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EFFECTS OF FIBRE MORPHOLOGY ON HYGROEXPANSIVITY OF PAPER - A MICROMECHANICS APPROACH

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ABSTRACT

Effects of fibre morphology on in-plane hygroexpansivity of paper have been studied using a general micromechanics formula and experimental results obtained for different fibre fractions. It was deduced from the micro-mechanics analysis that the major fibre geometry factors affecting paper hygroexpansivity are fibre width, wall thickness, and fibre length, all of which control the stress transfer ratio parameter defined in the formula. The microfibril angle was found to be another major factor affecting the paper hygroexpansivity through the hygroexpansivity of a single fibre.

The results from the cut-fibre experiment showed that decreasing fibre length increased the hygroexpansivity, but the effect was small within the range of fibre length more than 1 mm. The results from Bauer-McNett classification, on the other hand, showed considerable increases of hygroexpansivity as the fraction became shorter. This large variation was attributed to the cell wall structure, in particular microfibril angle and cell wall thickness, both of which directly affect the key parameters in the formula. Fibre fractionation was found to be a very effective tool to consistently change all the fibre morphology factors for controlling dimensional stability of paper.

INTRODUCTION

Hygroexpansivity is one of the most basic paper properties determining performance of paper and board in the printing, converting and end-use processes. Impacts of fibre morphology, such as fibre length, coarseness, fibre width, curl, and S_2 angle, have been the subject of active discussions among papermakers who wish to optimize furnish compositions, in addition to traditional papermaking variables, such as refining and drying restraint, for improving dimensional stability.

Studying the effects of fibre morphology is, however, not straightforward, because many of the fibre parameters are not independent properties of the fibre, (for example, in natural fibres, fibre length and coarseness are closely interrelated), and the manifestation of the effects of fibre morphology always depends on the papermaking conditions used (pressing, drying restraint, additives). Therefore, we need to understand the fibre morphology effects within the context of the interactions with other morphological and papermaking variables.

In this study, we have used a micromechanics approach as a general guideline to interpret and predict various effects of fibre morphology, and interactions with other variables. The main morphological variables experimentally studied are fibre length, and microfibril angle of the cell wall. The objectives of this study are to evaluate, at least semi-quantitatively, the impacts of fibre morphology, and to find a possible fibre strategy to improve dimensional stability of paper.

MICROMECHANICS APPROACH

The main objective of micromechanics is to predict macroscopic mechanical and physical properties in terms of its constituent properties and the structure of the material. A first attempt was made by Salmén and coworkers (1) who modeled paper as a laminate structure of the cell wall layers, and the cell wall was modeled as a unidirectional fibre-reinforced composites consisting of cellulose microfibril and hemicellulose matrix. Later, the model was further refined in terms of calculation of hygroexpansion of the cell wall structure and incorporation of the void effect (2,3). Because of the laminate assumption, the effects of fibre morphology are not explicit except the effect of microfibril angle. Another approach is to model paper as a bonded fibre network where a single fibre or fibre segment is treated as a structural unit (4, 5, 6, 7). In an extreme case where the fibres are completely bonded without leaving any void space, Schulgasser (5) obtained an exact expression for hygroexpansion coefficient of paper.

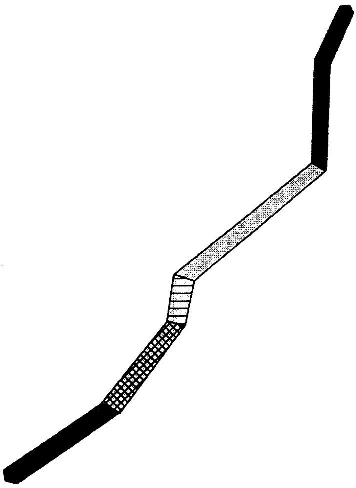

Fig. 1. A fibre consisting of many line segments.

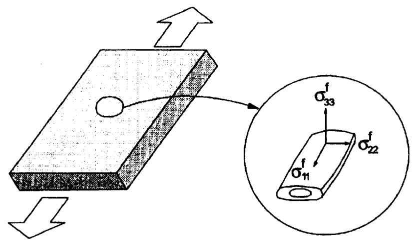

Fig. 2. Stress components of a fibre in the sheet subjected to a uniaxial tension.

