The relationship between bending stiffness and moisture cycling

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1. Introduction

Paper is a highly hygroscopic material since it is made from hydrophilic materials such as cellulose and hemi-cellulose. Thus paper is to be affected by the change of outside environmental conditions that include relative humidity. Most of the paperboard grades are multi-ply products. If each ply of these grades differs in its sensitivity to moisture, one of the plies may show greater hygroexpansion than other plies as the sheet absorbs moisture. This heterogeneity in the response to moisture can be a source of non-uniform distribution of stresses in paperboard [1].

Paper or paperboard needs to have proper levels of bending stiffness for good runnability on the printing presses, converting machines and its final use. It is well known that high bending stiffness of paperboard gives rigidity and strength. Unlike the in-plane tensile properties, the bending stiffness depends considerably on the macroscopic thickness and layered structure of paper or paperboard [2]. In view of fundamental mechanics, the bending stiffness, S_b, of paper is calculated from the following expression

$$S_b = \frac{E \cdot h^3}{12} \quad \cdots\cdots \text{Eq. (1)}$$

where E is elastic modulus and h is effective thickness. Here, it can be comprehensible that bending stiffness is sensitive to the distribution of elastic modulus through sheet thickness.

This study was intended to investigate the reversibility of bending stiffness of various handsheets under cyclic humidity conditions. Bending stiffness and elastic modulus were examined under cyclic humidity conditions, and thickness was simultaneously measured. Eventually, the relationship among the three factors based on Eq. (1), and the reversibility of those in a cyclic humidity environment was investigated and reported.

2. Experimental

Fig. 1 shows the procedures to prepare the long fibers fraction and the fines fraction from UKP (unbleached softwood kraft) stock. To produce a long fibers fraction, the stock was first beaten to 450 mL CSF using a laboratory Valley beater. The fines content of the stock was ca. 14.3%. The Kajanni FiberLabTM was used for analyzing fiber length. The average fiber length (length weighted) was 2.30 mm.

The fractionation was carried out with mesh screens using SWECO® VIBRO-ENERGY® separator. The fraction (P25/R50), which passed through 25 mesh wire and retained on 50 mesh wire, was selected as long fibers fraction. The average fiber length was 1.82 mm. Fines fraction was obtained after beating the original UKP stock until the average fiber length reduced to 0.29 mm

With the stocks prepared with the long fibers and fines fraction, various handsheets were formed according to TAPPI Test Method T205 sp-02. Single-ply handsheets containing different amounts of fines were made using a laboratory sheet mold. The oven dry weight of handsheets was nearly 100 g/m^2. Also two-ply handsheets containing different amounts of fines in each ply were produced. The oven dry weight for the top and bottom ply was 50 g/m^2.

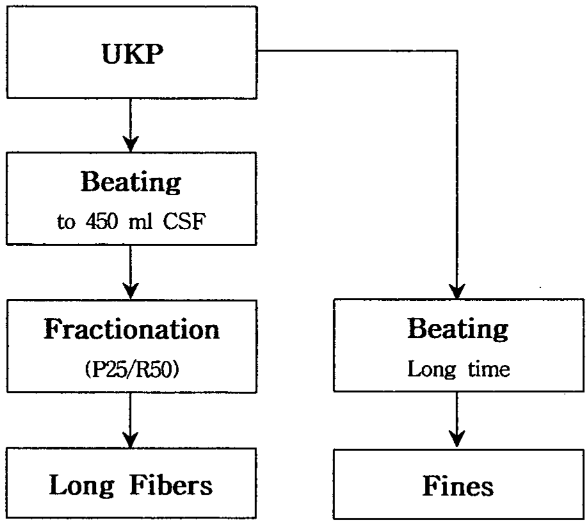

Figure 1. Procedures for the preparation of long fibers and fines fraction with UKP stock.

The samples were preconditioned to reach equilibrium at 51% RH, 23 ° C for at least 48 hour. These preconditioned samples were placed in a humidity chamber, where they were subjected to different humidity conditions until they reached a constant weight. The RH in the humidity chamber were changed from 74%, 94%, 51%, to 32% RH. The moisture content of the samples was simultaneously determined by measuring the weight of representative reference samples.

3. Results and discussion

To compare the elastic modulus, thickness and bending stiffness for single-ply and two-ply handsheets, single and two-ply handsheets containing the same amount of fines were made. These experiments were carried out to understand the difference of sheet properties for single and two-ply handsheets.

