Relationship of surface strength and bulk strength properties in uncoated woodfree paper

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ABSTRACT: Various uncoated woodfree papers produced on a pilot paper machine were characterized for picking resistance, using an IGT printability tester, and standard sheet properties. The papers were produced with and without surface sizing or a debonding agent, with different filler types (ground calcium carbonate [GCC] or precipitated calcium carbonate [PCC]) and levels (20% and 25%), and by varying the calendering conditions. The goal was to assess the relationship between surface strength of these sheets and their bulk strength properties, such as tensile strength and internal bond. Variables such as the use of a debonding agent or the application of surface size had equal effect on picking resistance and tensile strength. Increase of filler content in paper or replacement of GCC with PCC reduced picking resistance, tensile strength, and internal bond. Increase of the calendering load, for both GCC and PCC sheets, reduced picking resistance but left tensile strength and internal bond unaffected. Picking resistance of the 25% PCC-containing sheets was affected at a significantly larger extent by an increase in calendering load than picking resistance of the 25% GCC-containing sheets. These results point out that the surface of a highly filled PCC sheet is particularly sensitive to surface damage by calendering.

Application: The picking resistance method is useful for measuring surface strength of uncoated woodfree papers.

Current papermaking trends toward greater filler loading and use of recycled fibers have increased the importance of solutions to improve paper surface strength. Good surface strength is particularly critical in offset lithography, a process that uses tacky inks and subjects paper to considerable stress [1]. Paper failure during offset printing may take different forms, including picking, delamination, dusting, and linting [2–3]. Picking is the tearing off the paper surface, whereas delamination is the result of paper peeling apart and separating from within. Picking and delamination are generally runnability problems that occur very soon after printing starts. Dusting and linting are time-dependent runnability problems caused by removal of loose fiber and fines material from the paper surface and their slow accumulation on the printing blanket. Dusting and linting problems may be very severe, deteriorating image quality and requiring that the printing press be stopped for maintenance/washing. In offset printing and in electrophotographic processes, dusting and linting of paper are important quality criteria. In dry toner electrophotography, the static electricity and electrical charges applied are responsible for generating dusting from paper. The dusting accumulates on the transfer and photoconductive belts and causes print quality defects. Dusting may then increase component wear.

Different papermaking strategies have been proposed to optimize paper surface strength and prevent paper runnability issues during print press operations [4]. One approach consists of improving the bulk strength properties of paper (i.e., tensile, burst) through increased refining or addition of strength additives [4]. This approach is based on the assumption that surface bonding properties of paper should mirror its bulk strength properties. Other approaches include proper selection of wet-end additives for improved filler and fines distribution and the application of surface sizing chemicals for improved surface strength or water hold-out, or both [4]. Mechanical strategies include the application of higher press load for improved paper surface consolidation [4].

Many laboratory test methods have been proposed to measure paper surface strength and select the best papermaking strategy to optimize it [3,5], although their validity in predicting paper performance issues on a print press has been a subject of controversy. Lack of correlation between laboratory data and printing trial results was found in some cases [3], mainly because no simple laboratory method can reproduce all the variables affecting blanket contamination on the printing press [3,6,7]. In addition, laboratory devices usually apply significantly higher printing force than real printing press operations [8]. As a result, they remove relatively large areas of material at the paper surface and may be more suitable to predict picking or delamination phenomena rather than linting and dusting that involve removal of discrete particles from the paper surface [3].

A popular test used to measure surface strength of paper is the determination of picking resistance using the IGT printability tester [9]. The device uses a highly viscous oil to exert a pulling action force on the paper surface. In the standard method, the inked printing disc is placed under pressure against the paper sample mounted on a circular sector. The

sector is run against the disc under acceleration from zero to some preset end velocity. Surface strength of paper (pick resistance) is derived from the distance between the starting point of the print and the position on the print where the first damage occurs. The test is not easy to perform, and operator reproducibility is poor [10]. Furthermore, variables such as printing speed, printing pressure, ink film thickness, temperature, and humidity affect the picking test results [10–12]. Thus, a rigorous, consistent testing routine must be followed [10]. As for other tests, the IGT picking resistance method evaluates the bonding potential of fiber more than the true linting and dusting propensity of paper [3,5].

Although the picking resistance method has been used for more than 40 years in the paper industry to determine surface strength, to the best of our knowledge no systematic investigation has been carried out on how surface strength measured by the device relates to basic bulk strength properties of paper. This information is important to understanding the usefulness of the picking resistance method for measuring surface strength of a specific paper. It may also indicate the most appropriate paper property to control at mill level to prevent print runnability issues.

