Determining operating variables that impact internal fiber bonding using Wedge statistical analysis methods

SERGIO GIUSTE, JOEL PANEK, BABAK MIRZAEI, AND PETER W. HART

ABSTRACT: In this study, Wedge statistical analysis tools were used to collect, collate, clean up, plot, and analyze several years of operational data from a commercial paper machine. The z-direction tensile (ZDT) and Scott Bond tests were chosen as representative of fiber bond strength. After analyzing thousands of operational parameters, the ones with the most significant impact upon ZDT involved starch application method, starch penetration, and the amount of starch applied. Scott bond was found to be significantly impacted by formation and refining. Final calendering of the paper web has also shown an impact on internal fiber bonding.

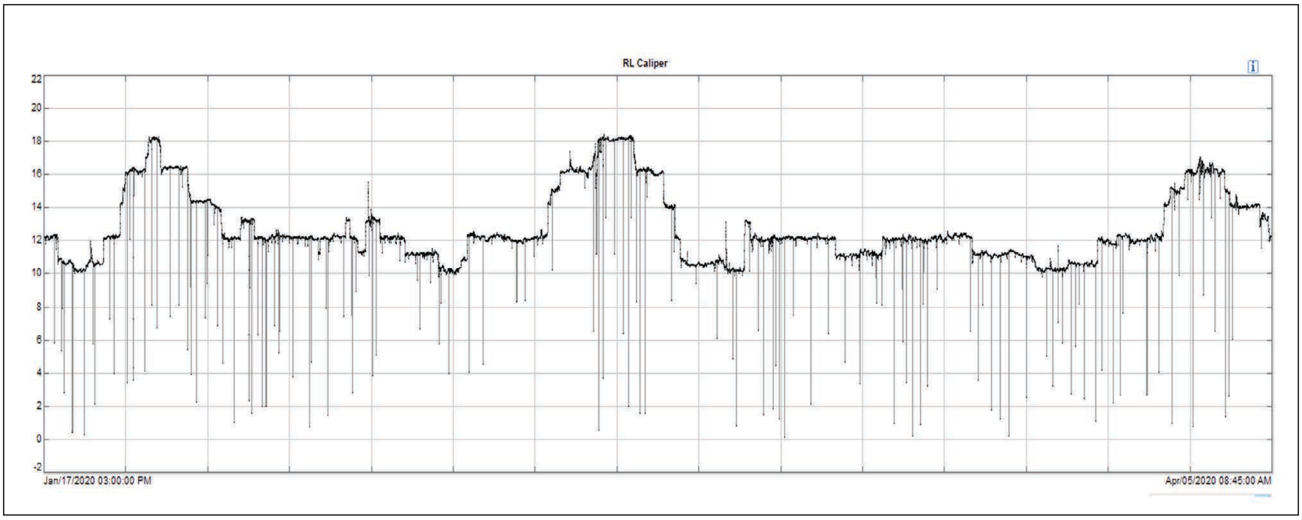
Application: Readers may use this information to understand paper machine variables affecting internal bond of paper fibers, as well as to troubleshoot internal bond issues in paperboard operations.

Products made from paperboard fulfill several distinct functions, which depend on mechanical properties, barrier resistance, thermal resistance, and appearance as determined by the end use. Additionally, paperboard products are often printed with complex imaging and characters that require proper surface characteristics, and they are converted and filled, which require proper physical and thermal resistance [1]. Several of these operations have the potential to damage the board. For example, when offset printing presses are used to print the board, delamination of the paperboard structure can occur when high tack inks are present. The printer speed also has a significant impact on how strong the paperboard must be in relation to fibers bonding and coating anchorage.

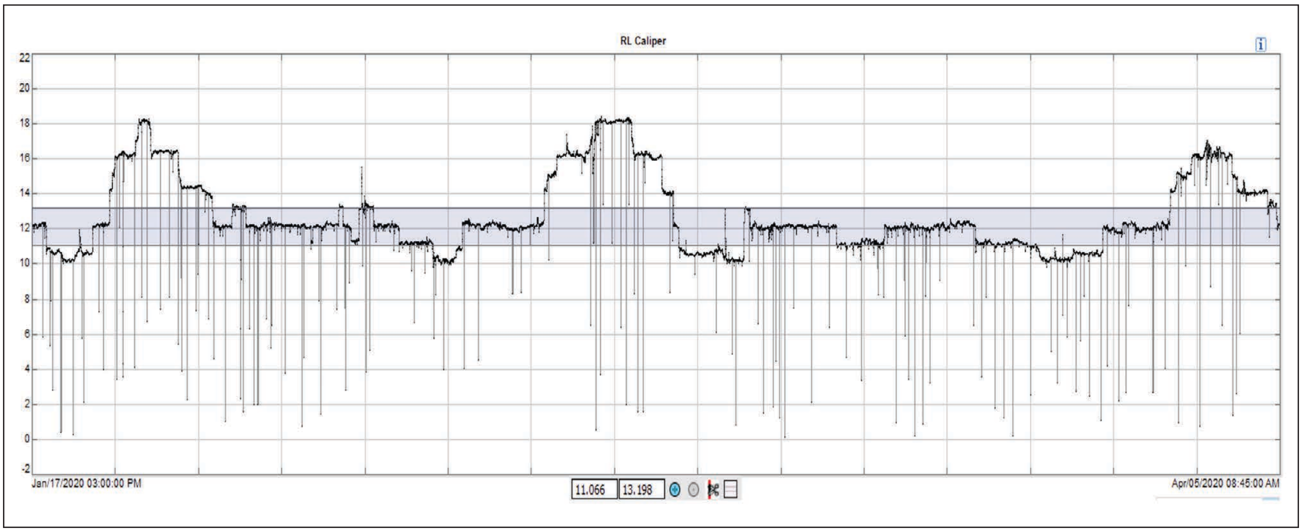
Scott internal bond (referred to here as Scott bond) and z-direction tensile strength (ZDT) are two common test methods for ensuring paperboard quality and predicting converting and end use performance related to internal strength. It is helpful to use both tests, because they represent distinct types of failures [2,3]. The ZDT test deforms the paperboard in tension and the maximum stress is reported as the ZDT. The internal bond strength (Scott type) test measures the energy required to rupture a sheet-type specimen. The rupture in the thickness direction is initiated by the impact of a pendulum against an L-shaped bracket attached to the sample. The geometry of the apparatus causes the tensile stress to be rotational in nature with negligible shear stress on the specimen [3]. The height of the pendulum swing after striking the bracket gives a measure of the energy lost to rupture the sample. The amount of energy lost by the pendulum is reported as Scott bond. The ZDT is believed to represent the strength of the weakest link in the fiber structure [2]. The weakest region in the structure will depend on the local formation and the distribution of starch through the thickness of the sheet (starch penetration).

A multitude of variables in the pulping and papermaking manufacturing process can impact intrinsic fiber strength and fiber bonding. Several key operational parameters that impact bond strength include pulp refining strategies; wet-end chemistry addition and order of chemical addition; sheet formation and pressing conditions; open draws (dimensional constraints); and starch application method, amount applied, and starch penetration into the sheet, resulting in a z-direction starch distribution, among others [4]. The number of parameters and their interrelationship make it difficult to identify what is driving effects and to control and maintain the properties within specification.