A general formula relating hygroexpansivity of paper and hygroexpansivity of a single fibre was derived by one of the authors (7) based on the Dvorak-Benveniste equation (8). Paper is modeled as a bonded fibre network; each linear segment consisting a single fibre is considered as a distinct elastic phase with anisotropy (Fig.1). Therefore, three-dimensional fibre orientation and any micro-deviation of straightness of the fibre are taken into account. Although the original formula is expressed for a general, three-dimensional orthotropic case (7), we can here derive a simpler expression convenient for considering the fibre morphology effects. By assuming transverse isotropy of the fibre and the paper (handsheet), the formula can be expressed in the following form:

$$\beta^* = \beta_L^f + \gamma \cdot (\beta_T^f - \beta_L^f) \tag{1}$$

where β^* is the hygroexpansion coefficient of the paper, and β^f_L and β^f_T are the hygroexpansion coefficients of the single fibre in the longitudinal and the transverse directions, respectively. The parameter γ is called the stress transfer ratio, representing the relative efficiency of the stress transfer to the longitudinal direction and the transverse direction of the fibres in the sheets:

$$\gamma = \frac{<\sigma^{f}_{22}>_{v}}{<\sigma^{f}_{11}>_{v}} \tag{2}$$

That is, γ is the ratio of the average stress transmitted in the transverse direction of fibres in the sheet ($<\sigma_{22}{}^f>_V$), to the average stress transmitted in the fibre axis direction ($<\sigma_{11}{}^f>_V$), when the paper is subjected to a uniaxial stress without any environmental change (Fig.2). If the fibres are infinitely slender (infinitely small fibre width), highly anisotropic (high ratios of the longitudinal stiffness to the transverse stiffness), or the bonded areas are infinitely small (pin-pointed network), most of the stress transfer occurs in the longitudinal direction ($\gamma \approx 0$), and therefore,

$$\beta^* \approx \beta^{f}_{L} \tag{3}$$

The hygroexpansion of the paper in this case is nearly equal to the hygroexpansion of the fibre in the longitudinal direction, and this is a lower bound of the hygroexpansion of the bonded fibre network. An exact estimate of γ is generally difficult for a realistic sheet structure.

However, under certain assumptions, an approximate estimate is still possible. Assuming that the fibres have in-plane orientation, fibres in the bonded region undergo the same deformation both in the longitudinal and the transverse direction, such as like a laminate, and the free fibre segments don't carry the transverse stress ($\sigma_{22}{}^f$), we can estimate the stress transfer parameter γ as

$$\gamma = \mathrm{v}_{\mathrm{bond}} \frac{\alpha + \nu_{12}}{1 + \nu_{12}} \tag{4}$$

where v_{bond} is the fractional bonded length, α is the ratio of the elastic constant of the fibre in the transverse direction to that in the longitudinal direction, and ν_{12} is the Poisson's ratio measured from the longitudinal and transverse strains when the fibre is subjected to the transverse tension (7). Because of the laminate assumption for the strain transfer in the bonded area, the above estimate of γ is considered to be an upper bound when the fibres are oriented in the sheet plane direction. Again, as the fibre becomes more anisotropic, α and ν_{12} decrease ($\gamma \to 0$) and the hygroexpansivity of paper approaches to that in the longitudinal direction. Increased fibre-fibre bonding increases γ through the parameter v_{bond}, but the overall impact of bonding on the paper hygroexpansivity depends on the magnitude of γ and the fibre hygroexpansivity in the longitudinal and the transverse directions.

Estimates of γ for a model bond system based on an empirical shear-lag analysis (6) and a finite element analysis (7) showed that the parameter is very small, being of the order of 0.01-0.03 when the fibres are completely oriented in the in-plane direction. This implies that although γ is a function of the degree of fibre-fibre bonding, fibre length, fibre width, and other fibre geometry variables, the contribution of the second term in Eq.(1) to the paper hygroexpansion is expected to be small because of the small γ. The parametric studies of the effects of fibre dimensions also support these predictions: the paper hygroexpansivity increased with decreasing fibre length and with increasing fibre width and the degree of fibre bonding, but the effects were small. In this case, the paper hygroexpansivity is principally controlled by the hygroexpansivity of the single fibre in the longitudinal direction. Therefore, the most important fibre morphology factor is the cell wall structure affecting the hygroexpansivity of the single fibre in the longitudinal direction. This prediction corresponds to the case when *the fibres are oriented in the sheet plane direction.*

However, the parametric study also showed that once the fibres are allowed to deform in the out-of-plane direction (undulation) to form bonds, such as seen in Fig.3, the stress transfer ratio γ sharply increases (12), and thus the effects of these fibre geometry factors and the bonded area are amplified. Major conclusions from these micromechanics considerations are summarized as follows:

- The hygroexpansion of a single fibre in the *longitudinal direction* has a significant contribution to the hygroexpansion of paper. Therefore, the cell wall structure, in particular the microfibril angle is expected to be an important fibre morphology factor.
- The structure in the bonded area, i.e. in-plane vs. undulation structures as seen in Fig.3, determines another important parameter γ. Papermaking factors affecting this structure are drying restraint and the in-plane and out-of-plane fibre orientation, and

the corresponding fibre morphology factors are expected to be the cell wall thickness and fibre width.
Other morphological factors, such as fibre length, are expected to have smaller effects than the above factors.

