

Mechanical Property Variables for Formed Fiber Packaging

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Introduction

Cellulose fibers have unique properties that allow them to be used for a variety of products—from low-density cushioning to high-density structural products. Knowing what types of fibers and processing methods to use for each product application requires an understanding of potential properties. Historically this understanding has tended to be more an art than a science. The paper industry has been gathering information on individual fiber properties, processing conditions, fiber formation, online fiber properties, and mechanical and physical properties of resultant paper. This work is moving papermaking toward a scientific approach that can be modeled and used to predict performance characteristics. Much of this information, however, is geared primarily toward papermaking processes and papers with sheet weights between 0.02 and 0.05 lb/ft² (100 to 250 g/m²) and densities between 31.2 and 50 lb/ft³ (500 to 800 kg/m³).

Modeling the performance of pulp molding is also starting to move from an art to a scientific approach. While pulp molding uses similar fibers as those used by the paper industry, the forming processes, fiber forming characteristics, densities, and structural functionality are much different than those of paper. Because of this difference, information specific to the pulp molding industry needs to be gathered to assist in developing the modeling constants. Once this information is obtained, some of the same techniques used in the paper industry (as well as those used in other composites industries) can be used to model pulp molded products. The goal is to design and predict product performance through computer modeling based on fundamental fiber characteristics and processing parameters.

The data presented here are results from initial tests of a long-term research program at the Forest Products Laboratory (FPL). The program will include both nondestructive and destructive tests to determine the mechanical properties of low- to high-density (15.6 to 62.4 lb/ft³ (250 to 1000 kg/m³)) fiber sheets. Various processing schemes and fiber types will be used in fabricating test sheets. For the study reported here, we attempted to simulate sheets that might fit the category of Thermoformed Fiber Packaging. Further testing will include methods to obtain the nine independent orthotropic properties of the sheet material at both 50% and 90% relative humidity (RH) conditions.

Background

For review, the goal in modeling is to obtain mechanical properties in all directions and then use these properties for computer analysis. We assume the properties of paper and pulp molded articles to be orthotropic; that is, the principal properties are orthogonal to each other, as illustrated by Figure 1. To fully model an orthotropic structure using finite element analysis techniques, nine independent material properties need to be determined:

$$E_{11}, E_{22}, E_{33}, \nu_{12}, \nu_{23}, \nu_{13}, G_{12}, G_{23}, G_{13}$$

where E_{11} , E_{22} and E_{33} are modulus of elasticity in the principal directions 1, 2, and 3; ν_{12} , ν_{23} , ν_{13} are Poisson's ratio for the principal planes 12, 23, and 13; and G_{12} , G_{23} , G_{13} are shear

modulus for the principal planes 12, 23, and 13. From these properties, the computer model can calculate stresses and strains in a three-dimensional model as a function of applied load.

Some of these properties are easy to obtain; others require special or sensitive testing apparatus. For example, the Poisson's ratio that measures strain through the thickness of a fibrous sheet is very small and sensitive equipment is required to accurately measure displacement.

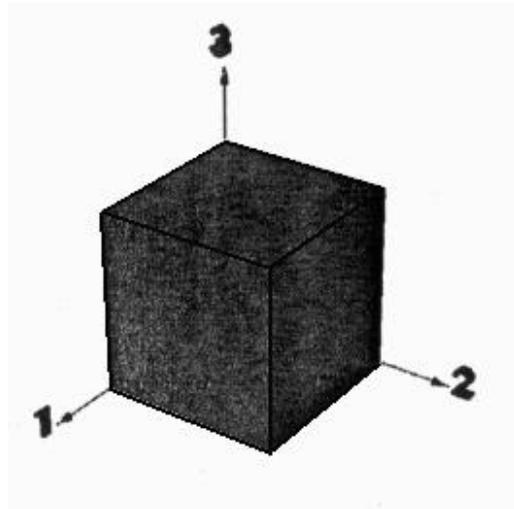


Figure 1. Representative cube showing principal directions for orthotropic material properties.

In most cases of orthotropic materials, directions 1 and 2 (Figure 1) represent the in-plane properties of the sheet and direction 3 represents the thickness of the sheet. In stationary flat sheet formation, the in-plane properties (1 and 2) are usually assumed to be the same or isotropic, while the properties through the thickness (3) are quite different. A number of factors influence properties in all three principal directions. In-plane properties, for example, are affected by water flow. As water flow increases in a particular direction, fiber alignment increases, resulting in increased material properties parallel to the flow and decreased properties perpendicular to the flow. Handsheets made on a static former are assumed to have uniform in-plane properties. However, once the process changes from static to dynamic, such as on a paper machine, the machine-direction and cross-machine-direction properties change. Setterholm (1973) showed that fiber alignment can significantly increase modulus of elasticity (MOE) in the fiber direction, E_1 , compared to cross-fiber direction, E_2 (Figure 2).

