Measuring the swelling pressure of paper

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ABSTRACT *A new technique measures the pressure created when water is added to dry paper sheets restrained in the z direction. Swelling curves obtained with commercial samples and with handsheets are interpreted in terms of fiber wall swelling, fiber shape recovery, and internal flow.*

Fiber wall swelling is the primary process in chemical pulp fibers, while the fiber shape recovery process predominates in mechanical pulp fibers. Internal flow results from the plasticizing effect of water, which causes the collapse of the paper structure. Swelling pressure develops rapidly and was measurable in less than 1 s. Consequently, water molecules diffuse into the cell wall much faster than is usually assumed.

There is an excellent relationship between the irreversible increase in thickness upon redrying and the increase in surface roughness.

KEYWORDS
Cell wall thickness
Chemical pulps
Diffusion
Fiber bonding
Fines
Mechanical pulps, Pulping
Smoothness
Stress relaxation
Swelling
Water absorption

In surface treatment or in the printing by an offset press or water-based flexography, interactions between water and paper may lead to undesirable changes in the paper structure. Surface roughening is one of the most important effects that impairs the print quality and is particularly noticeable with wood-containing papers (*1, 2*).

The processes that cause roughening include stress relaxation, swelling, and debonding (*1, 2*). A method for measuring stress relaxation during coating allows us to quantify the effect of stress relaxation on surface roughening (*3*). Tests for characterizing the extent of fiber swelling in water are determinations of the fiber saturation point (*4*) and the water retention value (*5*). These tests give the equilibrium value but not the kinetics of swelling. The results also characterize the isolated fibers but not the paper as a whole.

Hoyland described a technique based on electrical conductivity for measuring swelling (*6*). This method, however, requires that electrodes be embedded in the sheet, and it cannot be used with ordinary paper.

Here, we present a technique that measures the kinetics of paper swelling using ordinary paper. Results were obtained with commercial papers and with handsheets.

Measuring paper swelling: the experimental method

We used three commercial papers of different contents of kraft and mechanical pulp, or groundwood and thermomechanical pulp (TMP), as shown in **Table I**. We also used laboratory handsheets made of the individual components of these sheets.

Approach

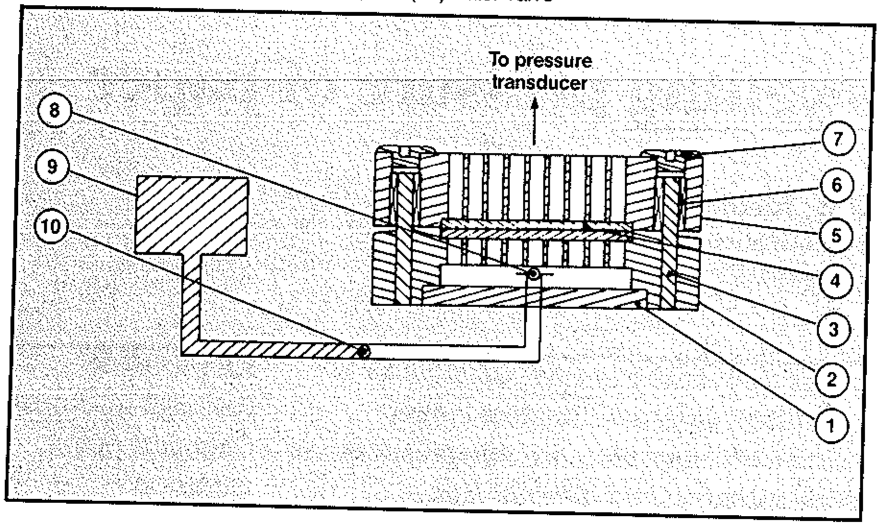
Water enters paper by two mechanisms. Liquid water flows into the interfiber capillaries and proceeds through the thickness of the sheet at a rate that depends on the amount of sizing. Simultaneously, water molecules diffuse into the fiber wall and exert an osmotic pressure that causes fibers to swell. The overall result should be either an increase in thickness or the development of swelling pressure.

