A MODEL TO PREDICT THE DENSITY PROFILE OF PARTICLEBOARD

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ABSTRACT

Certain mechanical properties of particleboard panels depend on the density variations that occur through the panel thickness (density profile). Particleboard density profiles result from the felting and hot pressing operations. Repeatedly altering a commercial particleboard manufacturing process to produce a predetermined density profile is undesirable from economic and production standpoints. An analytical tool to predict density profile as a function of the manufacturing processes was needed. Computer simulation modeling was employed to satisfy this need. A multilayer description of the density and moisture gradients resulting from the felting process provides input for this model. Inputs for the pressing process include platen temperature and press closing rate.

The model simulates the physical and mechanical processes that occur in the press and mat system. Heat conduction, gas transport, layer compaction, and water phase changes were included in the model. Thermal properties were taken from the literature, and gas transport properties required approximation.

A steeper density gradient with increasing platen temperature was predicted by the model. This result conforms to general expectations. Changes in press closing rates resulted in model-predicted density profiles that contradict the expected pattern. The probable reason for this effect is that the core layers remained at or near the ambient temperature, and the maximum mat resistance increased as closing rate increased. Simulation of an initially uneven moisture gradient resulted in increased heat penetration, as expected.

Keywords: Particleboard, density profile, simulation modeling.

INTRODUCTION

The objective of this study was to predict the density profile of a pressed, unsanded, conditioned particleboard through the use of computer simulation modeling. Toward this end, the hot pressing operation has been modeled. Many pressing and furnish parameters have been included as variables so that the complexity of popular manufacturing methods may be modeled. Knowledge of how these variables interact to produce a density profile can aid in the engineering of various mechanical properties into particleboard. Intended users of this model are researchers at forest products facilities and process engineers at particleboard plants.

Methods for physically measuring density profile may be classified as either direct or indirect. Virtually all direct methods may be described as gravimetric (i.e., weighing the sample is necessary). Gravimetric methods usually require the repeated removal of panel material via sanding. However, Stevens (1978) devised an apparatus that slices layers as thin as 1 mm. Indirect methods include measuring radioactive wave or particle opacity of the material and determining the density

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profile by relating these characteristics to density. The use of X-ray radiography to indirectly examine the density profile of particleboard has been described by Nearn and Bassett (1968). Further processing of these radiographs by a computer densitometer was described by Steiner et al. (1978). Laufenberg (1984, 1986) described the use of gamma radiation as another means of indirectly measuring density profile. For the purposes of quality control in commercial particleboard plants, layer density is usually measured by gravimetric methods, though indirect methods are faster and more precise. Even with an accurately measured density profile, altering the press cycle or furnish characteristics so that the profile is changed to meet predetermined specifications is essentially a trial-and-error process. One or more changes are usually made to the press cycle or furnish based upon mill experience. This process may be repeated a number of times before the resulting density profile meets the specification.

To improve the efficiency of this process, a prediction of density profile was needed. Computer simulation was used in this study for that purpose. A computer simulation is simply a program that acts as a real system. Events and reactions that occur in a real system will appear to occur in the computer model. With simulation, experimentation with a system can be performed quickly and inexpensively because experimental changes to the real system are not made. Rather, changes are simulated in the model, and the model predicts system responses to these changes. Later, changes can be made to the real system with greater confidence that the desired result will occur.

BACKGROUND AND RELATED STUDIES

A number of researchers have investigated the effect of density profile on various mechanical properties of particleboard. Shen and Carroll (1969, 1970) measured the torsion-shear of individual layers of particleboard and found a strong linear relationship between layer density and torsion-shear. They also found that torsion shear had a high correlation with internal bond strength when measured in the central plane.

Strickler (1959) examined a large number of manufacturing methods that affect the physical and mechanical properties of Douglas-fir flakeboard. The modulus of rupture (MOR) appeared to be closely correlated with the density of the first intermediate layer beneath the surface. Kieser and Steck (1978) worked with oriented strand board and found that MOR was affected by density profile and that optimizing press conditions could increase values for that property. In presenting an on-line thickness measurement technique for particleboard, McCarthy and Steffens (1980) showed that knowledge of the precured surface layer of particleboard would have significant influence on production and economic returns by allowing for proper sanding.