Process parameters also affect paper properties. For example, the pulp molding process influences the level of restraint on the pulp molded fiber sheet. As the level of restraint increases so does MOE. Setterholm (1976) discussed the effects of various levels of restraint on MOE for paper (Figure 3). Starting at zero dimensional change, if wet-to-dry dimensional change decreases, as is the case in unrestrained pulp molding drying, MOE decreases. If wet-to-dry dimensional change increases, as in stretching, MOE increases. These effects of wet-to-dry dimensional change are also evident with fiber-aligned paper sheets (Figure 3).

Moisture, our ever-present friend and foe, significantly affects paper properties. Previous research at FPL explored the effect of equilibrium moisture content on MOE in the machine and cross-machine directions for kraft linerboard paper (Figure 4). Typically, properties related to

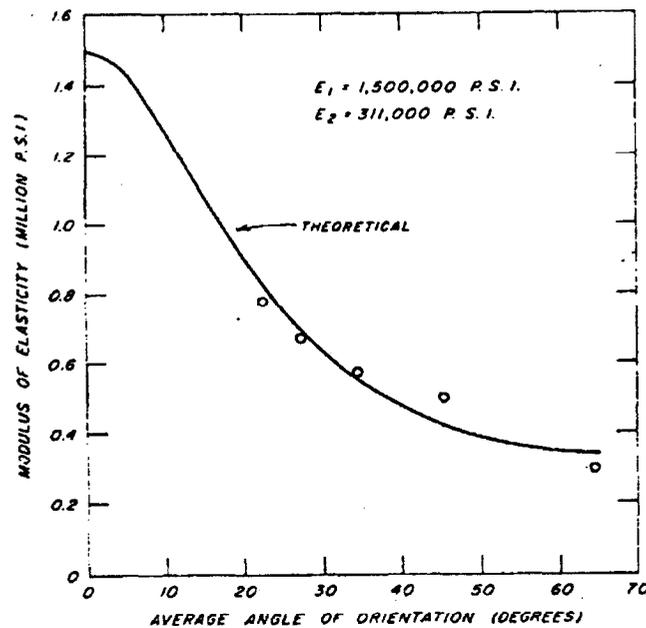


Figure 2. Effect of fiber orientation on MOE in principal directions 1 and 2 for kraft pulp handsheets restrained from shrinkage during drying (Setterholm 1976).

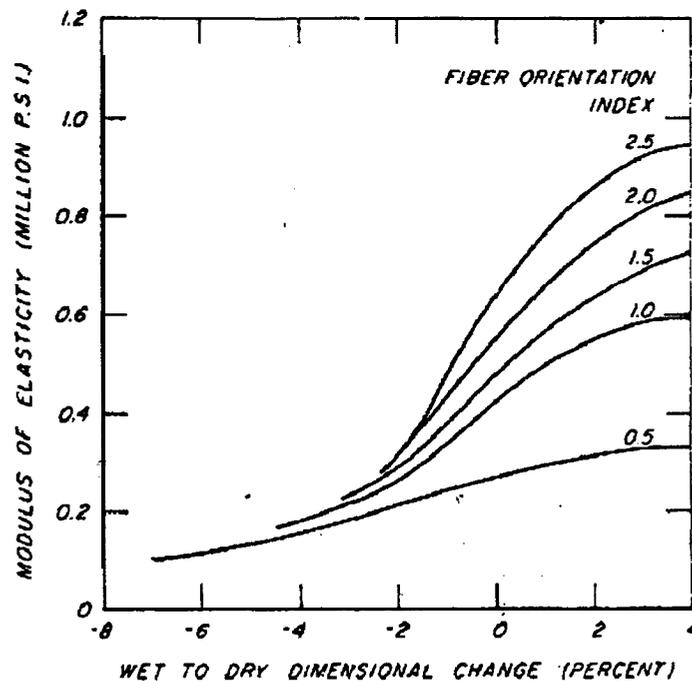


Figure 3. Effect of restraint during drying on MOE of kraft pulp handsheets at five levels of fiber orientation: negative dimensional change indicates shrinkage; positive dimensional change indicates stretch; point at beginning of each curve is unrestrained (Setterholm 1976).