Apparatus

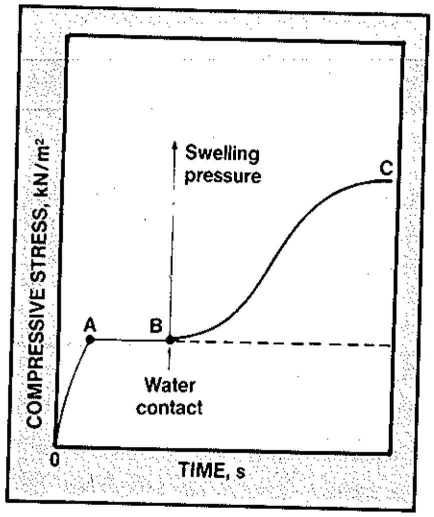
The development of swelling pressure was monitored as a function of time using a specially designed attachment (**Fig. 1**) to an Instron™ tensile testing machine. The attachment replaces the Instron's conventional sample-holding clamps and consists of two parallel platens that compress two plates placed between them (Pointers 2 and 5). The Instron's load cell may then measure the resultant force exerted when a sample, restrained between the two plates, swells in distilled water.

Each plate contains a fritted glass disc embedded at its surfaces (Pointer 4). The lower plate (Pointer 2) is connected through a length of Tygon tubing to a distilled water reservoir (Pointer 9). Small holes have been drilled in the lower plate, perpendicular to the fritted glass disc and connected to it. These holes transport the water uniformly from the fritted

1. Apparatus for paper swelling measurement. Pointers: (1) plug, (2) bottom plate, (3) alignment post, (4) fritted glass disc, (5) top plate, (6) instrument ball bushing, (7) plug, (8) male hose connector, (9) distilled water reservoir, and (10) water valve



2. The swelling curve is enhanced by precompressing the sheet.



glass to the sample. The upper plate (Pointer 5) has similar holes to allow air and excess water to escape. To ensure that the two plates remain parallel and in perfect alignment as they are brought into contact, the lower plate is fitted with two posts (Pointer 3) on opposite sides, corresponding to holes in the upper plate. Instrument ball bushings (Pointer 6) ensure that the vertical movement of the plates is smooth.

I. Composition of commercial papers

	LWC basestock	Newsprint TMP	Newsprint Groundwood
Basis weight, g/m²	36	47	48
Bleached kraft, %	40	10	12
Thermomechanical, %	0	30	0
Groundwood, %	0	0	88
Double-screened groundwood, %	60	60	0

Procedure

Each paper sample was cut into a disc 4.75 cm in diameter and placed between the dry fritted glass discs with the felt side of the sample facing the lower plate. Experiments showed that the swelling curve could be enhanced by precompressing the sheet.

Accordingly, the paper disc was compressed to an initial value of 17 kN/m², as represented in **Fig. 2** by the curve between 0 s and Point A. The disc was allowed to reach a new internal equilibrium under this stress (Point A to Point B). Opening the valve indicated by Pointer 10 in Fig. 1 started the water flowing from the reservoir of Pointer 9.

Constant water pressure was maintained by positioning the water level in the reservoir 18 mm above the sample. To monitor the time, we started a stopwatch at the moment we saw the water reach the lower glass disc. The tensile tester recorded the increase in force (Curve B-C), caused by the swelling of the sample. The experiment continued until there was no further apparent increase in force. (A typical experiment lasted 1-2 h.)

The wet sample was removed. Before starting the next sample, we dried the fritted glass discs with hot air and returned the discs to room temperature with cold air.

A paper swelling curve was obtained from the average of 5 runs. **Figure 3** illustrates the curve with standard deviations for the lightweight coated (LWC) basestock.

Thickness recovery during redrying

After removing the wet sample from between the plates, we measured thickness immediately with a TMI 400 Precision Micrometer. The sample was placed between blotters and allowed to dry overnight under standard conditions. Thickness and surface roughness were measured on the reconditioned sample using the Parker Print-Surf Tester (at 490 kPa).