In this study, we characterized a variety of woodfree papers for picking resistance and bulk strength properties. The papers were produced on a pilot paper machine using systematic changes of operational and chemical parameters: with and without surface sizing or a debonding agent, with different filler types and levels, and by varying the calendering conditions.

EXPERIMENTAL

Pilot paper machine studies

Two trials were conducted on a pilot paper machine at Stora Enso Research Center, Imatra, Finland, to produce the papers used in the current investigation. The furnish used in trial 1 consisted of 76% total fiber (75% birch and 25% pine) and 24% scalenohedral precipitated calcium carbonate (PCC) collected at a local mill. The retention program consisted of the combination of anionic flocculant added before the screen at a dose of 0.4 kg/ton and silica microparticles, added after the screen at a dose of 4 kg/ton. In addition, 5 kg/ton of cationic starch was added at the exit of the mixing chest. The internal sizing agent was alkenyl succinic anhydride (ASA) emulsified with starch in ratio 1:3 and added at the fan pump at a dose of 1 kg/ton. The paper produced had a basis weight of 75 g/m². **Table I** summarizes variables applied in trial 1 to produce the paper samples used in the investigation. Two paper samples were produced with surface size and two others without surface size. For each of the two sets, one sample was produced with and the other one without a debonding agent, which was added to the machine chest.

Sample	Debonding Agent	Surface Sizing
A	no	yes
B	yes	yes
C	no	no
D	yes	no

I. List of paper samples produced in trial 1.

Sample	Filler Type	Filler Content	Calendering
		%	kN/m
E	GCC	20	50
F	GCC	25	50
G	PCC	20	50
H	PCC	25	50
I	GCC	20	15
J	GCC	25	15
K	PCC	20	15
L	PCC	25	15

II. List of paper samples produced in trial 2.

In trial 2, the furnish fiber composition was similar (75% birch and 25% pine). The filler used was ground calcium carbonate (GCC, Omya H-HO MEA, Omya Inc., Proctor, VT, USA) or scalenohedral precipitated calcium carbonate (PCC) produced onsite at a local mill. For each filler type, two filler levels were used, 20% and 25%. Each paper was calendered at two different loads, 15 or 50 kN/m. The retention program consisted of the combination of cationic flocculant, added before the screen at a dose of 0.4 kg/ton, and silica microparticles, added after the screen at a dose of 4 kg/ton. In addition, 5 kg/ton of cationic starch was added at the exit of the mixing chest. The internal sizing agent was alkyl ketene dimer (AKD) added to the thick stock at the stuff box at a dose of 1.5 kg/ton. The paper produced had a basis weight of 80 g/m². All paper samples produced in trial 2 were surface sized. **Table II** summarizes variables applied during their production.

IGT picking resistance test

All printing trials were performed at constant temperature and humidity conditions (23°C, 50% RH) using an IGT AC2 model electrically driven printability tester. A 10-mm-wide aluminum printing disc (inking surface of 20.4 cm²) was inked on an IGT AE inking unit with high viscosity pick test oil supplied by IGT Testing Systems (Amsterdam, The Netherlands).

At the start of each set of 10 prints, a fixed amount of pick test oil (referred to also as ink in the paper) was added to the top roller of the inking unit. The amount was determined such as to reach the desired film thickness on the inking unit. The ink was left to distribute for 10 min. Following ink distribution, the printing disc was inked for 45 s and inserted, after being weighed, on the upper printing shaft of the printability tester.

A print was made on the test strip in accelerating mode, using a printing force of 300 kN. The end speed selected was 1 or 2 m/s. Preliminary runs on the examined papers showed that these speeds, in combination with high-viscosity pick test oil,

were the optimal ones for good detection of the point of pick on paper. The printing disc was reweighed after printing. A second printing disc was inked in the same position of the inking unit and used for printing. Every two prints, a fixed amount of ink was added to restore the original amount of ink supply depleted by the printing. The ink was allowed to distribute for an additional 2 min before inking the next printing disc.

In the picking experiments we conducted, the inking unit (total inking surface of 1187 cm^2) was inked with various ink amounts to attain ink film thicknesses of 4, 6, 8, 10, and 12 µm. The corresponding ink amounts transferred to the printing disc were 3.2 ± 0.1 g/m^2, 4.8 ± 0.1 g/m^2, 6.1 ± 0.1 g/m^2, 7.5 ± 0.1 g/m^2, and 9.0 ± 0.1 g/m^2.