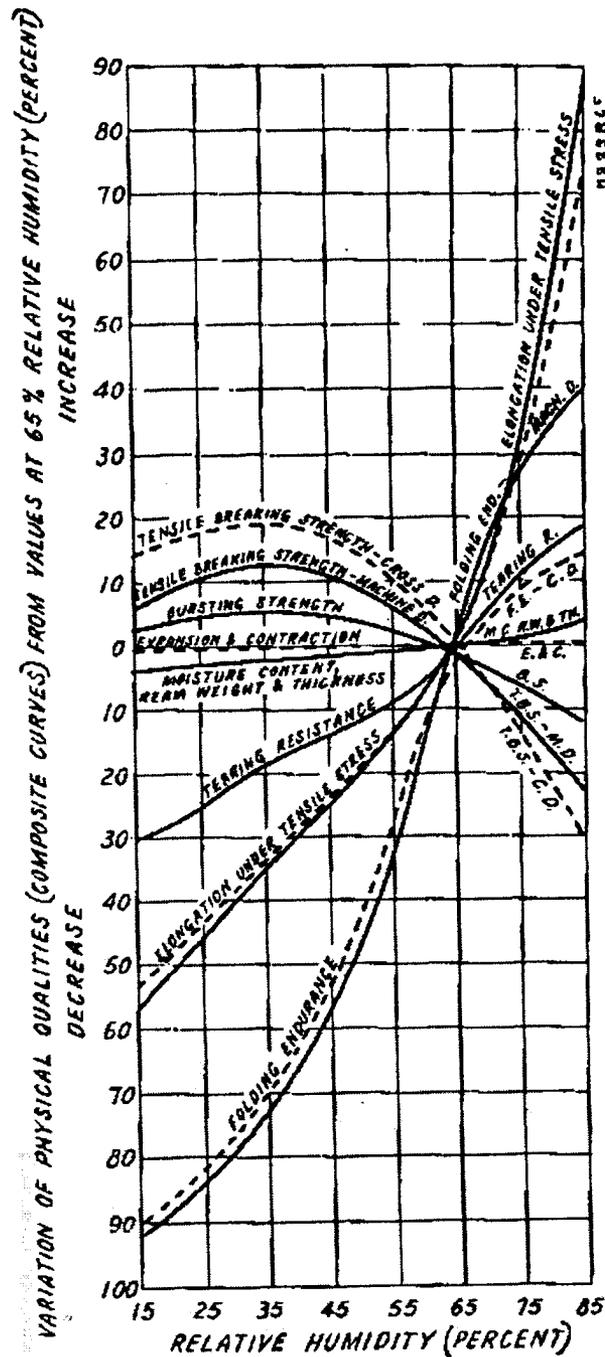


Figure 4. Variations of physical qualities of kraft paper from values based on 65% RH.

strength and stiffness decrease as moisture content increases, while properties related to toughness or ductility increase while moisture increases.

Research at the FPL is focused on measuring the mechanical and physical properties of panels made from a variety of fibers that have been pressed and dried using different processing schemes. We will attempt to correlate mechanical and physical properties with fiber type and processing conditions. The resulting information can be used to model and design a pulp molded

structure based on performance needs that can be used to specify appropriate process conditions and fiber type or mixture.

Experimental Methods

Fiber Furnish

Three fiber types were used for this study: old newsprint (ONP), old corrugated containers (OCC), and a commercial furnish (COM). The ONP was obtained from a local newspaper company. Glossy inserts were removed from the ONP prior to pulping to maintain a more consistent mixture of the fiber type. The OCC was obtained from the FPL shipping department. Both ONP and OCC were pulped using a small laboratory Valmet high-consistency (10%) hydropulper for 40 minutes in warm water. The commercial pulp molding furnish was shipped to FPL and dewatered to 36% consistency for cold storage.

Processing Method

Fiber sheets were formed using a 19- by 19 inch (48.3- by 48.3-cm) forming box. The target sheet weight was 0.088 lb/ft² (430 g/m²). A consistency of 0.33% was used for forming. The sheets were wet-formed with no dewatering press prior to press drying. Initial moisture content averaged around 84%. After forming, each sheet was placed between two fine bronze screens and two aluminum cauls. The sheets were pressed to a specific thickness until dry in a 324°F (162°C) hot press. Target densities were 15.6, 31.2, 46.8, and 62.4 lb/R³ (250, 500, 750, and 1000 kg/m³). After drying, the sheets were cut in half. Half of the sheets were placed in a room maintained at 50% RH-72°F (22°C) and the other half in a 90% RH-80°F (22°C) conditioning room. Equilibrium moisture content for the samples in the conditioning rooms was 5.7% and 11.1% for the 50% and 90% RH conditioning rooms, respectively.

