Influence of the "Giertz effect" on development of short-span compression strength

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ABSTRACT

The "Giertz effect" explains how fiber shrinkage during drying can influence sheet mechanical properties. This paper discusses the Giertz effect and demonstrates its influence on the development of short-span compression strength for linerboard-type furnishes. The results show that the z-direction shrinkage of wet sheets during drying is related to the degree of cell-wall swelling. Moreover, wet-sheet shrinkage in the z-direction can be used to assess potential fiber shrinkage during drying. Short-span compression strength is shown to be linearly related to the wet-sheet shrinkage in the z-direction during drying.

Application:

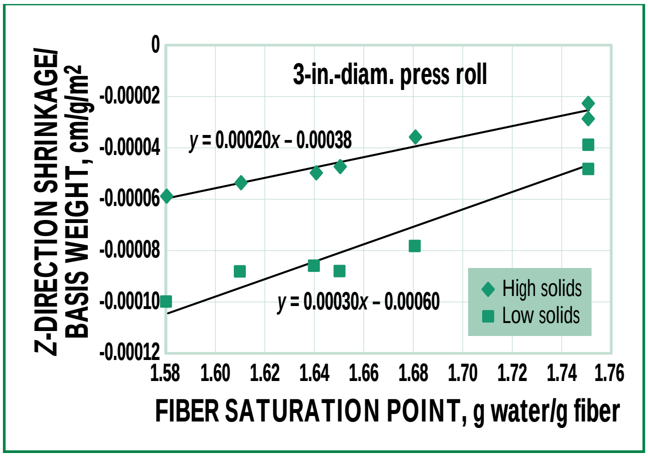
Demonstrates the importance of fiber hydration and drying restraint on strength development of the sheet.

A WOOD PULP FIBER CONSISTS OF cellulosic fibrils embedded within a matrix of hemicelluloses and lignin. During pulping, a major portion of the lignin and part of the hemicelluloses are removed. In the wet state, the fiber is swollen by water contained within the cell wall and in the matrix between fibrils. The amount of water is significant because of the great affinity of holocellulose for water molecules. In chemical pulps, the weight of this "water of swelling" can greatly exceed the fiber weight, depending on the degree of beating. (Beating breaks the fibrils loose and removes some of the restriction on hemicellulose swelling.) During pressing, some of this intracell-wall water is removed along with interfiber water *(1)*. The final removal of intracell-wall water ("water of swelling") is accomplished during drying. Water evaporation is accompanied by a measurable change in web dimensions and greatly affects its structure.

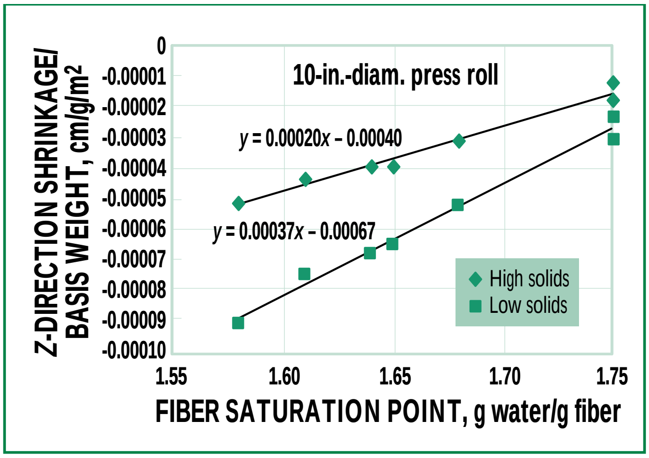
Rance *(2)* distinguished between the effects of interfiber and intracell-wall water removal on web consolidation. Removal of interfiber water draws the fibers together by surface tension (Campbell effect), but the evaporation of the water of swelling has a very important effect because of cell-wall shrinkage. During sheet formation, the fibers are laid in the plane of the web. During pressing, these fibers are flattened into thin ribbons containing water of swelling. During drying—when the water of swelling is removed—the cell wall must shrink in volume. However, because of the rigid nature of the cellulose fibrils, cell contraction takes place mainly in the thickness and lateral dimensions of the fiber. Rance *(2)* argued that the shrinkage of individual fibers is communicated totally or partly to the web. He further noted that free contraction should be equally divided between sheet thickness and its area. However, the lateral restraint of web contraction within its plane may favor contraction in web thickness. The mechanism that communicates fiber shrinkage to the web structure is essentially dependent upon the formation of bonds between fibers. The frequency and strength of bond formation is high enough that shrinkage exerts axial deformation in the crossing fiber, thus causing planar contraction of the web.