Test results are expressed in terms of pick velocity, which is the velocity at which picking starts. Each sector on the printed strips corresponds to a specific velocity. All the printing tests were performed with the same high-viscosity pick test oil at constant temperature and humidity conditions. Pick velocity values (expressed in m/s) can be converted to pick resistance values (expressed in N/m) by multiplying them by the viscosity of the pick test oil (110 Pa•s). Thus, the terms "pick velocity" or "pick resistance" can be used interchangeably to discuss the results we present. For each paper type and condition, printing was repeated five times. The confidence limit at 95% significance level was 11% of the pick velocity values.

Paper properties

Paper sheets were conditioned in a constant temperature and humidity room (23°C, 50% RH) for 24 h before testing.

Caliper

Sheet caliper was measured by using an L&W Micrometer (Lorentzen & Wettre, Kista, Sweden) at eight random positions on every sheet using a foot pressure of 50 ± 2 kPa. A total of five sheets per sample were analyzed. Caliper and grammage values were used in the calculation of sheet bulk.

Permeability

Sheet permeability was measured by using an L&W Bendtsen tester, equipped with a 10 cm^2 measuring head. Eight measurements per sheet were performed, and a total of five sheets per sample were analyzed. Measurements were carried out at a standard pressure of 1.47±0.02 kPa according to the ISO 5636 method (ISO 5636-3 "Paper and board—determination of air permeance [medium range]—Part 3: Bendtsen method second edition").

Beta-formation

Beta-formation was measured by using an Ambertec Beta Formation Tester (Ambertec, Espoo, Finland). The instrument determines the deviation from the mean weighted sheet basis weight. Normalized formation values were obtained by dividing the standard deviation of the basis weight (formation) by the square root of the basis weight. Two measurements per sheet were performed, and a total of five sheets per sample were analyzed. Each measurement consisted of 400 measured points. The pulse counting time was 1.5 s.

Parker Print-Surf roughness

Sheet roughness was measured by using a Parker Print-Surf (PPS) roughness tester. Sheet samples were fixed between the measuring head and the base with a clamp pressure of 1 MPa (soft backing). Four measurements per sheet side were performed, and a total of five sheets per sample were analyzed.

Tensile strength

Tensile properties were measured using an Instron Model 1011 Electromechanical Tensile Tester (TestResources Inc., Shakopee, MN, USA). The span length used was 140 mm. The tensile load was applied at a constant speed of 25 mm/min. Measurements were carried out in both cross direction (CD) and machine direction (MD). Two measurements per sheet (CD and MD) were performed, and a total number of five sheets per sample were analyzed.

Scott bond

Scott bond of samples was measured using Model B Internal Bond Impact Tester from Precision Scientific (Bellwood, IL, USA). Five measurements per sheet were performed, and a total number of five sheets per sample were analyzed.

RESULTS AND DISCUSSION

Investigations on paper from pilot trial 1

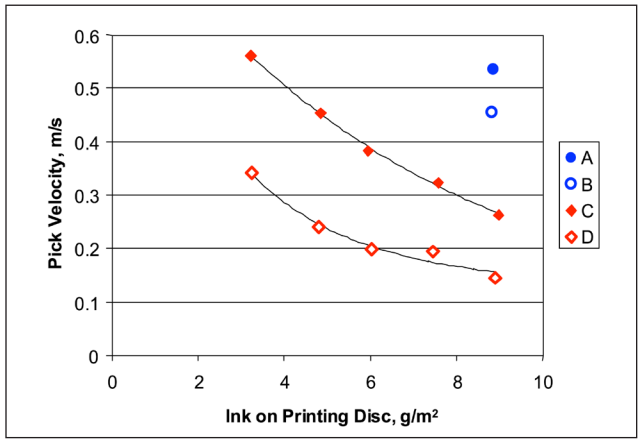
Two sets of paper were produced in trial 1. One set of two paper samples (A and B) was produced by applying surface size and a second set of two samples (C and D) without surface size (Table I). For each of the two sets, one sample was produced with (samples B and D) and the other without (samples A and C) a debonding agent. Surface size should strengthen the paper surface by binding filler and fiber on the surface. The debonding agent should mainly decrease the bulk strength of the paper and, as a result, influence surface strength to some extent.

Table III summarizes the sheet properties of the samples. Application of surface size to paper led to an increase of tensile index (geometric average of the MD and CD) of 22% for papers produced without debonder and 30% for paper produced with debonder. Scott bond increased to a larger extent upon application of surface size; 105% for the papers produced without debonder and 74% for the paper produced with debonder. Overall, the impact of the debonder itself on strength properties was less significant than that of surface sizing. It decreased tensile index and Scott bond by 6% and 40%, respectively, for the papers with surface sizing and by 13% and 19%, respectively, for the papers without surface sizing. Penetration of the surface size in the Z-direction of the base sheet and delamination of the sheet in layers close to the surface during Scott bond testing are likely the two factors contributing to the significant increase of Scott bond observed upon application of surface size to paper.

