The behavior of fibers in wet pressing

JIHONG HE, WARREN J. BATCHELOR, AND ROBERT E. JOHNSTON

ABSTRACT: A fiber shape factor and a twist angle of fiber cross section in paper were measured directly in the cross sections of handsheets with a technique involving resin embedding and confocal laser scanning microscopy. Wet pressing twists and collapses individual fibers as it brings fibers closer together. The degree of fiber collapse in the lightly pressed handsheets had an almost symmetrical distribution, but the distribution was narrowed and skewed to high values when the handsheets were pressed at the high pressures of 500 kPa and 4000 kPa. Measured out-of-plane deflections of the fibers showed no correlation between deflection and pressing pressure. The findings indicate that fiber twist, fiber collapse, and gap closure are the major mechanisms in paper structure densification. At low pressures, all three mechanisms act, but the gap closure is predominant. Increasing pressing pressure only increases the apparent density slightly, and the density increase is mainly contributed by the additional twist and collapse of the fibers at high pressing pressures.

Application: Research offers a better understanding of the mechanisms of densification in wet pressing by quantifying the way individual fibers change in a sheet.

A better understanding of the mechanisms of the changes of paper structure in wet pressing is important for improving paper quality. Paulapuro recently established that the effects of wet pressing on paper properties are related to changes in sheet density, or the *z*-direction density distribution created by pressing and by surface evenness (topography) [1]. Szikla and Paulapuro found that increasing fiber bonding is the dominant mechanism in the densifying effect of wet pressing [2, 3]. According to Gorres *et al.* [4], fiber collapse and the deflection of free fiber segments are the predominant mechanisms at low pressing pressure, whereas the completion of fiber collapse and perhaps other effects predominate at high pressure because all spaces in the sheet that can be filled by deflections have been filled [4]. From these studies, it appears that the mechanisms in the densification effect of wet pressing on paper structure are still incompletely understood.

In previous studies of fiber cross sections, researchers have measured the transverse dimensions of individual pulp fibers deposited on glass slides or embedded in resin [4–6]. Gorres *et al.* pressed very thin fiber networks (< 0.1 g/m²) on glass slides and used a stylus profilometer to evaluate the transverse dimensions of fibers in the networks [4]. However, no quantitative studies have been reported on the behavior of fiber cross sections in "true" paper in wet pressing, primarily because there has been no technique to measure fiber cross-sectional dimensions directly in a sheet. In a recent study, we developed a new technique to measure fiber transverse dimensions directly in the paper cross section [7]. This technique enables us to quantify the change of fiber cross sections in wet pressing and to investigate how fiber shape affects paper structure and paper physical properties.

The degree of collapse of fibers has been characterized in different ways, such as by the fiber aspect ratio [5] and the fiber collapse index, which is defined either as the reduction of fiber thickness [4] or the reduction of fiber lumen area [8]. For calculating the fiber collapse index, the original fiber shape must be assumed to be either circular or rectangular [4, 8]. The collapse index cannot be measured directly, and it describes only the shape of the fiber lumen area, while completely neglecting the shape of the fiber wall area.

One factor that has not been considered in studies of pressing is the twisting of the fibers so that their cross-sectional major axis rotates to be closer to parallel to the paper plane. The orientation of the fiber with respect to the paper plane could strongly affect the structure of the paper. Decreasing the number of twists in fibers will increase sheet strength [9].

In this paper, we define a fiber shape factor and a twist angle of the fiber cross section. We measured these parameters directly in handsheets to quantify the changes of fibers in the handsheets in wet pressing. We also studied the mechanisms by which wet pressing affects the densification of the paper structure.

THEORY

Definition of fiber shape factor and fiber twist angle

As shown in **Fig. 1**, the shape factor, f_m, is defined as the ratio of the fiber wall area, A_f, to the area of the smallest rectangular bounding box, A_s, that can completely enclose the irregular shape of the fiber. The two axes of the rectangular box are defined as the major and minor axes of the fiber cross section. When the fiber is in a cross section of paper, the angle between the major axis of the fiber and the paper plane is defined as the twist angle of the fiber cross section.

