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PART I - MODELING DRYING OF THREE-DIMENSIONAL PULP MOLDED STRUCTURES - EXPERIMENTAL PROGRAM

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ABSTRACT

Researchers at the USDA Forest Products Laboratory have developed a new three-dimensional structural panel, called FPL Spaceboard. This panel is formed using a U.S. patented three-dimensional mold capable of using a variety of fibrous materials with either the wet- or dry-forming process. Structurally, the panel departs from the traditional two-dimensional panel by integrally forming vertical ribs and face in one structure. In the literature, significant work has been conducted to model drying of two-dimensional panels, but no known work has been done on such a three-dimensional integral structure. To optimize the drying efficiency and structural performance for this type of panel, there is a need to understand the complex drying process that occurs within this new panel.

This paper is the first of three to discuss the modeling work. In this paper, the experimental data from two drying processes are presented. The first drying process, Condebelt, was developed by Jukka Lehtinen, Valmet, FINLAND. The second process used was two-sided drying in a conventional hot press.

INTRODUCTION

Molded pulp products are special wood fiber composites made from virgin or recycled fibers bonded naturally or with the use of binders. One such product or process is called FPL Spaceboard (Setterholm, 1985) which was developed by the USDA, Forest Products Laboratory (FPL). The basic structure for FPL Spaceboard can be described as an integrally formed three-dimensional structure having one flat (smooth) side and a structural rib pattern on the other side. A variety of structural panel configurations and sizes can be made using this process ranging from 0.3 mm to over 50 mm thick. One panel configuration uses two sheets glued together rib-to-rib to form a board with flat faces on both sides and a cellular interior, see figure 1.

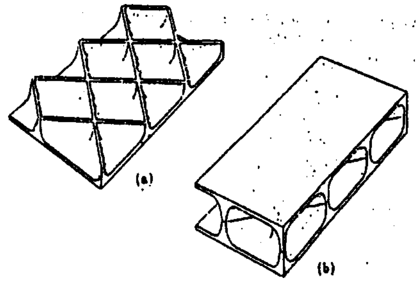


Figure 1. Spaceboard sample

Currently, FPL Spaceboard technology is being used to make 1.0 to 1.5 cm thick panels for use in office furniture (Scott et al., 1995a) and material handling applications (Hunt et al., 1997). Spaceboard has also been shown to have sufficient strength potential for use in heavier construction such as floor and roof panels (Scott et al., 1995b). In thinner configurations, it can be used in a wide range of packaging applications (Hunt et al., 1988).

The FPL developed this processing method to three-dimensionally form, dewater and consolidate, and dry fibrous sheets for improved material and structural efficiency. The key component is a forming screen with an array of resilient silicone pads attached to it. The fibers form in and around the silicone pads and are pressed and dried on the forming screen. To provide maximum inter-fiber bonding, hence panel strength, it is essential to provide some level of continuous Z-direction pressing force during drying. As pressure is applied, the silicone rubber pads deform vertically but expand horizontally to apply a pressing force on the fibrous ribs.

The current method of drying Spaceboard requires long drying times in a static hot press. To increase production, continuous press dryers and new dryer configurations to accelerate the drying time need to be developed. One continuous drying method, Condebelt (Kunnas, 1993), may provide improved drying rates for Spaceboard production. The principle of the process is as follows: A wet web is placed on a permeable wire between two steel plates. The top plate is heated and the bottom is cooled. The heat and mass transfer is based on the so-called heat pipe effect (Lehtinen, 1992), with the exception that the condensate is not allowed to move back to the evaporation zone. In a heat pipe, condensate return is necessary for continuous operation. Before the drying process starts, air is removed from the pores of the wet web and from those of the wire. When Z-direction pressure is applied, the hot metal plate contacts the wet web causing the water to pass through the web and the wire to condense on the cooled metal plate. This process has been shown to be a very efficient process for paper.

Many physical processes occur simultaneously and interact during hot pressing. The interacting processes include heat conduction, phase change of water, and convection. These are all complicated by the changes in thermal conductivity, permeability of the fibrous mat, and by continual loss of water during the drying process. The result is a complex three-dimensional variation in temperature, moisture content and vapor pressure with time. The only hope of understanding the system lies in mathematical modeling.