Testing

The test results reported here are from a non-destructive testing method that uses a stress wave flight-of-time to calculate sonic MOE. Strips, nominally 1.5 inch (3.2 cm) wide, were cut from each half-sheet in each conditioning room. A piezoelectric sensor and a computer data acquisition system were used to measure the time of flight for a stress wave to travel down and back (Ross et al. 1994). Sonic MOE correlates well with tensile MOE. The sonic MOE values were calculated using the formula

$$SMOE = V^2 d c (1/g)$$

where

$SMOE$ = sonic modulus of elasticity, GPa (lb/in⁴),

V = velocity, m/s (in/s),

d = density, kg/m³ (lb/in³),

c = conversion factor, N/kg (Setterholm 1976), and

g = gravitational constant, m/s (in/s).

This method is quick and could be used with pulp molded structures for estimates of material properties and quality control. This same technology is used in the paper industry for online quality control on and off the paper machine (Lindblad 1995). Additional tests are planned to measure tensile MOE and Poisson's ratio in-plane and through the thickness.

Results and Discussion

The following results are particular to the method of processing used for this study. Higher or lower values may be obtained by changing the processing parameters. It was beyond the scope of this study to cover all the various processing parameters. Further studies will be conducted to evaluate other processing parameters and their effects on properties.

Figure 5 shows the combined results of all the data points. The groupings show significant differences for specimens tested at 50% and 90% RH. However, the three different fiber furnishes tested within the same RH conditions showed no significant difference. Although the fiber types are quite different, the density of the finished product seems to eliminate significant differences in MOE. This implies that if a process were used to produce products with similar densities from different fibers, the stiffness properties of the products would be similar.

Figure 6 shows quadratic regression lines of best fit for all the data at the 50% and 90% RH conditions. As mentioned previously, these types of curves would be useful for determining estimated MOE values for finite element modeling purposes for a given process for a pulp molded structure at various densities.

Figure 7 compares sonic MOE values at 50% and 90% RH. MOE shows a linear trend for all densities. However, the trend is not linear or proportional for specific sonic MOE values. At low density (20 lb/ft^3 (320 kg/m^3)), sonic MOE values for sheets conditioned at 90% RH were approximately 16% less than sonic MOE values of sheets tested at 50% RH. As density increased to 55 lb/ft^3 (880 kg/m^3), the sonic MOE values at 90% RH were approximately 30% lower. This non-proportional reduction in sonic MOE was not expected. We would have assumed a proportional decrease over the range of densities. Further work is needed to determine the effects of moisture with increase in density.

These MOE results are preliminary since true mechanical properties will need to be measured using destructive methods. However, it is hoped that curves such as these for sonic MOE or other nondestructive methods might be used to correlate mechanical and physical properties without having to conduct an extensive testing program. The goal is to obtain the full range of mechanical and physical properties as a function of density and process that could be used for computer modeling, analysis, and design. If this is possible then we take another step to shifting the design of pulp molded products from an art to a scientific approach.