Strickler (1959) determined how press cycle, moisture content, and moisture distribution qualitatively affected properties of Douglas-fir flakeboard during pressing. Press temperature controlled the rate of heat conduction from platen to board surface. Vaporization of moisture caused heat convection as vapor migrated toward the lower-pressure board center. Moisture plasticized the wood particles and allowed for greater compaction and increased layer density. In other research, Engels (1978) showed that a change in glue recipe and press cycle could alter the density profile and suggested that the three were inextricably linked.

Smith (1980) noted that moisture removal from the board edges in the form of steam dissipation was a function of particle geometry. Flat particles used in flakeboard attained a horizontal orientation and molded together during pressing to provide few channels through which steam could pass. When compared to conventional particleboard or medium-density fiberboard, steam dissipation was slow and long press times were required. The resulting density profiles were relatively flat.

Suchsland (1967) theorized that horizontal density distribution was binomially distributed, and concluded that a particleboard mat was essentially a series of veneers, and that the difficulty in achieving good glue bonding was then similar to the difficulty in achieving good gluelines in plywood.

Analytical models of particleboard manufacture have thus far not concentrated on manufacturing methods, but rather have been used in analyzing economic situations that control the allocation of resources and selection of product lines. One exception is the mathematical model PARVCOST which considered wood, chemical, and energy flows within an operating flakeboard plant (Harpole 1979). The products within the model were distinguished by their profit contribution. Another model developed by Plumb et al. (1980) used numerical modeling for the convective drying of small wood particles. The model considered the wood loading method, gas temperature, gas velocity, and wood moisture content. The primary concern addressed by the model was dryer-efficiency as affected by the variables mentioned. Particle moisture variability was not considered.

RESEARCH METHODS

The formation of a density profile results from the interaction of temporally and spatially varying quantities acting within a material environment. Such a system is amenable to description by digital computer simulation.

The model is composed of a compiled FORTRAN simulation program and a compiled BASIC graphic output program. The simulation program was developed on a UNIVAC 1100/74 computer and adapted to an IBM Personal Computer. The user enters data by responding to program requests. The inputs required from the user describe press cycle, mat and furnish characteristics, and target density of the resulting board. Outputs include dynamic profiles of layer-temperature, layer-moisture content, and layer-density that are updated at specified time intervals during a simulated press cycle. Graphic sequences of dynamic profiles may be viewed on the computer screen upon completion of a simulated press cycle. Outputs also include a final density profile that represents the layer-density of a board at the end of a simulated press cycle. Final density profiles may be viewed on the computer screen in graphic form or may be printed in numeric form. A schematic diagram of the simulation inputs, outputs, and processes is displayed in Fig. 1.

The model depicts the closing of a single opening, constant-temperature hydraulic press. The closing process was modeled as a series of closing stages. A stage is distinguished by input values for ram area, power supply, and rate of closure. Termination of a stage occurs when maximum cylinder pressure is realized. Other inputs needed for a press cycle description are: initial mat temperature, press temperature, open time, and closing time parameters. Initial mat temperature refers to the temperature of the particles as they enter the press. The

