Compressive creep of stacked sheets of paper

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ABSTRACT: Compressive creep affects the capacitance of compressed layers of oil-impregnated capacitor tissue. Compressive creep was measured in stacks of capacitor tissue (20 sheets, nominal thickness 10 μm) under a range of mechanical loads. Sheet compression increased with increasing dwell time at (a) constant mechanical pressure and (b) increasing mechanical pressure up to 56 kPa. Pressures beyond this threshold did not increase compression, suggesting that creep is due to expulsion of air in voids rather than to collapse of the fiber network. Compression was greatest (35%) when air and moisture were extracted from the paper under vacuum. Compression under vacuum increased with increasing temperature, possibly because residual moisture was extracted more effectively at higher temperatures. Impregnation with oil did not affect compression under vacuum.

KEYWORDS: Capacitor papers, compression, creep, reaction time, pressure, temperature, thickness, vacuum.

Paper is a bonded, layered network of randomly arranged short fibers lying mainly in the plane of the sheet. The sheet has a denser core, while the rough outer layers on either side of the sheet consist of less-dense material and contain more air *(1)*.

When a compressive load is first applied to a stack of paper sheets at atmospheric pressure, the thickness decreases as the air between the fibers is expelled and the fibers nest or "pile" at the sheet interfaces and bed down in the mat. The reduction in thickness (compression) increases with increasing pressure and increasing dwell time of the load *(2–4)*. The initial compression comprises both elastic deformation (recovery) and inelastic deformation (permanent set). Subsequent time-dependent deformation is known as primary creep.

The compression of paper at atmospheric pressure increases with increasing moisture content *(2, 3, 5, 6)* and increasing void content *(6)*. Paper compression is much less dependent on temperature *(3, 6)*.

This study of the compressive creep of capacitor tissue was undertaken to facilitate the task of predicting the capacitance of stacks of such paper under compression, particularly under vacuum.

Experimental procedure

The paper studied was a nominally 10-μm-thick capacitor tissue having an apparent density of 1.22 Mg/m^3 and a nominal width of 100 mm. For the tests at atmospheric pressure, the paper was conditioned at 23°C and 50% RH for at least 24 h. Two parallel, circular (82.6-mm diam.), rhodium-plated brass plates were used for the compression tests. Paper sheets were cut to 120 mm x 100 mm to eliminate edge effects. The static load was applied by means of a pivoted beam with knife edges. The test apparatus is illustrated in **Fig. 1**.

For the tests under vacuum, the test cell shown in Fig. 1 was evacuated with rotary and diffusion pumps. The cell could be heated with internal heaters, and the temperature of the bottom plate was measured with embedded thermocouples. It was determined from compression tests on sheets of copper and glass that friction between the shaft and the vacuum seal had a negligible effect on the measured compressive creep.

The variation in the thickness of a stack of 20 sheets of paper was measured with a differential-capacitance displacement transducer attached to the pressure plates and connected in a bridge circuit with a precision inductive voltage divider *(7)*.

