Using peel as a measure of paper surface strength

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ABSTRACT: The force required to initiate delamination of paper when peeling a strip of adhesive tape can serve as a measure of paper surface strength. We obtained measurements which were insensitive to tape properties, peeling direction, and peeling velocity by using a 180° peeling geometry in which only the test tape was allowed to bend. We compared measurements of peel surface strengths to IGT surface strength velocities for 15 uncoated papers, including machine-made fine papers, newsprint, and filter paper. The newsprint and fine paper surface peel strengths were linearly correlated with the IGT results, whereas the filter paper data were poorly correlated. We believe the IGT test was compromised by excessive liquid pickup in the very porous filter paper. The peeling measurements offer the advantages that a force is directly measured, measurements from vastly different paper types can be directly compared, and the procedure does not require operator assessment of the onset of paper failure.

Application: Paper surface strength—an important property influencing coating, printing, and converting—can be reliably measured by this simple procedure based on peeling tapes from paper surfaces.

Paper surface strength is an important property for printing, coating, and converting operations because these processes apply significant stresses to paper surfaces. Paper failure in these operations can take many forms, including linting, fiber picking, blistering, or catastrophic delamination [1]. One approach to optimizing surface strength is to simply optimize bulk paper strength on the assumption that similar fiber strength and bonding properties determine both the surface and bulk properties, such as tensile and burst. However, it seems more appropriate to measure surface strength directly by methods which, to some extent, mimic the stresses applied during printing.

Although many methods have been proposed for measuring the surface strength of paper, the IGT test appears to be the most widely used. The IGT test involves accelerating a strip of paper through a nip consisting of a drive wheel contacting a disk coated with a test fluid. During a test, the drive wheel is accelerating, which means the forces applied to the paper surface increase with distance along the test strip of paper. The operator determines the location along the paper strip where the first fibers are picked. Thus, the primary output of an IGT test is a velocity. Because paper and paperboard span a large range of surface strengths, IGT provides three test fluids covering a range of viscosities. According to IGT Method-W31, the results are expressed as a product of the pick velocity and the test fluid viscosity. An advantage of the IGT test is that it simulates some types of printing nips. However, reading the IGT strength from a picked paper surface is operator-dependent, and the reproducibility was found to be poor among different laboratories [2]. Comparing results from tests that use different test fluids may also be difficult.

In this work, we compare results from the IGT test to a modified peeling test as an assessment of surface strength. Using peel to measure paper properties has a long history in paper science. Half a century ago, the Graphic Arts Research Laboratory in Sweden proposed peeling pressure-sensitive adhesive tapes from paper as a measure of paper surface strength [3]. That method used a peeling geometry similar to the T-peel test used in adhesives technology. The maximum peel force was used as the paper surface strength. The measured forces were dependent on peel rate, suggesting that measured forces were sensitive to the viscoelastic properties of the adhesive. We suspect that this is because the peel geometry in the testing was not fixed and because energy was consumed in bending both the test paper and the adhesive tape. Our approach uses a peeling geometry in which the paper does not bend. The results show that it is possible to achieve a peel-rate independent measure of paper surface strength that is strongly correlated to the IGT strength, with added advantages.

EXPERIMENTAL

Materials

Table I describes the 15 uncoated papers tested in this study, including fine paper, newsprint, and filter paper. The fine paper samples were made elsewhere on pilot paper machines for an ASTM paper-aging research program.

Each peel test involved three adhesive tapes:

- A "peeling adhesive tape" (3M Scotch Brand 9974B, 25 mm wide, 77 µm thick), which was used to apply stress to the test paper surface
- A double-sided "fixing tape" (tape 9974B), which was used to fix the test paper to a metal panel
- A single-sided transparent "separation tape" (Grand & Toy Ruban Invisible), which was used to facilitate the initiation of peeling.