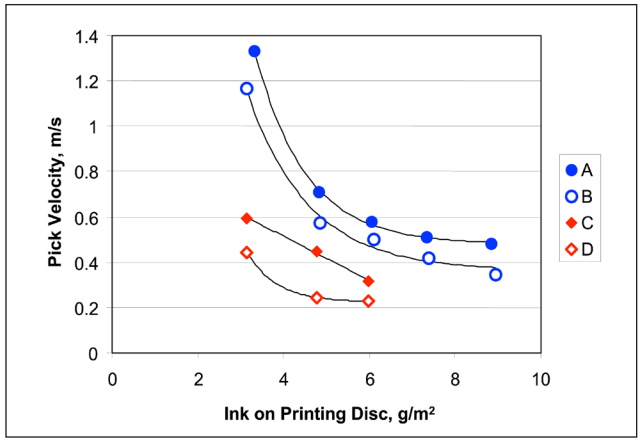
IGT pick resistance tests were performed on the four pa-

Sample	BW	Ash	Bulk	N.Formation	PPS Rough. Felt Side	PPS Rough. Wire Side	Tensile Index MD	Tensile Index CD	Scott Bond
	g/m²	%	cc/g	√g/m	µm	µm	Nm/g	Nm/g	J/m²
A	74.5	23.5	1.20	0.609	6.62	6.80	58.1	33.8	469
B	74.7	23.0	1.24	0.587	6.32	6.36	55.9	31.1	335
C	73.3	24.0	1.22	0.620	6.19	6.26	48.2	27.3	229
D	72.1	23.4	1.21	0.581	5.18	5.16	41.9	24.5	192

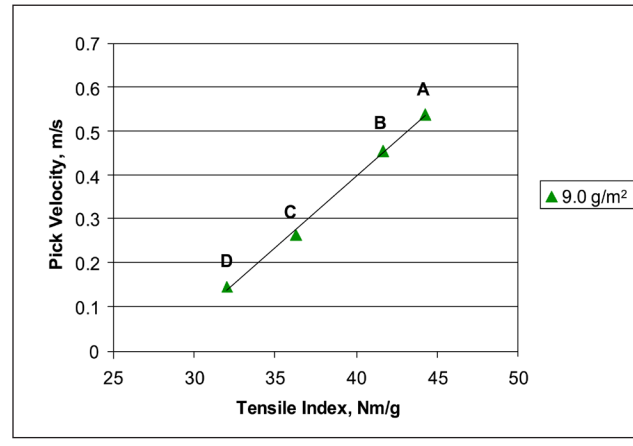
III. Properties of paper samples produced in trial 1.



1. Pick velocities of paper samples A, B, C, and D, determined at a printing speed of 1 m/s with different amounts of ink on the printing disc.



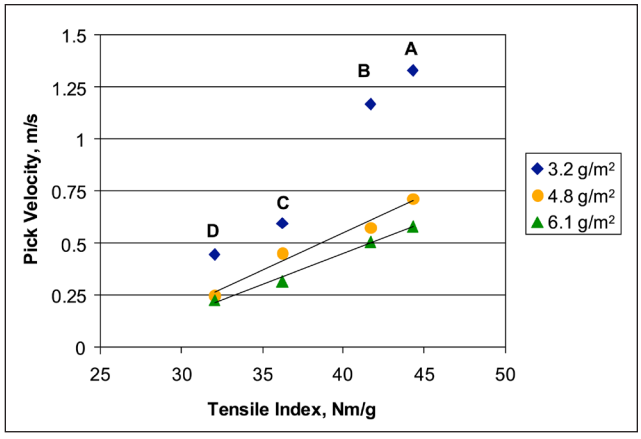
2. Pick velocities of paper samples A, B, C, and D, determined at a printing speed of 2 m/s with different amounts of ink on the printing disc.