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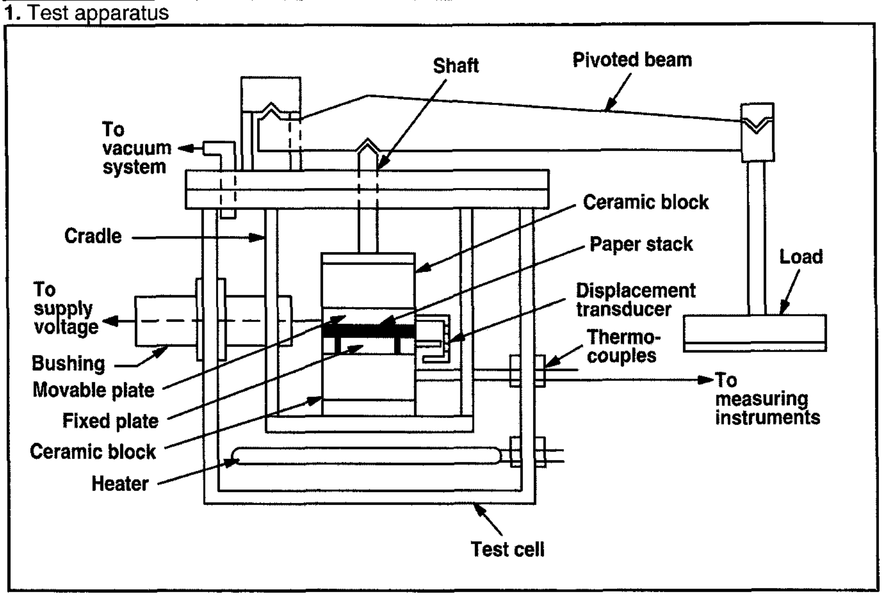
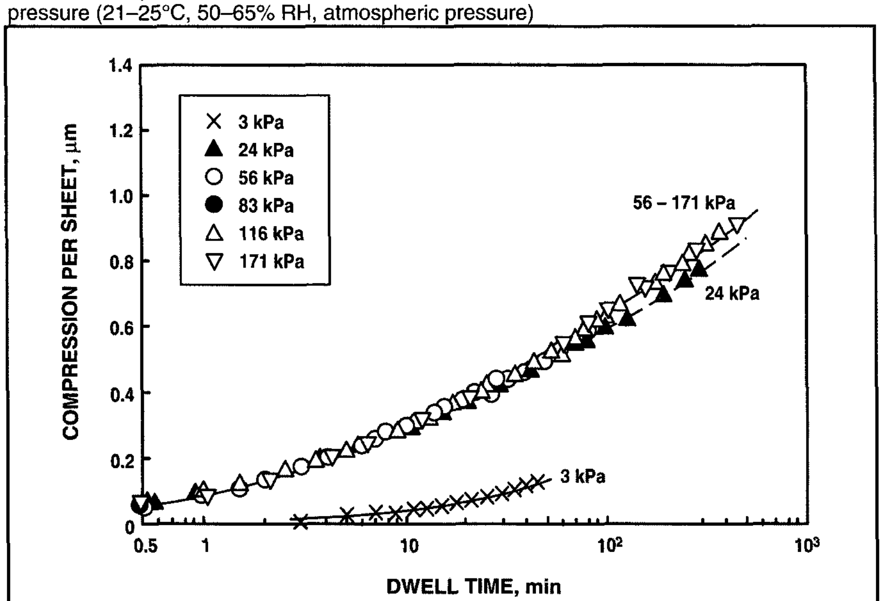
1. Test apparatus



2. Sheet compression as a function of dwell time under load at six levels of mechanical pressure (21–25°C, 50–65% RH, atmospheric pressure)



Results

The effects of mechanical pressure and dwell time on sheet compression at ambient temperature are shown in **Fig. 2** for sheets tested at atmospheric pressure and in **Fig. 3** for sheets tested under vacuum. The effects of temperature and oil impregnation on the compressive creep of a stack under vacuum are illustrated in **Fig. 4**.

Discussion

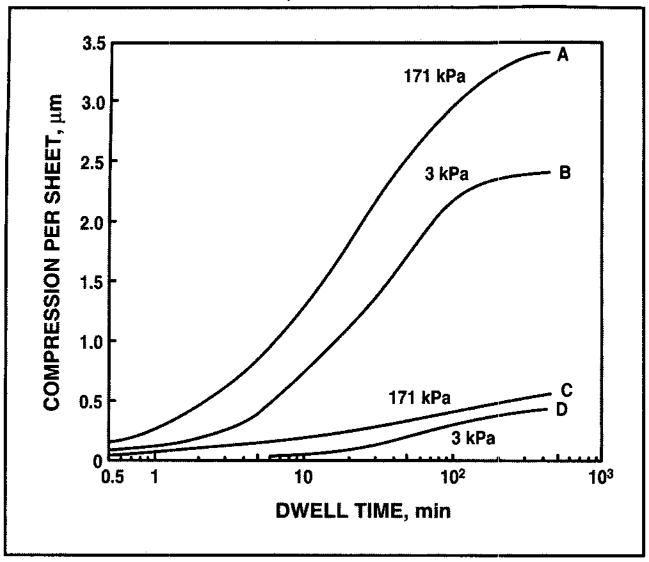
Figure 2 shows that stack compression increased with increasing dwell time at constant mechanical pressure for stacks tested at ambient temperature and pressure. Compression also increased with increasing mechanical pressure up to 56 kPa. A common compression-vs.-dwell characteristic was observed for sheets subjected to pressures in the range 56–171 kPa. This suggests that the creep is due to the slow release of air in the voids rather than to a collapse of the fiber network.

This suggestion appears to be confirmed by the results shown in Fig. 3 for the stacks compressed as the air pressure was reduced from atmospheric to 27 Pa during the initial 10 min of compression (curves A and B). It is seen that the compression of the stack with a mechanical pressure of 171 kPa increases with increasing dwell time towards a value of 3.5 µm per sheet, which is more than 35% of the nominal 10-µm thickness.