Page and Tydeman *(3)* have confirmed Rance's hypothesis *(2)* that interfiber shrinkage is the origin of web shrinkage. They freely dried sheets containing dyed fibers by floating them on mercury. The planar shrinkage of the sheets and the longitudinal shortening of the dyed fibers were found to be equal. Since no relative movement of the fibers at points of crossing was observed, they concluded that the shortening of the fiber is due to shortening of the distance between bonds because of the longitudinal crimping of the fiber at the bond sites. Of course, this can only occur in the presence of sufficiently strong fiber-to-fiber bonds. Page and Tydeman *(3)* also provided proof supporting the view that strong fiber-to-fiber bonds are forming while the fibers are still wet and in their swollen state. These bonds are sufficiently strong to allow the formation of microcompressions at bond sites. Structurally, this enforces longitudinal shortening of fiber segments between bonds.

Giertz *(4–6)* fully understood the implication of intrafiber shrinkage on sheet mechanical properties. Realizing that not all fiber segments are straight, he recognized that the effect of fiber shrinkage would be to straighten these segments, forcing them to participate in the load-bearing mechanism. He termed this as the "activation" of "passive" fiber segments. Thus—for sheets restrained during drying—fiber shrinkage shortens the distance between bonds in straight segments, while in segment contain-



1. Wet-sheet z-direction shrinkage as a function of fiber saturation point (after fines removal) for the 3-in.-diam. press roll



2. Wet-sheet z-direction shrinkage as a function of fiber saturation point (after fines removal) for the 10-in.-diam. press roll

ing defects, shrinkage cures these defects. The probability that a segment will be fully activated depends on

1. Bond frequency (i.e., distance between bonds)
2. The degree of nonstraightness
3. Bonded area
4. Intrinsic potential shrinkage
5. Resistance of the fibers to axial compression
6. Strength of the fiber-to-fiber bond during shrinkage.

Following Page *(7)*, we will refer to this phenomenon as the Giertz effect. The work of Giertz has not been fully recognized, despite its importance in the development of sheet mechanical properties during papermaking. This paper was written to increase awareness of the Giertz effect by demonstrating its contribution to development of compressive strength.

KEYWORDS

Compression strength, liner boards, board machines, unbleached pulps, z direction, development, shrinkage, drying, swelling, mechanical properties, equations, fiber bonding, fiber saturation point.

EXPERIMENTAL

Seven pulp samples were collected before the base refiner of a southern linerboard machine at about two-hour intervals during a period when the pulp quality was unstable. This was done to identify the pulp characteristics responsible for the instability. The fiber saturation point of the pulps was measured after fines removal using a Britt jar. The pulps were not refined, and handsheets of 205 g/m^2 basis weight were made and pressed in the laboratory using one of two roll presses. One press has a 3-in.-diam. roll and is operated at a low speed. The other has a 10-in.-diam. roll and is operated at a speed of 1600 ft/min. Two levels of press solids (32% and 45%) were achieved using each press by varying the number of passes.

The wet and the oven-dry sheets were weighed, and the solids content at the press exit was calculated. The dried sheets were conditioned according to TAPPI T 402, and short-span compressive strength and sheet density were measured.

ASSESSMENT OF POTENTIAL CELL-WALL SHRINKAGE

The potential fiber shrinkage is related to the wet-sheet shrinkage in the *z*-direction during drying. So let us derive an expression for the *z*-direction shrinkage of the wet sheet. The *z*-direction shrinkage is defined as the difference between its caliper at midnip and its dry caliper. The sheet caliper at midnip is calculated from its solids content, with the assumption that it contains only water and cellulose.

Consider a sheet with an area of 1m^2 and unit basis weight, i.e., containing 1 g of fiber. The volume of this sheet at its minimum thickness at midnip, V_w, can be calculated from the volume of its constituents. Therefore,

$$V_w = (1/1.55) + V_1 + V_2 + V_3 \qquad (1)$$

where

V_1 = volume of water in the cell wall
V_2 = volume of water contained in the lumen
V_3 = volume of water contained between fibers.

Cellulose density is assumed to be 1.55 g/cm^3. The volume of the sheet at its minimum thickness at midnip, V_w, is measured in cubic centimeters.