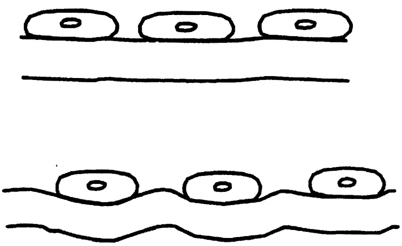

Fig. 3. The undulation structure in the bond area increases the stress transfer in the transverse direction.

EFFECTS OF FIBRE LENGTH

Although there have been numerous results for the effect of fibre length on mechanical properties of paper, there has been little data for the effect on hygroexpansivity (9,10). In Fig. 4, values of hygroexpansion coefficient and elastic modulus for an unbeaten, bleached softwood kraft pulp are plotted against fibre length (length-weighted average) and wet pressing pressure. Fibre length was varied by cutting the fibres of the original pulp. (Experimental details are given in the last section.) The hygroexpansivity showed only a modest increase with decreasing fibre length and with increasing wet pressing pressure. Considering the fact that the fibre length was drastically changed from 2.58 mm to 0.68 mm, the effect of fibre length was rather small.

The basic effect of fibre length is to alter the stress transfer efficiency in the longitudinal direction of fibres. As fully described in the finite fibre-length network models (4, 11), the efficiency of the force transmittance from the network to a typical fibre depends on fibre length and the degree of fibre bonding: the fibre carries more force in the longitudinal direction as the fibre length increases and the bonding increases. From the view of the result of elastic modulus shown in Fig. 4, this finite fibre length effect appears to take place only at the shortest fibre length, as the significant reduction in elastic modulus occurred only at the shortest fibre length. Therefore, the inherent effect of fibre length on hygroexpansivity for sheets dried under restraint is considered to be limited only in the range of shorter fibre length (e.g. less than 1 mm). Kijima and Yamakawa (9), however, reported a significant increase of hygroexpansivity with decreasing fibre length for *freely-dried sheets*. This result is expected from the previous micromechanics analysis that the out-of-plane fibre undulation in the bonded area, as seen in freely-dried sheets, amplifies the effects of fibre geometry and fibre bonding.

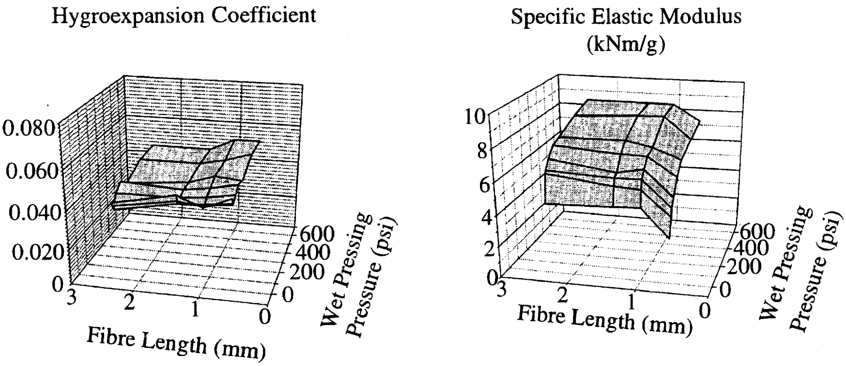

Fig.4. Hygroexpansion coefficient and specific elastic modulus as a function of wet pressing pressure and fibre length.

EFFECTS OF FRACTIONATION

In recent years, there is a growing interest among papermakers in using different fibre fractions to achieve optimum end-use performance of paper. Fines is probably the best-known fraction that affects mechanical, surface, and dimensional properties of paper. In this study, we have determined effects of fibre fractionation on hygroexpansivity to demonstrate the fibre morphology effects.

Figure 5 shows results of the hygroexpansivity of different Bauer-McNett fractions of an unbeaten, bleached softwood kraft pulp. The shorter fibre fractions show consistently higher hygroexpansion coefficient than the longer fibre fractions. For freely-dried sheets, the hygroexpansivity increased by 79%, and for restraint-dried sheets by 56%, when the fraction went from R28 to P100/R200. Table 1 shows the corresponding results of average fibre length, density and elastic modulus. As expected, fibre length decreased from 2.57 mm to 0.40 mm, and density slightly increased accordingly. However, elastic modulus significantly decreased as the fibre fraction became shorter.