Peel tests

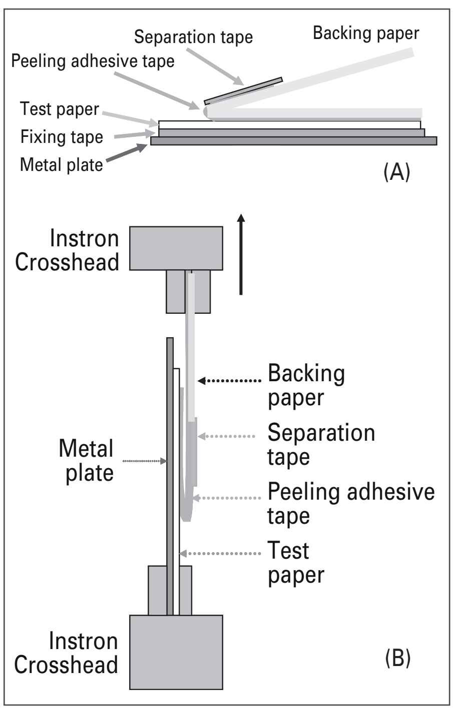
The preparation of peel test samples was based on our previous work [4]. Each test sample consists of two types of paper and three adhesive tapes. The two papers are the "test paper" whose surface strength is being measured, and the "backing paper" (Canon copy paper, 0.1 mm thick, basis weight 77g/m^2), which is used to cover the peeling adhesive. **Figure 1** shows the test sample construction.

We placed 2.5 cm x 4 cm strips of peeling tape across a sheet of Canon copy paper trimmed to 2.5 cm (i.e. to

Sample	Pulp Type 1	Pulp Type 2	pH	pH Control Chemical	Calcium carbonate	Internal size	Paper density (Kg/m³)
ASTM paper 1	100% BNSWK	None	5	Alum	None	2#/T Rosin	649
ASTM paper 2	100% BNSWK	None	8.1	Na_2CO_3	5% PCC	None	658
ASTM paper 5	100% Cotton	None	5	Alum	None	2#/T Rosin	642
ASTM paper 10	20% BNSWK	80% HW-BCTMP	8.1	Na_2CO_3	5% PCC	None	609
ASTM paper 11	50% BNSWK	50% BNHWK	8.1	Na_2CO_3	None	None	680
ASTM paper 12	50% BNSWK	50% BNHWK	8.1	Na_2CO_3	5% PCC	None	593
ASTM paper 13	50% BNSWK	50% HW-BCTMP	8.1	Na_2CO_3	5% PCC	None	614
ASTM paper 14	50% BNSW	K50% HW-BCTMP	5	Alum	None	2#/T Rosin	631
ASTM paper 15	50% BNSWK	50% BNHWK	8.1	Na_2CO_3	5% PCC	4#/T AKD	550
Newsprint 1	100% TMP	—	—	—	—	—	662
Newsprint 2	100% TMP	—	—	—	—	—	683
Newsprint 3	100% TMP	—	—	—	—	—	624
Filter paper 1	100% Cotton	—	—	—	—	—	505
Filter paper 4	100% Cotton	—	—	—	—	—	459
Filter paper 5	100% Cotton	—	—	—	—	—	534

1 - symbol list. BNSWK: bleached softwood kraft. BNHWK: bleached hardwood kraft. BCTMP: bleached chemithermomechnical pulp. SGW: stone ground wood. TMP: thermomechanical pulp. 2 - Most ASTM paper samples were made by Herty Foundation pilot paper machine except ASTM paper 5 which was made by Crane & Co. Inc. All these samples were provided through the ASTM paper-aging program. 3 - All newsprint samples were provided by Donohue Inc. in Montreal, Canada. The filter papers 1, 4, and 5 are Whatman Filter No.1, No. 4, and No. 5.

I. Paper samples.



1. Experimental setup for using peel as a measure of paper surface strength, showing (A) construction of the 180° peel test samples and (B) geometry of the 180° peel test.

match the adhesive width), yielding a paper tail that extended more than 10 cm beyond the tape. Next, the white backing was removed from the other surface of the adhesive tape. We placed a 2.5 cm x 1 cm strip of the separation tape across the front edge of the adhesive surface with the sticky side facing the adhesive layer to serve as a separation or release layer to help initiate the peel crack. The resulting tape strip consisted of a 4 cm adhesive layer, 10 cm bare paper backing tail, and 1 cm separation tape across the front edge of the adhesive surface. The paper backing offered little resistance to folding and also gave much stronger adhesion between the backing and the adhesive.

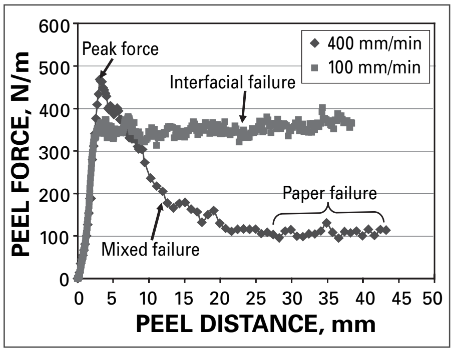
We trimmed a conditioned (23°C, 50% RH) test paper strip to 5 cm x 6 cm so that the peeling direction corresponded to the machine direction. The paper strip was fixed onto the surface of a stainless steel panel (1 mm x 7.5 cm x 10 cm) using the fixing tape. We then applied the strip of peeling adhesive tape to the middle of the mounted test paper (see Fig. 1A) and pressed the laminate with 10 passes of a 2.04 kg rubber coated roller (ChemInstruments, USA).

