

Measuring the thickness of stacked sheets of paper

Vincent T. Morgan

ABSTRACT: *The experimental results demonstrate the effects of several test parameters on mean sheet thickness as determined by measuring stacked sheets with a parallel-faced dead-weight micrometer. Mean sheet thickness increases with increasing face area and decreases (a) asymptotically with increasing dwell time at constant pressure and (b) exponentially with increasing pressure up to 1 MPa. At constant pressure, the number of stacked sheets has a variable effect on mean sheet thickness. For stacks containing 20 or fewer sheets, thickness decreases with increasing number of sheets. Beyond this threshold, sheet thickness increases with increasing number of sheets.*

KEYWORDS: *Capacitor papers, measurement, paper, pressure, sheet stacks, thickness.*

Paper consists of a bonded layered network of short cellulose fibers arranged randomly, with most of the fibers lying within the plane of the sheet (1). The sheet has a denser core and rough outer layers of less-dense material containing much air. Sheet thickness varies from point to point (1, 2), so the method of measurement will influence the measured thickness. A thickness gauge with small spherical feet usually yields a lower thickness value than a gauge with parallel-plane faces. The reason for this is that the former device measures the thickness of a small area, while the latter measures the maximum thickness of a larger area and is thus more likely to encounter local high spots (3).

The international standards for measuring the thickness of single (4) and stacked (5) sheets of paper specify the use of a dead-weight micrometer with parallel-plane faces. The movable face should have a diameter of 16.0 ± 0.5 mm, and the diameter of the opposing fixed face should be at least as large. Thus, the area of the test section is nominally 200 mm². The preferred pressure between the two faces is 100 ± 10 kPa, and the approach velocity of the movable face toward the fixed face should not exceed 3 mm/s. The error attributed to nonparallel faces should not exceed 5 μ m or 1%, whichever is greater. Neither the indication error nor the standard deviation should exceed ± 2.5 μ m or $\pm 0.5\%$, whichever

is greater. The standard atmosphere for testing is 23°C and 50% RH. When measuring stacked sheets, at least five, and preferably ten, sheets should be used. At least four test stacks should be employed, and the number of readings should be at least 20.

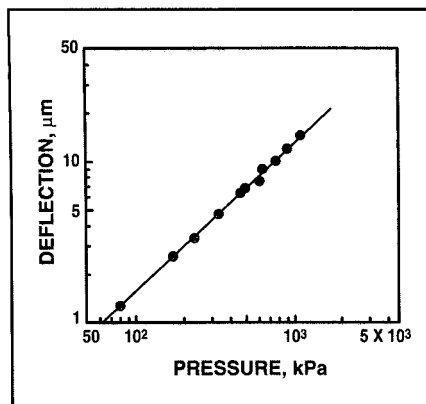
The ASTM standard (6) calls for a movable face with a diameter of 6.35 ± 0.03 mm and a pressure of 172 ± 14 kPa. The approach rate is 1.14 ± 0.38 mm/s. Ten sheets should be stacked, and at least five but preferably ten, readings should be taken. The standard atmospheric conditions for testing are 23°C and 50% RH.

Regardless of which method is used, application of a compressive load to an individual sheet or to a stack of sheets will result in a decrease in sheet thickness as the individual fibers bed down into the mat (7) and air between the fibers is expelled (8). At much higher compressive stress, there will also be compression of the fibers (9, 10). The extent to which the paper is compressed depends on the magnitude of the stress and the duration of applied pressure (10, 11). When the load is removed, there will be elastic recovery, long-term creep recovery, and some permanent set (11).

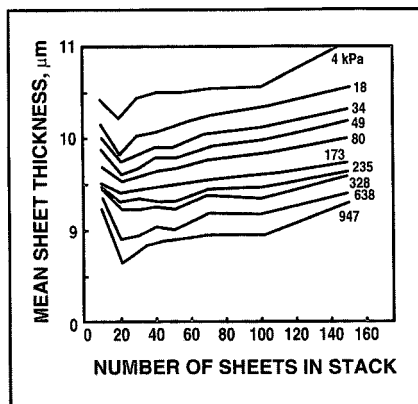
This report presents the results of experiments that were conducted to establish the effects of several test parameters on mean sheet thickness as determined by measuring stacked sheets using a dead-weight micrometer with parallel-plane faces. The parameters examined in this study were test pressure, number of sheets in the stack, dwell time under pressure, and area of the micrometer's movable face.

Morgan is an honorary research fellow, CSIRO Division of Applied Physics, Lindfield 2070, Australia.