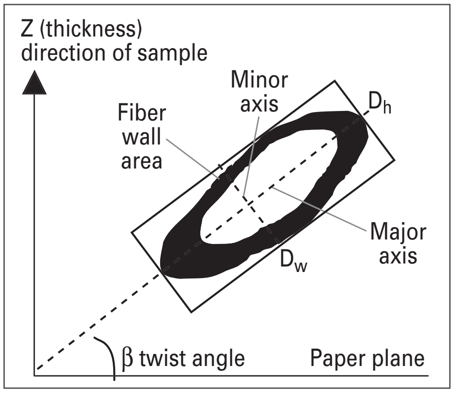
To examine the relationship between the shape factor and the degree of collapse of the fiber, we begin by assuming that the fiber cross section before wet pressing is circular with diameter, D, and wall thickness, t, and that the fiber wall area, A_f, is constant with wet pressing. We assume that if the thickness decreases by a distance δ_D, then the width will increase by the same amount (**Fig. 2**). Accordingly, f_m is:

$$f_m = \frac{A_f}{A_s} = \frac{A_f}{(D-2\delta_D)(D+2\delta_D)} = \frac{\pi t(D-t)}{D^2-4\delta_D^2} \qquad (1)$$

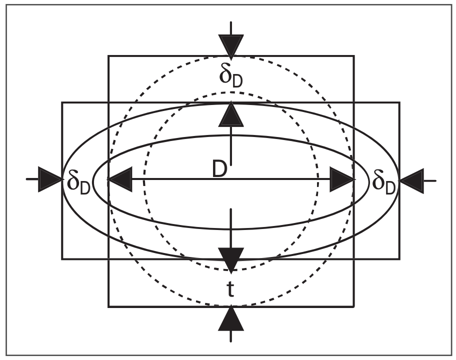
Equation 1 can also be written as:

$$f_m = \frac{\pi^2 (t/P)(1-t/P)}{1-(\delta_D/r)^2} \qquad (2)$$

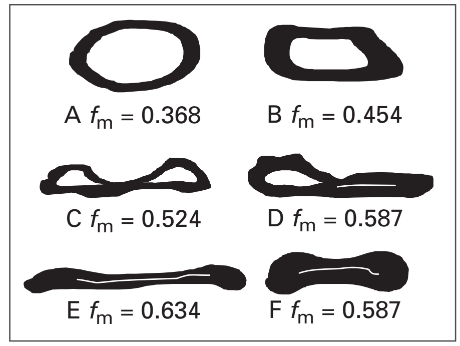
where P is the fiber perimeter and r is the fiber radius.



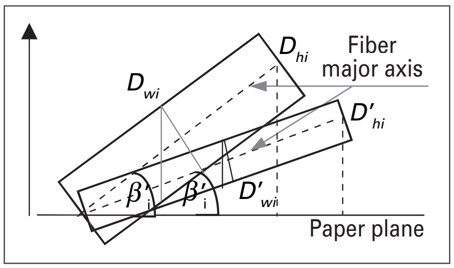
1. Definition of the fiber shape factor and twist angle.



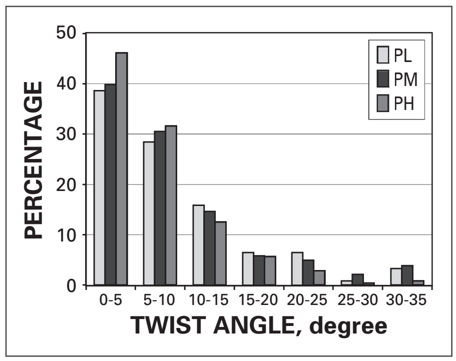
2. Model fiber.



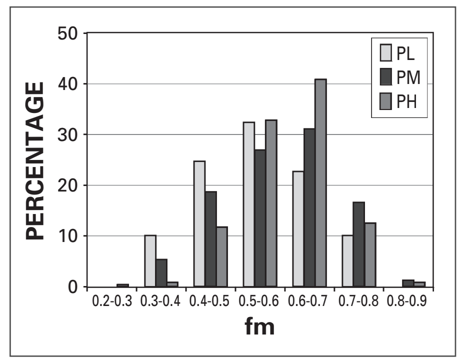
3. Different collapse states of fiber: uncollapsed fibers (A, B), partially collapsed fibers (C, D), and fully collapsed fibers (E, F).



4. In any layer of a sheet, fiber twist and fiber collapse contribute to the reduction in paper thickness.



5. Frequency distribution of twist angle of fiber cross section.



6. Frequency distribution of the fiber shape factor.

The collapse index, *CI*, is defined as $CI = (\delta_D/r)^2$ [10]. For a thin-walled fiber, $t << P$, and $(1 - t/P) \approx 1$, and Eq. 2 becomes:

$$f_m = \frac{\pi^2 (t/P)}{1 - CI} \tag{3}$$

Obviously, uncollapsed fibers and fully collapsed fibers will have the minimum and the maximum values of f_m, respectively. These maximum and minimum values can be used to create an approximate scale to separate fibers in a sheet into three collapse states—collapsed fibers, partially collapsed fibers, and fully collapsed fibers (**Fig. 3**). The validity of using the boundary values of f_m in describing the collapse state of a fiber will be verified here.