A model to simulate the heat conduction, the phase change of water, and the convection must incorporate such material properties as the thermal conductivity and the permeability, and their influence on density, temperature and moisture content of the mat throughout the drying cycle. The experimental program and data which will be used for mathematical modeling using the finite element method of analysis are presented.

EXPERIMENTAL

Two drying methods, Condebelt and conventional two-sided heating, were used for this experiment to study three-dimensional drying effects. In both methods, we used the same three-dimensional mold to measure temperature during drying. The overall size of the forming screen was 228.6 by 228.6 mm. An array of silicone pads was arranged in a nominal 25.4 mm square pattern. After forming, thermocouples were placed in specific locations in and around the fiber mat. For the Condebelt drying method, we only used thermocouples in location nos. 1, 2, 3, and 5. For the conventional drying method, three additional thermocouples (4, 6, and 7) were used, see figure 2 for the thermocouple locations.

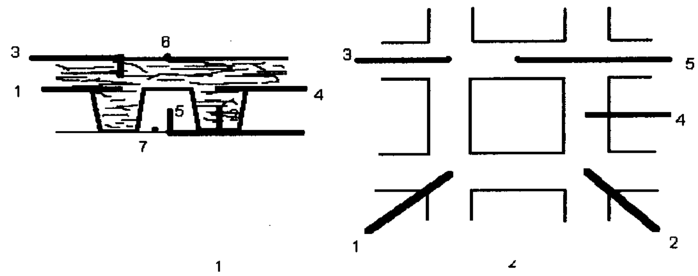


Figure 2. Location of thermocouples (Condebelt 1, 2, 3 and 5, conventional all)

Fiber for the experiments were hydropulped at FPL from recycled old corrugated container fibers. After hydropulping, the fibers were kept moist and stored in a cold room. The mats were formed by mixing 85 g of fiber (dry weight) with water to make a 0.4 % consistency fiber/water slurry. The slurry was poured above the mold, agitated, then formed with vacuum assistance. After forming the mat was wet-pressed using 9 bar pressure for 1 minute. After wet pressing, the mats had 130 to 140 % (dry basis) moisture content. The thermocouples were inserted into the mat after the mat had been wet-pressed.

The drying parameters for both processes are shown in table 1. For the Condebelt process, six top and bottom platen temperature combinations, four pressures, and several drying times were used for the drying parameters. For the conventional process, two temperatures, three pressures, and several drying times were used for the drying parameters. The Condebelt process data was obtained using static laboratory equipment in Valmet's Inkeroinen, FINLAND facility. The conventional process data was obtained using static laboratory equipment in FPL's facility.

In addition to the temperature vs. time data we calculated overall moisture content vs. time. For the conventionally dried mats, we also measured rib density through the thickness of the mat and sonic elastic modulus of elasticity across the flat face. Overall moisture content was obtained by measuring the weight of the mats before and after hot-pressing and at oven-dry conditions. We measured fiber density through the thickness of the ribs. The mat density through the thickness was calculated from fiber weight per layer and physical dimensional measurements. Weight per layer was obtained by weighing 101.6 by 101.6 mm square sections from each specimen before and after grinding each of 8 layers off the ribs. Physical dimensions were obtained from microscope photographs taken at each layer and from an overall cross section microscope photograph. Sonic modulus of elasticity across the flat face was obtained using stress wave velocity calculated from:

$$E=\frac{\upsilon\ dc}{g} \tag{1}$$

where V = velocity (m/sec), d = density (kg/m^3), c = conversion factor (N/kg), and g = acceleration (m/sec^2).

