, showing a slight increase in friction with repeated slidings.



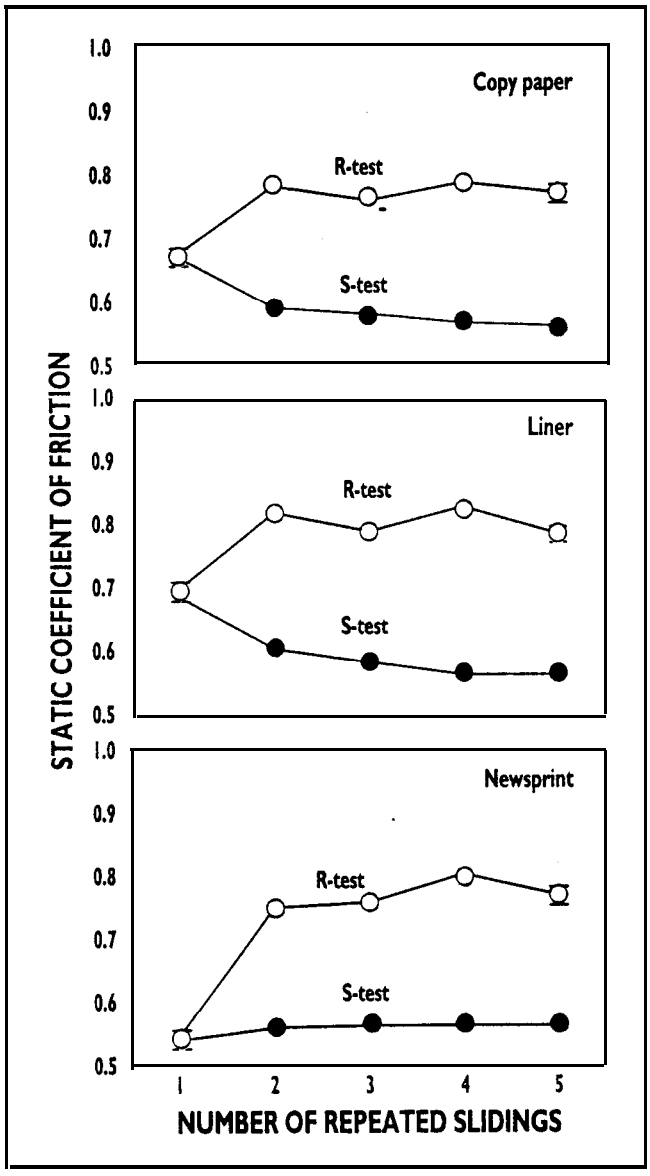


8. Influence of hand contact with the test surfaces on the static coefficient of friction for copy papers. (All values are relative to the coefficient of friction of the contact-free surfaces.)

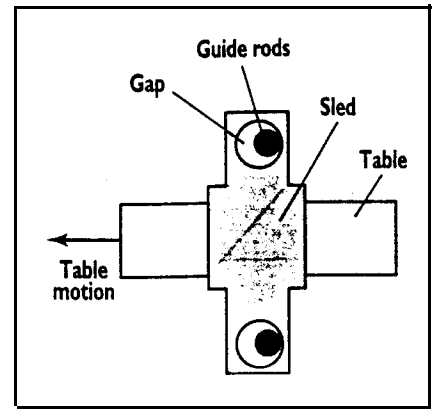


9. Static coefficient of friction as a function of repeated slidings in the same direction over different sliding distances for copy paper. (The confidence interval for each data point is depicted by the size of the symbol.)

When repeated slidings were in alternating directions, the friction for all papers increased significantly at the first reversal of sliding direction and then remained essentially constant. The final difference between the S- and R-tests



10. Static coefficient of friction as a function of repeated slidings for three papers with the S- and R-tests (sliding distance = 30 mm



11. A gap between guide rods and sled was created to test the effect of sliding before measurement. (Apparatus depicted as seen from above.)

is about 0.2 COF units.

Sliding before measurement

The results in Fig. 10 also indicate that the friction measurement could be compromised if the sled is moved backward against the sliding direction before the measurement. The importance of not moving the sled after lowering it onto the test sheet was demonstrated by creating gaps of zero, 0.1 mm, and 0.5 mm between the guide rods and the sled, as seen in Fig. 11.

The sled was lowered onto the table by the automatic lowering mechanism until the surfaces came into contact with each other. During the lowering phase, the sled was pressed against the guide rods so that the gap occurred in only one direction. The sled was then pushed by hand either a very small distance forward in the measurement direction or backward against the measurement direction, whereafter the measurement was started. The same procedure was repeated before each sliding.