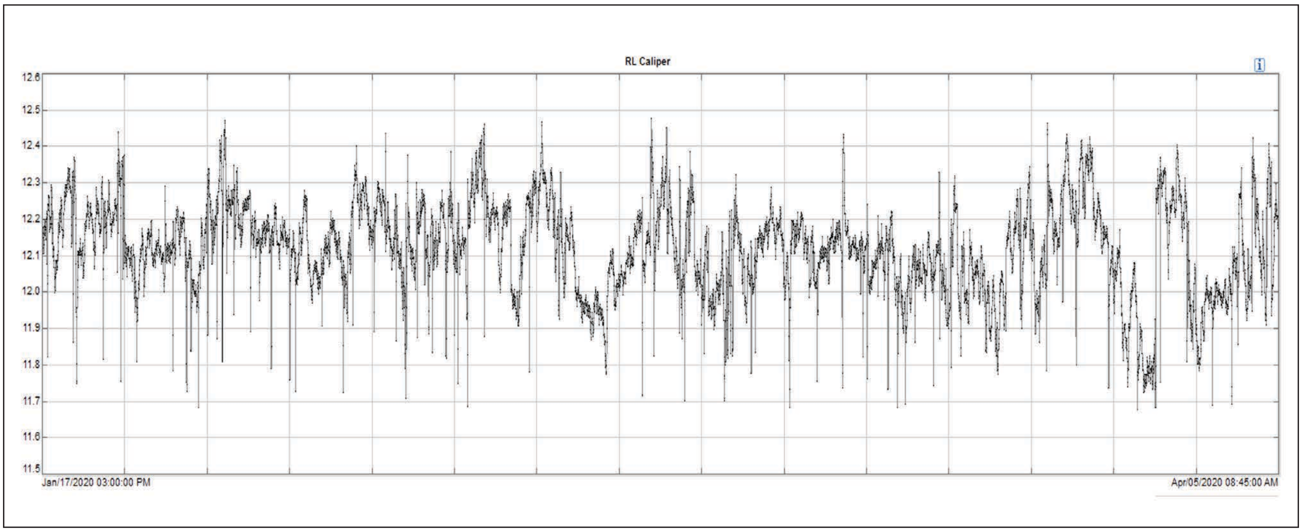
Operating data were collected from a commercial paper machine for a specific caliper range and grade of paperboard over the course of a couple of years. These large data sets were subjected to sorting and analysis using the Wedge data collection tool (Trimble Inc.; Sunnyvale, CA, USA). Selected process variables were analyzed to understand the impact on fiber bonding. Several of the collected data sets were obtained from periods where specific effort was made to ensure only one specific variable was changed for analysis purposes. During these times, every effort was made to keep the rest of the process variables as stable as possible for a paper machine. For this study, when possible, the evaluation of a single variable was performed when such variable showed an independent, statistically significant change, rather than performing a multivariable analysis. To enhance the number of variables examined, several of the studies were performed under a Design of Experiments (DOE) method. Additionally, laboratory work was performed, in some cases, to validate and emphasize



1. Data before filtration.



2. Selection (using cursor) of desired range.



3. Data after all filtrations were applied. Note the change in the y-axis scale as compared to Figs. 1 and 2.

some of the results from the variables identified for the production machine.

Several production variables from a paper machine making coated solid bleached sulfate (SBS) grades were analyzed using the Wedge program by correlating them with Scott bond and ZDT. More than 2000 process variables were studied during several production timelines when ZDT values showed statistically significant variability. Most of these times, DOE was applied during controlled production trials. The critical parameters correlating with Scott bond and ZDT values will be shown, and the hypothetical reasons for such correlations will be discussed.

DATA ANALYSIS METHOD

The mill PI System (OSIsoft LLC; San Leandro, CA, USA) data historian was used to gather process information while running this specific paper machine, which produces a variety of paperboard grades, mostly used for tobacco and folding carton grades. Typical basis weight varied from 196 to 293 g/m^2, and caliper varied from 254 to 457 µm.

Wedge software (version 8.2) was used for data analysis. The trademarked Wedge software (Wet End Diagnostic Genius) application is a paper machine diagnostic of temporal variations and was developed by the Finnish Pulp and Paper Institute in 1991. The Wedge software allows data filtration within the charts, which simplifies and expedites the evaluation process. **Figures 1 through 3** show examples of data obtained from continuous production periods with data point outliers removed from the data set. For example, reel caliper values were collected every minute, measured by an on-line scanner (QCS), and trended for the selected time range. By using the computer cursor, the desired caliper range was selected, and the filter tool was applied (scissors symbol corresponding to "remove exceeding values from data"). This sequence is shown in Figs. 1–3. Furthermore, all other variables are also constrained to the time interval for the filtered data.

The Wedge program also provides some basic statistical information, such as average, standard deviation, maximum, and minimum values, as shown in **Table I**.

Additionally, one specific product was selected using the "state measurement" tool in Wedge. This feature allows a quick selection of a specific grade of paperboard on this paper machine. The analysis process started by selecting the time when only one variable had a significant statistical variation (standard deviation) and then performing the filtration work and best correlation analysis using Wedge, as **Fig. 4** shows. Subsequently, the data was plotted to understand causal vs. effectual variables on the studied variable by studying time delays.

It is important to note that the list of correlators based on the correlation coefficient, R (which measures the strength and direction of a linear relationship between two variables on a scatter plot), values among more than 2000 variables can be quite overwhelming, thus requiring some papermaking experience to concentrate the analysis on the critical variables.

MATERIALS AND METHODS

The test results presented here were commercial grade coated solid bleached sulfite (SBS) paperboard samples, with the exceptions of the refining study and the calendering study. Most of the paperboard was nominally 305 µm (12 pt) and 220 g/m^2. The refining study was completed on handsheets (TAPPI Standard Test Method T 205 sp-18 "Forming handsheets for physical tests of pulp") produced from industrially refined pulp. The calendering study was completed on commercial grade SBS paperboard that was calendered off-machine on a 305-mm-wide online pilot hard-hot calender with 305- and 230-mm dia. rolls at speeds of 120 m/min.

Internal bond strength (Scott bond) was measured following TAPPI T 569 om-14 "Internal bond strength (Scott type)." The ZDT was measured following TAPPI T 541 "Internal bond strength of paperboard (z-direction tensile)."

A sheet split method was used to quantify the thickness (z) direction distribution of formation and starch. Paperboard sheets were split using a pouch lamination method (**Fig. 5**). With this method, the paperboard specimen is first laminated and then peeled apart to separate into two splits. Each split