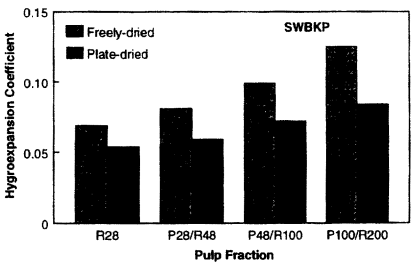

Fig. 5. Hygroexpansivity for different fibre fractions for an unbeaten, softwood bleached kraft pulp.

	R28	*P28/R48*	*P48/R100*	*P100/R200*
Fibre length*1, (mm)	2.57	1.37	0.81	0.40
Elastic modulus (kNm/g) FD*2	5.92	5.26	4.67	4.16
Elastic modulus (kNm/g) RD*2	7.02	6.28	5.95	5.72
Density (kg/m^3) FD*2	497	519	513	512
Density (kg/m^3) RD*2	497	506	522	525

*1: Length-weighted average
*2: FD (Freely-dried), RD (Restraint-dried)

Table 1: Density, elastic modulus, and fibre length of an unbeaten softwood BKP.

The higher hygroexpansivity of the shorter fibre fractions may be attributed to 1) decreased fibre length, 2) increased fibre bonding, 3) increased out-of-plane undulation in the bonded area, and 4) cell wall structure. As discussed in the previous section, the inherent fibre length effect on hygroexpansivity is small for restraint-dried sheets: only about 10-20% when fibre length was decreased by 73%. Therefore, it is not enough to quantitatively explain the variation of hygroexpansivity (Fig.5) in terms of the inherent fibre length effect. Fractionation is well-known to classify the fibres according to fibre length and wet fibre flexibility which is affected by coarseness. It may be speculated that the shorter fibre fractions have a higher degree of bonding, and produced higher hygroexpansivity. However, the systematic study of the effect of fibre bonding (12) predicts that the observed change in density in Table 1 is too small to cause any significant change in hygroexpansivity. However, the flexible nature of the shorter fibre fractions (thin cell wall) is very likely to create the undulation structure and to increase hygroexpansivity. Another possible factor is the cell wall structure, in particular the microfibril angle. This aspect will be considered in the next section.

Figure 6 shows results for restraint-dried handsheets made from a CTMP. A more exaggerated trend can be seen; the P100/R200 fraction showed about 145% higher hygroexpansivity than the R14 fraction. In this case, the increased fibre bonding (the second factor) and the undulation (the third factor) should have played a very significant role, as exemplified in the results of density and elastic modulus in Table 2: both density and elastic modulus increased greatly as the fraction became shorter.

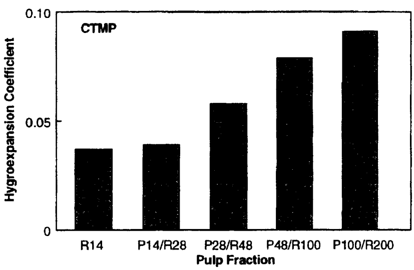

Fig. 6. Hygroexpansivity for different fibre fractions for CTMP.

	R14	*P14/R28*	*P28/R48*	*P48/R100*	*P100/R200*
Fibre length*1, (mm)	3.15	2.28	1.22	0.61	0.35
Elastic modulus (kNm/g)	2.99	2.60	2.93	4.35	6.42
Density (kg/m^3)	169	152	196	293	414

*1: Length-weighted average

Table 2: Density, elastic modulus, and fibre length of a CTMP.

Although it is not included in Figures 5 and 6, fines is known to increase hygroexpansivity (13). Figure 7 shows the effect of fines for low-yield sulphite (LYS) and groundwood (GWP) pulps when the fines are removed from the original pulps and re-added to them. The fines increases hygroexpansivity considerably; in particular the chemical pulp (LYS) fines gave a larger increase than the mechanical pulp (GWP) fines. Assuming a simple mixture rule for the hygroexpansion coefficient within the fines content range tested:

$$\beta^* = (1 - x) \cdot \beta_{\text{fines-free}} + x \cdot \beta_{\text{fines}} \tag{5}$$

where x is the fines content, we can estimate the hygroexpansivity of the fines fraction as 2.8 times higher than that of the fines-free fraction for the LYS, and 2.0 times for the GWP. These large values are understandable from the view of the micromechanics analysis that, because of the very low length-width ratio and the high bonding potential of the fines particles, the stress is transferred effectively in the direction perpendicular to the microfibril direction, increasing γ and thus the hygroexpansivity of the sheet.