Reduction in paper thickness by fiber twist and fiber collapse

Assuming the paper has a layered structure, fibers in each layer are twisted and collapsed in wet pressing, which reduces the thickness of each layer. The total reduction in the paper thickness is the sum of the thickness reduction of each layer.

Figure 4 shows the i^{th} fiber in a layer of a sheet before and after it is pressed. Before the fiber is pressed, the fiber has width, D_{wi}, thickness, D_{hi}, and twist angle, β_i. After it is pressed, the width, thickness, and twist angle are D'_{wi}, D'_{hi}, and β_i', respectively. If the paper has *m* independent layers and each layer has *n* fibers, the total reductions in paper thickness from the fiber twist and from fiber collapse are given by Eqs. 4 and 5, respectively:

$$\overline{\Delta T}_{twist} = \frac{m}{n}\sum_{i=1}^{n}\left[D_{wi}\sin\beta_i - D'_{wi}\sin\beta'_i\right] \tag{4}$$

$$\overline{\Delta T}_{collapse} = \frac{m}{n}\sum_{i=1}^{n}\left[\frac{D_{hi}}{\cos\beta_i} - \frac{D'_{hi}}{\cos\beta'_i}\right] \tag{5}$$

MATERIALS AND METHODS

Sample preparation

Laboratory-made, never-dried, radiata pine kraft pulp, cooked to 45.6% yield with kappa no. 30, was used. Five sets of 60 g/m² square handsheets were made on a Moving Belt Sheet Former. Each set of handsheets was pressed at 100 kPa, 200 kPa, 500 kPa, 2000 kPa, or 4000 kPa. Each handsheet, sandwiched between blotters and an iron plate, was pressed for 2 min, so the handsheet would be transferred to the iron plate. The handsheets were dried under restraint at 23°C and 50% RH.

Cross sections of handsheets pressed at 100 kPa, 500 kPa, and 4000 kPa, which are denoted as P_L, P_M, and P_H, for low, medium, and high pressure, were examined in a confocal microscope. The method for sample preparation for the confocal microscope is based on the technique developed by Williams [11] and by Dickson [12]. The method involves embedding precut samples in an epoxy resin and grinding the resin block to expose the cross sections of the samples with progressively finer abrasive paper [7].

Measurement of fiber shape factor and twist angle

Fiber wall areas were measured in images that were acquired several microns beneath the surface of the sample cross section so as to remove artifacts left from sample preparation [7]. Fiber orientations in the cross section were measured by following the positions of individual fibers in successive sheet cross sections scanned at different

SAMPLE	WET PRESS PRESSURE, kPa	SHAPE FACTOR, f_m, %	FIBER WALL AREA mm²,	OUT-OF-PLANE ANGLE, °	NUMBER OF FIBERS MEASURED	PAPER APPARENT DENSITY, kg/m³	PAPER THICK-NESS, µm	TENSILE INDEX, kNm/kg
P_L	100	0.548±0.014	206±9	5.13±0.61	247	286	239	34.45
—	200	—	—	—	—	375	172	36.98
P_M	500	0.589±0.013	198±9	4.49±0.48	241	522	125	45.98
—	2000	—	—	—	—	590	109	48.04
P_H	4000	0.603±0.011	205±9	4.64±0.52	247	596	107	49.95

± is 95% confidence interval.
The fiber wall area and fiber axes have been corrected by the fiber's angle to the surface of the paper cross section.

I. Handsheet properties and mean fiber transverse dimensions.

depths from the sample surface.

To measure f_m and the twist angle β, we need first to create the smallest rectangle which encloses the irregular shape of the fiber. In practice, it is difficult to calculate this smallest rectangle. The bounding box we used in this study was a rectangle with its major axis parallel and equal in length to the longest dimension of the fiber cross section. For most types of fiber shape, this bounding box is similar to the smallest rectangle in the definition of f_m. The measurement error is significant only for square-shaped fibers. However, square fibers were rare in the pulp we used and were discarded during measurement. About 5% of the measured fibers were discarded in Sample P_L, about 1% of the fibers were discarded in Sample P_M, and no fibers were discarded in Sample P_H.