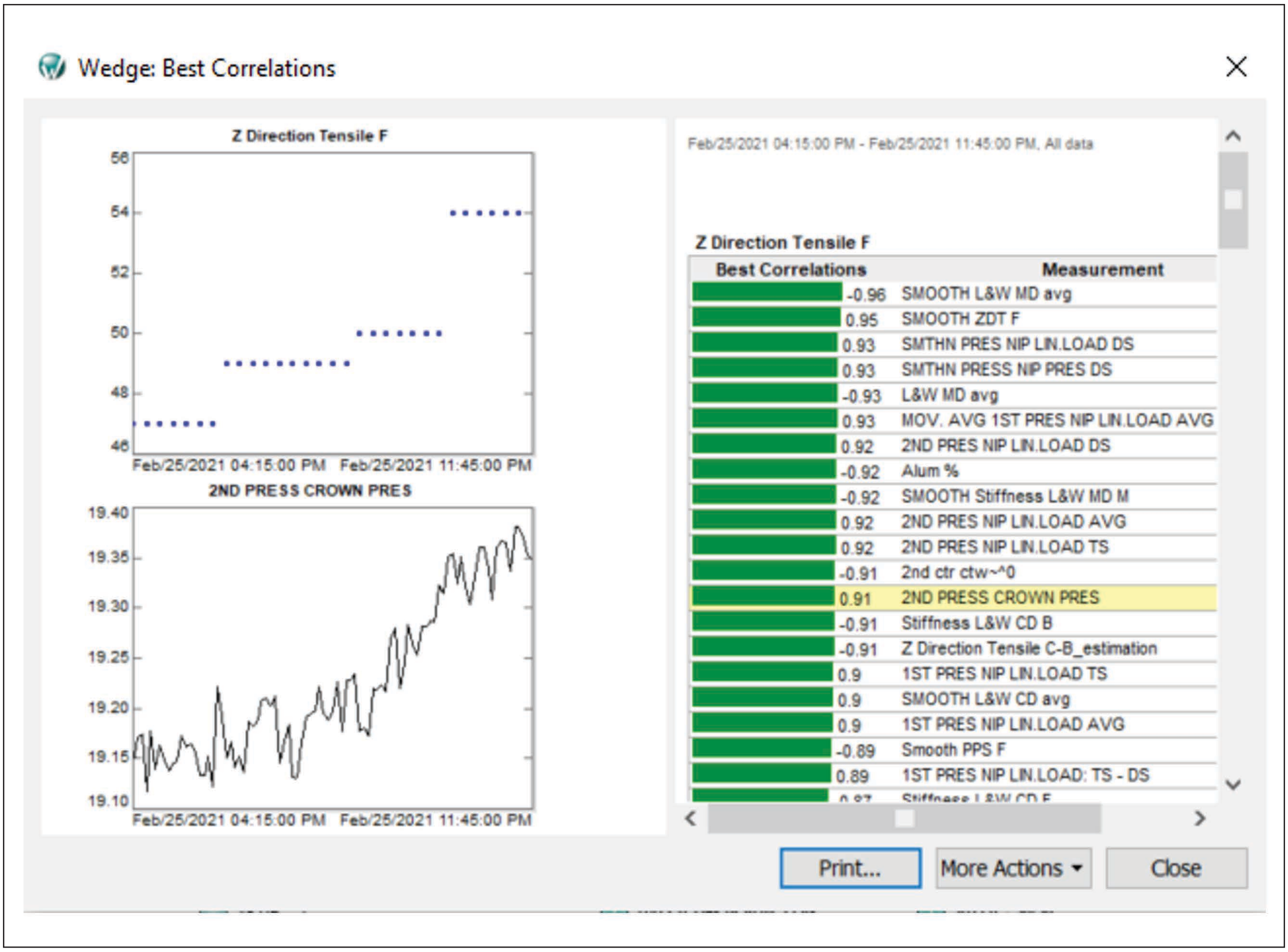
Wedge: Statistics

Jan/17/2020 03:00:00 PM - Apr/05/2020 08:45:00 AM, All data

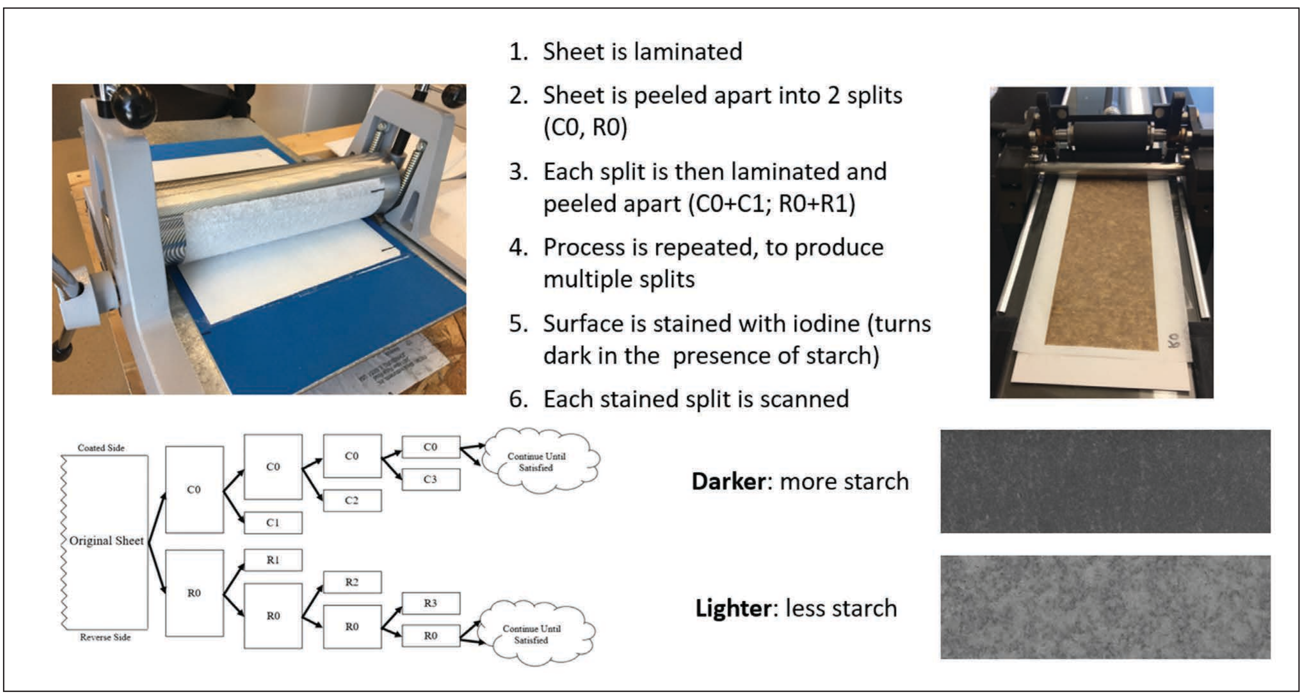
Measurement	Unit	Average	Deviation	Maximum	Minimum
RL Caliper		12.12	0.1268	12.48	11.68

Print... Columns More Actions Close

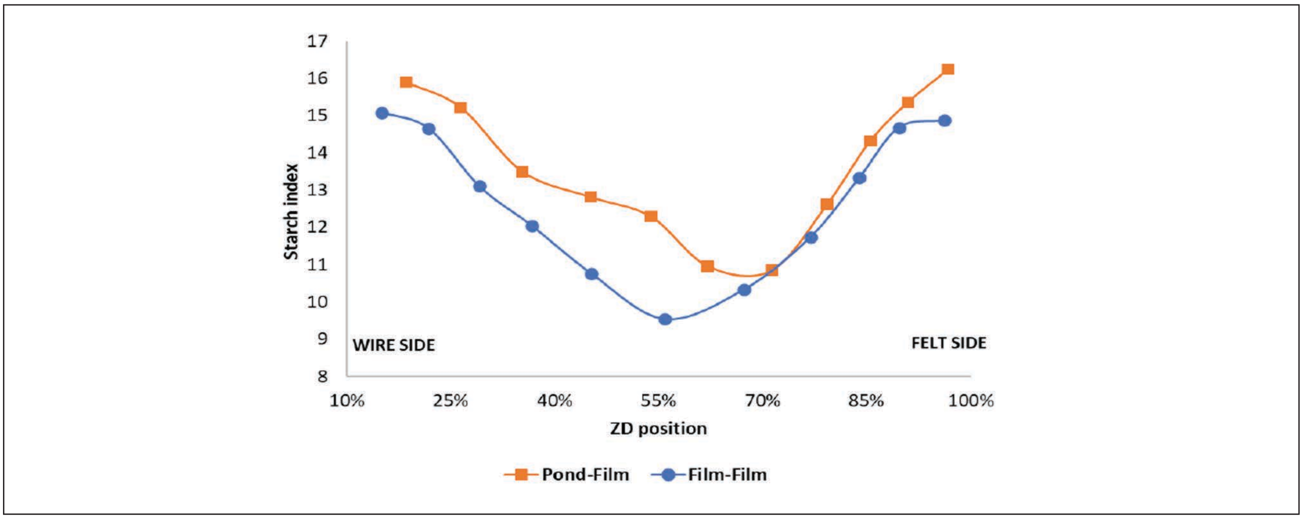
I. Basic statistical information provided by Wedge software.