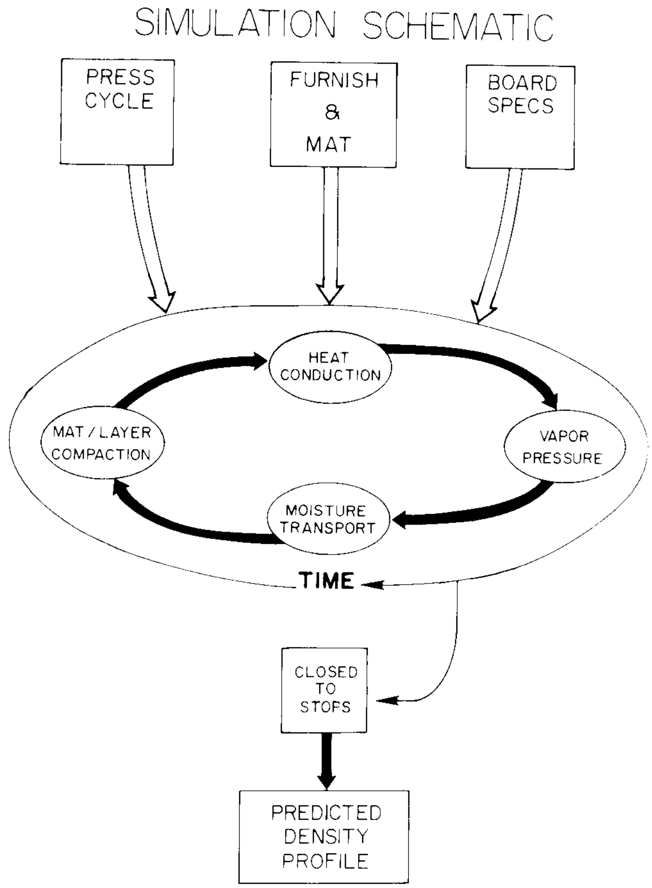

FIG. 1. Schematic of user inputs and simulation.

press temperature is the temperature of the press platens and is presumedly constant. Open time extends from the moment the mat rests on a platen to the moment the upper platen first contacts the mat. Closing time begins when the open time ends and extends to the moment the board reaches final thickness.

An accurate description of the mat as it enters the press is critical to the prediction of a density profile. A mat must be described as a series of levels. A level consists of two or more mat layers positioned symmetrically with respect to the center plane of the mat. Mat layers within a level must be homogeneous and identical with respect to moisture content, bulk density, and specific gravity. While a variety of species may be used, an average density value for the mixture must be input. A change of species or species mix within a mat that measurably changes the bulk density or specific gravity must be noted. Required inputs for a board description are target density, stop thickness, and board area. The area must be that of the mat in the press. Pressed thickness is achieved when the stops are reached.

At the end of any simulated press cycle, the predicted density profile represents layers of different temperature and moisture. Since both temperature and moisture affect the density of layers, a final conditioning step was added to provide uniform temperature and moisture in all layers regardless of press or furnish conditions. This step was modeled by adjusting the layers to a standard equilibrium condition (70 F and 65% relative humidity). Conditioning allows valid comparison of predicted density profiles between multiple runs of the model.

Heat conduction

The primary means of heat transfer is that which occurs due to heat conduction between the press platens and the particle mat. Heat transfer occurs along a line perpendicular to both platens. Strictly speaking, this presumes that the model panel is infinitely long and wide so that no other panel boundaries exist. It is also assumed that constant platen temperature is maintained.

Heat conduction between platens was described by Siau (1971) and an expanded form was used in the model:

$$c_p * D * \frac{\partial T}{\partial t} = \frac{\partial K}{\partial x} * \frac{\partial T}{\partial x} + K * \frac{\partial^2 T}{\partial x^2}$$

where:

t = time, sec
T = temperature, Kelvin
x = location, meter
K = thermoconductivity, Watt/(meter*Kelvin)
D = density, kg/(meter)^3
c_p = specific heat, Joule/(kg*Kelvin)

The model board was constructed of 30 layers, and finite difference equations were used to represent the partial derivatives:

$$\frac{\partial T}{\partial t} = \frac{T^*(i) - T(i)}{\Delta t}$$

$$\frac{\partial^2 T}{\partial x^2} = \frac{T(i + 1) - 2 * T(i) + T(i - 1)}{\Delta x^2}$$

$$\frac{\partial K}{\partial x} = \frac{K(i + 1) - K(i - 1)}{2 * \Delta x}$$

$$\frac{\partial T}{\partial x} = \frac{T(i + 1) - T(i - 1)}{2 * \Delta x}$$

where:

Δt = change in time (increment), sec
Δx = change in avg. element thickness, meter
T = current temperature, Kelvin
T^* = next temperature, Kelvin
i = element number

Lewis (1967) studied the effect of density and temperature on the thermoconductivity of particleboard and was able to describe the relation as:

$$K = 0.018152 + 0.0001484*D + 0.0001441*(T - 297)$$

where:

K = thermoconductivity, Watt/(meter*Kelvin)
T = temperature, Kelvin
D = density, $kg/(meter)^3$

This equation was used in the model to update thermoconductivity for each simulation increment.

Specific heat was calculated via a method of mixtures. The mixture in this case was water and wood. The specific heat of water was assumed to be constant, while that for wood varied with temperature. A specific heat equation developed by McMillin (1969) for loblolly pine was used:

$$c = 0.0115321 + 0.0009497*T$$

where:

T = temperature, Kelvin
c = specific heat, cal./(g*Kelvin)

Specific heat of wood was used in the model to calculate temperature change within the mat.

