Impact of Z-Direction Fiber Orientation on Performance of Commercial and Laboratory Linerboards

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The Opportunity

Cellulose fibers, being rod-like with multiple axes, provide the opportunity for

- tome ZDFO (Z-direction fiber orientation). ZDFO affects the structural properties of paper and paperboard, influencing their performance in various applications.

-commence the ZDFO measurement process provides a mechanism to evaluate this aspect of paperboard quality.

Commercial Linerboards

The Tests

Table 1: Physical properties and ZDFO test result comparisons between three linerboards. The results are an average of three replicate samples. The error bars correspond to the standard error of the mean. The primary conclusions are summarized in Table 1.

<table>
<thead>
<tr>
<th>Linerboard</th>
<th>MD Property</th>
<th>CD Property</th>
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<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td></td>
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<tr>
<td>C</td>
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</table>

The Measurement

In Figure 2, a micrograph shows the presence of ZDFO in a commercial linerboard. ZDFO is typically characterized by the tilt of fibers in the direction perpendicular to the machine direction (MD). The measurement involves analyzing the angle distribution of fibers in the Z-direction across the sheet thickness.

- Figure 2: Micrograph showing ZDFO in a commercial linerboard.

- Figure 3: Graph comparing ZDFO measurements across different linerboards, demonstrating the variation in ZDFO across different commercial grades.

Conclusion—Linerboard Tests

As anticipated, the study revealed a strong association between ZDFO and the out-of-plane shear performance of laboratory linerboards. The results confirmed that ZDFO significantly affects the mechanical properties of linerboards, particularly in the Z-direction. The study also highlighted the importance of ZDFO in optimizing the performance of commercial linerboards.

Conclusions—Handsheets Using Synthetic Fibers to Create ZDFO

Handsheets Using Synthetic Fibers to Create ZDFO

Materials

- Three synthetic fiber types: cellulose, rayon, and carbon fibers.
- Aqueous suspension of fibers with high solids content (>50%).

Testing

- Tensile tests of stiffness and strength are expected to be insensitive to ZDFO.
- Double-notch shear (DNS) strength tests are expected to be sensitive to ZDFO.

Figure 4: Graph illustrating the ZDFO measurements for three tested synthetic fibers. The results indicate a significant improvement in DNS strength for the carbon fiber compared to the cellulose and rayon fibers.

Appendix: The Double-Notch Shear Test

The double-notch shear test is a method for determining out-of-plane shear strength. The test involves cutting notches into a sample to create shear surfaces, then subjecting the sample to a load that causes shear failure. The test provides a measure of the strength in the Z-direction.

Figure 5: Diagram of the double-notch shear test setup. The sample is loaded in a testing machine, and the force required to cause shear failure is measured.

References

2. TAPPI. In TAPPI Test Methods, “Bending resistance (stiffness) of paper and paperboard (Taber-type tester in basic configuration),” Method T545-99, 2009.
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Abstract

Fibers tilted in z-direction by hydraulic forces associated with rushing or dragging the sheet can bond multiple strata together, resulting in improved out-of-plane shear strengths. Tilted fibers are difficult to identify microscopically; however, their presence can result in different measurements of Scott internal bond when tests are carried out in the two opposing machine directions. These tests identified differing fiber tilts that correlated with differing amounts of out-of-plane shear strengths in three otherwise comparable linerboard samples. The effect was duplicated in handsheets in which stiff, non-bonding carbon fibers were added to pulp to produce three-dimensional structures that interfered with the tendency of draining fibers to stratify. Even though the substitution of 10% carbon fibers produced a loss of bonding sites, the out-of-plane shear strength of the handsheets improved by an average of 15%. The search is on for methods to control fiber tilt in commercial paperboard. Success will result in improved mechanical performance without additional fiber costs.

Introduction

Although paper is a highly stratified material, hydrodynamic forces in the forming process of a Fourdrinier machine are likely to cause one end of a machine-direction- (MD-) oriented fiber to migrate downward toward the wire side. Paper made under drag conditions is likely to have fibers with ends closest to the reel lying closer to the wire side [1]. Tilt is reversed for papers made under rush conditions. Cross-flows associated with fiber misalignment can produce similar tilt effects for cross-machine-direction- (CD-) oriented fibers.