As depicted in Fig. 2 and Fig. 3, elastic modulus, thickness and bending stiffness was measured as a function of moisture content for single-ply(S1-20) and two-ply(S2-2020) handsheet with the same amount, 20% of fines. Bending stiffness and elastic modulus decreased as moisture content increased. Thickness, however, increased with moisture content. And elastic modulus showed quite reversible change with moisture content in most cases. But there was irreversibility in bending stiffness, which were different from results of bending stiffness_calculated, i.e. slight or quite high bending stiffness was observed during de-hydration

Elastic modulus of two-ply handsheet was almost similar to that of single-ply handsheet when subjected to a change in moisture content. Two-ply handsheet showed irreversible change in bending stiffness as single-ply handsheet. In other words, there were difference in bending stiffness as handsheets adsorbed and desorbed moisture, and higher bending stiffness was observed in de-hydration. Characteristically, the increase of bending stiffness due to irreversibility was much smaller in two-ply handsheet than in single-ply handsheet. This suggests that the properties of each ply in two-ply handsheets must be taken into account when analyzing the results.

In summary, two-ply handsheets with the same amount of fines as single-ply handsheet had slightly higher elastic modulus over the entire moisture cycle. It might be due to the fact that two-ply handsheet have more uniform distribution of fines in thickness dimension than single-ply handsheet.

Two-ply handsheets showed much greater bending stiffness than single ply handsheets at all humidity conditions. This is partly due to the fact that two-ply hand sheet is bulkier in structure compared with that for single-ply handsheet as shown in thickness results. In terms of bending stiffness, the bulk of paper is the most important because it is proportional to the third power of thickness as shown in Eq. (1). Also the improvement of fines′distribution in thickness dimension as stated above might lead to high bending stiffness in two-ply handsheet.

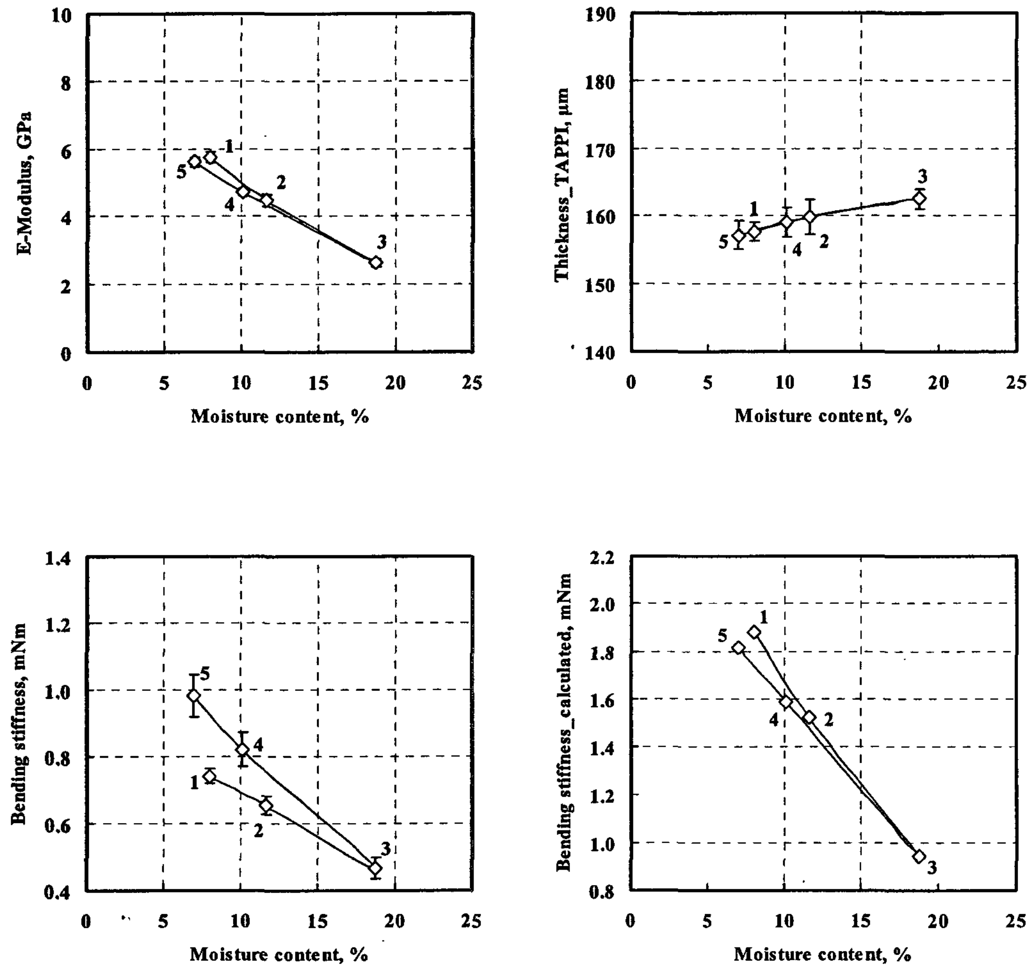

Figure 2. Elastic modulus, thickness and bending stiffness of single-ply handsheet as a function of moisture content. It was made of UKP with 20% of fines.(S1-20)