These finite difference equations do not explicitly describe the isothermal phase change of water at its boiling point. Some intervention was necessary to model this event. Though proper use of the finite difference equation requires that the surface elements come to an instantaneous equilibrium with the heat source, these layers also remain at the boiling point until all moisture has evaporated. When the temperature of a layer exceeds the boiling point of water, any additional energy is applied to the evaporation of moisture, and the temperature of the layer is set to 373.1 K. When all the moisture is evaporated, the layer is once again allowed to change temperature as governed by the finite difference equation.

Mat compaction

In its simplest form, a press cycle is simulated by use of a single constant closing rate. Multiple rates of closure may be simulated if the user specifies the hydraulic cylinder pressure(s) at which closing rate changes. Hydraulic pressure, P, is calculated in the model at each time increment by the equation:

$$P = P_r*A_m/A_r$$

where:

P_r = resistance pressure, psi
A_m = mat face area, $in.^2$
A_r = ram (cylinder) area, $in.^2$

The closing rate may become variable if power limitations are encountered. The power required to maintain a specified closure rate is calculated by:

$$Power = P_{ar}*A_m*D/\Delta t$$

where:

P_{ar} = average mat resistance, psi
A_m = area of mat face, in.^{2}
D = incremental displacement, in.
Δt = change in time (increment), sec

If the power required to maintain the closure rate is greater than that available, then displacement is calculated by solving the power equation for displacement by using the maximum power in the equation. With this calculated displacement, new platen position and closing rate are also calculated.

Layer compaction

Layer compaction in the model is a process of setting mat resistance pressure and compacting each layer according to empirical data until the total thickness of 30 layers matches the position of the press platen. These empirical data resulted from an experiment that was part of this research. The purpose of the experiment was to determine the stress-strain relationship for wood particle mats at various temperatures. Mats of southern yellow pine particles were felted. Those mats tested above ambient temperature were heated throughout in a press that was closed to compact the mat a small amount. An assumption made was that each layer of the mat would possess the stress-strain behavior of an entire mat. Platen displacement and pressure were recorded as the press was closed to stops. Four temperatures were used: ambient (approximately 75 F), 160 F, 200 F, and 260 F. The results showed that increasing the temperature resulted in a higher strain-to-stress ratio (see Table 1). To incorporate these data into the model, a transformation was made from stress-strain data to stress-porosity data. A critical assumption was made that given a specific stress, a specific porosity results. Porosity was defined as the ratio of the total void volume to the total volume, and was calculated considering only dry cell-wall material as solid substance. During simulation, the resistance pressure is found among the stress data for the appropriate temperature of each layer. The corresponding porosity becomes the porosity of the layer. Knowing the original porosity, the resulting strain is calculated and the layer thickness determined. Layer compaction is assumed to result in unrecoverable strain, so that a layer's density may only increase.

Gas transport

Movement of both air and water vapor within a mat during pressing was modeled. Siau (1971) derived an unsteady-state equation for gaseous flow and this equation was used as the basis for gas transport within the model.

TABLE 1. *Stress-strain data collected at four temperatures.*

Temperature: ambient		Temperature: 165 F		Temperature: 200 F		Temperature: 260 F	
Stress (psi)	Strain (inch)	Stress (psi)	Strain (inch)	Stress (psi)	Strain (inch)	Stress (psi)	Strain (inch)
0	0.000	0	0.000	0	0.000	0	0.000
250	0.503	250	0.544	250	0.574	250	0.610
596	0.686	497	0.701	491	0.705	428	0.730
760	0.728	867	0.754	628	0.727	600	0.756
901	0.755	1,163	0.781	826	0.753	796	0.783
1,289	0.782	1,392	0.795	1,156	0.780	918	0.798
1,530	0.798			1,378	0.797		

$$\frac{\partial m}{\partial t} = \frac{-K*A*M}{2*R*T}*\frac{\partial P^2}{\partial x}$$

where:

m = mass of gas, mg
P = gas pressure, Pascal
x = position, meter
t = time, sec
T = temperature, Kelvin
M = molecular wt., mg
A = cross-sectional area, $(\text{meter})^2$
R = universal gas constant, Pascal*$(\text{meter})^3$/mol*Kelvin
K = superficial gas permeability, $(\text{meter})^3$*sec/kg