The wet-sheet thickness at midnip, t_w, measured in centimeters, is given in Eq. 2.

$$t_w = V_w/10^4 = [(1/1.55) + V_1 + V_2 + V_3]/10^4 \qquad (2)$$

Similarly the dry sheet thickness, t_d, is

$$t_d = [(1/1.55) + V_4 + V_5 + V_6]/10^4 \quad (3)$$

where

V_4 = volume of air in the porous cell wall
V_5 = volume of air in the lumen
V_6 = volume of air between fibers.

Air content within the dry cell wall is the result of incomplete fibril collapse. The degree of fibril collapse depends on the force acting on the fibrils during drying due to the meniscus of water in the cavities between fibrils. This is the Campbell force inside the cell wall. Reducing the liquid surface tension, therefore, results in a lower degree of fibril collapse. The volume of air in the dry cell wall must be proportional to the original volume of water V_1 and the degree of fibril collapse, thus

$$V_4 = k_1 V_1 \quad (4)$$

where k_1 is a proportionality constant that depends on liquid surface tension.

Similar forces act to collapse the cell-wall lumen, and the volume of air in the dry cell-wall lumen must also be proportional to the volume of the original water contained in the lumen of the wet cell wall. Thus

$$V_5 = k_2 V_2 \quad (5)$$

where k_2 is a proportionality constant that also depends on liquid surface tension.

The volume of water left in the lumen of the wet cell wall depends on press loading and on the volume of water in the cell wall. The water in the cell wall acts as a plasticizing agent, and the more water there is in the cell wall, the easier it is for the lumen to collapse. We will assume that the water contained in the lumen, V_2, is linearly related to V_1. Thus,

$$V_2 = a - (b V_1) \quad (6)$$

where a and b are constants that may depend on cell-wall thickness.

The void volume between fibers in the wet state is controlled by cell-wall plasticity. Because cell-wall plasticity increases with the amount of water inside the cell wall, wetter fibers flow more easily into thinner ribbons, hence reducing the volume between fibers. As the fiber dries, the cell wall shrinks in both the thickness and lateral directions. The difference between the interfiber water in the wet state and the interfiber air in the dry state must equal the reduction in cell-wall volume plus any reduction in volume resulting from the Campbell forces that draw the wet fibers closer to one other. Thus we assume that the quantity $(V_3 - V_6)$ is linearly related to V_1, as shown in Eq. 7.

$$V_3 - V_6 = c + (d V_1) \quad (7)$$

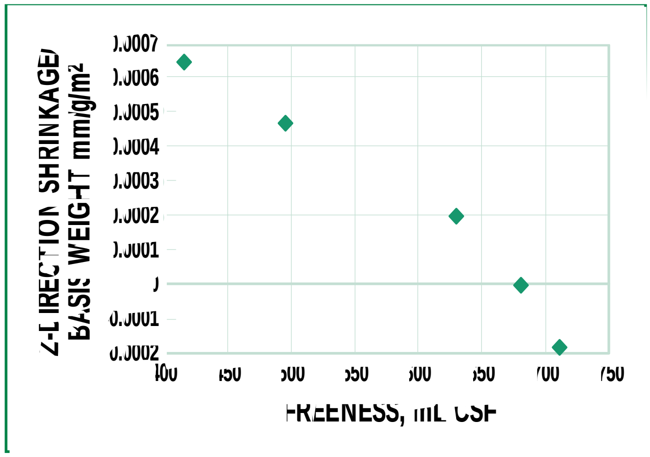
where c is the reduction due to Campbell forces and d is a constant.

The calculated z-direction shrinkage is given by Eq. 8.

$$\text{ZD shrinkage} = t_w - t_d - S_p \quad (8)$$

where S_p is the amount of springback (measured in centimeters) after the wet sheet immediately exits the press nip due to its elastic recovery. Substituting Eqs. 1–7 in Eq. 8 results in the expression for z-direction shrinkage given in Eq. 9.

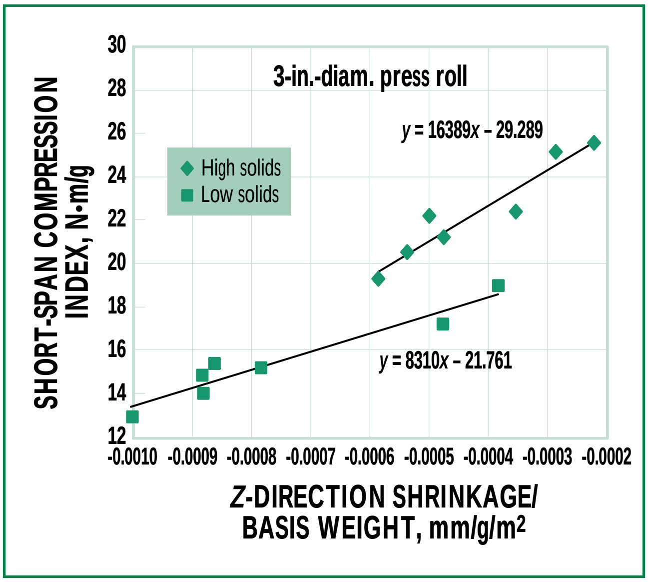
$$\text{ZD shrinkage} = \{[(1-k_1-b-bk_2+d)/10^4]V_1\} - \{S_p-[(a-ak_2+c)/10^4]\} \quad (9)$$



