Load-Elongation Behavior of Fiber-Oriented Manila Hemp Sheets

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Abstract: Fully restrained fiber-oriented sheets, machine-made paper, and handmade sheet by the standard method were prepared from Manila hemp pulp. Strain-to-failure of the fiber-oriented sheets was almost the same in both the machine (MD) and the cross machine (CD) directions, while a distinct direction-dependence was observed in the machine-made paper. This indicates that a degree of fiber orientation of paper is not a dominant factor controlling strain at break. Furthermore, dried-in shrinkage in CD of the machine-made paper can be simply estimated by comparison of strain-to-failure of this paper with that of the fully restrained fiber-oriented sheet or the handmade sheet prepared. Uneven profile of strain-to-failure in CD of the machine-made paper is observed over the width direction. This profile may possibly be explained by analogy of the geometrical and mechanical conditions of the wet web at the dryer pocket with those of the short span thin body. Notable acoustic emission (AE) from the specimens sampled from both edge and center of the dried web in the elongation test was not observed except at the final stage of plastic region. The result indicates that difference of strain-to-failure between them is attributed to a different degree of dried-in shrinkage since structural breakage like bond failure or fiber breakage which may happen in plastic deformation causes emission of elastic wave.

1. Introduction

A machine-made paper has anisotropy in various kinds of mechanical and physical properties. It has been proved by many studies [1-5] that tensile strength of the paper is pronouncedly affected by a degree of fiber orientation. A method for determining fiber orientation from the measurement of a zero-span tensile strength has been adopted experimentally based on this fact [6-9]. On the contrary, initial slope or plastic deformation behavior in the elongation test is mainly controlled by both drying tension and fiber orientation [5,10,11]. Complicated micro-structural features of the fiber network contributing to the plastic deformation are developed in the paper making process [12-17].

It was proved in a previous report [18] that there is no dimensional change in the handmade sheet dried on the metal plate, and that the dried-in shrinkage introduced into the partially restrained sheet is extended quantitatively in the elongation test. The fiber-oriented sheet having no drying shrinkage introduced into the partially restrained sheet is extended quantitatively in the elongation test. The fiber-oriented sheet having no drying shrinkage is able to be prepared by adoption of this fully restrained drying method. Then, comparison of the load-elongation behavior of the fiber oriented sheet made by this method with that of the machine-made paper under the same degree of fiber orientation will bring us a possibility of separation of the dried-in shrinkage from the total strain-to-failure of the machine-made paper.

A commercial paper web is manufactured on a papermaking machine with longitudinal drying
tension. According to the computer calculation results using the finite element method applying to the rectangular thin body whose width was more than two times wider than its length under prohibition of lateral movement at the top and bottom grip ends, tensile force was generated laterally [19]. The shape of the thin body and the geometrical condition of this calculation are analogous to those of wet web at the open draw. The laterally generated tensile force in the wet web may influence the amount of drying shrinkage in the cross machine direction (CD). Consequently, variation of strain-to-failure over CD of the machine-made paper is also discussed. Since a generation pattern of acoustic emission (AE) in the elongation test gives some useful information on failure mechanism of the fiber network [20,21], AE measurement is also applied to the elongation test of the machine-made paper.

In a previous report [18], softwood bleached kraft pulp sheet was used. By only our domestic reason, Manila hemp instead of this wood pulp is only available for a large amount pulp stock to manufacture the machine-made paper when this experiment started. No dimensional change in Manila hemp sample dried on the metal plate was also confirmed beforehand.

2. Experimental

2.1 Sample
Manila hemp pulp was refined by a double disk refiner to a freeness time of 40 sec. The freeness time is defined as the drainage time of pulp suspension (1.2 g of pulp in 76 of water) through 150 mesh wire from the standard sheet machine vessel.

2.2 Sheet Preparation

2.2.1 Machine-made Paper
A paper web with an expected basis weight of 90 g/m² was manufactured by an experimental paper machine installed in the Research Institute. Speed of the machine was 10 m/min, and width of the paper was 450 mm.

2.2.2 Fiber-oriented Sheet
A centrifugal dynamic sheet former manufactured by Kumagai Riki Co. was used. The degree of fiber orientation of the sheet was varied by changing the ratio of jet speed of the pulp suspension to rotating wire speed (J/W ratio). A wet mat formed on the wire with an expected basis weight of 90 g/m² was taken out together with the wire, and then couched with blotter papers. The wet sheet was cut quickly with scissors into a round shape to be placed on the metal plate. The sheet was finally dried according to JIS P8209.