The measurement of swelling pressure and other physical tests were performed in a controlled atmosphere (23°C and 50% relative humidity). The paper samples were always preconditioned for a minimum of 20 h prior to testing.

Results and discussion

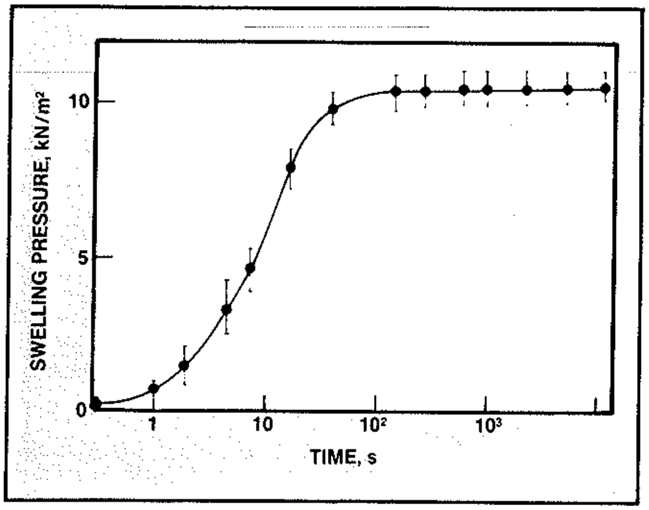
Commercial papers

The swelling pressure developed in less than 1 s. The swelling pressure developed more rapidly for the two newsprints than for the LWC basestock and reached a final pressure that was four times higher (**Fig. 4**). The newsprint made with TMP pulp developed a higher pressure than the newsprint made with groundwood pulp.

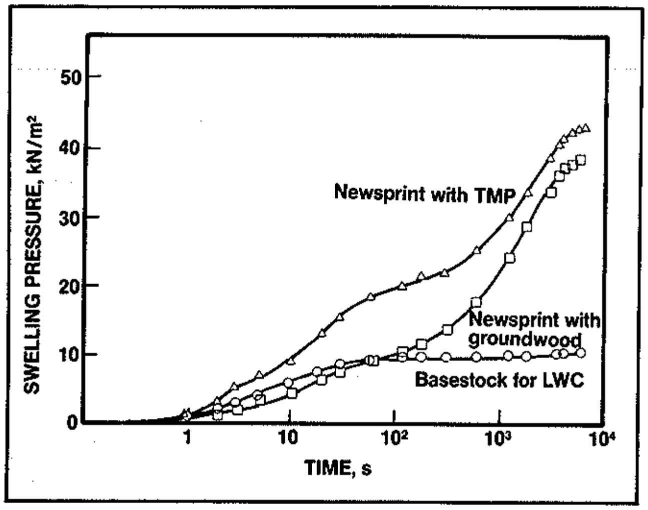
Handsheets

The swelling curves of handsheets made of the different pulps are shown in **Fig. 5**. The curve for the TMP newsprint is shown for reference. All handsheets swelled much more slowly than the TMP newsprint, and they all reached a lower final swelling. The groundwood handsheet swelled the most, but this was only 50% of the swelling of the newsprint. Surprisingly, handsheets prepared from whole

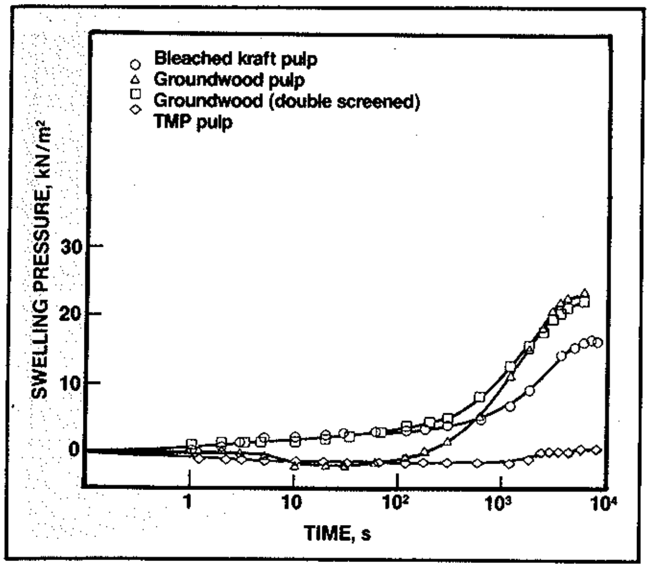
3. Swelling curve for lightweight coated basestock