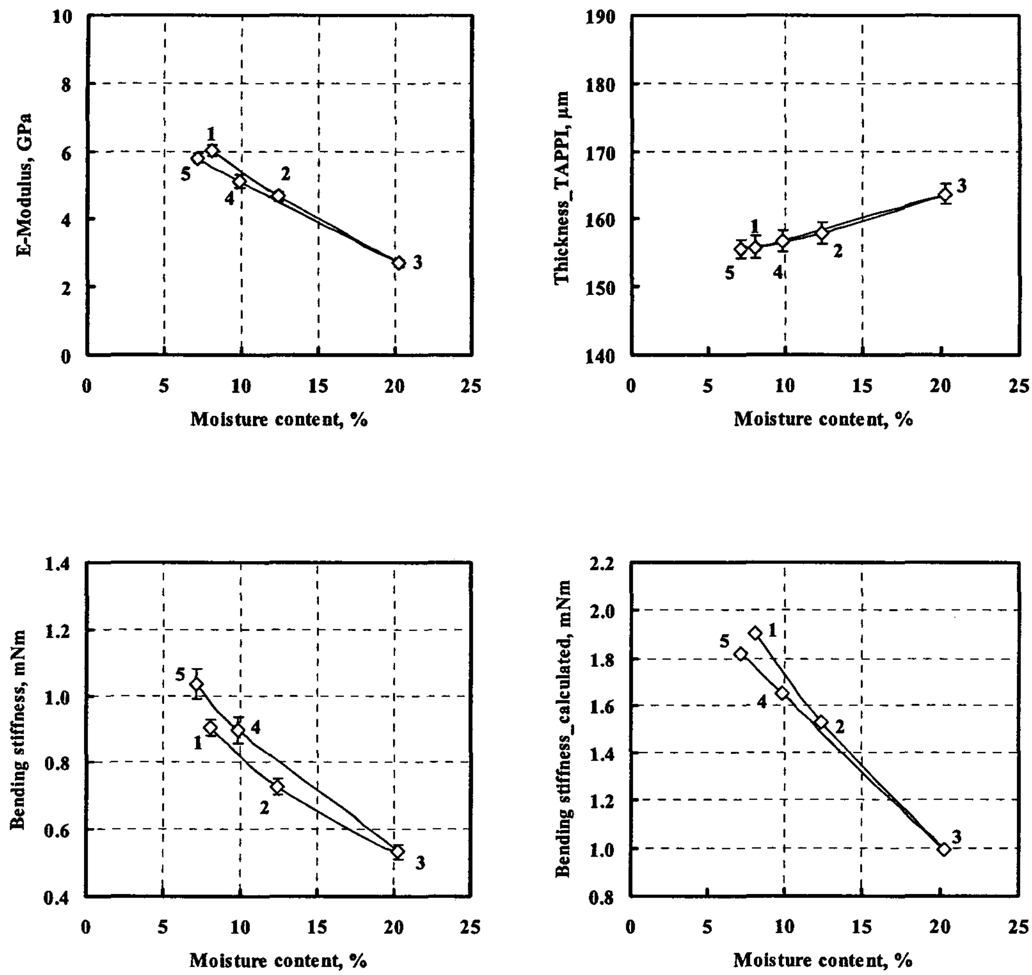

Figure 3. Elastic modulus, thickness and bending stiffness of two-ply handsheet as a function of moisture content. It was made of UKP and consisted of top and bottom plies with 20% of fines. (S2-2020)

And as the moisture content changed, there was a corresponding decrease of bending stiffness regardless of the type of handsheets. However, there was concededly some difference between the two. Two-ply handsheets had higher bending stiffness than single-ply handsheets at initial humidity condition. Two-ply handsheets showed slightly but obviously higher bending stiffness in the humid state compared with single-ply handsheets. Finally, it shows that the z-directional distribution of fines or long fibers is the most significant factor to guarantee good bending performance under humid environment.

After initial humidity cycle, the samples were exposed again to various humidity conditions, which consisted of 94% RH, 51% RH, 94% RH, and finally 51% RH followed by complete drying at 105 ° C. As shown in Fig. 4, there was quite high relationship between moisture content and bending stiffness. Also it is very interesting to note that bending stiffness for handsheets showed a reversible change with $R^2 > 0.98$.

Figure 4. Relationship between moisture content and bending stiffness under cyclic humidity environment. (Left side: S1-20, Right side: S2-2020)

The bending stiffness for S1−20 and S2−2020 changed reversely irrespective of the irreversibility in previous initial humidity cycle. This reversibility in bending stiffness could be found for all handsheets tested in this investigation and thus should be very general phenomenon. And it could be concluded that the change of bending stiffness with successive humidity cycles was dependent considerably on moisture change.

4. Conclusions

As handsheets absorbed moisture, there was a corresponding decrease in bending stiffness and elastic modulus, and a corresponding increase in thickness. In humid condition, the bending stiffness of handsheets was not improved by the increase of thickness, which indicated the elastic modulus played very important role in this case.

Under cyclic humidity environments, bending stiffness of handsheets was considerably dependent on moisture change in all cases. Consequently, it was demonstrated that bending stiffness of handsheets changed quite reversibly with successive humidity cycles.

5. References

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