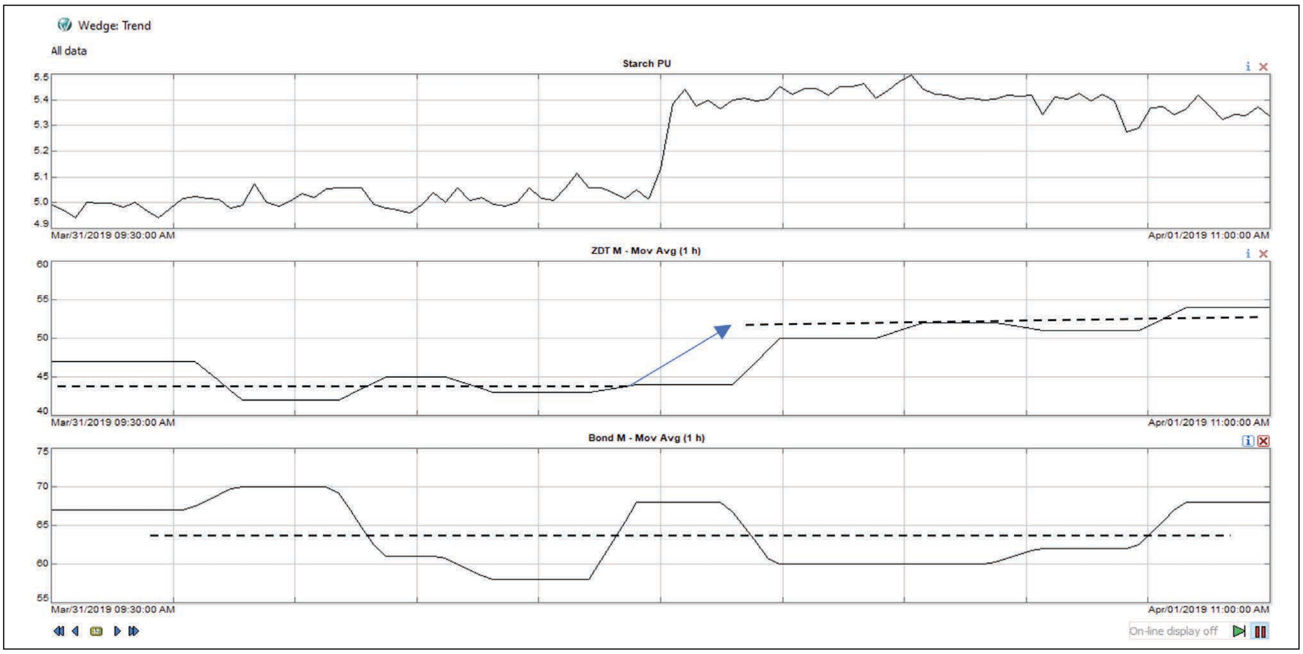
4. Example of a best correlation analysis using Wedge software. The correlation coefficient (R) values are shown.



5. Experimental method for determining starch penetration.



6. Starch distribution in the z direction of the sheet for different application methods.



7. Starch pickup, z-direction tensile strength (ZDT), and Scott internal bond results over a specific timeframe.

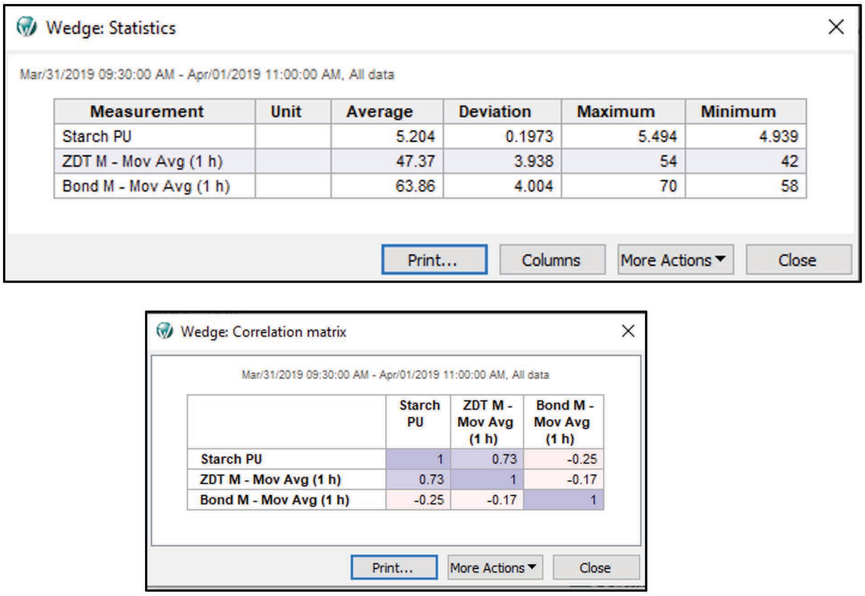
is then laminated again and peeled apart again. This process continues until the sample can no longer be uniformly peeled apart. For each split, basis weight and caliper were measured, and the contribution of the laminate sheet was subtracted. The formation of each split was measured using TechPap 2D Lab Formation Sensor (TechPap; Gières, France); this sensor measures transmitted light formation and reports a formation index number (LT) as a variation measurement (higher number = worse formation). Each layer was then stained with iodine utilizing a Phantom proofer with an anilox roll (Harperimage; Charlotte, NC, USA). Iodine is used because it selectively darkens starch, thus highlighting the presence of starch. The proofed area of each split was scanned using an Epson (Los Alamitos, CA, USA) photo scanner at the resolution of about 5 megapixels, and then scanned images of each split were analyzed for gray scale levels using ImageJ software (National Institutes of Health; Bethesda, MD, USA). Because lower gray scale values represent darker images (i.e., more starch), the reciprocal of gray scale values are used. A higher starch index corresponds to a higher gray scale value, thus more starch. The starch index is then plotted against the cumulative thickness to produce starch penetration charts.

Figure 5 shows an overview of the method used. Examples of starch penetration charts are shown in the results (**Fig. 6**).