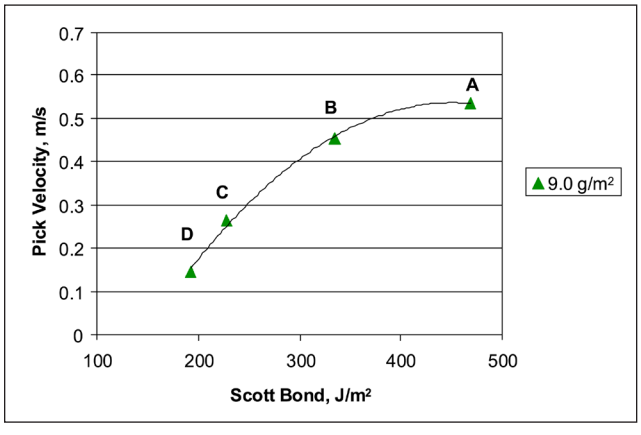
3. Pick velocities of paper samples A, B, C, and D, determined at a printing speed of 1 m/s and plotted versus corresponding tensile index values (geometric average of MD and CD). Pick velocities were determined using 9.0 g/m² of ink on the printing disc.

pers using different printing speeds and ink amounts on the printing disc. In all tests, high-viscosity pick test oil was used. **Figure 1** gives the results of testing at a printing speed of 1 m/s, and **Fig. 2** gives results at a printing speed of 2 m/s. At a printing speed of 1 m/s, the two papers produced without surface size (C and D) could be tested using printing disc amounts of 3.2, 4.8, 6.1, 7.5, and 9.0 g/m². A differentiation in picking point could only be obtained for the two papers produced with surface size (A and B) using a printing disc ink amount of 9.0 g/m². At a printing speed of 2 m/s, papers A and B could be tested using printing disc amounts of 3.2, 4.8, 6.1, 7.5, and 9.0 g/m². The picking point of papers C and D could only be clearly detected at printing disc ink amounts of 3.2, 4.8, and 6.1 g/m². As shown in Fig. 1, for papers C and D, a linear relationship was found at a printing speed of 1 m/s between pick velocity and amount of ink on the printing disc. At a printing speed of 2 m/s, a minimum in pick velocity was found upon increasing the amount of ink on the printing disc for papers A, B, and D (Fig. 2). This type of profile with a minimum was observed before [11,12], and explained by means of two effects: (1) coverage of paper by ink (increases picking tendency) and (2) decreasing tack forces with increasing film thickness. Thus, all picking velocity data determined at different printing disc ink amounts were fitted in the graphs using a first-order exponential decay function.

In **Fig. 3**, pick velocities for the four papers determined at a printing speed of 1 m/s and amount of ink on the printing disc of 9.0 g/m² are plotted versus corresponding tensile index values. A linear relationship was found between pick velocity and tensile index. At a printing speed of 2 m/s (**Fig. 4**), the relationship was only linear for printing disc ink amounts of 4.8 and 6.1 g/m². For a printing disc ink amount of 3.2 g/m², the pick velocities of the two surface sized papers A and B were significantly higher than those of papers C and D without surface size, on the basis of what could be derived from

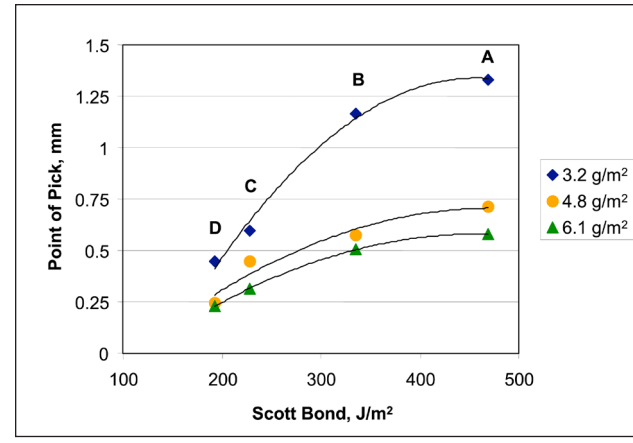


4. Pick velocities of paper samples A, B, C, and D, determined at a printing speed of 2 m/s and plotted versus corresponding tensile index values (geometric average of MD and CD). Pick velocities were determined using amounts of ink on the printing disc of 3.2, 4.8, and 6.1 g/m².



5. Pick velocities of paper samples A, B, C, and D, determined at a printing speed of 1 m/s and plotted versus corresponding Scott bond values. Pick velocities were determined using 9.0 g/m² of ink on the printing disc.

their tensile index values. In conclusion, for most conditions, when a linear relationship was found between pick velocity and tensile index, the IGT picking test simply evaluated the bonding potential of fibers.



6. Pick velocities of paper samples A, B, C, and D, determined at a printing speed of 2 m/s and plotted versus corresponding Scott bond values. Pick velocities were determined using amounts of ink on the printing disc of 3.2, 4.8, and 6.1 g/m².