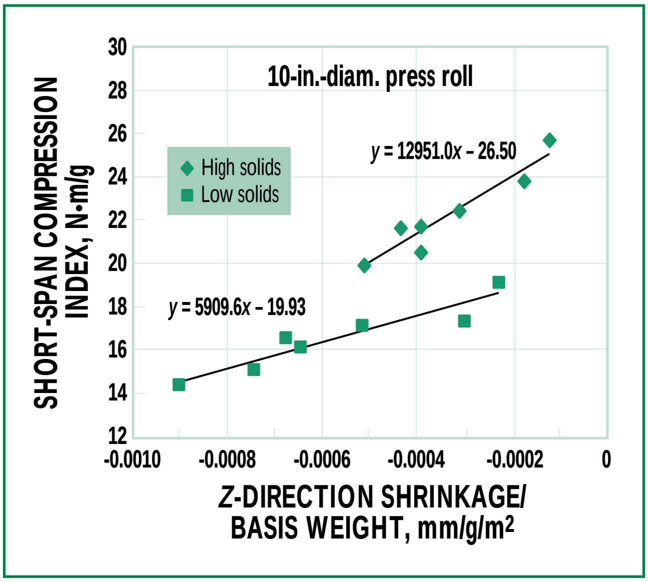
3. Wet-sheet z-direction shrinkage as a function of the degree of refining

For low-press solids where water has not been expressed out of the cell wall, V_1 can be equated to the fiber saturation point. However, for high-press solids where water *has* been expressed out of cell wall, V_1 can only be a fraction of the fiber saturation point. The constants in Eq. 9 must also depend on the press loading and hence on the resulting press solids. Equation 9 shows that z-direction shrinkage can be negative for low values of fiber saturation point.

Figures 1 and 2 show the relationship between z-direction shrinkage and the fiber saturation point of the pulp (after fines removal) for the handsheets pressed with the 3-in.-diam. roll and the 10-in.-diam. roll, respectively. These results agree well with the form of Eq. 9. Therefore, z-direction shrinkage contains information on the degree of cell-wall swelling. As z-direction shrinkage increases, the degree of cell-wall swelling increases and, hence, the fiber potential shrinkage. A confirmation of this is given in **Fig. 3**, which shows the effect of refining on the z-direction shrinkage of a washer pulp sample. The z-direction shrinkage can, therefore, be used to assess fiber potential shrinkage.



4. Short-span compression strength as a function of wet-sheet z-direction shrinkage for the 3-in.-diam. press roll



5. Short-span compression strength as a function of wet-sheet z-direction shrinkage for the 10-in.-diam. press roll

RESULTS AND DISCUSSION

Figures 4 and 5 show a linear relationship between short-span compression index and *z*-direction shrinkage for the handsheets pressed with the 3-in.-diam. roll and the 10-in.-diam. roll, respectively. Note that for the same *z*-direction shrinkage, the pulp pressed to a higher press solids produced higher short-span compression index. This is because higher press solids are also associated with higher sheet density.

Higher sheet density means higher fiber-to-fiber bonding. It also results in a higher Giertz effect at the same fiber potential shrinkage. The pulp samples in this study were unrefined. However, the fiber hydration, as indicated by *z*-direction shrinkage, was different for different samples, thus producing different compression strength. Differences in hydration between samples is presumably due to differences in pulp yield.

We have shown that higher *z*-direction shrinkage increases the short-span compressive strength of the paperboard. We have also shown that high *z*-direction shrinkage is due to high levels of intrafiber water, which is responsible for cell-wall shrinkage and hence high strength. This is a clear demonstration of the Giertz effect.

CONCLUSIONS

The Giertz effect explains how fiber shrinkage during drying can influence sheet mechanical properties. The results of this study show that the Giertz effect plays a significant role in the development of short-span compressive strength of unbleached pulps. TJ

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