To measure fiber dimensions automatically, we wrote a macro in the software we used. For each sample, 60 frames of consecutive images of the paper cross section were acquired and processed. In each group, images were scanned at different depths to measure the fiber orientation. The frame size was 100 × 100 µm with a resolution of 512 × 512 pixels; therefore, the inspected cross section of each sample was 6 mm wide.

The twist angle was the angle measured between the longest dimension of the fiber cross section and the horizontal frame of the image. This reference direction has to be used because the position of the paper plane is unknown during the measurement. However, if the horizontal frame of the image is at an angle of $-\alpha$ to the paper plane, then for a randomly oriented handsheet, $\bar{\beta} = \alpha$.

We estimated the angle by averaging the measured twist angles. The twist angle was also corrected by the angle, θ, of the fiber to the surface of the paper cross section. If the fiber length axis is not perpendicular to the paper cross section, then one axis of the fiber image will be lengthened by a factor of cos θ. Thus, unless $\beta = 0$, this distortion of one axis will cause an error in the measured value of β. It can be shown from geometry that the true angle β is given by the formula $\beta = \arcsin(\sin \beta_m / \cos \theta)$, where β_m is the measured twist angle. All measured twist angles were first corrected by the angle α and then by the angle θ using this arcsin formula.

RESULTS AND DISCUSSION

Figure 5 shows the twist angle distribution of fibers in the three samples P_L, P_M, and P_H. As the pressing pressure is increased, the number of fibers with twist angles less than 10° increases, while the number of fibers with twist angles more than 10° decreases. As the figure shows, 67% of the fibers in Sample P_L have a twist angle less than 10°, and this percentage is increased by wet pressing to 71% for Sample P_M and to 78% for Sample P_H. This reduction in fiber twist will reduce the amount of space taken by the fiber in the paper structure, thereby reducing the void space and increasing the density of the paper. The reduction in fiber twist could also increase the potential bonding surface area of the fibers, especially for collapsed fibers.

Table I summarizes the fiber dimensions and the sheet properties measured. As the table shows, the fiber wall area was not changed by wet pressing, and the mean value of f_m increases with increasing wet pressing pressure. The frequency distributions of f_m for the fibers in the three samples P_L, P_M, and P_H are shown in **Fig. 6**. For Sample P_L, f_m has an almost symmetrical distribution. When the pressing pressure is increased, the distribution of f_m skews to a higher f_m range and becomes narrower.

Since the three samples were made from the same pulp, fibers in the three samples should have the same wall thickness and perimeter. In that case, according to Eq. 3, the value of f_m should be mainly affected by the degree of collapse of the fibers. The trends in f_m are therefore most likely indicative of fiber collapse.

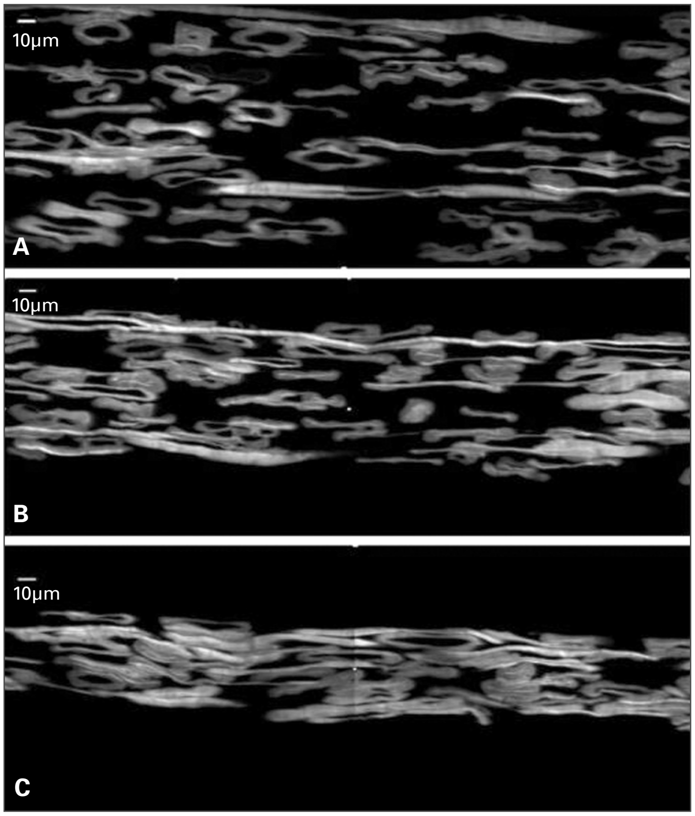
Fiber collapse

As mentioned, the maximum and the minimum values of f_m can be used to assign the fibers as collapsed, partially collapsed, or uncollapsed. The boundary values of f_m used to do this were set somewhat arbitrarily. Fibers with f_m less than 0.50 were treated as uncollapsed fibers, fibers with f_m greater than 0.60 were treated as fully collapsed fibers, and fibers with f_m in between 0.50 and 0.60 were treated as partially collapsed fibers. Using this classification, 35% of fibers in the slightly pressed Sample P_L were uncollapsed, and 33% were fully collapsed (Fig. 6).