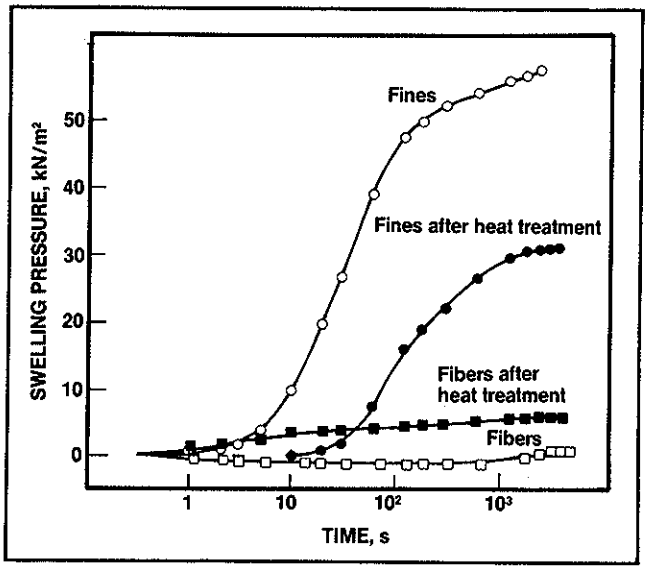
4. The increase in swelling pressure as a function of time in three commercial papers



5. The development of swelling pressure in handsheets made of different pulps



6. The development of swelling pressure in handsheets made of fines or fibers only



TMP pulp did not develop any swelling pressure.

Mechanical pulps contain a lot of fines, and handsheets made only of the fines developed a swelling pressure many times that of handsheets made with only the fibers (**Fig. 6**). However, in handsheets made of the whole pulp (Fig. 5), we did not observe this extent of swelling of the TMP fines. The reason for this lack of swelling is probably that these fines are combined with rigid TMP fibers in a handsheet of low density where there is enough interfiber space in the sheet to accommodate fines swelling.

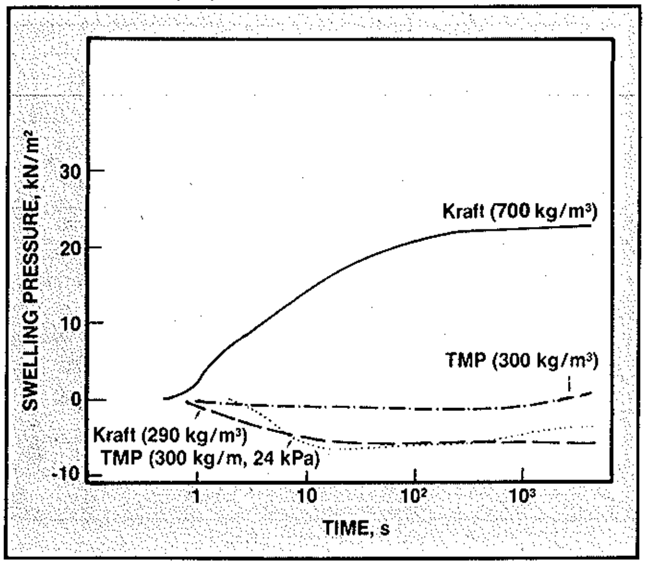
The swelling behavior of groundwood fines (not shown) was similar to that of the TMP fines. Except at short times, the handsheets made from fines swell more extensively than the corresponding newsprints.

By diffusing into the fiber wall, as mentioned, water molecules exert an osmotic pressure that causes the fiber to swell. The swelling force is transmitted in the z direction through the points of fiber-fiber contact. At the same time, however, the water molecules plasticize the fibers, which can now bend and deform under the pressure. Interfiber debonding caused by water would provide more freedom for these motions.