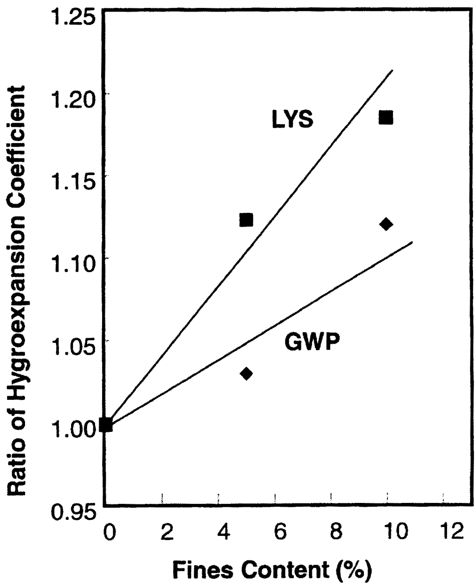

Fig. 7. Effects of fines on hygroexpansivity.

EFFECTS OF MICROFIBRIL ANGLE

The hygroexpansivity of paper is determined by three factors: the first two are related to the hygroexpansivity of a single fibre, and the third factor is the stress transfer ratio (γ) associated with the average efficiency of the stress transfer between the longitudinal and the transverse directions of the fibre. The previous discussions mainly concern the third factor which is a function of paper structure and fibre morphology. In this section, we consider the hygroexpansivity of a single fibre (or fibre segment) in terms of cell wall structure.

Although in the literature (14, 15) the microfibril angle has been well known to affect mechanical properties of wood pulp fibres, it is not known how the difference in the cell wall structure is translated in *paper* hygroexpansivity. Assuming an uncollapsed fibre consisting of a single cell wall layer (S_2 layer) with a microfibril angle θ (Fig. 8), we can express the hygroexpansion coefficients of the single fibre in the both directions in terms of the hygroexpansion coefficients of the microfibril in the fibril direction ($\beta_L{}^m$) and its transverse direction ($\beta_T{}^m$):

$$\begin{aligned} \beta_T^f &= \cos^2\theta \cdot \beta_T^m + \sin^2\theta \cdot \beta_L^m \\ \beta_L^f &= \sin^2\theta \cdot \beta_T^m + \cos^2\theta \cdot \beta_L^m \end{aligned} \tag{6}$$

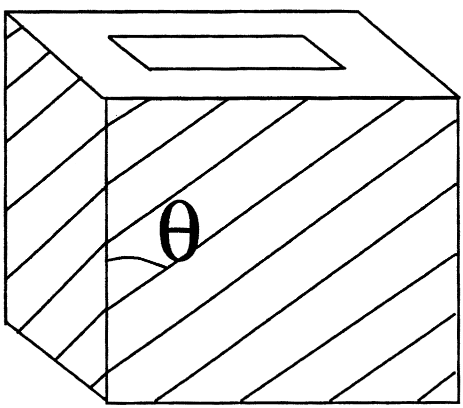

Fig. 8. A cell wall model.

The micro fibril angle can also affect the parameter γ through the elastic constants of the single fibre. The parametric study conducted in the previous report (12) showed that γ is relatively independent of the longitudinal-transverse anisotropy ratio of the single fibre. (This is because the interlayer shear modulus of the cell wall plays a major role in the stress transfer rather than the elastic moduli in the longitudinal and the transverse directions.) Assuming that γ is an independent variable of the microfibril angle, and substituting Eq.(6) to Eq.(1), we obtain the result in Fig. 9. In this example, the ratio $\beta_L{}^m/\beta_T{}^m$ was assumed to be 0, i.e. the microfibril doesn't expand or shrink in the longitudinal direction (1). Figure 9 shows that the paper hygroexpansivity increases with the micro fibril angle, but as the parameter γ increases (e.g. by increasing fibre bonding), the dependence on the fibril angle decreases. Since in this sample calculation, the contributions of the other layers (S_1 and S_3 layers) were ignored, the magnitude of the effect of the micro fibril angle shown in Fig. 9 may be considered to be overestimated.

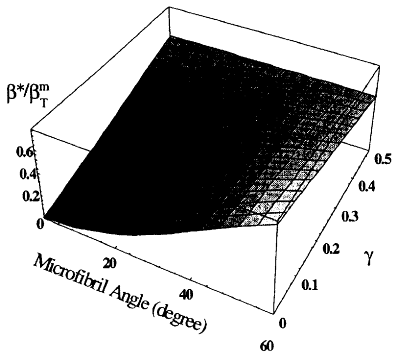

Fig. 9. Non-dimensional hygroexpansion coefficient of paper as a function of microfibril angle θ and the stress transfer ratio γ.