Pick velocity values are plotted versus Scott bond values in **Figs. 5** and **6**. The fitting curves in these graphs were added to improve data visualization. In all cases, the relationship found between picking velocity and Scott bond was not linear. As previously pointed out, penetration of the surface size into the paper and the point of delamination during testing largely influence Scott bond results.

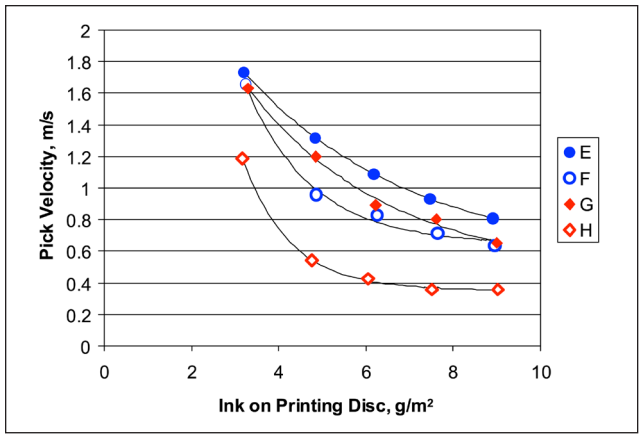
Investigations on paper from pilot trial 2

The second study included papers produced on a pilot paper machine using two different filler types (GCC or PCC) and filler levels (20% and 25%). In addition, each paper was calendered at two different loads, 15 or 50 kN/m. Table II provides the list of papers included in this investigation. **Table IV** summarizes the sheet properties of the samples.

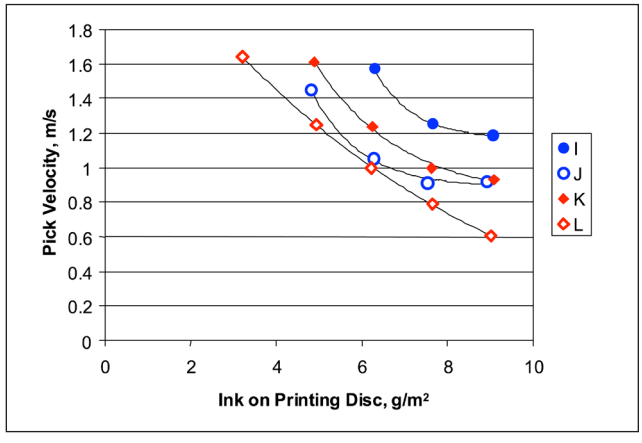
Internal bond (Scott bond) was found to correlate with tensile strength for these papers. The strength property results found were consistent with what was previously reported and known from practical applications. While PCC filler provided

Sample	BW	Ash	Bulk	N.Formation	PPS Rough. Felt Side	PPS Rough. Wire Side	Tensile Index MD	Tensile Index CD	Scott Bond
	g/m²	%	cc/g	√g/m	µm	µm	Nm/g	Nm/g	J/m²
E	80.3	18.8	1.36	0.699	6.99	6.92	67.4	32.1	479
F	78.6	24.4	1.34	0.739	7.06	6.77	56.4	27.0	376
G	79.9	20.0	1.42	0.672	6.27	6.50	52.3	30.5	399
H	77.4	24.9	1.36	0.676	5.69	5.64	45.7	26.0	311
I	78.9	18.8	1.48	0.702	8.26	8.25	66.9	31.6	428
J	78.1	24.5	1.44	0.745	8.07	7.83	56.5	26.2	379
K	81.2	19.6	1.57	0.663	7.88	8.06	51.7	30.6	424
L	78.0	24.9	1.54	0.654	7.48	7.73	45.7	25.4	319

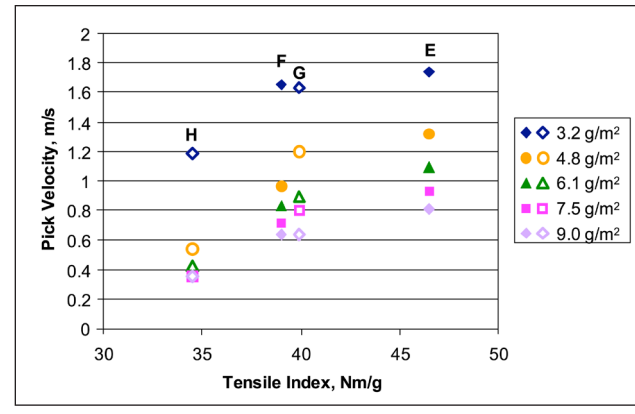
IV. Properties of paper samples produced in trial 2.