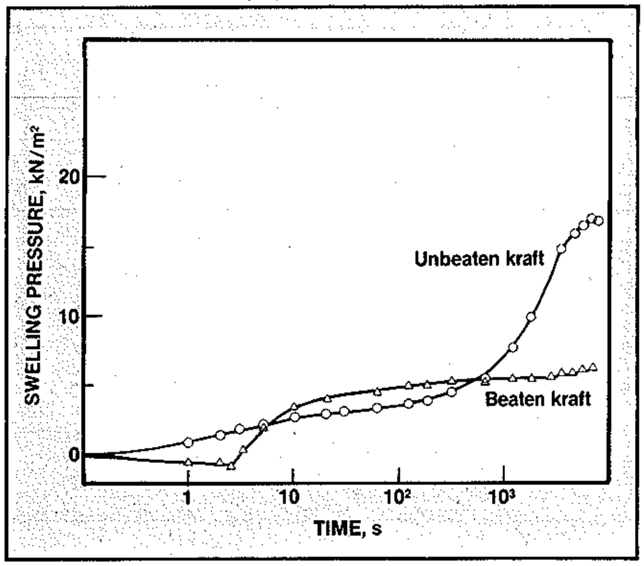
The force that we measure on the tensile tester is the result of these two effects. If the plasticizing effect is strong and the sheet is of low density, a collapse is observed, as **Fig. 7** shows for uncalendered TMP and kraft of low density. The collapse is even more drastic if the prepressing pressure is increased from 17 kPa to 24 kPa (low-density TMP in Fig. 7). If the sheet is of high density, the swelling effect predominates, as shown by the curves for high-density kraft in **Fig. 8** and calendered TMP in **Fig. 9**.

If fiber plasticization or fiber-to-fiber debonding precedes swelling, then we could have a collapse followed by swelling, as seen in the case of the highly beaten handsheet in Fig. 8. However, one would expect the beaten

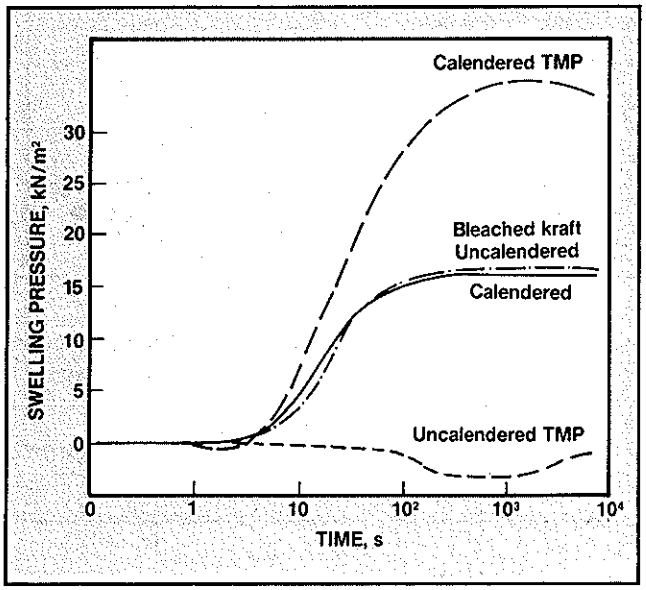
7. The development of swelling pressure in handsheets of different density and fiber rigidity