RESULTS AND DISCUSSION

Surface starch application

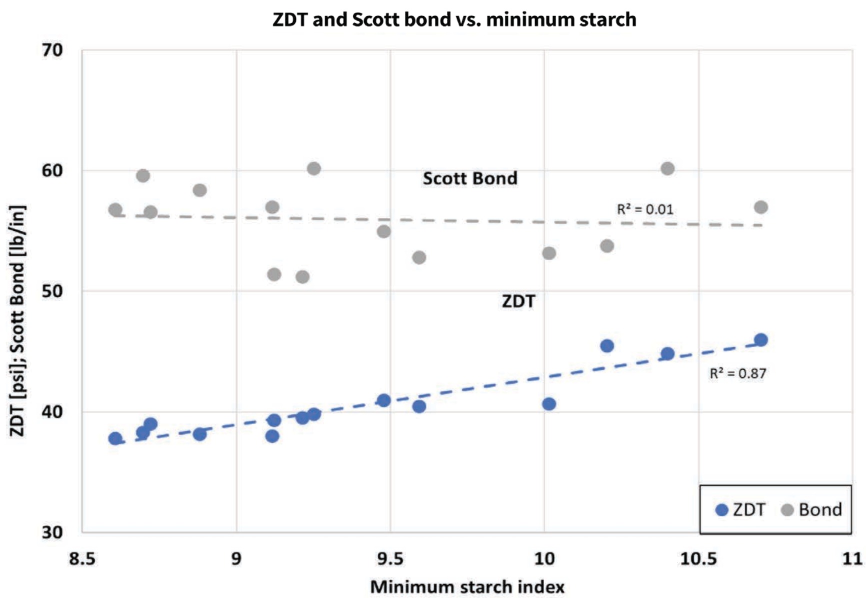
Fig. 7 and **Table II** compare the amount of surface starch (applied by a size press) with Scott bond and ZDT for the



Measurement	Unit	Average	Deviation	Maximum	Minimum
Starch PU		5.204	0.1973	5.494	4.939
ZDT M - Mov Avg (1 h)		47.37	3.938	54	42
Bond M - Mov Avg (1 h)		63.86	4.004	70	58

	Starch PU	ZDT M - Mov Avg (1 h)	Bond M - Mov Avg (1 h)
Starch PU	1	0.73	-0.25
ZDT M - Mov Avg (1 h)	0.73	1	-0.17
Bond M - Mov Avg (1 h)	-0.25	-0.17	1

II. Impact of size press starch addition on ZDT and Scott bond as calculated using Wedge software's statistics.



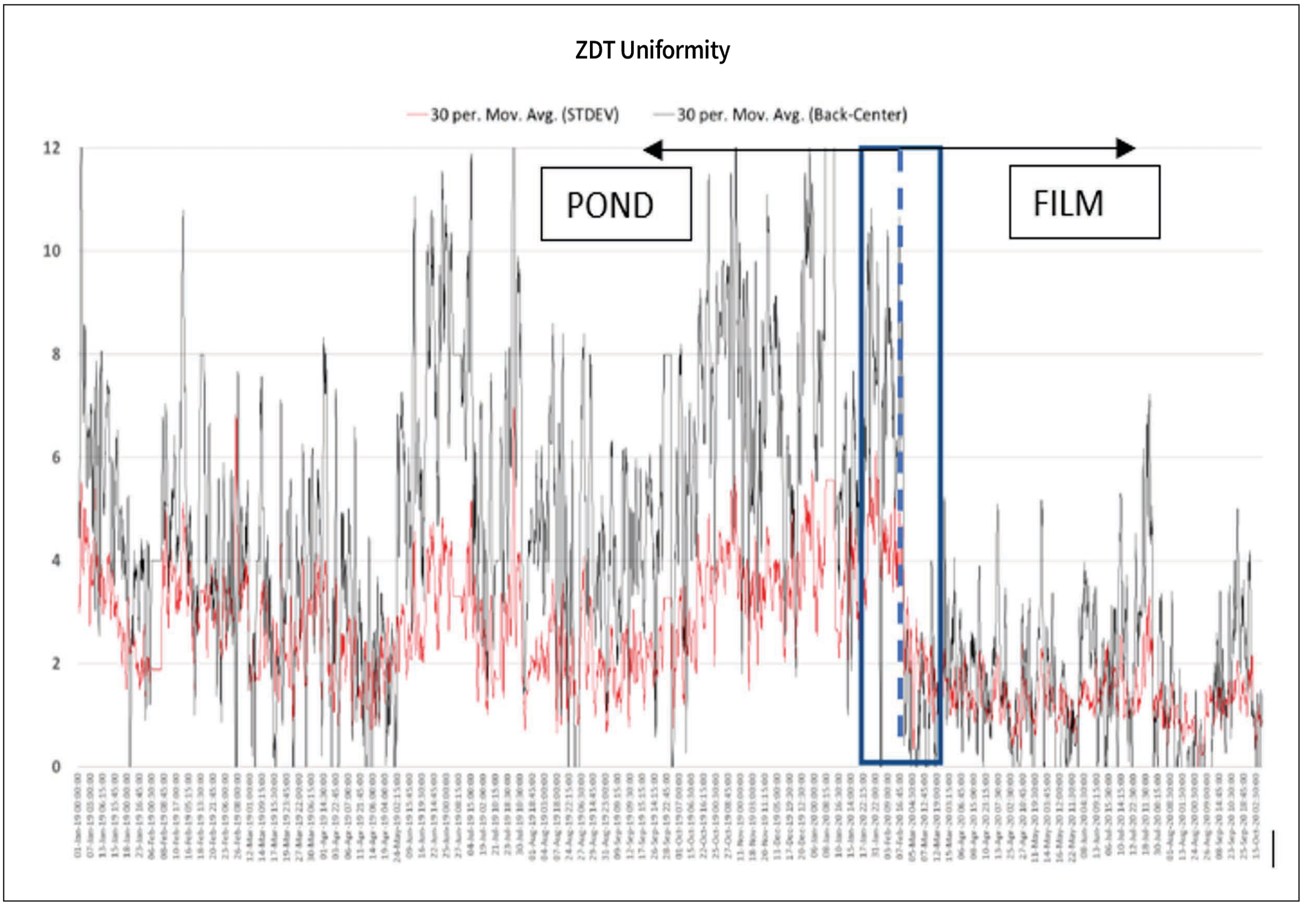
8. Effect of minimum starch on ZDT and Scott bond.

studied paperboard grade. It shows that, for this specific condition and type of starch used, surface starch had a much higher impact on ZDT values than on Scott bond. An increase in total starch pickup by about 8% corresponds to an increase of approximately 18% in ZDT. However, Scott bond values were not clearly impacted by the surface starch increase under these operating conditions.

Additionally, different starch application methods were utilized at the size press to understand their impact on starch penetration and distribution in the z direction. The application methods were pond and film (rod metering) modes.

Figure 6 shows the distribution of starch in the z direction of the sheet for both pond and film application methods. Important findings include:

- The highest amount of starch is applied on the surface, with a minimum amount in the middle.
- The location of the minimum starch amount is located between 50%–70% of the total thickness
- Film-film size press application provided less starch in the middle of the web.



9. The ZDT difference between edges and middle of the web in the cross-machine direction (CD) for pond size press and film size press application modes.