During simulation, the amount of gas exchanged between adjacent layers is calculated. The sign of the result indicates the direction of gas flow. The mass of gas calculated represents both air and water vapor. These quantities are maintained separately within the model. The partial derivatives used within the model are represented by finite differences as follows:

$$\frac{\partial P^2}{\partial x} = \frac{P^2(i) - P^2(i-1)}{\Delta x}$$

Gas pressure is calculated using the ideal gas law:

$$P*V = n*R*T$$

where:

P = gas pressure, Pascal
V = volume, $(\text{meters})^3$
n = number of moles of gas
R = universal gas constant, Pascal*$(\text{meter})^3$/mol*Kelvin
T = temperature, Kelvin

The volume occupied by the gas is the void space within the layer. The initial gas pressure within all layers is assumed to be 1 atmosphere. Initially, all gas within the mat is assumed to be air. The amount, n, is calculated by the gas law equation. The temperature is not necessarily that of the surroundings, because the mat may have been formed from particles dried at a higher temperature. Evaporation, condensation, and the flow of gas will determine the molar amount of gas in a layer. Pressure is calculated after every time increment with current values for the variables in the gas law equation.

RESULTS

The expected result of changing platen temperature was realized with the model. Increasing the platen temperature produced a steeper gradient in the density profile. Figure 2 shows the model-predicted density profiles resulting from platen temperatures of 360 F (182 C) and 420 F (216 C), respectively. A higher platen temperature resulted in a density profile with higher densities near the faces, and