Fibers with segments tilted only a few degrees can intersect multiple fiber layers. By forming bonds within adjacent layers, fibers tie the layers together, potentially increasing ply-bond and out-of-plane shear [2]. These are known to be important components of compression strength [3]. The term z-direction fiber orientation (ZDFO) is used here to indicate the presence of these tilted fiber segments. We believe that ZDFO can play an important role in improving compression strength of structural paperboard without the expense of additional fiber.

The distribution of ZDFO in terms of the concentration of tilted fiber segments and their lengths and angles are important parameters, but no direct measurement is known. Scanning electron micrograph (SEM) images of paper surfaces occasionally show a fiber segment on top of some fibers but below other fibers that appear to be in the same stratum. In our experience, this is difficult to evaluate even in a qualitative way. The principal demonstration for ZDFO has been
tape pulls, especially pulls in two opposite directions [1,4,5]. These show greater or less fiber pickup, or peel force, according to the sense of fiber tilt in the pull direction. These tests emphasize fiber tilt at or near the paper surface. There is no guaranty that ZDFO implied by these tests exists throughout the volume of the sheet, as would be appropriate for compression-strength enhancement.

Vahey and Considine [6] conducted Scott internal bond testing [7] on papers in two opposing machine directions (MD+ and MD–) and cross-machine directions (CD+ and CD–) to determine any differential that could be taken as a measure of ZDFO through the volume of a sheet. Roughly ten times the number of replicates normally used for the Scott bond test were required to obtain statistically significant results.

Table 1 shows the Scott-bond differential and other physical properties for three tested linerboards, designated as either A, E, or F. By coincidence, the three liners showed distinctly different characteristics of ZDFO: F had ZDFO in the MD only, E had no ZDFO, and A had ZDFO in the CD.

The symbol ~0 indicates values that were not statistically different than 0 at the 95% confidence level. Scott-bond test values averaged over both directions are also shown in Table 1. Sample E had the largest value. It may have had ZDFO of a type not measured by directional testing; alternatively, it may simply have had better ply-to-ply bonding without any ZDFO.

Samples A, E, and F span a range of ZDFO possibilities that motivated us to perform a battery of conventional strength and stiffness tests on each of them. Along with testing linerboard samples we fabricated and tested handsheets containing 10% carbon or rayon fibers. Because carbon fiber and rayon do not bond with cellulose in paper, strength values should be smaller than in control samples. An opposite observation may suggest that synthetic fibers are conducive to the generation of ZDFO. Handsheets containing synthetic fibers also offer an opportunity for more direct observation of ZDFO using synchrotron image slicing and radiography.

**Materials and Tests**

Linerboards A, E, and F were discussed in previous publications [2,6,8]. Linerboards A and E are believed to be of commercial manufacture. Although linerboard F has many mechanical properties similar to commercial grade (and generally superior to those of A), it may have come
from a pilot-scale paper machine. This may have facilitated the significant MD ZDFO observed in the sample and limited cross flows that could produce CD ZDFO.

Three types of handsheets were made:
1. 100% eucalyptus fiber, the control, Brazilian plantation grown, 630 ml CSF
2. 90% eucalyptus fiber, 10% rayon fiber (by weight)
3. 90% eucalyptus fiber, 10% carbon fiber (by weight)

The basic idea was to create a three-dimensional (3-D) structure during handsheet forming to disrupt the tendency of cellulose fibers to stratify, thereby producing ZDFO. A handsheet former modified from TAPPI T 205 [9] was designed to accomplish this. Modifications [8] were intended to increase the probability for synthetic fibers to land vertically on the forming screen and fiber mat and then fall over one another creating an open 3-D network that could be filled in by non-stratified cellulose fibers. We expected that carbon fibers, being much stiffer than rayon, would better accomplish this. The eucalyptus fibers had a weighted average fiber length of only 0.57 mm and were believed more likely than longer fibers to fill in the open network without stratification. Refining of the fibers was limited for the same reason. Handsheet basis weights were 205 g/m².

Testing of the handsheets was limited to tensile and double-notch-shear (DNS) [10]. Figure 1 shows a schematic of the DNS strip configuration. The test is conducted like a standard tensile test.

In this work, the span between notches was 2 mm for handsheets and 1.59 mm (1/16 in.) for linerboards, and notches were cut to the approximate middle of specimen caliper. The notches determined a failure surface. Only tests failing in the shear-lap region were considered valid.