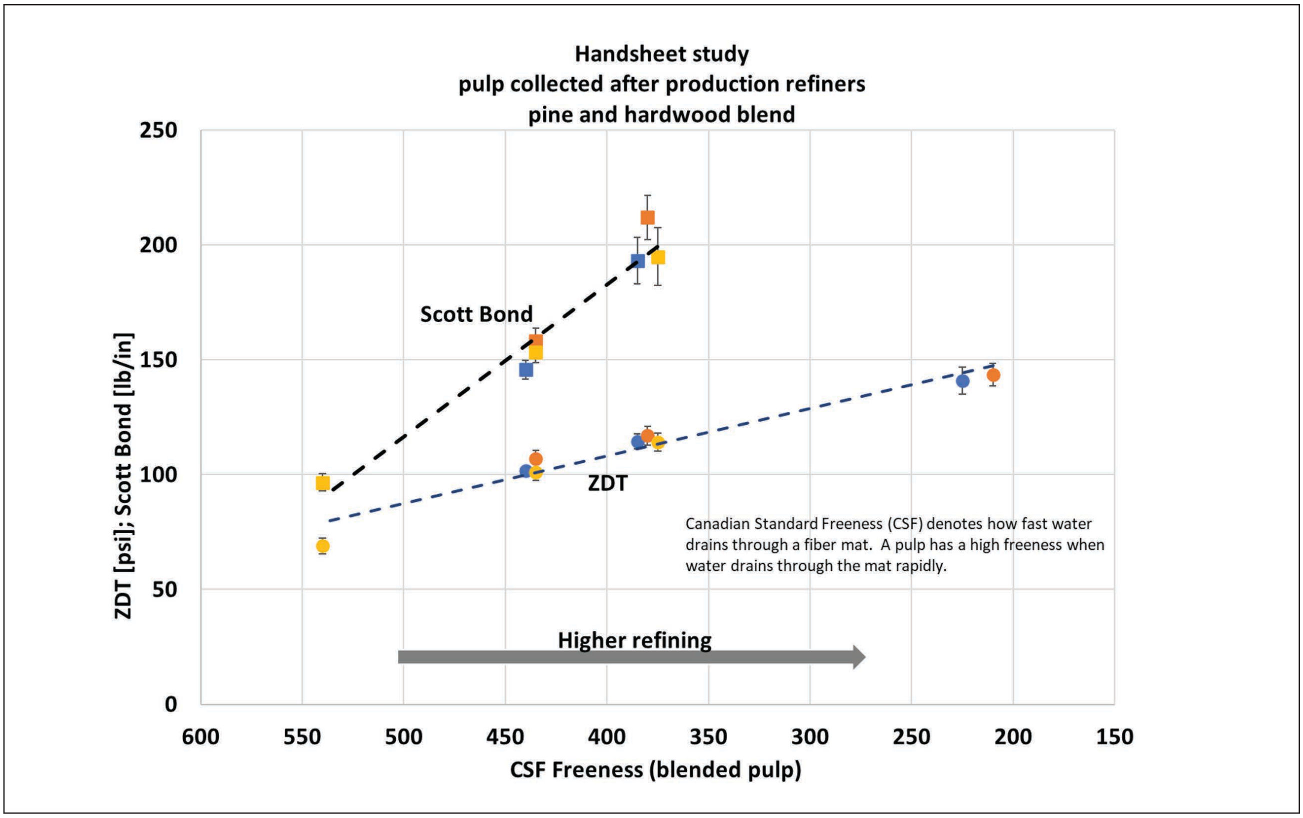
These results were corroborated by investigating the direct relationship between the minimum starch index from the z-direction profiles and measured ZDT of production samples, as shown in **Fig. 8**. A good correlation was detected between the minimum starch and ZDT. However, there is no correlation between the minimum starch and Scott bond. This particular result is also in agreement with the Wedge observations shown in Fig. 7. These results confirm that ZDT indicates the initiation of failure where starch reinforcement is minimal and is therefore related to ZD starch distribution. For materials composed of natural fibers, it has been reported in the literature that fracture energy is significantly influenced by fiber-bridging toughness, while strength indicates the initiation of fracture only [5]. These two phenomena are analogous to Scott bond energy and ZDT in paperboard, respectively.

Efforts were made to determine the impact of both application methods on ZDT values in the cross-machine direction (CD) across the paperboard web. Film application at the size press provided a more uniform ZDT CD profile than with in-pond mode. This can be explained by more uniform starch distribution across the web width with a rod metering size press (film) vs. pond (less influence of uneven web moisture profiles, **Fig. 9**).