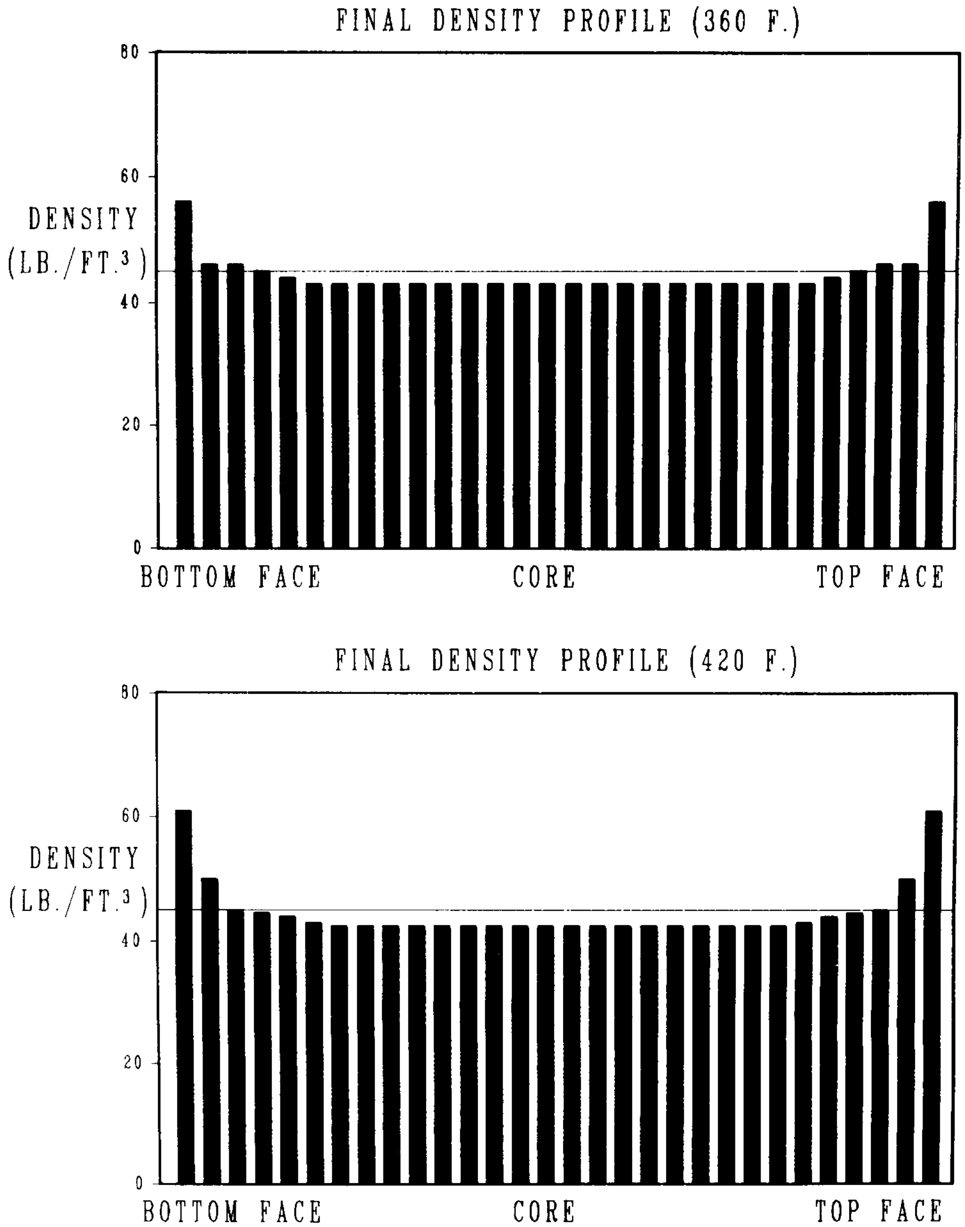

FIG. 2. Model-predicted density profiles for platen temperatures 360 F and 420 F.

lower densities within the core. The predicted face-to-core density ratio was 1.32 for the 360 F run, and 1.44 for the 420 F run.

Ten simulations were run with various closing rates in order to examine the sensitivity to this parameter. Figure 3 shows how certain layers varied in density as a function of closing rate. Data for this figure were taken from simulations at 420 F, but the pattern of change for the same layers at different temperatures (360

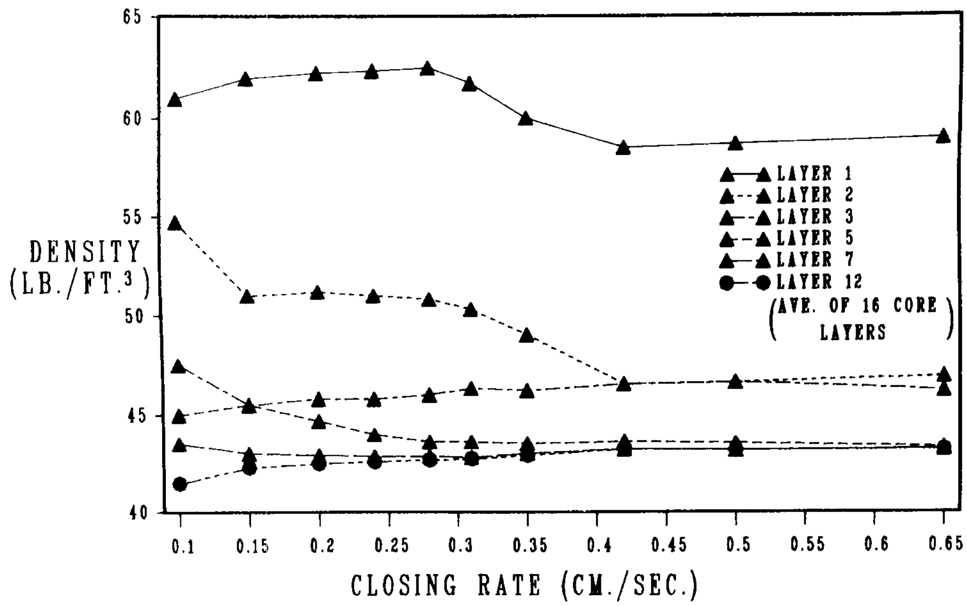

FIG. 3. Changes in density for model-predicted profile layers 1, 2, 3, 5, 7 and 12 with changes in press closing rate.

F, 380 F, and 400 F) was almost identical. Each line in Fig. 3 represents the density of one layer of the model-predicted profile except for line 12, which represents the average density for the middle 16 layers. Line 1 represents the face layer and the other lines represent layers successively more distant from the face. The model should have shown that the density of the layers near the face increased and that the density of the core layers decreased as the press closing rate increased. However, this was not observed. The layers near the face actually decreased in density and the core layers increased in density with increases in press closing rate. The probable reason for this effect is that the core layers remained at or near the ambient temperature in each of these runs, and the maximum mat resistance increased as closing rate increased. The maximum mat resistance pressure was 800 psi in the slowest closing rate and was 870 psi at the fastest closing rate. The core layers increased in density faster than did all other layers. With faster closing rates and greater mat resistance pressures, the stress range over which core layers gained density also increased. As a result of this density increase, other layers (most notably the second layer) realized a density decrease. Practically speaking, a closing rate of approximately 0.25 cm/sec is considered a relatively fast closing rate. Exceedingly fast closing rates theoretically can result in only small differences in layer densities because there is little or no heat migration to sublayers. This is what the model shows in Fig. 3 for closing rates in excess of 0.40 cm/sec.