After the sample was pressed at 500 kPa, the percentage of uncollapsed fibers dropped to 24%, and the percentage of fully collapsed fibers rose to 49%. After the sample was heavily pressed, the percentage of fully collapsed fibers increased to 54%, and the percentage of uncollapsed fibers fell to 13%. The percentage of partially collapsed fibers stayed relatively stable at around 30% in all three samples.

These results are quite different from those reported by Gorres and his coworkers, who found that fibers of a softwood kraft pulp can be totally collapsed at a pressing pressure of 2240 kPa [4]. This result indicates that the collapse behavior of fibers on glass slides is different from the behavior of fibers in paper.

There are two major factors that may cause the observed nonuniform collapse of fiber. First, fibers collapsibility will vary between fibers and at different points along fibers. Second and perhaps more importantly, the nonuniform structure of paper causes an uneven pressure transfer in the network, which results in the nonuniform collapse of fiber.



7. Images of cross sections of Samples P_L (A), P_M (B), and P_H (C).

Figure 7 shows typical cross-sectional images of the three samples P_L, P_M, and P_H. The sample thickness and the void space are reduced with increasing pressing pressure. In sample P_L, it can be seen that most fibers are uncollapsed and partially collapsed, but there are also some fully collapsed fibers. In Sample P_M, the number of uncollapsed fibers is dramatically reduced, and most fibers are partially or fully collapsed. In Sample P_H, there are still a few uncollapsed fibers. These observations are consistent with the quantitative analysis already discussed.

Sheet density

The apparent density of the handsheets increased from 286 kg/m³ to 522 kg/m³ as the pressure increased from 100 kPa to 500 kPa. However, pressing at 4000 kPa increased the sheet density only slightly, to 596 kg/m³, compared to pressing at 500 kPa (Table I). Gorres *et al.* found a similar relationship between the density of paper and the wet pressing pressure [4]. They failed to explain the continuing increase in density at high pressure, where they believed that fibers are totally collapsed. One reason for this belief is that they used the measured degree of the collapse of fibers pressed on glass slides to represent the degree of collapse of fibers in paper, which is a different situation as we have discussed. Another reason is that they did not take into account the contribution of fiber twist to the density of paper.

Gorres and Luner developed a model for the apparent density of paper [13]. For their model, they assumed that increasing fiber deflection with increasing wet-pressing pressure is a major mechanism in the densification of paper. However, no evidence was offered to support this relationship. In our study, the out-of-plane deflection angles of fiber segments in Samples P_L, P_M, and P_H were measured. We found that if the sample is not arranged exactly vertically, an error will arise for the measured value of the out-of-plane deflection angle. To avoid this error, we carried out a correction for each individual fiber, similar to the correction for the twist angle measurements.

As the results (Table I) show, the average out-of-plane deflection angle of fiber segments in the three samples ranges from 4.49° to 5.13°. No regular increase with wet pressing pressure can be observed. The distribution of out-of-plane deflection angles, presented in **Fig. 8**, also shows no regular trends with pressing level. If the out-of-plane angle of the fiber segment stays constant, the deflected distance of the fiber segment will be reduced as the pressing pressure is increased, because wet pressing reduces the distance between fiber–fiber contacts. This movement will close the gaps between layers, which is what we refer to as "gap closure."

To quantify the contributions that fiber twist, fiber collapse, and gap closure make to the measured reduction in paper thickness, we use Eqs. 4 and 5 and assume that the samples have 10 layers and that the number of layers stays constant as the pressing pressure is changed. These data were used to calculate the $\Delta \bar{T}_{twist}$ and $\Delta \bar{T}_{collapse}$ between Samples P_M and P_L and between Samples P_H and P_M. The results are given in **Table II**.