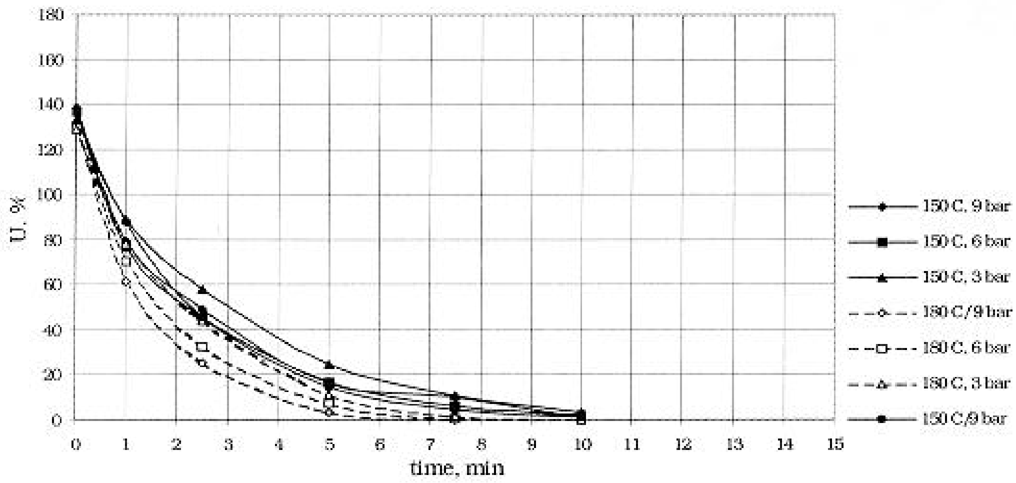
Table 1. Drying parameters used for the Condebelt and conventional drying experiments.

Condebelt Pressing					Conventional Pressing			
mat no.	Hot temp. °C	cold temp., °C	Pressure, bar	time, min.	mat no.	temp °C	pressure, bar	time, min.
6	100	40	3	5	1	150	9	1
7	100	40	3	12	2	150	9	2.5
8	100	40	3	12+7	3	150	9	3.5
9	180	40	3	5	4	150	9	5
10	180	40	3	10	5	150	9	7.5
11	180	40	9	5	6	150	9	10
12	180	40	9	10	7	150	6	1
13	180	40	6.4	5	8	150	6	2.5
14	180	40	9	5	9	150	6	5
15	180	40	9	10	10	150	6	7.5
4	180	40	9	5	11	150	6	10
5	180	40	9	5	12	150	6	1
16	180	100	7.5	5	13	150	3	2.5
17	180	100	7.5	10	14	150	3	5
18	180	100	7.5	15	15	150	3	7.5
19	180	100	6	15	16	150	3	10
20	180	100	6	10	17	180	9	1
21	180	100	6	5	18	180	9	2.5
22	180	100	6	15	19	180	9	5
23	180	100	6	10	20	180	9	7.5
24	180	100	6	5	21	180	9	10
25	180	100	3	15	22	180	6	1
26	180	100	0.3	15	23	180	6	2.5
27	180	100	6	7.5	24	180	6	5
28	180	100	6	3.5	25	180	6	7.5
29	180	100	6	7.5	26	180	6	10
30	150	60	6	7.5	27	180	3	1
31	150	60	6	15	28	180	3	2.5
32	150	60	6	7.5	29	180	3	5
33	150	60	3	15	30	180	3	7.5
34	150	60	3	7.5	31	180	3	10
35	180	60	6	10	Temp1	150	9	10
36	180	60	6	5	Temp2	150	6	10
37	180	60	3	10	Temp3	150	3	10
38	180	60	3	5	Temp4	180	9	10
41	180	100	3	7.5	Temp5	180	6	10
					Temp6	180	3	10

RESULTS AND DISCUSSION

The following figures 3, 4, 5, and 6 are presented here as selected data collected for this study. Figure 3 shows drying moisture content vs. time for the conventional drying process. As temperature and pressure increases, moisture content loss vs. time is constant until the breaking point on the curves. The breaking point of the drying curves is between 2, 5 and 5 minutes for 180 °C and between 5 and 7, 5 minutes for 150 °C. Figure 3 also shows the effect of pressure, as pressure increases moisture content (U) vs. time decreases.

a)



b)