Another simulation was run to examine the effect of initially uneven moisture gradient on model results. A furnish description was entered that created 4 layers of 18% moisture content (27% of the total mass weight) near each face. The remaining layers were at 7% moisture content. Heat penetration significantly increased when moisture distribution was uneven, and moisture vapor penetrated

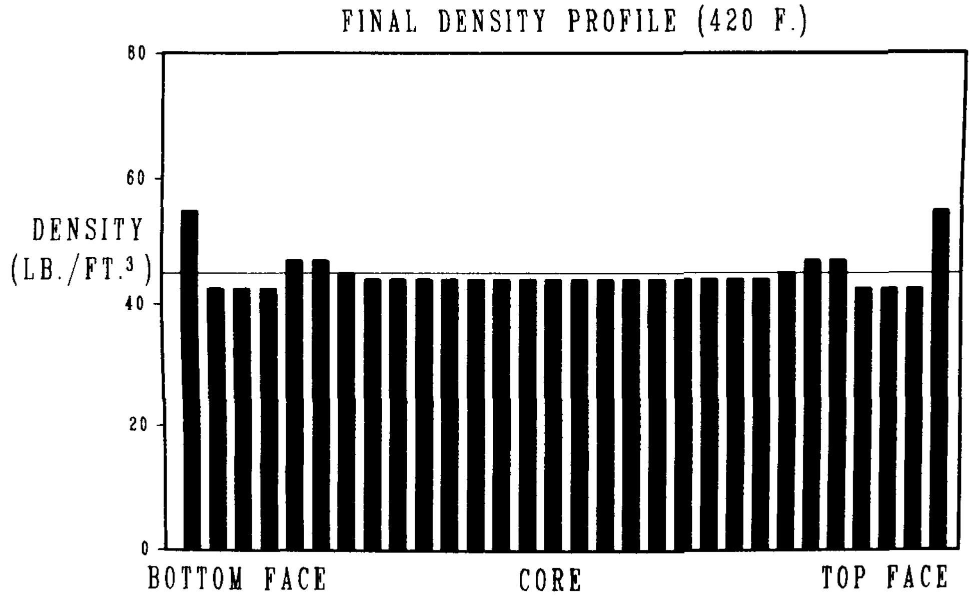

FIG. 4. Model-predicted density profile resulting from an uneven initial moisture distribution.

farther into the panel before condensing. Figure 4 shows the model-predicted density profile for the uneven moisture distribution. The density depression realized in the second through fourth layers in Fig. 4 resulted from the loss of moisture when adjustments for equilibrium moisture were made. The unconditioned density profile would have shown that layers two through six had approximately the same density. In the case of layers two through four, water contributed greatly to the density values. When equilibrium adjustments were made, density decreased markedly in those layers.

MODEL LIMITATIONS

A typical measured-density profile shows that the layers of greatest density are not the face layers. Resin cure and moisture plasticization reduce the density of the face layers relative to layers just below the surface. Both of these factors are excluded in the model, and predicted density profiles show greatest density in the face layers. Although the impact of this limitation depends on panel type, commercial boards are normally sanded to reduce low-density surface layers.

Modeling of the compaction process currently terminates when the press platen reaches the final thickness. Changes in the density profile that might occur after closure due to differential relaxation have been ignored.

The model of gas transport assumes a linear relationship between superficial gas permeability and porosity. The finite difference equations used to predict gas flows may overreact to the pressure gradients. Successive overreactions result in erratic pressure gradients, and local minimum pressures at one moment became local maximum pressures at the next moment. Left unrestrained, the oscillations eventually cause the evacuation of gas from a layer. Arbitrary safeguards have been installed in the model to deter this oscillation and to set a maximum amount of gas that may exit a layer.

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