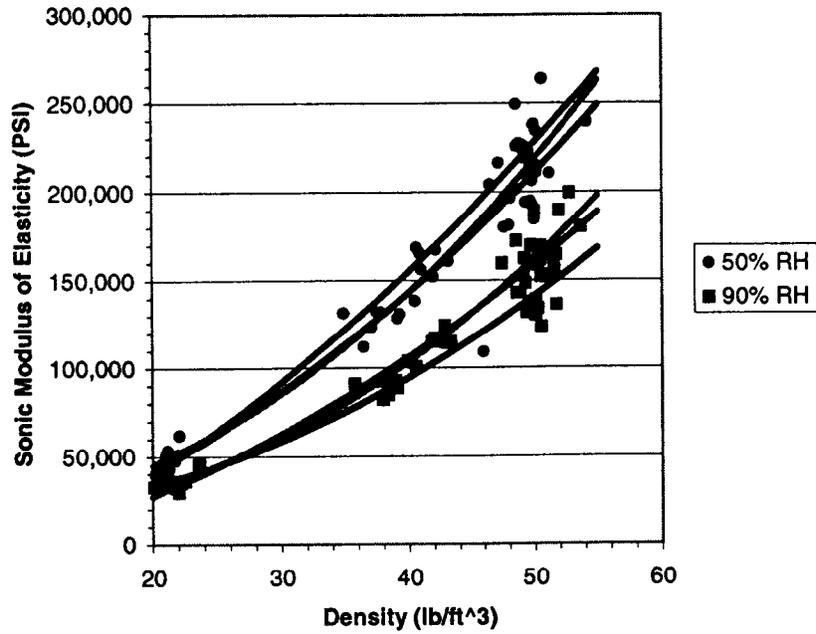


Figure 5. Sonic MOE as a function of density for all data at 50% and 90% RH conditions.

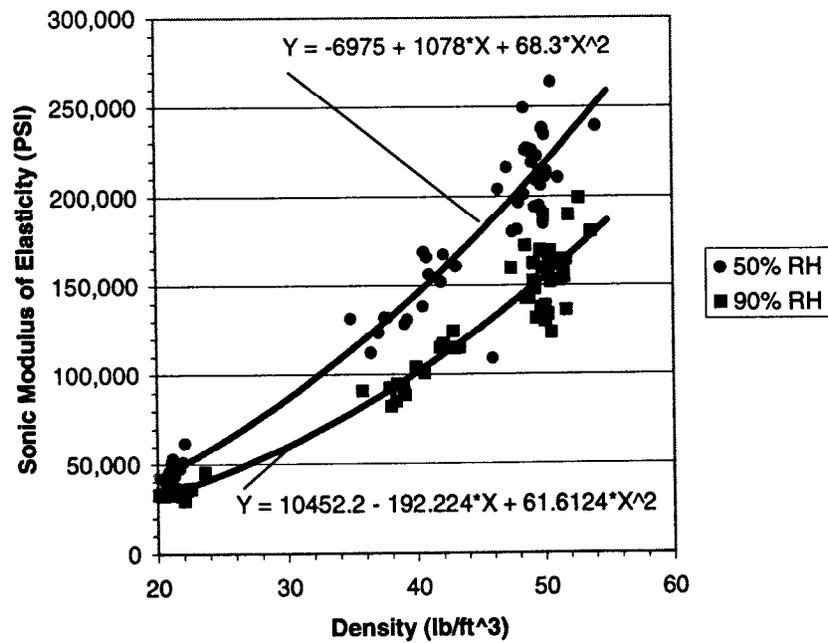


Figure 6. Sonic MOE as a function of density for all data at 50% and 90% RH conditions and quadratic regression lines of best fit for each fiber furnish.

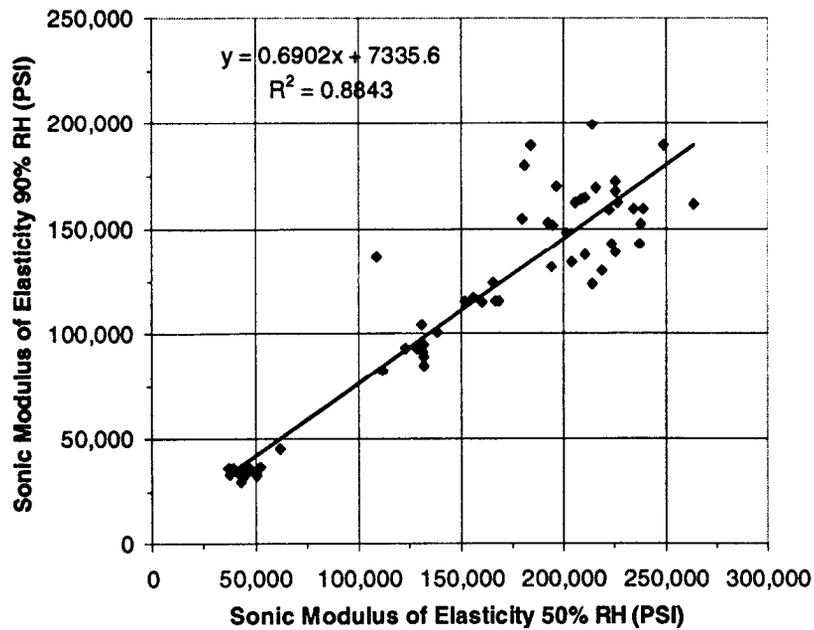


Figure 7. Comparison between sonic MOE at 50% and 90% RH showing a near-linear reduction in stiffness.

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=== SEMINAR PROCEEDINGS ===

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