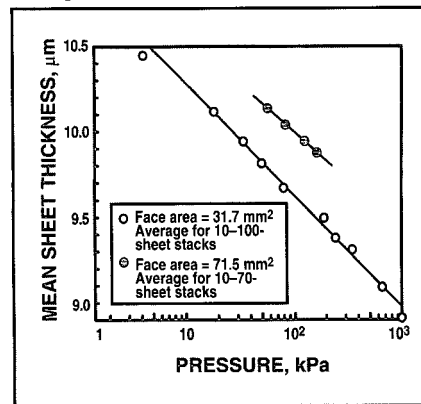
1. Deflection of the measuring system as a function of pressure with no paper between the faces (face area = 31.7 mm²)



2. Mean sheet thickness as a function of the number of sheets in the stack at various pressures (face area = 31.7 mm²)



3. Mean sheet thickness as a function of pressure as measured using two different face areas (average values for stacks containing 10–100 sheets)



Experimental procedure

The paper studied was a nominal 10-μm-thick capacitor tissue with an apparent density of 1.22 g/cm³ and a nominal width of 100 mm. The paper was conditioned at 23°C and 50% RH for at least 24 h before testing.

A dead-weight dial-gauge micrometer with parallel-plane faces (movable-face diameter of 6.35 mm and area of 31.7 mm²) was used to measure the thickness of stacks containing 10–150 sheets at different pressures. The sheets were cut to 60 mm x 100 mm, and thickness was measured at positions at least 20 mm from the edges. A total of 20 measurements were made at each pressure for each stack. Dial readings were recorded after a 5-s dwell time for the movable face on the stack surface.

Some tests also were performed using a micrometer with a movable-face area of 71.5 mm². Both micrometers were calibrated using a range of thickness gauges.

Experimental results

The measured thicknesses were corrected to account for the deflection of the loaded measuring system with no paper between the faces. Figure 1 shows the deflection-vs.-pressure curve for the micrometer with the faces in

direct contact. Figure 2 shows the corrected mean sheet thickness as a function of the number of sheets in the stack at various pressures. Figure 3 shows mean sheet thickness as a function of pressure for stacks of 10–100 sheets as measured using two different face areas.

The effect of cycling the pressure up and down on sheet compression is illustrated in Fig. 4. The effect of the dwell time on sheet compression is shown in Fig. 5.

Discussion

It is obvious from Fig. 1 that all thickness measurements needed to be corrected to account for the deflection of the measuring system, particularly at higher pressures. The curves presented in Fig. 2 show that at a constant pressure, the mean thickness per sheet decreases to a minimum value for test stacks containing 20 sheets and then increases with an increasing number of sheets in the stack. The initial decrease in mean sheet thickness is probably due to the “bedding down” of fibers and the expulsion of air between the fibers. The subsequent increase in mean sheet thickness is probably attributable to differential pressure through the stack and a less effective bedding-down process as the number of interfaces in-

creases.

Figure 3 shows that mean sheet thickness decreases exponentially with increasing pressure. (The data points in Fig. 3 are averages obtained for stacks containing 10–100 sheets.) The equation for the curve is

$$T = 10.92 - 0.28 \ln P$$

where

T = apparent mean thickness per sheet, μm

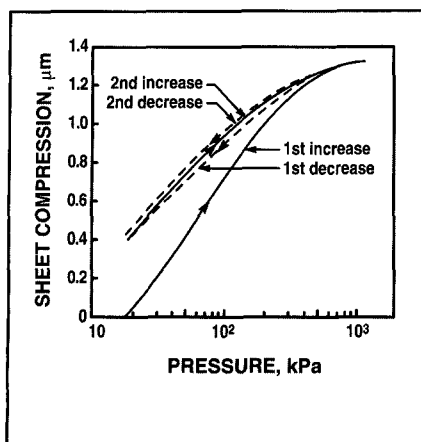
P = pressure, kPa.

Figure 3 also shows that mean sheet thickness increases with increasing area of the movable face at constant pressure. This is because a face with a greater area is more likely to encounter areas of high local thickness.