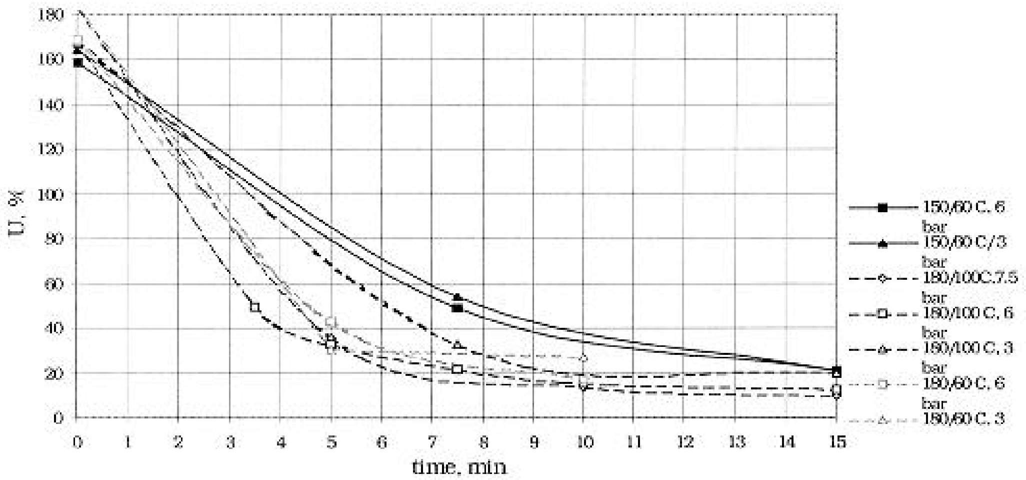


Figure 3. Drying curves for conventional drying (a) and condebelt drying (b)

A typical temperature vs. time curves (Condebelt: 180/100 °C, 7.5 bar; conventional: 180 °C, 9 bar) are shown in Figure 4. Thermocouple no. 3 located just beneath the flat surface heated up very fast for both processes. For conventional drying, thermocouple no. 5 showed similar temperature rise as no. 3. For Condebelt drying we observed a large temperature gradient through the thickness of the mat for almost the entire drying time. However, the conventional drying process posed a more complicated interaction. For example, in the first two minutes thermocouples 1/4 and 2/5 show similar values, because these are at similar level within the rib (1 and 4 at the bottom, 2 and 5 at the middle of the rib). After two minutes, under these drying parameters, the temperature relationships change significantly. The temperature for thermocouples 1, 4, and 5 actually decreases for a time before they rise to the platen temperature. Thermocouple 5 is the first to start heating up again. This thermocouple was placed in the middle of the rib. Thermocouples 1 and 2 show the lowest heating rate after the initial temperature rise. These two thermocouples were placed in the intersection of the rib, which is the location of the lowest density. It’s possible that a significant amount of moisture or fluid was either forced into or moisture condensed in this region of lower density. The temperature raises again after the moisture content is below about 20 %. A similar phenomenon can be seen on the Condebelt temperature curves.