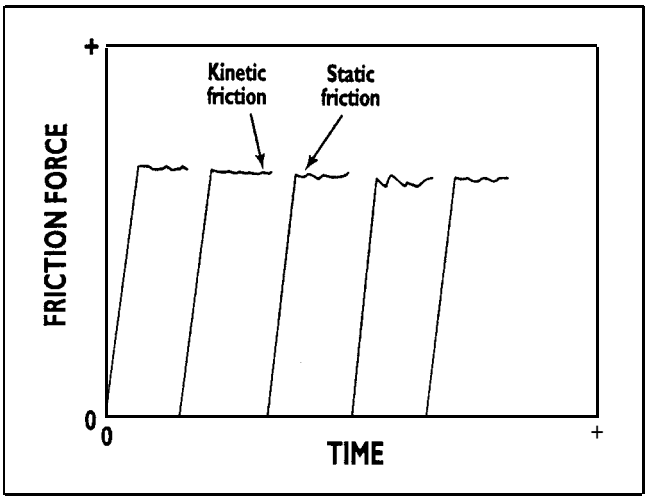
A presliding of 0.1 mm forward in the measurement direction had no influence on the static friction, as seen in Fig. 12. If, on the other hand, the sled was pushed backward (opposing the direction of the intended measurement), the static friction result was significantly higher than the "no presliding" result. The effect was of the same magnitude for presliding distances of 0.1 mm and 0.5 mm. Apparently, even very small preslidings can significantly affect the static friction results.

Kinetic friction

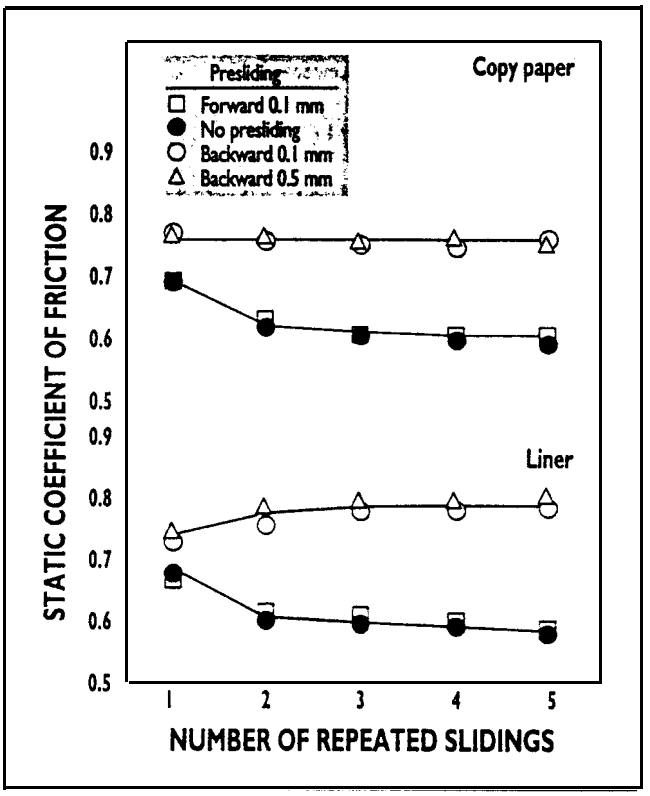
The work described in this report included few quantitative measurements of kinetic friction, Nevertheless, some attention was given to the relationship between the kinetic and static coefficients of friction and to the effect of sliding speed.

Fig. 13 shows the friction force between liners that were drawn five times over each other at a low speed of 0.2 mm/s and a distance of 0.3 mm for each slide. There was a slight decrease in the force required for successive slidings. The important findings here was that the static friction force before each sliding was the same as the final kinetic friction force in the previous sliding. This relationship was generally valid at low speeds for all the papers investigate, but it was not valid at higher sliding speeds.

A serious problem in the measurement of kinetic friction is the stick-slip phenomenon. This is characterized mainly by sequential buildup and release of stored energy in elastic components, resulting in a cyclical acceleration and deceleration of the sled (visible as a ragged force variation). Since the apparatus is very rigid, there was no noticeable stick-slip, as evidenced by the results in **Fig. 13.** To simulate a conventional manual friction apparatus, the sled was fastened to a string on the yoke and lowered manually onto the tab1e (see **Fig. 5B,** zero angle). Manual placment did not prevent the sled from wobbling during the sliding. The line, functioning as a spring caused a strong stick-slip force variation that was greater at low sliding speeds, as seen in **Fig. l4.**



13. Friction force as a function of time for a liner. (The sliding distance was about 0.3 mm.)



12. Static coefficient of friction as a function of repeated slidings for two papers subjected to various levels and types of presliding

DISCUSSION

The results demonstrated that the test surfaces must not be not touched by hand or contaminated by contact with another surface during either cutting or measurement.