The linerboard materials and additional tests performed on them are described in detail in Considine et al. [8]. They include tensile strength and stiffness [11,12], short-span compression strength [13], and Taber stiffness [14]. The important comparisons to be made have to do with relative values: the three linerboards compared with each other and the synthetic-fiber handsheets compared with the control.

**Results**

Table 2 shows the results of strength and stiffness testing of linerboards. Results were normalized by dividing by basis weight (or by density, in the case of Taber stiffness). Values for

Figure 1. Geometry for the DNS test.
Table 2. MD and CD physical properties of linerboards A, E, and F

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<tbody>
<tr>
<td>Scott-bond directional differential (ZDFO) (%)</td>
<td>~0</td>
<td>~0</td>
<td>2.9</td>
<td>2.9</td>
<td>~0</td>
<td>~0</td>
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<td>Tensile strength index (N·m/g)</td>
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<td>3.99</td>
<td>4.58</td>
<td>4.84</td>
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<tr>
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<td>18.7</td>
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<td>Taber stiffness index (kN/m/g)</td>
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<td>2.57</td>
<td>3.04</td>
<td>2.97</td>
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<td>Out-of-plane shear index (DNS) (N·m/g)</td>
<td>9.11</td>
<td>8.32</td>
<td>11.83</td>
<td>5.23</td>
<td>5.28</td>
<td>5.49</td>
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</table>

*Highlighted cells indicate the largest MD and CD values for a given test.*

linerboard F tend to be the largest and values for A the smallest. All values were further normalized to a percentage scale and plotted in Figure 2 for easier comparison. The various tests performed are ordered along the x axes of Figure 2, roughly in order of increasing sensitivity to ZDFO.

Tensile tests of stiffness and strength are expected to be insensitive to ZDFO. Short-span compression strength and Taber bending stiffness are more sensitive, and the DNS test is likely to be most sensitive to ZDFO. The error bars in Figure 2 represent one standard error.

Figure 3 shows results of tensile strength and DNS testing of eucalyptus handsheets. Nineteen tensile tests and 69 DNS tests are represented by the three plotted points, and the error bars represent two standard errors. Neither rayon nor carbon fibers bond with cellulose fibers in paper. Their presence should therefore reduce the strength of handsheets compared with the control. This is the case for handsheets containing rayon fibers with regard to both tensile and DNS testing. The loss of tensile-strength and DNS indices in the handsheets containing rayon is 18% and 16%, respectively. However, it is not the case for handsheets containing carbon fibers, in which the tensile-strength index loss is less than 1% and the DNS gain is 14%.

**Analysis and Discussion**

Among MD strength and stiffness tests of samples A, E, and F, DNS strength of sample F was significantly larger than for either A or E. This strength advantage was missing in CD testing. It is easiest to associate this result with the finding of ZDFO in the MD of F but not in the CD of F, and not in E.
Figure 2. Relative performance of linerboards A, E, and F; (a) MD, (b) CD.

Figure 3. Results of DNS out-of-plane shear testing of eucalyptus handsheets.
In compression and bending stiffness tests, F and E performed comparably. Recall from Table 1 that E had the largest average Scott-bond value. The implied large ply-bond may have helped E to match the performance of F in tests other than DNS.

Perhaps a better comparison is between F and A, because both had comparable Scott-bond values but different ZDFO. Sample F is superior to A in all MD and CD tests; however, the relative performance of A is greatly improved in all the CD tests. This is consistent with the observation of CD-ZDFO in sample A and the absence of CD-ZDFO in sample F. Sample A also improves relative to sample E in most CD tests.

Among CD strength and stiffness tests of samples A, E, and F, the relative improvement of sample A relative to E and F reinforces a possible correlation with ZDFO. Among the differences in the three sheets that could influence the interpretation of results, sheet squareness is probably the most important. An average of MD/CD ratios for the strength and stiffness tests of the sheets gives 1.86 for A, 1.89 for E, and 2.08 for F. The MD ZDFO may make the linerboard F ratio higher, whereas CD ZDFO may decrease the ratio for linerboard A. In that case, the three sheets may have similar underlying squareness, and the present interpretation of results stands.