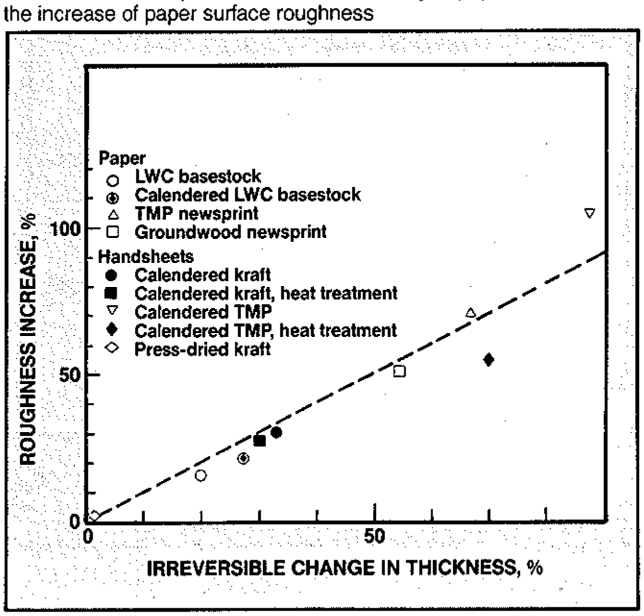
8. The development of swelling pressure in handsheets made of unbeaten and beaten kraft pulps



9. The development of swelling pressure in calendered and uncalendered handsheets



10. The relationship between the irreversibility of paper thickness and the increase of paper surface roughness



fibers to exert a greater final swelling force than the unbeaten fibers. We know that the fiber saturation point, which is a measure of cell wall swelling, increases with beating (7). Consequently, a possible explanation is that the fines created during beating are squeezed into the interfiber spaces, where they swell freely and without contributing to the measured pressure.

Results obtained after calendering (Fig. 9) could perhaps be explained by introducing a third component, that of fiber shape and shape recovery. The uncalendered TMP handsheet collapsed: the plasticizing effect of water helped collapse the tube-like fibers. After calendering, however, the pressure development was rapid. This phenomenon is the result of the flattening of the fibers under the calendering pressure and their recovery to a natural shape as allowed by the intrafiber swelling stresses. Indeed, the effect of calendering was slight on kraft handsheets (Fig. 9) because, even in the uncalendered state, the fibers are already well collapsed into ribbons.

Irreversible change in paper thickness after swelling and redrying

The thicknesses of the papers increased during wetting and decreased during redrying. However, recovery was not complete (**Table II**). The thickness recovery of LWC basestock during redrying was better than that of both newsprints, but the results were similar after the basestock had been calendered to a similar roughness.

Handsheets made of kraft pulp showed better thickness recovery than handsheets made of mechanical pulps. Especially good reversibility

II. Thickness irreversibility of commercial papers and laboratory handsheets

Paper or handsheet	Density, kg/m^3	Thickness increase, %	Irreversibility, %
LWC basestock	0.47	35	57
Calendered LWC basestock	0.50	38	74
Newsprint (TMP)	0.51	70	81
Newsprint (groundwood)	0.50	71	76
Kraft pulp	0.49	37	67
Kraft pulp (press dried)	0.51	22	5
Beaten kraft pulp	0.54	53	28
TMP fibers	0.31	28	150
TMP fibers (calendered)	0.53	65	120
TMP fines	0.46	28	25
TMP pulp (calendered)	0.61	112	88
TMP pulp (calendered + heat)	0.61	89	71
Groundwood fibers	0.35	27	144
Groundwood fibers	0.45	38	39

Irreversibility = [(final − initial thickness)/initial thickness] × 100.

was obtained with press-dried kraft handsheets. While the thickness recovery of handsheets made of mechanical pulp fines was good, that of handsheets made of TMP or groundwood fibers was poor. In fact, the handsheet thickness *increased* during redrying.

Irreversible change in paper thickness and surface roughness of paper

There was a good relationship between the increase in surface roughness and the increase in thickness after redrying. **Figure 10** shows the data plotted from Table II. This relationship held for commercial papers and calendered handsheets. The surfaces of heat-treated and press-dried sheets were least affected by the wetting.

Conclusions

We have developed a technique to measure the swelling pressure exerted when paper is contacted by water. Results obtained with commercial and handsheet samples indicate that the development of the swelling pressure is rapid and measurable within 1 s.

Because the processes leading to the development of the swelling force involve the diffusion of water molecules into the fiber wall, these findings confirm the suggestion (*7, 8*) that the diffusion process, contrary to general assumption, is extremely fast.

For mechanical pulps, the tendency of fibers to recover to the natural round shape may contribute to the pressure measured, in addition to swelling of the cell wall.

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