The metal panel was clamped into the lower crosshead of an Instron machine (Model 411) located in a TAPPI standard controlled temperature and humidity room. The separation tape aided the final step, which was gently to fold back the test tape tail and fix it to the top crosshead, giving a 180° peeling geometry (see Fig. 1B). The initial distance between the lower and top crossheads was 11 cm.

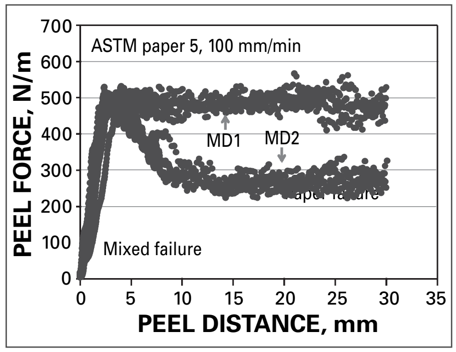
Peel tests were performed within 2 min of lamination. The peel trace for an individual experiment was recorded as a force/distance curve. We tested each paper sample at least six times at a given peel rate. The methods of data analysis and error estimation are described in the results section.

IGT surface strength test

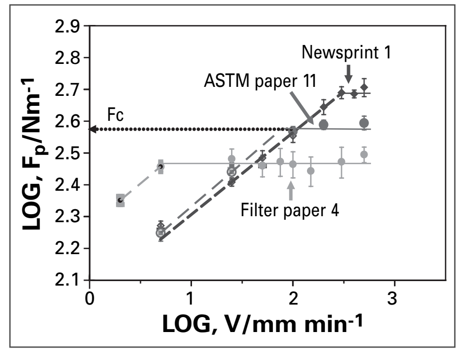
The IGT surface strengths of the paper samples were measured on an IGT (model A1C2) tester in the Paprican Printability Laboratory in Montreal, Quebec, Canada, following the standard ISO 3783 method as closely as possible. The test oil was applied to inking rollers of the IGT inking systems. We allowed the test oil to set about 10 min so that it was more evenly distributed on the ink-



2. Typical peel curves and failure modes. Peeling PSA tape 9974B from newsprint 1 at peel rates of 100 mm/min and 400mm/min. Interfacial failure is defined as the absence of apparent fiber layer picked out from paper surface; paper failure is defined as the presence of at least one fiber layer embedded in the tape surface after peeling; mixed failure is the intermediate state between interfacial and paper failure.



3. Peeling tape 9974B from ASTM paper 5 along two of its machine directions (MD1 and MD2) at 100 mm/min.



4. Peel data analysis by plotting log (Fp) against log (V). Fp is the peak peel force, i.e. the maximum force in peel traces. V is the peel rate. Open symbols are for interfacial failure; solid symbols are for paper failure. Fc is the critical force for paper failure.

ing rollers. Then, the IGT printing disk was placed against the inking rollers for 1 min. Next, we attached the inked disk to the IGT tester against the paper sample mounted on an acceleration wheel and printed the paper under acceleration from zero to a preset end-velocity, V_{final}. We used the standard IGT oil of middle viscosity (IGT Testing Systems, Inc.) for all of the samples in this study.

Paper samples were cut into strips around 5 cm x 35 cm along their machine direction. We then mounted the paper strip to the IGT acceleration wheel, smooth side facing up. Preliminary tests were performed to identify an appropriate end-velocity so that the fiber picking would occur near the middle of the strip. The print surface was examined for picked fibers under low angle illumination. The velocity at which the first pick occurred ($V_{pick,}$) was reported as the surface strength of the paper.

RESULTS

Virtually everyone who has tried to peel tape from paper knows that the tape will cleanly separate from the paper (i.e. interfacial failure) if peeled very slowly, whereas rapid peeling causes catastrophic failure of the paper surface. **Figure 2** shows examples of peel curves illustrating these two cases. The interfacial failure curve is characterized by a force plateau, while the paper failure curve is characterized by a peak force F_p and a lower steady-state force. We define interfacial failure as the absence of a fiber layer on the adhesive surface after peeling. Paper failure corresponds to at least one fiber layer embedded in the tape surface after peeling. The mixed failure region shown in Fig. 2 is a transitional region leading to complete delamination.