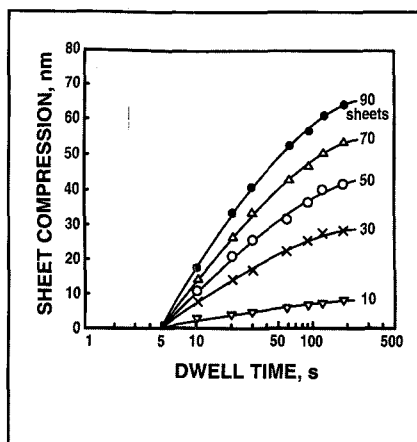
Figure 4 illustrates the hysteresis that occurs following a single application of pressure in the test device. As the pressure initially increases, sheet compression increases asymptotically, resulting in a compression of about 1.33 μm at pressures in excess of 1 MPa. As the pressure is reduced the first time, elastic recovery offsets some of the initial compression, but there is some permanent set. The second pressure cycle has little effect on sheet compression. This type of behavior has also been reported for the cyclic variation of capacitance with pressure for capaci-

Paper Testing

4. Sheet compression as a function of pressure for two cycles of increasing and decreasing pressure (face area = 31.7 mm²)



5. Sheet compression as a function of dwell time (at 111 kPa) for stacks containing 10–90 sheets (face area = 71.5 mm²)



tance papers (8).

Some standard test methods specify the dwell time as 2–4 s (6) or 2–5 s (4). In another standard (5), dwell time is defined as the time taken for the dial reading to become steady. Other researchers have used a dwell time of 5 s (12, 13). As seen in Fig. 5, sheet compression increases asymptotically with dwell time over the range of 5 s to 180 s when using a dwell time of 5 s as a reference. This clearly demonstrates the need to specify a standard dwell time when measuring the thickness of paper sheets with a dead-weight micrometer.

Conclusion

The experimental results revealed several important considerations that should be taken into account when measuring the thickness of a stack of sheets with a dead-weight micrometer.

- All thickness measurements should be corrected to account for any deflection of the measurement system under load when there are no sheets between the faces.
- At constant pressure, sheet thickness decreases as more sheets are added to the stack up to a threshold of about 20. The decrease in thickness is the result of fibers "bedding down" and the expulsion of air be-

tween the fibers. As more sheets are added to the stack, the bedding process becomes less effective, and sheet thickness increases.

- With a constant number of sheets, the mean thickness per sheet decreases exponentially with increasing pressure up to 1 MPa.
- Mean sheet thickness increases with increasing area of the movable face at a given test pressure.
- Mean sheet thickness undergoes hysteresis during the first cycle of increasing and decreasing pressure, the result of a permanent set as the fibers bed down. There is little hysteresis for subsequent pressure cycles.
- At constant pressure and with a constant number of sheets, mean sheet thickness decreases asymptotically as the dwell time of the pressure increases. Consequently, a standard dwell time, say 5 s, should be specified.

Measurements were made using a micrometer with a movable-face area as specified by the ASTM method. There is no reason to doubt that the general shapes of the curves will also apply to a micrometer with a movable face that matches the ISO specification. However, the absolute values of thickness will differ. [7]

Literature cited

1. McLean, D. A., Birdsall, H. A., and Calbick, C. J., *I&EC* 45(7): 1509(1953).
2. Church, H. F. and Krasucki, Z., "The aging of power capacitors: Effects due to ions and the structure of paper," Paper 112, CIGRE, Paris, 1966.
3. Souder, W. and Newman, S. B., "Measurement of the thickness of capacitor paper," Circular 532, National Bureau of Standards, Washington, DC, July 1952.
4. "Paper and board—determination of the thickness of single sheets and method of calculation of the apparent density of board," ISO 534-1980, International Standards Organization, Geneva, Switzerland, 1980.
5. "Paper—determination of bulking thickness and apparent density," ISO 438-1980, International Standards Organization, Geneva, Switzerland, 1980.
6. "Standard test methods for thickness of solid electrical insulation," ASTM D374-79, American Society for Testing Materials, Philadelphia, 1979.
7. Lehmhaus, F., "Report on the activities of Study Committee No. 18, Capacitors," Paper 159, CIGRE, Paris, 1962.
8. Fainerman, I. D. and Vaisman, L. M., *Soviet Phys.—Tech. Phys.*, 1(11): 2410(1957).
9. Brecht, W. and Schädler, M., *Papier* 17(11): 626(1963).
10. Jackson, M. and Ekström, L., *Svensk Papperstid.* 67(20): 807(1964).
11. Ivarsson, B., *Tappi*, 39(2): 97(1956).
12. Wink, W. A. and Baum, G. A., *Tappi J.* 66(9): 131(1983).
13. Yamauchi, T., *Appita* 40(5): 359(1987).

The author thanks A. McKenzie, CSIRO Division of Forest Products, for helpful discussions.

Received for review June 18, 1992.

Accepted July 10, 1992.