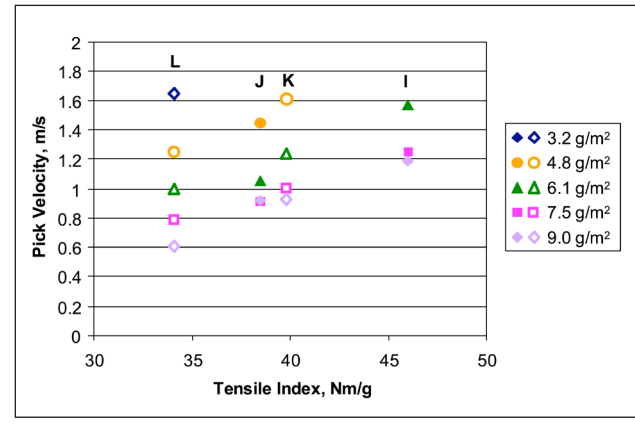
7. Pick velocities of paper samples E (20% GCC; calendering load: 50 kN/m), F (25% GCC; calendering load: 50 kN/m), G (20% PCC; calendering load: 50 kN/m), and H (25% PCC; calendering load: 50 kN/m) determined at a printing speed of 2 m/s with different amounts of ink on the printing disc.



8. Pick velocities of paper samples I (20% GCC; calendering load: 15 kN/m), J (25% GCC; calendering load: 15 kN/m), K (20% PCC; calendering load: 15 kN/m), and L (25% PCC; calendering load: 15 kN/m) determined at a printing speed of 2 m/s with different amounts of ink on the printing disc.



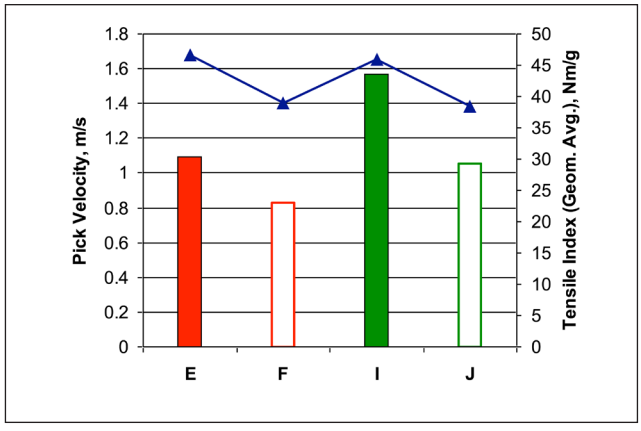
9. Pick velocities of paper samples E (20% GCC; calendering load: 50 kN/m), F (25% GCC; calendering load: 50 kN/m), G (20% PCC; calendering load: 50 kN/m), and H (25% PCC; calendering load: 50 kN/m) plotted versus corresponding tensile index values (geometric average of MD and CD). Pick velocities were determined using amounts of ink on the printing disc of 3.2, 4.8, 6.1, 7.5, and 9.0 g/m².



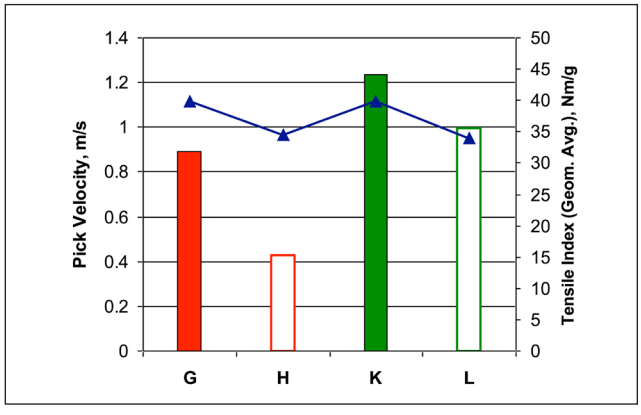
10. Pick velocities of paper samples I (20% GCC; calendering load: 15 kN/m), J (25% GCC; calendering load: 15 kN/m), K (20% PCC; calendering load: 15 kN/m), and L (25% PCC; calendering load: 15 kN/m) plotted versus corresponding tensile index values (geometric average of MD and CD direction). Pick velocities were determined using amounts of ink on the printing disc of 3.2, 4.8, 6.1, 7.5, and 9.0 g/m².

good bulk and improved smoothness compared with GCC (Table IV), the PCC-filled sheets exhibited reduced strength.