The resting time and ramp time had no influence within the investigated time interval, so it is reasonable to use a rest period of about one second. The ramp time must be compatible with the data-collection capability, and the system acceleration must not be so high that inertia affects the true maximum static friction force. A ramp time of 0.5-5 seconds is recommended.

In practical situations where friction occurs, the hardness and flatness of the backings can vary. In this study foam rubber, hard rubber, a pad of the tested paper grade, and a metal were tested as backings. The thin paper was more sensitive to the hardness of the backing than thick carton board. The scatter also was higher with a hard than with a soft foam-rubber backing. It was therefore decided to carry out the subsequent measurements with a soft foam-rubber as backing. This is also the recommended backing for future standardization work.

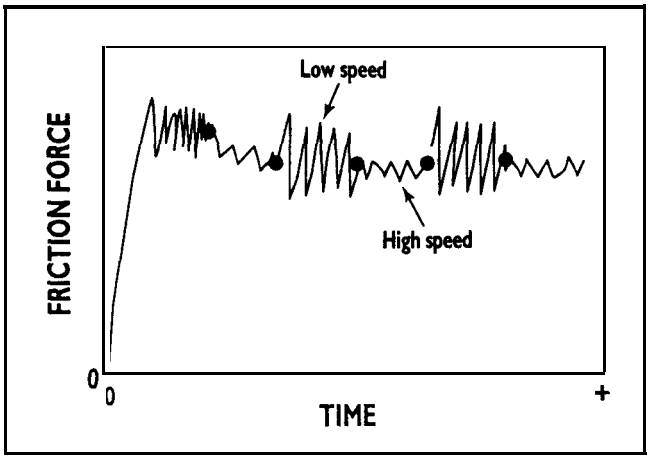
The apparent surface pressure did not influence the friction of the investigated papers within the interval of 0.4-6.1 kPa (with the soft foam-rubber backing) Therefore, sled weight can be chosen by practical considerations. It shouldn't be too heavy to handle, yet it should also function as an efficient and practical fastening device.

A weight of 800 g, which corresponds to a surface pressure of 2.2 kPa, is proposed as a suitable weight in a future standard. The experience of this investigation is that an average technician should have no difficulty in handling a sled of this weight. An additional advantage with this weight is to assure uniform contact when measuring curly, high-grammage papers.

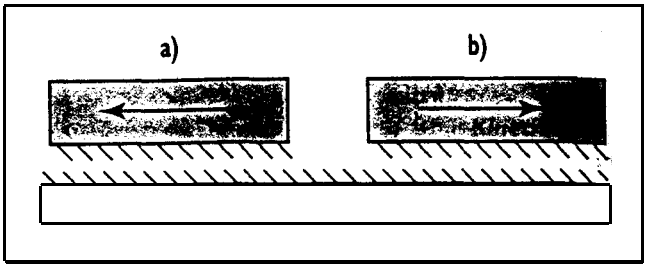
During repeated slidings between the same surfaces, the static coefficient of friction decreased for all the papers studied except for the newsprint, where the friction increased. When the loading direction was changed between each sliding, the friction increased gradually or remained constant. This effect was also observed with slidings as short 0.1 mm, which means that great accuracy is required when lowering the sled onto the table. A sled must not, for example, be drawn backwards to stretch the line to which it is fastened when the surfaces are in contact with each other. A guidance system is needed to keep the orientation of the sled parallel to the table. Even slight wobbling of the sled can produce lower values for the coefficients of friction.

The change in friction that occurs with uncontrolled sliding is proposed to be the result of structural surface changes produced by the sliding action. An orientation of structural elements in the surface can be imagined as depicted in **Fig. 15.** In the case of repeated slidings in the same direction, the structure is oriented in the same direction. When the sliding direction alternates, the structure is reoriented, and this requires a greater force.

Measurements showed that static friction values and kinetic friction values were essentially the same when the latter was measured at very low sliding speeds. Differences between the two arose from heat, wear, and aerodynamic conditions during more rapid sliding. It is evident that there is no *inherent* kinetic friction value for the material tested. Clearly, measures of kinetic friction must always be associated with specified contact pressure, speed of sliding, and slide distance.