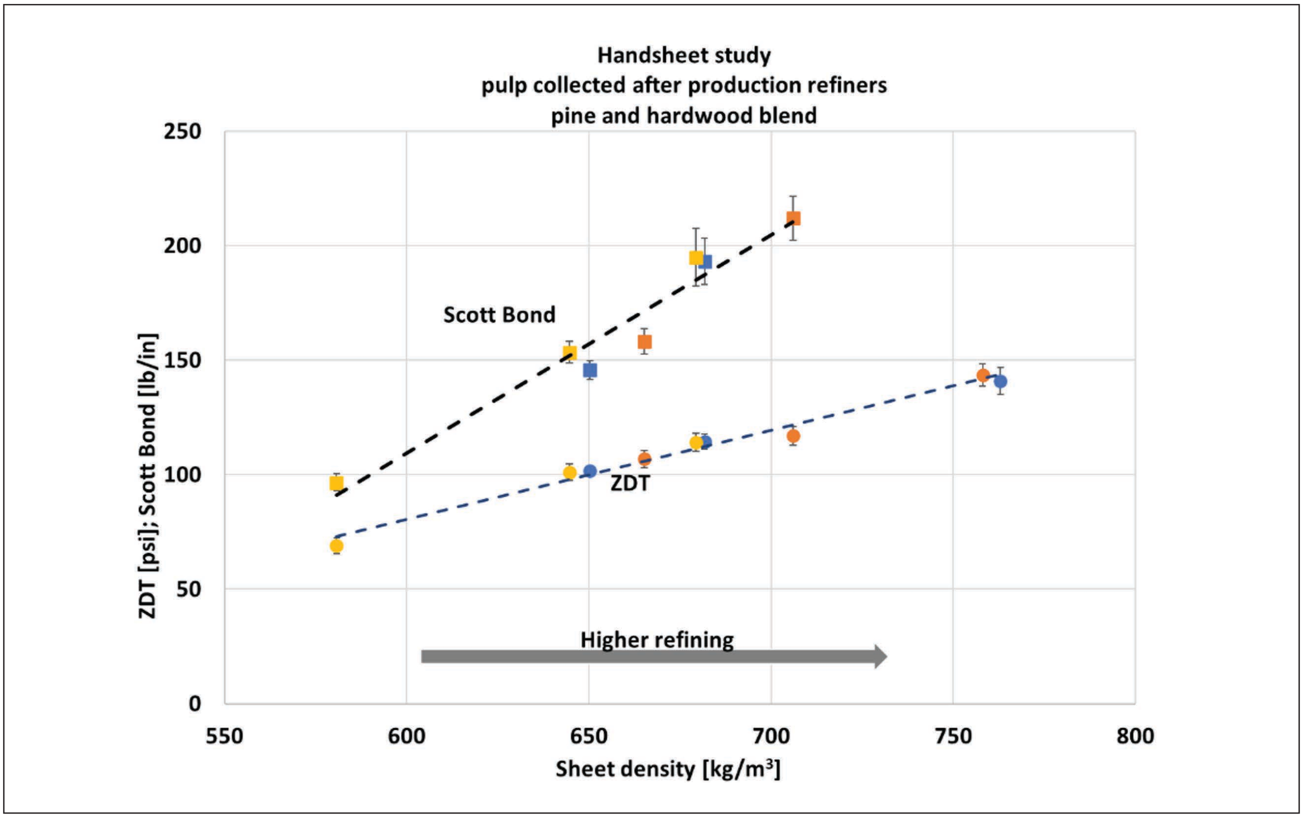
Sheet forming

Forming and consolidation of the paper web are impacted by refining, among other operational processes. One of the main variables to control forming is the freeness (drainage rate) of the stock, which is controlled by the amount of refining. As refining increases, the freeness (drainage rate) decreases. Controlling forming via refining has the consequence of also affecting consolidation of the web and sheet density [6]. **Figure 10** shows that changes in freeness via refining had a marked impact on Scott bond and ZDT, while **Fig. 11** shows that both increase linearly with sheet density. The impact was greater for Scott bond (~100% increase over the freeness change of 540 to 380 CSF) than for ZDT (~67% increase over the same freeness change). While an increase in strength properties with density is qualitatively expected, quantification of the differences in the rate of increase between Scott bond and ZDT is useful and insightful information [7]. Note that a handsheet study was performed for this work, since refining levels and fiber composition were reasonably stable over the production periods studied.

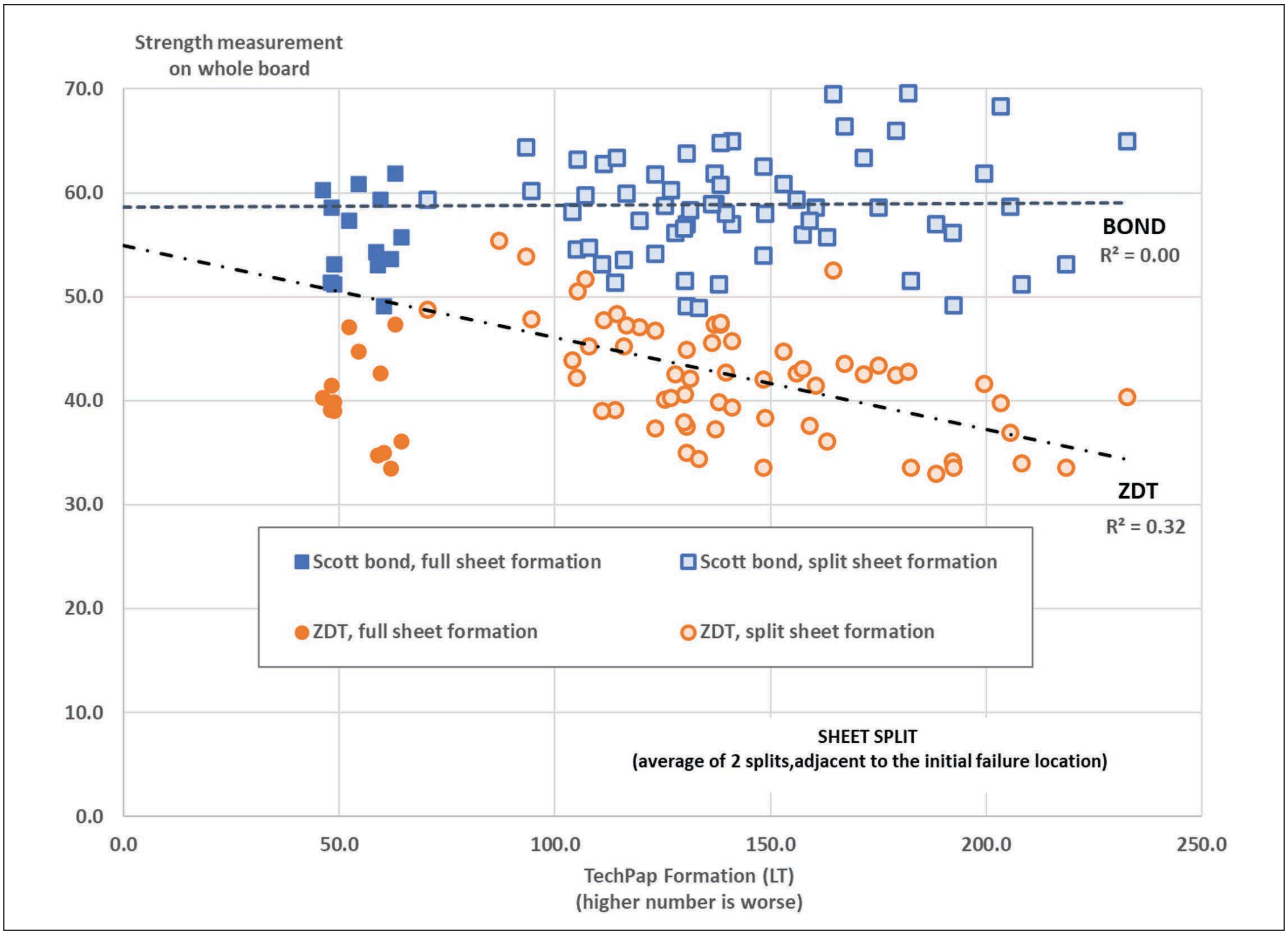
Figure 12 compares Scott bond and ZDT with both full sheet and sheet split formation. As the sheet split formation got worse (higher formation number), ZDT decreased while



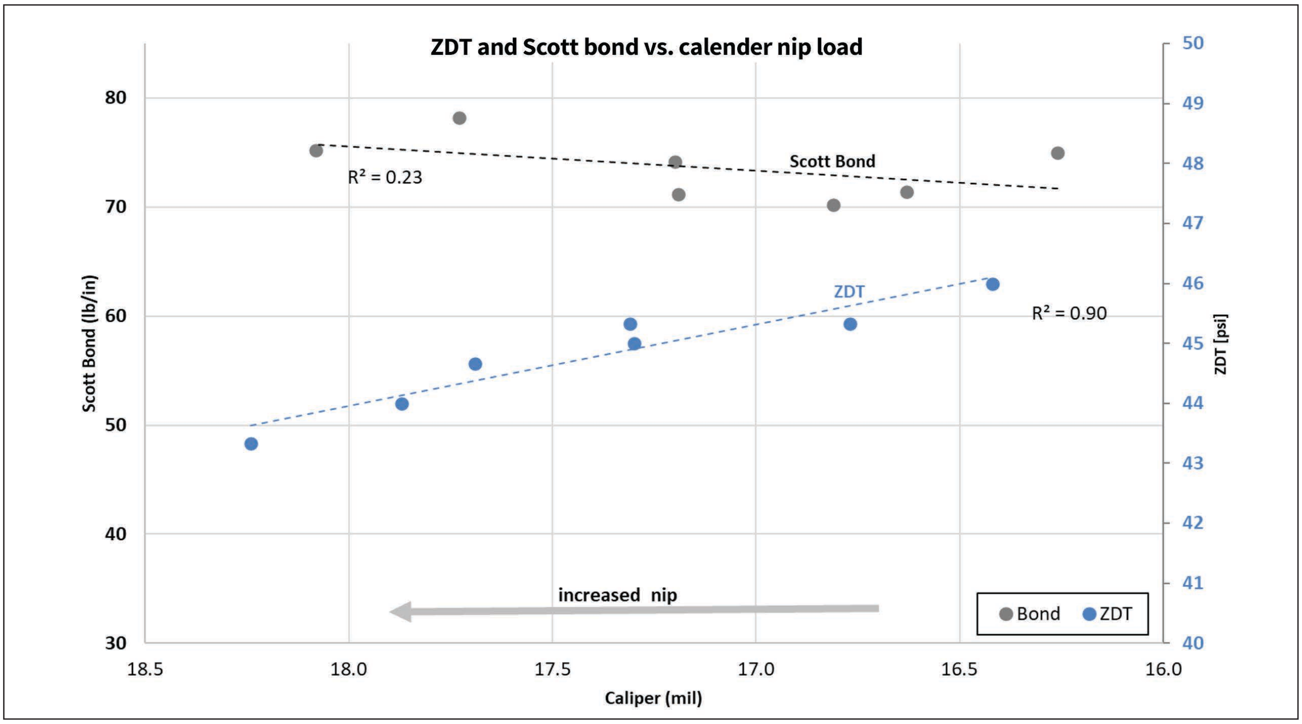
10. Effect of freeness on Scott bond and ZDT for handsheets made from refined pulp. Note that there are no Scott bond values at the highest freeness level because the test reaches a maximum at 250.