We know that the tendency of a paper to delaminate in peel can be very sensitive to peeling direction, apparently reflecting whether the fiber ends are orientated up or down in the z-direction, which in turn is a function of the drag-to-rush ratio [5, 6, 7]. **Figure 3** shows replicated peeling traces obtained with ASTM paper #5 at 100 mm/min. One half of the data was obtained by peeling one way in the machine direction (MD 1) whereas the other half was peeled in the opposite machine direction (MD 2). The MD 2 peels all lead to paper delamination with a reproducible steady state peel force. By contrast, the MD 1 peels gave reproducible interfacial peel curves with a much higher steady-state peel force. Fortunately, the peak force F_p for the MD 2 experiments corresponded to the steady-state MD 1 results suggesting the F_p is a direction-independent parameter.

In previous work, we showed that peak force F_p increases monotonically with peel rate until paper failure, after which peak force is independent of peel rate [4]. This behavior is illustrated in **Fig. 4**, which shows plots of log (F_p) versus log (V). F_p is the mean of at least six observations. It equals the stable interfacial force in the interfacial failure domain and the peak force in the paper failure domain. The error bars in Fig. 3 were calculated as:

$$Log(\frac{F_p \pm SD}{F_p})$$

where SD is the standard deviation of F_p based on six replicates.

The results for each tape-paper combination in Fig. 4 consisted of two linear segments on the log-log plots. The segment with the positive slopes corresponded to interfacial failure (open points in Fig. 4), whereas the horizontal segments corresponded to paper failure (solid points). The intercept of the segments gives the critical peel rate at which paper failure starts. Previous work showed that the critical peel rate was difficult to identify accurately for papers with weak surfaces, such as newsprint [4]. By contrast, F_c, the peak peel force corresponding to paper failure can be measured accurately. Therefore, we propose to use F_c, which we call *surface peel strength,* as a measure of paper surface strength.

Table II summarizes the paper surface strengths as measured by the peel and IGT tests. The surface peel strength (F_c values) were calculated as the mean of the peak peel force values (F_p) for those peel rates which induced paper failure. The corresponding standard errors (SE) were calculated as:

$$\sqrt{\left(\sum_{1}^{m}(SD^2/n)\right)/m}$$

Sample	Fc, N/m	SE, %	V_{final}, cm/s	V_{pick}, cm/s	SE, %
ASTM paper 1	430	3	300	128	4
ASTM paper 2	506	4	300	142	4
ASTM paper 5	620	2	600	234	8
ASTM paper 10	545	3	500	246	3
ASTM paper 11	383	2	200	86	3
ASTM paper 12	347	4	150	86	2
ASTM paper 13	518	2	400	189	2
ASTM paper 14	459	3	400	204	5
ASTM paper 15	595	2	600	300	3
Newsprint 1	494	3	200	86	4
Newsprint 2	398	3	100	55	2
Newsprint 3	401	4	100	53	5
Filter paper 1	399	2	700	327	4
Filter paper 4	295	3	600	360	4
Filter paper 5	481	3	700	522	3

II. Paper surface strength as measured by peel and IGT tests.

where SD is the standard deviation of F_p of n (n >= 6) replications at each peel rate, at which paper failure occurred; m is the number of paper failure points. For example, consider the newsprint peel results in Fig. 4. Only the results from the highest three peel rates induced paper failure, so these were used to calculate F_c (i.e. m=3) and the corresponding SE.

The IGT results in **Table II** consist of V_{pick} values, the mean of the wheel velocity corresponding to the initiation of fiber picking. The corresponding standard errors were based on five replicates of each paper sample.

The percentage standard errors of the peel and IGT results in Table II span the same range. The peel surface strengths are plotted against the corresponding IGT values in **Fig. 5**. For newsprint and the uncoated fine papers, although the data points were scattered, there was a good linear correlation between F_c and V_{pick} with correlation coefficient (R^2) 0.71. For the three filter papers, there was no correlation between the methods. The IGT results suggested that the filter papers had the highest surface strengths, whereas the peel tests ranked the filter papers in the bottom half of surface strengths and included the weakest paper.