2.3 Mechanical Test

2.3.1 Tensile Test
An Instron type of elongation tester (Toyo Boldwin, Tension III-500 type) was used. The standard test in a 100 mm span was carried out at a rate of 5 mm/min at 20°C and 65% RH.

2.3.2 Wet Zero-span Tensile Test
The wet zero-span tensile test to calculate the degree of fiber orientation of the machine-made paper and the fiber-oriented sheets was carried out by cutting out of the samples at every 15° to the machine direction (MD) according to TAPPI standard T231 using a Trouble Shooter manufactured by M & K Co.

2.4 Measurement of Acoustic Emission
The measurement system adopted in this study was described previously [18].

3. Results and Discussion

3.1 Fiber Orientation of the Sheets
The results of the wet zero-span tensile test for the fiber-oriented sheet no.1 to no.4, the machine-made paper, and the handmade sheet are shown in Table 1. The zero-span tensile strength was expressed in a unit of kN/m². Zero degree in this table corresponds to MD. Then, a degree of fiber orientation of these sheets was calculated using the 2-term cosine function, \( f_2(\theta) \), which was first employed by Perkins and Mark [22]:

\[
f_2(\theta) = 1/\pi(1 + \eta_1 \cos 2\theta + \eta_2 \cos 4 \theta)
\]

(1)

The orientation coefficients, \( \eta_1, \eta_2 \) were calculated by the least squares method and the results are shown in Table 2. Since the value of \( \eta_2 \) for all the sheets were found to be negligible, the 1-term cosine function, \( f_1(\theta) \), adopted by Kallmes and co-workers [23,24] is adequate for the samples used in this study:

\[
f_1(\theta) = 1/\pi(1 + \eta_1 \cos 2 \theta)
\]

(2)

As a matter of course, the value of \( \eta_1 \) shown in Table 2 is increased with decrease in the value of J/W ratio or with increase in a wire speed of the dynamic sheet former. The ratio of elastic modulus in MD of the fully restrained fiber oriented sheet to that in CD can be expressed by the value of \((6 + 4\eta_1 + \eta_2)/(6 - 4\eta_1 + \eta_2)\) when Eq. (1) is used as the fiber orientation function in
Table 1 Wet zero-span tensile strength for all samples tested.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>J/W Ratio</th>
<th>Basis Weight g/m²</th>
<th>Thickness mm</th>
<th>Wet Zero-Span Tensile Strength kN/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0°</td>
</tr>
<tr>
<td>1</td>
<td>0.69</td>
<td>91.8</td>
<td>0.109</td>
<td>1.74</td>
</tr>
<tr>
<td>2</td>
<td>0.85</td>
<td>95.0</td>
<td>0.116</td>
<td>1.68</td>
</tr>
<tr>
<td>3</td>
<td>1.00</td>
<td>90.0</td>
<td>0.108</td>
<td>1.72</td>
</tr>
<tr>
<td>4</td>
<td>1.29</td>
<td>94.5</td>
<td>0.115</td>
<td>1.47</td>
</tr>
<tr>
<td>Machine-made Paper</td>
<td></td>
<td>96.0</td>
<td>0.126</td>
<td>1.32</td>
</tr>
<tr>
<td>Handmade Sheet</td>
<td></td>
<td>93.7</td>
<td>0.119</td>
<td>1.21</td>
</tr>
</tbody>
</table>

Table 2 Calculation results of the fiber orientation coefficients, η₁ and η₂ in Eq.1.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>J/W Ratio</th>
<th>η₁</th>
<th>η₂</th>
<th>(6 + 4η₁ + η₂) / (6 - 4η₁ + η₂)</th>
<th>Z_MD/Z_CD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.69</td>
<td>0.37</td>
<td>0.03</td>
<td>1.66</td>
<td>2.32</td>
</tr>
<tr>
<td>2</td>
<td>0.85</td>
<td>0.36</td>
<td>0.00</td>
<td>1.65</td>
<td>2.15</td>
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<tr>
<td>3</td>
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<td>0.33</td>
<td>0.00</td>
<td>1.56</td>
<td>2.05</td>
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<td>1.29</td>
<td>0.12</td>
<td>0.01</td>
<td>1.17</td>
<td>1.26</td>
</tr>
<tr>
<td>Machine-made Paper</td>
<td></td>
<td>0.12</td>
<td>0.03</td>
<td>1.18</td>
<td>1.35</td>
</tr>
</tbody>
</table>

the Cox theory [25]. This ratio and the ratio of wet zero-span tensile strength in MD to that in CD, (Z_MD/Z_CD), are also listed in this table for subsequent discussion.