These uncertainties justify the use of handsheets to study the basic relationship between ZDFO and strength. The dramatic results of Figure 3 need no elaboration. A 10% addition of non-bonding synthetic carbon fibers actually increases shear strength without loss of tensile strength. Handsheet studies also improve the opportunity for direct observation of ZDFO.

A working model for ZDFO creation by carbon fibers emphasizes their length and stiffness. At 3 mm length and too stiff to bend under the hydraulic forces of papermaking, they are unlikely to stratify. Figure 4 is an optical micrograph showing a dark carbon fiber in a cross-section of handsheet. The tilt angle of 7º is consistent with the fiber’s length and the handsheet caliper of about 0.4 mm.

Figure 4. Cross section of a eucalyptus handsheet containing 10% carbon fiber by weight.
Cellulose fibers encountering this structure are less likely to stratify. Cellulose fibers with z-direction projections ultimately bond with each other and with stratified fibers to give the observed effects. Some evidence of z-oriented fibers is seen in Figure 4, though this could also represent disruption caused in preparing the specimen.

A different view is afforded by synchrotron x-ray microtomography. Figure 5 shows a surface rendering of an interior section of a carbon fiber handsheet. Several straight fiber segments, presumed to be carbon, are seen oriented diagonally within the image. One in the upper right of the image appears to dive into the surface. A circular arc of disruption, not expected in a paper structure, appears to be associated with this event. The scale of the disruption is about 0.35-mm diameter, comparable to the weighted-average eucalyptus fiber length of 0.57 mm.

Figure 6 shows synchrotron x-ray radiographs taken through the cross section of eucalyptus handsheets containing carbon and rayon fibers [15]. The images have been enhanced to improve the visibility of the synthetic fibers. Vertical projections of carbon fibers are common in Figure 6a. Because the fibers are 3 mm long, these are projections of fibers that generally extend into or out of the plane of the image. In Figure 6b, rayon fibers are seen to blend more with the general cellulose structure. In the lots from which the imaged samples were taken, average density of carbon-fiber handsheets was 480 kg/m³. For sheets with rayon, density was 530 kg/m³. For control handsheets, density was 560 kg/m³. Carbon fiber had 2.7 times the effect on density that rayon fiber had, indicating the greater degree of disruption to the cellulose structure.

Summary and Conclusions

Three linerboards with different degrees and orientations of ZDFO were subjected to a battery of conventional tests to determine if the effects of ZDFO on strength and stiffness could be broadly characterized. Linerboard F, with ZDFO limited to fibers generally oriented in the MD, gave the
highest test values 64% of the time, in both MD and CD testing. However, only one test, double-notch-shear strength, was statistically differentiated from results for linerboard E, which had no evidence of ZDFO. Although shear strength is understood to be important for compression strength [3], this expectation was not realized by present tests and requires more study.

A third linerboard, A, was previously found to have CD ZDFO. This linerboard gave the lowest test values from among the three sheets 79% of the time. However, it performed relatively better in CD testing than in MD testing in general, and in double-notch-shear testing in particular. MD double-notch-shear test was the only one where linerboard E, without ZDFO, was statistically inferior to both A and F, with ZDFO.

Comparisons like these tacitly assume the three sheets are equivalent in all ways other than ZDFO. This is not the case. The most likely difference that could be influencing conclusions is sheet anisotropy, especially if F is most MD-oriented and A is least MD-oriented. Resolution of this issue is difficult because the various tests themselves provide a wide range of anisotropies.

Studies with eucalyptus handsheets and synthetic fibers get around the difficulties in comparing commercial papers. The sheets have the same basis weight and are isotropic. A compelling model can be based on the relative stiffness of carbon and rayon fibers. X-ray images show that carbon fibers do not stratify in handsheets, and logic (if not actual images) suggests that cellulose fibers acquire ZDFO as they encounter these stiff structures just before they encounter the fiber mat. Rayon, a form of cellulose, is more like papermaking fibers in stiffness. X-ray images show rayon fibers to be stratified and integrated in the cellulose network.

Rayon produces a loss of bonding sites that translates to a loss of strength. Carbon fiber produces a loss of bonding sites as well. It compensates by producing ZDFO to couple strata together for an increase in shear strength and maintenance of tensile strength.
References

7. TAPPI. In TAPPI Test Methods, “Internal bond strength (Scott type)”, Provisional Method T 569 pm-00. TAPPI Press (2000).