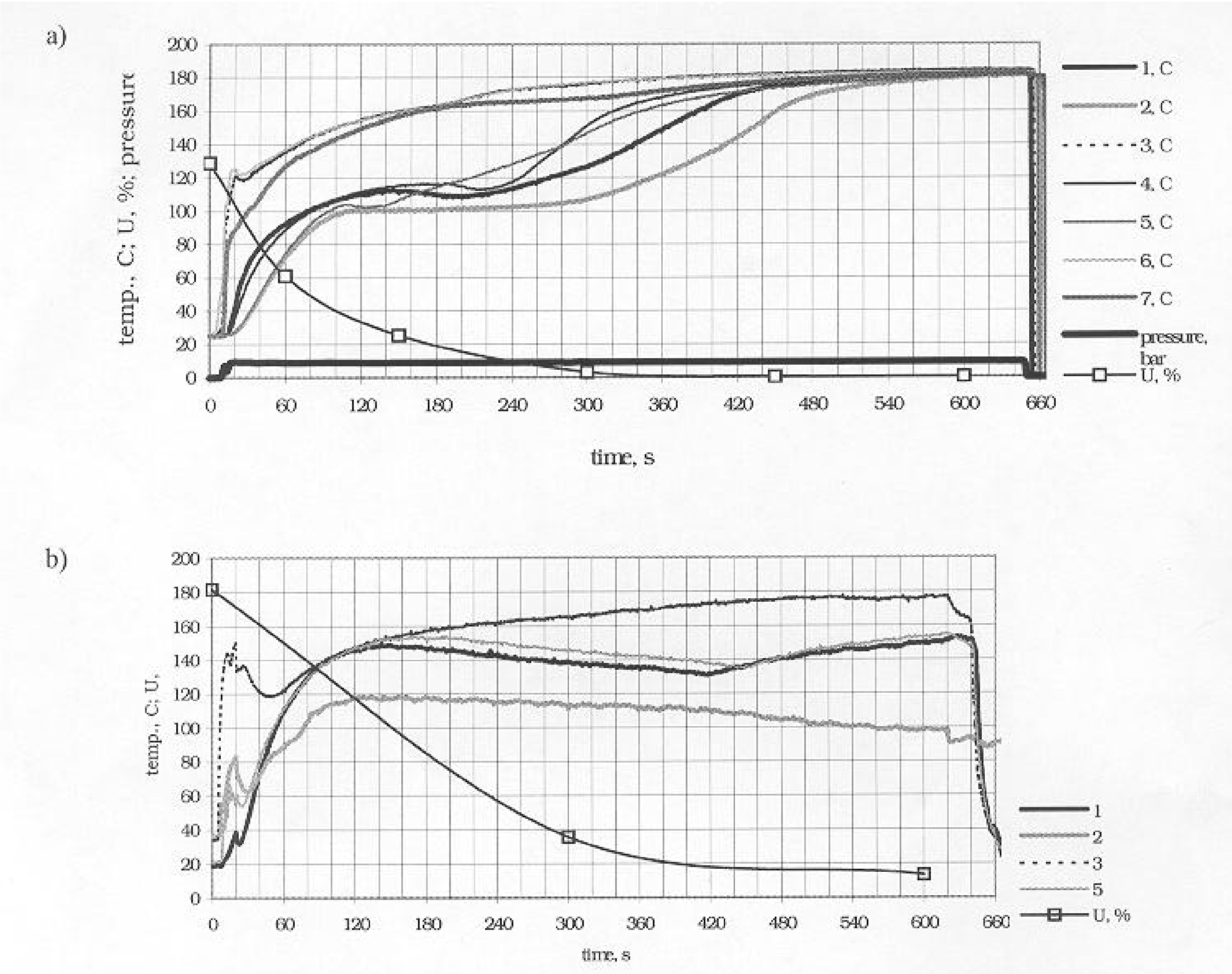


Figure 4. Temperature curves, a) conventional drying, b) Condebelt drying.

The results of the density measurements are shown in Figure 5. The density varies between 0.45 and 1.05 g/cm^3. The highest density value is in the flat sheet. At the bottom of the ribs, average density is a minimum and is primarily located at the intersection of the ribs. Rib density at the intersection increased with pressure. The density increased in the direction toward the top of the rib. In the last layer, on top of the rib, the density is again lower. Rib density information is critical in estimating heat and mass transfer equations. We believe mold geometry significantly influences the density development for the rib. These results show the need for improved mold design to help eliminate low-density areas. Improved mold design would provide more uniform rib densification.