3.2 Load-Elongation Behavior of the Sheets

The value of η₁ and η₂ listed in Table 2 for the machine-made paper and the fiber-oriented sheet no.4 indicate that both samples have an almost identical degree of fiber orientation. Then, comparison of mechanical properties between the two was made. Load-elongation curves of these samples in MD and CD are summarized in Fig. 1. Although tensile strength of the machine-made paper (A) in MD and that of the fiber-oriented sheet (B) in CD were slightly higher than the respective directions of the other specimen, the value of the two samples in MD and CD were fairly close. Further precise comparison of tensile strength is difficult, however, because of the different papermaking conditions between them. The wires used and drainage condition in the two papermaking processes could not be standardized in this study. For example, difference of fine content in the two samples may to some extent contribute to their respective tensile strength. However, the results shown in Fig. 1 indicate that at least a degree of fiber orientation is a significant factor controlling tensile strength of paper as reported in the previous studies [1-5].

Fig. 1 Load-elongation behavior for the machine-made paper (A) and the fiber-oriented sheet no.4 (B). CD sample of the machine-made paper was cut out of the center part of the web. C (dotted line): the handmade sheet. Freeness time of all samples: 40 sec.

load-elongation curve of the handmade sheet made from the same stock is also shown as a dashed line in this figure. Tensile strength of this sheet was between that of MD and CD of the other two samples.

It was also proved from this figure that both MD and CD samples of the fiber-oriented sheet no.4 were elongated at much the same level before failure. All the fiber-oriented sheets tested showed a similar tendency. Almost the same results were reported by Htun and Fellers [26]. They prepared the fiber-oriented sheets
with restrained drying using the specially designed drying frame. The result is distinctly different from the well-known behavior for a machine-made paper. This indicates that fiber orientation is not a critical factor affecting strain-to-failure of the machine-made paper. Strain-to-failure of the fiber-oriented sheet no.4 and the handmade sheet were fairly close irrespective of difference in a degree of fiber orientation. The same amount of strain-to-failure seems to be attained for any kinds of sheets prepared from the same stock, as far as they are dried on the metal plate with full restraint. Based on the result shown previously, a sheet dried on the metal plate did not shrink [18].

Strain-to-failure of the partially restrained softwood bleached kraft handmade sheets was assumed to be composed of the following two factors [18]. One is inherent strain of the fiber network introduced in various ways during drying [12-17], equivalent to that of the fully restrained sheet. The other is strain due to extension of the dried-in shrinkage. Therefore, a difference in strain-to-failure in CD between the two fiber-oriented samples or between the machine-made paper and the handmade sheet is attributed to shrinkage built into the paper in the dryer part of the paper-making machine.

Figure 2 shows the relationship between the ratio of Young’s modulus in MD to that in CD, $E_{MD}/E_{CD}$, and the ratio of wet zero-span tensile strength in MD to that in CD, $Z_{MD}/Z_{CD}$, for all the sheets tested. A linear relation was found for the fiber-oriented sheet no.1 to no.4, while the plot for the machine-made paper (A) was separated from the regression line. The slope of the line was not unity. The separated plot of the machine-made paper from the line is attributed to the fact that elastic modulus of the paper is affected by both a degree of fiber orientation and anisotropy of drying shrinkage. As described before, the value of $E_{MD}/E_{CD}$ for the fully restrained fiber-oriented sheets could possibly be predicted by the value of $(6+4\eta_1+\eta_2)/(6-4\eta_1+\eta_2)$, where $\eta_1$ and $\eta_2$ were shown in Eq. (1). The relationship between these two variables expressed as a dotted curve is shown in the same figure. A linear relation between these two variables was not found in this study. The plot for the machine-made paper (A) was also located far from the dotted line.

Figure 3 shows the plots of the ratio of tensile strength in MD to that in CD, $T_{MD}/T_{CD}$, and the ratio of strain-to-failure in MD to that in CD, $S_{MD}/S_{CD}$, against the ratio of wet zero-span strength in MD to that in CD, $Z_{MD}/Z_{CD}$. A linear relation between the two strength ratios can be observed among the fiber-oriented sheets, supporting the assumption that tensile strength is primarily a function of fiber orientation anisotropy. On the other hand, the strain-to-failure ratio, $S_{MD}/S_{CD}$ was close to unity over the degree of fiber orientation range tested. Nevertheless, strain-to-failure in CD was slightly smaller than that in MD for all the fiber-oriented samples tested. A typical result was already shown in Fig. 1; this reproducible result may imply that fiber orientation slightly affects strain-to-failure of the sheets. Since the machine-made paper holds a remarkable anisotropy in strain-to-failure as described above, the value of the ratio was inevitably small.