The measured total thickness reduction between Samples P_M and P_L is 114 µm, of which the contributions from the fiber twist and fiber collapse account for only 16%. We believe that the rest of the thickness reduction is caused by closing the gap between the layers. The total reduction in paper thickness between Samples P_H and P_M is 18 µm, which is mostly contributed by fiber twist and fiber collapse.

As these findings show, fiber twist, fiber collapse, and gap closure occur simultaneously at low pressing pressures, and the gap closure is the predominant mechanism in paper structure densification at low pressures. When the pressing pressure was increased from 500 kPa to 4000 kPa, the density increased only slightly. This density increase is caused mainly by the additional twist and collapse of the fibers at the high pressure.

CONCLUSIONS

A fiber shape factor and twist angle of fiber cross section in paper have been defined for the purpose of quantifying the changes in the transverse dimensions of fibers in paper in wet pressing. Fiber twist, fiber collapse, and gap closure were found to be the major types of movement of fibers in paper in wet pressing. In particular, fiber twist has been found and quantified for the first time.

The results show that wet pressing reduces the number of fibers with twist angles greater than 10°. The shape factor of fibers in the lightly pressed handsheets showed an almost symmetrical distribution, which indicates that the degree of fiber collapse is symmetrically distributed. The distribution was narrowed and skewed to the high value range when the handsheets were pressed at 500 kPa or at 4000 kPa. These results show that fibers in the handsheets cannot be totally collapsed by wet pressing even when pressed at the very high pressure (4000 kPa). The experimental data also suggest that the out-of-plane fiber deflection angle is independent of wet-pressing pressure.

Fiber twist, fiber collapse, and gap closure occur simultaneously at low pressing pressures, and the gap closure is the predominant mechanism in paper structure densification at low pressures (less than 500 kPa). Increasing pressure only increases the apparent density slightly, and the density increase is mainly contributed by the additional twist and collapse of the fibers at the high pressing pressure (greater than 500 kPa). **TJ**

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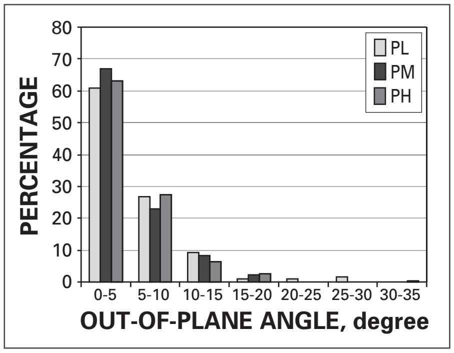

8. The frequency distribution of out-of-plane angle of Samples P_L, P_M, and P_H.

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	P_M-P_L	P_H-P_M
Fiber twist	7	3
Collapse	11	10
Gap closure	96	5
Measured,[a]	114	18

[a]Measured total reduction in thickness.
Samples pressed at low (P_L), medium (P_M), and high pressure (P_H).

II. Reduction in paper thickness, μm.

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INSIGHTS FROM THE AUTHORS

Wet pressing is one of the main operational units in the papermaking process. It can significantly affect the microscopic structure of paper. Previously we developed a new technique that enables us to quantify fiber shape and orientation within the sheet. In this study, we used the technique to examine changes introduced by wet pressing.

We found that fiber twist, fiber collapse, and gap closure are the major mechanisms in paper structure densification. These mechanism are different from the fiber deflection mechanism that has been reported previously. In fact, we found no correlation between fiber deflection and wet pressing pressure.

We also found that fiber in handsheets cannot be totally collapsed by wet pressing even when a very high pressing pressure of 4000 kPa is used. This phenomenon explains why the apparent density of paper continuously increases when it is pressed at increasingly high pressures.

The most difficult part of this research was the problem of generating the smallest rectangular bounding box that can completely enclose the irregular shape of the fiber. We actually failed to generate such a bounding box in this study. Instead, we used a close approximation to this bounding box. This aspect of the study is one that needs to be refined in the future.

In our work, we discovered that fiber twist is an important kind of fiber movement in wet pressing. We also quantified, for the first time, the behaviors of individual fibers in handsheets. A new parameter defined in this study, the fiber shape factor, has been successfully used for describing the collapse behavior of fibers in sheets. On the whole, the new ideas for the mechanisms by which the paper structure becomes more dense were the most important results of this study.

Using the technique reported here, we intend to further analyze how fibers with different dimensions behave. The results of the next study will provide useful information for mill personnel when they want to choose from different fiber materials for their particular purposes.

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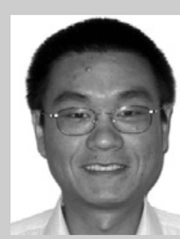

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