It has been shown in the literature (16, 17) that the microfibril angle in the S_2 layer of the cell wall is strongly correlated to fibre length. In addition, thin-walled springwood fibres tend to have higher fibril angle than coarse summerwood fibres (18). Since the Bauer-McNett classifier has a strong tendency of fractionating fibres according to both fibre length and coarseness (or wet fibre flexibility), it is suspected that the fibres from the different fractions have different fibril angles. Figure 10 shows the distribution of the extinction angle of the fibre cell wall, as a measure of the microfibril angle, from the different Bauer-McNett fractions of the softwood bleached kraft pulp used for the previous experiment. Table 3 is the corresponding result for the average extinction angle of the different fractions. As the fraction becomes shorter, the extinction angle distribution is clearly shifted toward a larger angle. This result suggests that the microfibril angle is another important factor contributing to the large variation in hygroexpansivity observed among different fibre fractions.

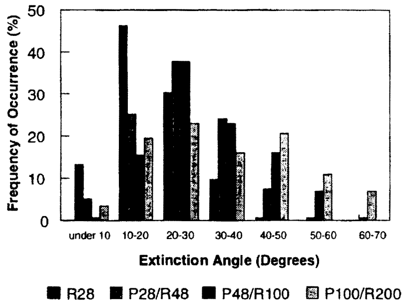

Fig. 10. Frequency distributions of extinction angles for different fibre fractions.

	R28 & P28/R28	*P28/R48*	*P48/R100*	*P100/R200*
Average (degree)	19	25	31	34
95% Confidence limit	±1	±1	±2	±2

Table 3. Extinction angle of different fibre fractions.

Table 4 shows comparisons of hygroexpansivity for mature, juvenile, and top wood fibres taken from two Douglas-fir trees. In both unbeaten and beaten cases, juvenile and top wood fibres, having higher fibril angles than the mature wood fibres, indeed showed higher hygroexpansivity.

Sample		*Extinction angle (degrees)*	*Hygroexpansion coefficient*	*Elastic modulus (kNm/g)*
DF1, unbeaten	Mature	16	0.035	5.54
	Top	22	0.044	7.24
DF2, beaten	Mature	14	0.044	12.59
	Juvenile	18	0.053	12.66
	Top	19	0.053	12.70

DF: Douglas-fir

Table 4. Comparison of mature, juvenile and top wood fibres.

CONCLUDING REMARKS

Hygroexpansivity of paper is affected by fibre morphology in a complex manner. The general micromechanics formula, in combination with some numerical calculation, can predict various effects of fibre morphology systematically. It is predicted that increasing fibre length and decreasing fibre width have positive effects on dimensional stability, especially for sheets dried under less restraint. In addition, high cell wall thickness (relative to fibre width) and smaller microfibril angle are also expected to improve dimensional stability.

From the view of controlling all important fibre morphology parameters determining hygroexpansivity, such as fibre length, microfibril angle, and cell wall thickness/coarseness, fibre fractionation is a very effective way to consistently vary all these parameters.

EXPERIMENTAL DETAILS

For the study of the effect of fibre length, a long fibre fraction of a bleached kraft pulp was made into a highly oriented sheet using a dynamic sheet former, cut in different lengths, and then made into standard handsheets with different densities. In addition, two unbleached kraft pulps made from two different trees of Douglas-fir were used. These pulps were originally made for studying papermaking potential of second-growth tree fibres containing mature, juvenile, and top wood (19). Handsheets were made from these pulps, one of which was beaten at 300 rev. by a PFI mill.

The hygroexpansivity of different Bauer-McNett fractions was determined for two bleached kraft pulps and a CTMP. Fines, defined as P200, was removed. To obtain information on the fibril angle in the S_2 layer of the fibre cell wall, an extinction angle was determined for each fraction of the bleached kraft pulp under the incident-illumination condition with crossed polars using Page's method (20).

Hygroexpansivity, expressed as hygroexpansion coefficient (% strain/% moisture content change), was determined using the procedure previously developed (21). Elastic modulus was determined using an in-plane ultra-sonic tester. Elastic modulus is expressed as the specific elastic modulus unit (kNm/g). All tests were conducted under the standard constant humidity and temperature condition (50% RH, and 23°C).

REFERENCES

1. Salmén, L., Carlsson, L., de Ruvo, A., Fellers, C., and Htun, M., *"A treatise on the elastic and hygroexpansional properties of paper by a composite laminate approach"*, Fibre Sci. Tech., 20: 283-296 (1984).

2. Åsa Laureil Lyne, *"Hygroexpansivity of unfilled and filled laboratory-made fine papers"*, MS thesis, Royal Institute of Technology, Stockholm, Sweden (1994).