IGT pick resistance tests were performed on all the papers at a printing speed of 2 m/s using different ink amounts on the printing disc. **Figure 7** gives pick velocity values found for papers E, F, G, H and **Fig. 8** gives those found for papers I, J, K, and L. Only for paper L a linear relationship was found between pick velocity and ink applied on the printing disc (Fig. 8). For all the other papers, a minimum in pick velocity was found upon increasing the amount of ink on the printing disc. In **Fig. 9** (papers E, F, G, and H) and **Fig. 10** (papers I, J, K, and L), pick velocity values are plotted versus tensile index (geometric average of the MD and CD). For both paper sets, no linear relationship was found. In particular, both the picking resistance test and basic strength measurements predicted that PCC would produce a weaker sheet than GCC. However, only the picking resistance test was able to detect the damage on the surface induced by calendering. As shown in **Fig. 11** for GCC, increasing calendering load reduced the pick velocity of the 20% and 25% GCC sheets by 44% and 28%, respectively. Increasing calendering load of the 20% and 25% PCC sheets reduced pick velocity by 39% and 133%, respectively (**Fig. 12**). For both GCC and PCC sheets, no significant change in tensile index (or internal bond) was found upon increasing calendering. No change in tensile strength upon increasing calendering was reported before for other uncoated woodfree papers [13,14]. Overall, the results point out that the surface of a highly filled PCC sheet is particularly sensitive to surface damage by calendering. Papermaking strategies to minimize filler detachment during printing for this type of paper may include the modification of calendering conditions or changes in surface size formulation.



11. Comparison of pick velocities (bars) and tensile index values (geometric average of MD and CD [line]) of paper samples E (20% GCC; calendering load: 50 kN/m), F (25% GCC; calendering load: 50 kN/m), I (20% GCC; calendering load: 15 kN/m), and J (25% GCC; calendering load: 15 kN/m). Pick velocities were determined at a speed of 2 m/s using 6.1 g/m² of ink on the printing disc.



12. Comparison of pick velocities (bars) and tensile index values (geometric average of MD and CD direction/line) of paper samples G (20% PCC; calendering load: 50 kN/m), H (25% PCC; calendering load: 50 kN/m), K (20% PCC; calendering load: 15 kN/m), and L (25% PCC; calendering load: 15 kN/m). Pick velocities were determined at a speed of 2 m/s using 6.1 g/m² of ink on the printing disc.

CONCLUSIONS

The relationship between surface strength of paper, as determined from pick resistance measurements performed with an IGT printability tester, and its bulk strength properties, such as tensile strength and internal bond (Scott bond), was analyzed in detail for a series of uncoated woodfree papers. Surface strength for these papers is very important to minimize dusting (release of filler) phenomena in offset and electrophotographic printing processes. Application of a debonding agent during paper production or surface sizing affected the papers examined equally, for picking resistance of paper and its tensile strength. Replacement of GCC with PCC or increased filler content in paper reduced picking resistance, tensile strength, and internal bond simultaneously. These results are consistent with the knowledge that fillers interfere with interfiber bonds and the smaller the size of the filler particle, the greater the reduction in fiber bond area. Increased calendering load, for both the GCC and PCC sheets, reduced picking resistance but left tensile strength and internal bond unaffected. Thus, an increase of the calendering load weakened the surface of the paper only. At high filler load, this effect was significantly higher for the sheets containing PCC than for the sheets containing GCC, suggesting larger morphologic changes of the PCC-containing sheet surface upon increasing the degree of calendering.

Overall, the results we obtained point out that the picking resistance test is valid for the measurement of surface strength of uncoated woodfree papers. If surface strength of paper mirrors its bulk strength properties, as shown for some of the papers analyzed, then it is advisable to use (especially at mill level) tests that are easier to perform and with higher reproducibility, such as tensile strength and Scott bond testing. **TJ**

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ABOUT THE AUTHORS

In the current economic environment, the paper industry continues to work hard to do more with less. Fiber is one of the most expensive raw materials, so increased use of recovered paper and substitution of fiber for filler are growing trends to reduce manufacturing costs. The associated challenge is the reduction of paper strength that affects both papermaking and printing operations. The decrease of surface strength makes the paper more prone to loose fillers and fines materials during printing. Dusting and linting phenomena reduce print runnability and impair print quality.

Because of the importance of surface strength, we decided to revisit the picking resistance method that has been used traditionally to determine surface strength of paper. We focused on examining the relationship between surface strength and bulk strength properties of a complete set of papers produced on a pilot paper machine using systematic changes of operational and chemical parameters.

An interesting finding was that the picking resistance test was able to detect surface damage of paper caused by an increase in calendering pressure, as opposed to tensile strength and internal bond measurements.

Our next step is to examine other test methods with improved operator reproducibility that may predict dusting and linting propensity during printing.

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