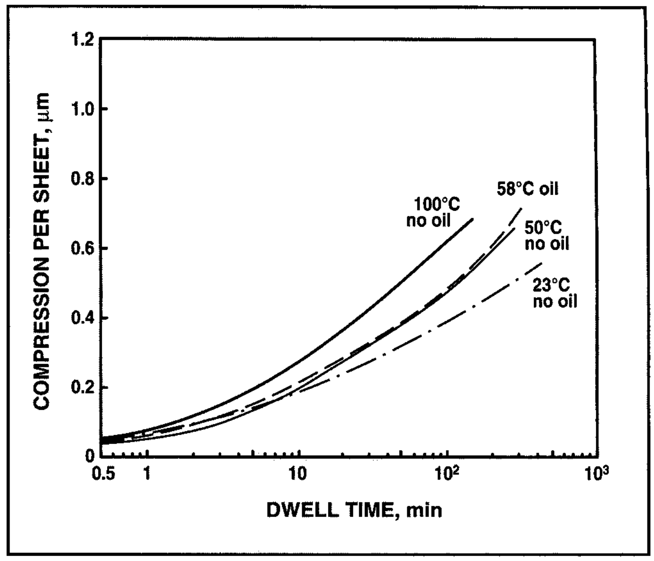
The density of dry cellulose is 1.5 Mg/m^3, and the density of the paper before compression was 1.22 Mg/m^3 at atmospheric pressure and 23°C. The measured moisture content of the paper was 7% of dry weight, hence it can be calculated that the volume of air in the paper was 18.7% and the volume occupied by the moisture was 10.5%. Since the measured compression under vacuum at a mechanical pressure of 171 kPa was 0.55 µm per sheet after 400 min (Curve C in Fig. 3), the reduction in volume from creep alone was approximately 5.5%. Thus the calculated total potential reduction in volume is 34.7%, i.e., the calculated total potential compression at 400-min dwell time is 3.47 µm per sheet. It is seen from Curve A of Fig. 3 that the measured compression at 400 min was 3.42 µm per sheet, which shows reasonable agreement between measured and calculated compression.

It is seen from curves C and D in Fig. 3 that the compression under vacuum increased by about 0.12 µm per sheet—about 1.2%—as the mechanical pressure was increased from 3 kPa to 171 kPa. This increase prob-

3. Sheet compression as a function of dwell time under load at two levels of mechanical pressure applied at two levels of air pressure (21–25°C). Curves A and B: air pressure reduced from atmospheric to 27 Pa during initial 10-min period; Curves C and D: air pressure held at 7 Pa for duration of experiment.



4. Sheet compression as a function of dwell time under a 171-kPa load at four temperatures under vacuum (air pressure 27 Pa). One sample was impregnated with oil (58°C), while the other three were not.



ably is due to compaction of the fiber mat, which under vacuum is less impeded by air trapped between the fibers and by moisture adsorbed on the fibers.

The similarity between the curves at 58°C (oil-impregnated paper) and 50°C (no oil) in Fig. 4 indicates that impregnation with oil had no effect on the compressive creep of the paper stack under vacuum. On the other hand, the curves in Fig. 4 show that the compression under vacuum increased with increasing temperature, possibly because residual moisture was extracted more effectively at higher temperatures.

An interesting feature of the compressive creep of a paper stack at atmospheric pressure is that the slope of the compression-vs.-dwell characteristic increases in discrete steps. For example, the slope of the upper curve in Fig. 2 increases at dwell times of 1.5 min, 13 min, and 50 min. This implies that the creep progresses as the sum of a series of exponential curves. Similar behavior was noted during compression tests (not described here) on polyethylene, polymethyl methacrylate, polypropylene, celluloid, and cork. The behavior is thought to result from the coiling of long-chain molecules *(8)*.

Conclusions

Compressive creep was measured in stacked sheets of capacitor tissue. The experimental results showed that:

- The compression of a stack of paper sheets increased with increasing dwell time at constant mechanical pressure.
- At atmospheric pressure, sheet compression increased with increasing mechanical pressure between 3 kPa and 56 kPa. Applied pressures in the range 56–171 kPa produced the same results, suggesting that creep is due to the gradual expulsion of air in the voids rather than to a collapse of the fiber network.
- Under a gradually applied vacuum, sheet compression showed a marked increase. After compression at 171 kPa for 400 min, sheet thickness was reduced by approximately 35%. The increase in compression is due to the extraction of air and adsorbed moisture from the sheets as the vacuum was applied.
- Sheets compressed at constant mechanical pressure under vacuum showed the least compression, since the air and much of the moisture in the sheets had been removed prior to the application of mechanical pressure.
- Under vacuum, sheet compression increased with increasing temperature at constant mechanical pressure, possibly because residual moisture was extracted more effectively at higher temperatures.
- Impregnation with oil did not affect sheet compression under vacuum. TJ

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