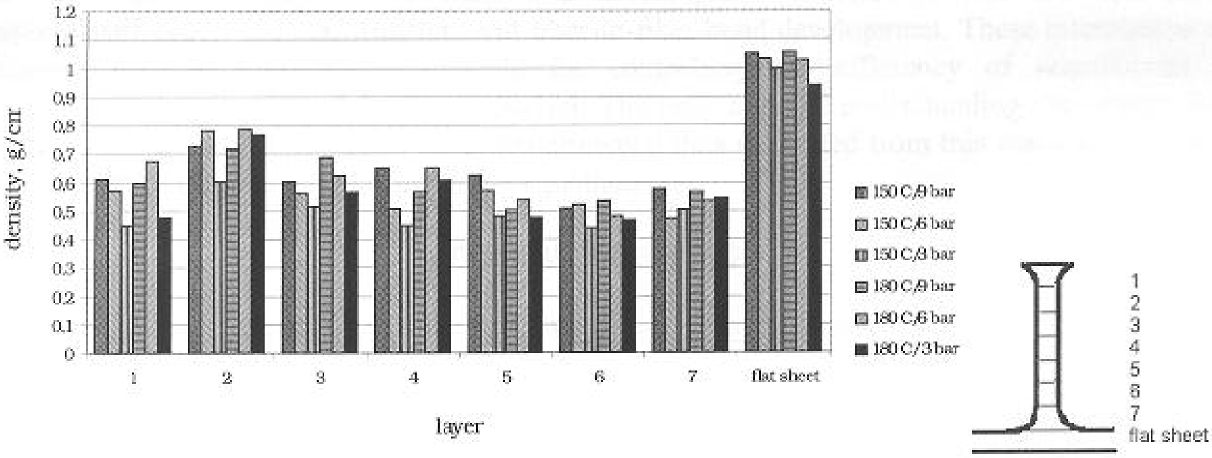


Figure 5. Conventional drying density distribution, 180 °C, 9 bar, 10 minutes.

The sonic modulus of elasticity is a parameter to compare the strength of the samples (Figure 6). The modulus increases with drying time until 7.5 minutes. There is no significant difference between the samples dried at 150 °C and 180 °C. We have found sonic modulus correlates well with critical drying moisture content for property development for the fiber structure. The measurements relate primarily to the critical drying time for the flat face rather than the entire structure, because the stress wave was only measured across the face.

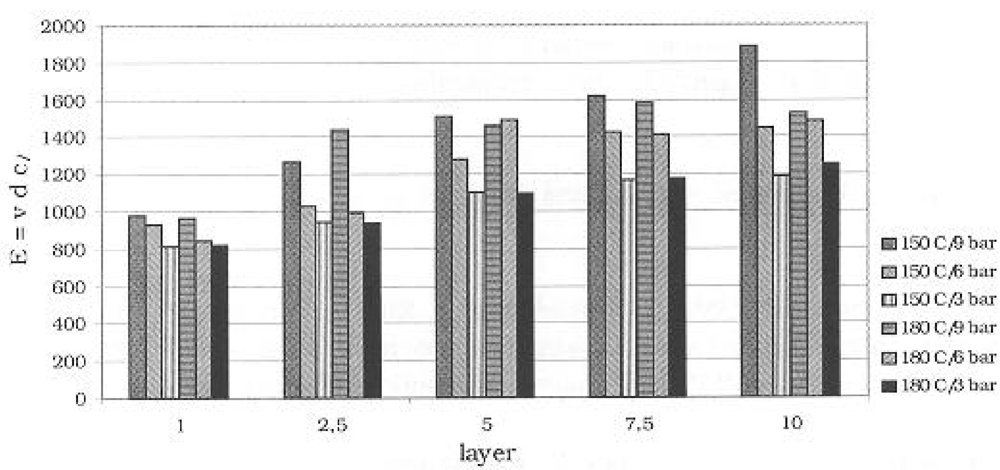


Figure 6. Sonic modulus of elasticity.

The Condebelt drying method did not give the expected faster drying rates. We believe the slow drying rates may be due to energy used to heat the mass of the silicone pads and significant condensation on the internal areas of the silicone pads during the initial stages of drying. However, the temperature measurements still provide useful information concerning the drying process inside the web that will be used in modeling three-dimensional drying.

CONCLUSION

Three-dimensional fiber based composite materials have potential in an ever widening range of applications. The realization of this potential depends on improving the processing and properties of this material. This can only happen if we understand the complex interaction of mass and heat transfer, viscoelastic plastification and densification, and fiber-to-fiber bond development. These interactions must be examined, because they are responsible for controlling the efficiency of manufacture and physical/mechanical properties of the fiber material. The only hope of understanding the system lies in mathematical modeling. The complete set of experimental data generated from this study will be used to help formulate finite element analysis modeling equations.

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