3. Lu, W., Carlsson, L.A., and Anderson, Y., *"Micro-model of paper Part 1: Bounds on elastic properties"*, Tappi 78(12):155-164 (1995).

4. Perkins, R.W., Sinha, S., and Mark, R.E., *"Micromechanics and continuum models for paper materials of medium and high density"*, Proc. 1991 Int. Paper Physics Conf., Kona, Hawaii, pp. 413-435.

5. Schulgasser, K., *"Moisture and thermal expansion of wood, particle board and paper"*, Proc. 1987 Int. Paper Physics Conf., Mont Gabriel, Quebec, Canada, pp.53-63.

6. Uesaka, T., *"Hygroexpansion coefficient of paper" in "Mechanics of Wood and Paper Materials"*, AMD-Vol. 112, The American Society of Mechanical Engineers (1990).

7. Uesaka, T., *"General formula of hygroexpansivity of paper"*, J. Mats. Sci. 29: 2373-2377 (1994).

8. Dvorak, G.J., and Benveniste, Y., Proc. Royal Soc. London A 437:291 (1992).

9. Kijima, T., and Yamakawa, I., J. Japan Tappi 32(12): 722-728 (1978).

10. Kijima, T., and Yamakawa, I., J. Japan Tappi 33(7): 483-490 (1978).

11. Seth, R.S., and Page, D.H., *"The stress-strain curve of paper"*, in "The Role of Fundamental Research in Papermaking", Mech. Eng. Pub., Bury St. Edmunds, UK. (1981).

12. Uesaka, T., and Qi, D., *"Hygroexpansivity of paper - Effects of fibre-to-fibre bonding"*, J. Pulp & Paper Sci. 20(6): J175-J179 (1994).

13. Salmén, L., Boman, R., Fellers, C., and Htun, M., Nordic Pulp and Paper Res. J. 4:127-131 (1987).

14. Page, D.H., El-Hosseiny, F., Winkler, K., and Lancaster, A.P.S., *"Elastic modulus of single wood pulp fibres"*, Tappi 60(4):114-117 (1977).

15. Mark, R.E., *"Filament winding angles"* in "Cell Wall Mechanics of Tracheids", ed. by R.E. Mark, Chap. 7, Yale Univ. Press, New Haven, pp. 162-186 (1967).

16. Preston, R.D., *"The organization of cell wall of the conifer tracheid"*, Phil. Trans. Royal Soc. London B 224:131-173 (1934).

17. Dadswell, H.E., J. Inst. Wood Sci. 1(1):1-32 (1958).

18. Wellwood, R.W., Ifju, G., and Wilson, J.W., *"Intra-incremental chemical properties of certain western Canadian coniferous species"*, in "Cellular Ultrastructure of Wood Plants", ed. by W.A. Côte, Jr., pp. 539-550 (1965).

19. Hatton, J.V., and Hunt, K., *"Kraft pulping of second-growth Douglas-fir", Proc. 1989 Tappi Pulping Conference, Seattle, WA, pp. 424 (1989).*

20. Page, D.H., *"A method for determining the fibrillar angle in wood tracheids",* J. Microscopy 90(2): 137-143 (1969).

21. Uesaka, T., Moss, C., and Nanri, Y., *"The characterization of hygroexpansivity of paper",* J. Pulp & Paper Sci. 18(1): J11-J16 (1992).

Transcription of Discussion

Effects of Fibre Morphology on Hygroexpansivity of Paper: a Micromechanics Approach

Tetsu Uesaka, Director, Paprican, Canada

Bruce Lyne, Senior Manager, International Paper, USA

In the text you mentioned that you thought the hygroexpansivity of the fibre in the longitudinal direction was more important than in the transverse direction in determining the overall hygroexpansion of the sheet. This is a radical view. The transverse hygroexpansion in fibres is much larger than the longitudinal. Since roughly 50% of the surface area of the fibre in printing papers is tied up in bonding to other fibres the transfer function gamma should be very high. Thus the basic micro mechanical phenomenon during free shrinkage of paper is one of bond site corrugating via the transfer of transverse fibre shrinkage forces. These corrugated regions then expand and contract very easily with the changes in the relative humidity. Can you offer direct evidence showing the importance of macro segments or that the corrugated bond site model and high transfer function approach in the literature is wrong.