### 3.3 Strain-to-Failure Profile in CD of the Machine-made Paper

Figure 4 shows the profile of strain-to-failure and tensile strength in CD over the width direction of the machine-made paper. Strain-to-failure of the specimen sampled from near edges of the paper web was higher than that from the center part, while tensile strength remained almost constant across the width direction.
Fig. 3 Plots of the tensile strength ratio ($T_{MD}/T_{CD}$) and the strain-to-failure ratio ($S_{MD}/S_{CD}$) against the wet zero-span tensile strength ratio ($Z_{MD}$)/($Z_{CD}$). ○: the fiber oriented sheets, △: the machine-made paper.

The reason for appearing the uneven profile of deformation at break in the machine-made paper has not fully elucidated, although the phenomena is widely admitted [11,27]. One of the conceivable reasons will be discussed next.

As mentioned before, mechanical and geometrical conditions of the paper web running at the dryer pocket are analogous to the short span tensile state as described in the literature [19]. The short span is defined as a rectangular thin body whose width is fairly larger than its test span [28]. The web is pressed on the surface of the cylinder by the canvas, which prohibits lateral shrinkage of the web. This geometrical boundary condition generates tensile stress laterally. Kimura has already calculated stress and strain profiles of a dried paper in this short span tensile state [19]. Here, as one of the examples, the calculation result of the tensile stress profile in the lateral direction under the longitudinal tensile force for the dried paper is reproduced in Fig. 5. Although a set of the elastic constants adopted in the computer calculation for the paper were much higher than that for the wet web, similar stress and strain profiles should be expected so long as calculated under the same mechanical and geometrical boundary conditions. The lateral tensile stress at the center part of the web was found to be

Fig. 4 Change of strain-to-failure and tensile strength in CD over the width direction of the machine-made paper.

Fig. 5 A profile of tensile stress generated in CD of the dried sheet as a short span thin body, reproduced from Ref. [19]. The calculation was carried out under the following elastic constants; $E_y$: 450 kgf/mm², $E_x$: 200 kgf/mm², $G_{xy}$: 120 kgf/mm², $\nu_{yx}$: 0.180, $\nu_{xy}$: 0.405, respectively. y and x correspond MD and CD. 0.1555 mm / 15 mm of enforced-equal-displacement and the restriction of lateral movement were given at the nodal points on both gripped ends.
higher than that at both edges. The tensile stress generated laterally restrains drying shrinkage in CD. Then, the plot of strain-to-failure of the machine-made paper against width direction shown in Fig. 4 may be explained this way. On the contrary, no dependence of sampling position in the width direction on strain-to-failure in MD was observed.

3.4 Measurement of Acoustic Emission (AE)

Figure 6 shows acoustic emission events generated during elongation for three samples prepared from the machine-made paper. E and C in this figure denote the paper web position cut out of the edges and the center as the test sample. A number of acoustic emissions were detected at the final stage of the elongation test for all three samples. No elastic wave was generated except at the sheet failure stage, which was consistent with the previous results where the handmade sheets partially restrained from drying shrinkage were used as model sheets [18]. Although strain-to-failure in CD of the specimens sampled from both edges of the web was higher than that from the center, a similar tendency of AE event was observed. This indicates that almost no structural breakage in the fiber network causing emission of elastic waves in CD of the machine-made paper occurred even at the middle stage of the plastic region in the elongation test. The fact also supports the assumption that the difference in strain-to-failure between the edge and the center samples is due to extension of dried-in shrinkage in the elongation test.

4. Concluding Remarks

A large value of strain-to-failure in CD of a machine-made paper is widely observed although a small effort inquiring into reason of the phenomena has made. By comparing strain-to-failure between CD of the machine-made paper and that of the fully restrained fiber-oriented sheet at the same degree of fiber orientation, the difference between these values was found to be due to the amount of dried-in shrinkage. Subsequently, an uneven profile of strain-to-failure over the width direction of the machine-made paper was assumed to be attributed to an unequal tensile force distribution generated in CD at the open draw. A pattern of acoustic emission of the machine-made paper in both MD and CD was similar to that of the partially restrained handmade sheet reported in a previous paper. The result indicates that no structural change like bonding failure or fiber breakage takes place. Thus, this result also supports the assumption on the elongation mechanism described above.

This study was presented at the annual meeting of this society held in Tokyo, July, 1994.

References