14. Friction force as a function of time for copy paper. (Sliding distance about 0.3 mm at a sliding rate of 0.2 mm/s, and 10 mm at 5 mm/s.) A strong stick–slip motion is visible at the low speed, with a much smaller effect at high speed. The transition between the different speeds is marked with a solid circle.



15. The structure of the surfaces during sliding in the same direction (a) and when the sliding direction alternates (b)

There is no combination of sliding distance and speed that could represent the wide range of conditions encountered in the real world. Indeed, existing standards tend to employ very low sliding speeds. For example, ISO 8295 for plastic film specifies three slides of 60-mm length at 1.67 mm/s. Sliding time is 36 s per slide. Tappi T 549 pm-90 for writing and printing paper specifies a single slide of 130 mm length at 2.5 mm/s. Sliding time is 52 s.

If the purpose of the sliding motion is to wear-condition the specimen prior to measuring static friction, it can be argued that a higher sliding speed is more realistic. On the other hand no practical laboratory friction apparatus can produce the high speeds and extended slides occurring in actual printing and converting operations.

The speed and distance criteria used in the proposed standard are a step toward more realistic sliding speeds. The suggested sliding speed for future standardization-20 mm/s during the last 40 mm of the 60-mm travel-is quite feasible for a laboratory instrument. An additional advantage of higher sliding speeds is that the testing time is reduced.

KEYWORDS
Equipment, friction, measurement, paper, static electricity, STFI, test equipment, test facilities, variables.

When the stick-slip phenomenon occurs, the measurement of kinetic friction is invalidated. During stick-slip, the relative speed between sled and table test pieces is erratic, since the sled accelerates and decelerates with respect to the table. Acceleration forces are significant when compared with friction forces. In extreme cases, the sled may actually stop in each stick-slip cycle. Relative motion becomes a sequence of static-kinetic "spurts" in which static friction and acceleration forces are high. When this happens, it is not possible to determine a kinetic coefficient of friction from the force-time record. Consider the following two recording conditions:

1. Even if a true record of the force-time diagram is obtained, one cannot realistically separate force components for static friction, kinetic friction, and mass acceleration.
2. Suppression of the dynamic record by a recording system with a low response characteristic does not improve the situation. On the contrary, not only is the resulting record an erroneous indication of kinetic friction. but the system may mask the fact that stick-slip behavior is occurring.

In practice, this means that:

- Stick-slip must be eliminated by the design of the apparatus.
- The recoding system must faithfully reproduce the force-time response.
- When stick-slip does occur, kinetic friction cannot be evaluated.

PROPOSAL FOR A STANDARD METHOD

The paper industry needs a better method for measuring paper friction Different laboratories testing the same specimens often yield different results Indeed, friction measurements within a given laboratory can show unacceptable variability.

The present investigation shows that measurement of friction is sensitive to test procedures, some of which are not well defined in current tests standards. Friction measurements are also susceptible to operator error.

We believe that this situation can be improved by developing an apparatus–and a set of test procedure that controls key variables and eliminates the "operator" variable.

An effective, practical, and useful standard method must be fast and reproducible. The associated test apparatus must also be a technically and economically practical machine. Moreover, the method and the apparatus must:

- Accept laboratory handsheets
- Control significant variables
- Minimize vulnerability to operator differences
- Represent real-life circumstances to the degree possible.

Table III suggests a set of operating parameters for a standardized method of measuring friction on paper. In our view, this is a practical proposal that balances the range of requirements for measuring paper friction. TJ

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Parameter	Proposed measurement condition
Resting time	I s
Ramp time	0.5–5 s
Handling of samples	Contact free from cutting to measurement
Backing	A 2-mm soft, closed-cell neoprene cellular rubber sheet on the table
Sled contact area with the paper	60 mm × 60 mm
Apparent surface pressure	2.2 kPa
Vibrations	Negligible
Lowering of the sled	Automatic and controlled so that the sled descends straight and does not slide or wobble on the table before measurement
Position where driving force is applied to the sled	Maximum 5 mm above the plane between the paper surfaces
Force transfer from paper surface to load cell	As rigid as possible to avoid stick–slip motion
Sled sliding mode	Straight and without wobbling of the sled on the table
Sliding speed	20 mm/s
Sliding distance	60 mm
Number of repeated slidings	Three, where the static value is reported before the first and third slidings. (The first gives the friction for an untouched surface and the third is a measure of the wear on the surfaces.) Kinetic friction can be evaluated as the average value between 40–60-mm sliding distance during the third slide if there is no stick–slip motion.

III. Proposed measurement conditions for standardized test method for measuring friction on paper (cf. Table I)