11. Effect of sheet density on Scott bond and ZDT for handsheets made from refined pulp.



12. Worse formation (measured on sheet splits) causes a decrease in ZDT.



13. Effect of pilot calendering on ZDT and Scott bond.

Scott bond did not show a trend. The full sheet formation did not show a correlation with either Scott bond or ZDT. This is because sheet split formation is more effective at highlighting defects in the interior of the sheet [8]. ZDT is believed to be more sensitive to internal defects than Scott bond because it is a strength measure and more sensitive to the weakest point in the structure, while Scott bond is an energy measure of the full structure and will mask the presence of defects [2]. To increase ZDT, sheet split forma-tion should be optimized.

Paperboard compression

During paperboard manufacturing, wet pressing for dewatering the paperboard and calendering for surface and caliper control affect fiber bonding. Generally, when the paperboard web is wet (e.g., solids lower than 50%), paperboard compression (wet pressing) has shown to improve fiber bonding [9]. The impact of wet pressing could not be clearly seen in this study, because when wet-press nip load changes occurred, several other parameters had a stronger impact on fiber internal bonding measurements. Conversely, when the paperboard is dryer than 90%, stresses generated by calendering deteriorate fiber bonding to a certain degree, depending on the types of fiber being utilized to form the fiber matrix.

The plot in **Fig. 13** clearly displays the adverse effect of calendering on ZDT and Scott bond properties of paperboard at about 7% moisture content and ambient temperature. In this experiment, samples from the same production paperboard with the initial caliper of about 18 mils were fed into a hard hot lab calender at 10, 25, and 40 kN/m nip loads. Unsurprisingly, increased calendering nip load reduced the paperboard caliper. The ZDT shows stronger inverse correlation with the nip load pressure than does Scott bond, as shown in Figure 13. The increased nip pressure damaged fiber bonding and reduced the internal strength. It may be possible to minimize damage by calendering at a higher moisture.

ABOUT THIS PAPER

Cite this article as:
Giuste, S., Panek, J., Mirzaei, B., et al., *TAPPI J.* 20(11): 683(2021). https://doi.org/10.32964/TJ20.11.683

DOI: https://doi.org/10.32964/TJ20.11.683

ISSN: 0734-1415

Publisher: TAPPI Press

About this journal

CONCLUSIONS

This work demonstrates the value of combining a "big data" analysis software, analytical sample evaluation tools, controlled experiments, and knowledge to provide insight into the factors that affect the internal strength of commercially produced paperboard. The Wedge analysis tool provided a

ABOUT THE AUTHORS

We chose to study this topic due to paperboard operation needs. It is unique in that it uses the Wedge statistical analysis method to a analyze thousands of production data.

The most difficult part of this research was to determine cause and effect based on a multitude of variables. This difficultly was addressed by either running a design of experiments (DOE) or independently confirming cause/effect by performing lab work.

We found paperboard manufacturing variables have an independent effect on the internal fiber bonding, depending on the way it is measured. Surprisingly, we discovered that due to the specific ways Scott bond and ZDT are measured, they can be affected by the same variables or not.

Paperboard mills can use the method presented here to better understand variables impacting internal fiber bonding, either measured by Scott bond or ZDT. Our next step is to develop a model to predict internal paper fiber bonding based on paperboard manufacturing variables.

Giuste

Panek

Mirzaei

Hart

Giuste is R&D manager, Papermaking and Structural Mechanics; Panek is senior principal R&D scientist; Mirzaei is senior R&D scientist; and Peter W. Hart is director of Fiber Science and Innovation for WestRock in Richmond, VA, USA. Email Giuste at sergio.giuste@westrock.com

rapid and meaningful approach to collect, organize, and analyze large data sets from the mill. The statistical tools provided reasonable insight into the operating variables that impacted internal strength. The sheet split method provided details on the internal structure, which highlighted differences that are not obvious from analysis of the whole paperboard and demonstrated the influence of starch penetration and internal formation on the internal strength. Controlled laboratory experiments on refining and calendering provided a method to study these processes in isolation without affecting normal production. Good papermaking and paper physics knowledge were required to filter the statistically determined variables and determine which parameters made sense and had a direct effect.

Both ZDT and Scott bond are improved by factors that increase fiber bonding, including refining, wet pressing, and starch addition; they are decreased by factors that damage fiber bonding, such as calendering. The ZDT is more sensitive to through-the-thickness differences, such as starch distribution and formation. This is because ZDT is determined by the weakest region through the thickness of the structure, whereas Scott bond is affected by deformation and failure of the full structure. Control strategy is to use bulk effects to affect both, and to use through-thickness distributions to affect ZDT alone.

Th next steps in this work include development of a model to predict internal strength based on process parameters. One major challenge is to capture factors, such as starch penetration, that are not directly measured. **TJ**

LITERATURE CITED

1. Mirzaei, B., Harksen, T., Smith, S., et al., *TAPPI J.* 20(2): 81(2021). https://doi.org/10.32964/TJ20.2.81.
2. Koubaa, A. and Koran, Z., *Tappi J.* 78(3): 103(1995).
3. Fellers, C., Östlund, S., and Mäkela, P., *Nord. Pulp Pap. Res. J.* 27(2): 231(2012).
4. Hubbe, M.A. *BioResources* 1(2): 281(2006). https://doi.org/10.3183/npprj-2012-27-02-p231-236.
5. Mirzaei, B., Sinha, A., and Nairn, J.A., *Mater. Des.* 87: 586(2015). https://doi.org/10.1016/j.matdes.2015.08.010.
6. Kang, T.A.P.H. and Paulapuro, H., *Pulp Pap. Can.* 107(7-8): 51(2006).
7. Sakaemura, T. and Yamauchi, T., *Jpn. TAPPI J.* 67(8): 900(2013). https://doi.org/10.2524/jtappij.67.900.
8. Hirn, U. and Bauer, W., "Investigating paper curl by sheet splitting," *EUCEPA Conf. Challenges Pulp Papermaking Technol.*, EUCEPA, Paris, 2006.
9. Koubaa, A. and Koran, Z., "Effect of press-drying parameters on paper properties," in *Pulp and Paper Processing* (S.N. Kazi, Ed.), IntechOpen, 2018, pp.87-107. https://doi.org/10.5772/intechopen.76508.