DISCUSSION

We propose that the peak peel force required to delaminate paper in peel can be used as a measure of paper surface strength. The advantage of using the peak force is that it is related to the initiation of failure at the paper surface. By contrast, past peel studies [7, 8, 9, 10, 11, 12, 13] have focused on the steady-state delamination force. Because of its layered structure, paper is relatively easy to delaminate once the failure has been initiated. Indeed, the steady-state delamination force is highly correlated to the internal bond strength and other measurements of z-direction strength [14].

Our peeling geometry differs from previous work [3]. By using 180° peeling with the test paper fixed to the stainless steel plate (Fig. 1), the paper is not required to bend. That means the results should be independent of the stiffness of the paper or paperboard.

Only peeling experiments that lead to paper failure give a measure of paper surface strength. Previous work with a series of tapes indicated that the surface strengths were insensitive to the tape type, lamination pressure, or dwell time [15]. This conclusion is reasonable because the adhesive layer does not fail during the tests of interest. However, we expect departures from tape independence with extremely thick tapes or tapes with stiff backings, which require significant work to bend. We recommend replacing the commercial tape backing with paper because the commercial backings are stiff and designed to easily separate from the adhesive layer. By contrast, the replacement paper backing strongly adheres to the adhesive and is flexible enough to ensure a stable 180° peeling.

The results in Fig. 4 show that in the paper failure regime, the results are insensitive to peel rate. Therefore, in a routine testing situation, surface strengths could be measured at only one peel rate. In this situation, sample preparation and testing could be completed within 10 minutes.

Surface strength determined by peel showed a reasonable correlation with the IGT results. The largest discrepancies were with filter paper where we believe the IGT results were poor because of excessive fluid pickup.

To summarize, we have shown that peak peel forces measured with 180° peel give a measure of the propensity of a paper surface to initiate failure. The advantages of using peel to characterize surface strength are that the method is rapid, there is little penetration of the adhesive into the paper structure, the result is a force, and the results are independent of operator judgement.

CONCLUSIONS

From this work, we can conclude that the peak peel force required to initiate delamination when a tape is peeled from a paper surface is a measure of surface strength we call the *paper surface peel strength*. The critical elements of the method include the following:

- The stiff release backing used for most double-sided tapes was replaced with a flexible paper backing
- The test paper was fixed to a metal panel so the paper did not bend during the test
- Only peak peel forces leading to paper delamination were used.

Paper surface peel strength is independent of peel rate up to 500 mm/min, the limit of our test equipment. *Paper surface peel strengths* were linearly correlated with the IGT surface strengths for uncoated fine paper and newsprint. By contrast, filter paper gave poor correlations possibly because excess penetration of IGT test fluid into the filter paper gave erratic results. The advantages of the peel-based test are that the procedure is rapid and operator independent, giving a quantitative force. **TJ**

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*IGT is an acronym for Institute for the Graphic Techniques (now the IGT Testing Systems, Amsterdam, The Netherlands) who manufactures the commercial IGT tester for measuring paper surface strength. The measured paper surface strength is called IGT surface strength.

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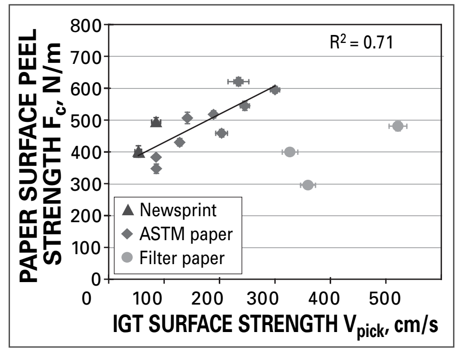

5. Comparison of paper surface strength by peel and IGT tests. The error bar is the standard error of the measurements.

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INSIGHTS FROM THE AUTHORS

This topic is an extension of our fundamental research of paper/adhesive interactions. This work suggests a simple surface strength test that mills could routinely use to monitor product quality.

Most previous peel studies have focused on steady-state peel force. We studied the force required to initiate delamination of paper and proposed it as a measure of paper surface strength. For the first time, the peel measurements were compared with the IGT surface strength measurements.

The most challenging aspect of the study was determining a rational approach to the analysis of peel adhesion results.

In the course of our research, we discovered that the peeling behavior of an adhesive tape is sensitive to paper surface properties. A particularly interesting observation was that paper delamination is relatively difficult to initiate. Once started, however, steady-state delamination is relatively easy to propagate because of the layered structure of paper.

A more detailed investigation is required to define the scope of the proposed test.

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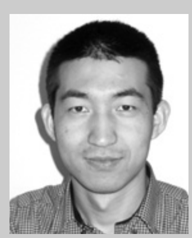

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