Tetsu Uesaka

I think it is a key point of this formulation. I had the exact same idea when we started this study since the transverse expansion of the fibres is far far larger than the longitudinal. We thought the transverse properties dominate the paper properties. However when looking at the results of the shrinkage of the paper during drying process, you can easily see that the overall drying shrinkage is about 3-5%, unless you destroy the whole pulp fibre. This is the order of the shrinkage of the single fibre in the longitudinal direction. It is not much larger then the longitudinal shrinkage of a paper may be twice or three times at most, I would say, as compared with the transverse shrinkage, which is 20% or 30%. That was when I started wondering whether the transverse properties do dominate the paper hygroexpansivity. Based on this question, I started looking at the effect density of bonding by putting in some bonding or debonding agent. If the transverse property dominates and controls the hygroexpansivity of paper, there must surely be a huge effect of relative bonded area and bonding itself. The result is that there is very little effect of bonding, and the gamma value is very small . The reason behind this is, if fibres are bonded in this way, then there is some transverse shrinkage . This transverse shrinkage or expansion cannot be effectively transmitted to the other fibre because of the low interlayer shear modulus. So that is one of the reasons why the gamma is very small. Talking about the corrugated structure, I have seen many microscopy pictures from all over the world, but I have not seen any evidence of this corrugated structure although I am not sure at this point.

Bruce Lyne, Senior Manager, International Paper, USA

If you increase the amount of fines you increase the bonding between the fibres effectively and that must increase gamma .

Tetsu Uesaka

Yes. However the fines have a different effect. You must have seen some paper structures which have a wrap-around structure of fibres and fines . This very much changes the bond structure rather than the bonding itself.

Bruce Lyne, Senior Manager, International Paper, USA

Lastly, if you have a high fibrilar angle you expect a higher transverse hygroexpansion ?

Tetsu Uesaka

Yes, but that is when the bonding is very poor. If you have a well bonded sheet you will not see a big effect of fibril angle.

Professor Jacques Silvy, Universidade da Beira Interior, Portugal

You focus your analysis on fibre properties but we look at the phenomena in terms of sheet deformations. You have variation in the density of the sheet this is very clear. Therefore it means that the number of cut fibres for a line drawn in the plane of the sheet must follow with the variation of density. It means that the more small fibres have a coarseness which is lesser giving a greater number of cuts, therefore the expansivity of the sheet is higher .

Tetsu Uesaka

I think this is a secondary effect of the fibre fractionation on hygroexpansivity. The shorter fibre fraction has a more flexible thinner wall so that you have the different bonding structure, the wrap-around bonding . Bonding itself does not have much effect, as I mentioned before.

Jacques Silvy

This is simply an effect of the coarseness and it is a geometric effect only. We could talk about flexibility but on a mathematical point of view we increase the number of links in the sheet independently of the nature of the links.

Tetsu Uesaka

Suppose we decrease coarseness while maintaining fibre width we are talking about a much thinner wall, then you have less dimensional stability with increased hygroexpansivity. On the other hand if you decrease coarseness and decrease fibre width while maintaining a fibre cross sectional area then you can actually decrease hygroexpansivity. it is very difficult to conclude on this matter because it is not only the coarseness which has an effect.

Dr Derek Page, IPST, USA

I can understand Bruce Lyne's point of view. What Tetsu said is totally heretical and is apparently against all the teaching that Bruce has had from me over many many years. What I said back in 1951 was that as the fibres shrink transversely they cause microcompressions in the crossing fibres. When you wet this structure the microcompressions expand and that is the driving force for dimensional instability. Tetsu is right and I am still right. Tetsu is absolutely correct when it come to plate dried sheets. Here we have few microcompressions and the dimensional stability comes from the axial fibre direction. Considering freely dried sheets the situation is as follows; the microcompressions are formed down the fibre axis and these are effectively changing fibril angle. The local angle of the fibrils can change from zero degrees to 30 degrees. This is a very dimensionally unstable fibre down the length of the fibre axis. So I am disappointed that Tetsu did not mention microcompressions because they are an important structural feature. But I think he included it in fibril angle. What he says is if the fibril angle is high then the dimensional stability is poor. That is the same as saying if you have microcompressions caused by free shrinkage then the dimensional stability is also poor. I would prefer however to consider microcompressions (which are induced) and fibril angle (which is a natural feature of the original wood) as separate structural features.

Professor Heinrich Baumgarten, Dresden University of Technology, Germany

Did you take a count of the relative big shrinkage in the thickness direction of the paper web when you tried to calculate the effect of the relative small in plane transverse shrinkage and axial compression of fibre on the MD and CD paper dimension?

Tetsu Uesaka

I think this is a very good point. I should have mentioned that this formulation is not built in two dimensions and in my previous paper we analysed the hygroexpansion coefficient in the thickness direction. At this moment although our knowledge is still limited we can say that fibre micro orientation and Z deviation has a huge effect on hygroexpansivity depending on drying restraints etc. The effect of drying restraint can be easily predicted by the model.