FUNDAMENTALS OF VERTICAL DENSITY PROFILE FORMATION IN WOOD COMPOSITES. PART I. *IN-SITU* DENSITY MEASUREMENT OF THE CONSOLIDATION PROCESS

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ABSTRACT

We have designed a radiation-based system for measuring density of wood composite mats during consolidation. The system is installed on a laboratory hot-press and has been used to study consolidation of medium density fiberboard (MDF) and oriented strandboard (OSB) mats. Measuring density of the wood mat during consolidation is a key parameter for understanding subsequent product performance. The *in-situ* measuring system provides for density measurement at three horizontal planes in the wood mat, at positions of 25%, 50%, and 75% of the mat thickness at any time during the press cycle. The system incorporates three cesium^{137} sources and electronic detection equipment, collimated to move in concert with the up-acting press platen. Radiation count data taken through the mat during pressing are converted to density after pressing. Press position and time are simultaneously recorded with the count data. Moisture migration during hot-pressing resulted in significant density changes as measured by the in-press radiation-based system. Clearly established in all laboratory pressing studies is the indication that the vertical density profile of wood composite panels is formed from a combination of actions that occur both during consolidation and also after the press has reached final position; measurements recorded in the press show that mat densification continues after the press has reached final position. A description of the radiation system and data from elementary pressing examples are presented, along with experimental results of the effects of moisture migration in the mat on measured density during pressing.

Keywords: Density profile, *in-situ* measurement, pressing, radiation, consolidation, wood composite, medium density fiberboard (MDF), oriented strandboard (OSB), moisture migration.

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INTRODUCTION

The pressing operation is one of the most important and complicated operations in wood composites manufacture (Bolton and Humphry 1988; Kamke and Casey 1988; Wang 1992; Winistorfer 1992). Complicated interactions of dynamic conditions occur during pressing, including heat transfer, moisture movement, development of gas pressure, wood stress relaxation, wood consolidation, resin curing and bonding between flakes, and eventual development of a nonuniform consolidation-induced density distribution through the panel thickness.

A density gradient through the thickness of flat-pressed panel products, that results from hot-pressing, has been well documented by researchers and producers (Suchsland 1962; Wang 1986, 1987; Wang and Winistorfer 1998, 1999; Wang et al. 1999a, b; Winistorfer 1992). The density gradient results from a complex interaction of conditions within the mat during pressing. Temperature, moisture, and gas pressure interact to influence the differential heat and mass transfer through the thickness of the panel during pressing, impacting plasticization and compaction of the individual particles within the mat. Variation in stress development and relaxation within individual particles result from these conditions. Because of the strong relationship between panel density, compaction characteristics, and subsequent panel properties such as bending strength, dimensional stability, surface quality, edge machining, and fastener performance, understanding the nature of the density gradient in wood composite panels is of critical importance to manufacturers and researchers.

A density gradient through the panel thickness is typically reflected by the presence of high-density face layers and low-density core layers within the panel, but may take on many forms depending on manufacturing conditions and desired end-product attributes. The density gradient has been referred to by many names including, vertical density gradient, vertical density profile, density prolife, and vertical density distribution. Density profile will be the term used in this paper.

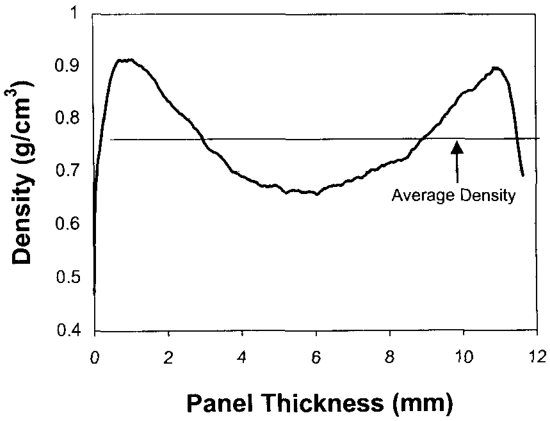

FIG. 1. Typical density profile shape that is nearly symmetrical through the board thickness.

When the density distribution through the panel thickness is plotted on an x-y axis, the resulting plot is frequently referred to as the "shape" of the density profile. Shape is a qualitative descriptive term used to refer to the relationship between face layer density, core layer density, and panel thickness. The density profile will commonly be nearly symmetrical in shape when viewed about a midpoint that is the centerline representing total panel thickness (Fig. 1). Most studies of the density profile have been empirical approaches that entail manufacture of panels under a variety of conditions and subsequent relation of panel properties to the density profile. Historically, the density profile has been measured using a gravimetric approach, but in the last decade nondestructive nuclear and X-ray instruments have become the standard means of analysis (Wang 1986; Haag 1992; Quintek Measurement Systems, Inc. 1999). A drill resistance technique and an air-coupled acoustic emission sensor technique were also used to measure density profiles in wood-based products (Winistorfer et al. 1995; Lemaster and Green 1992). In Europe an on-line system for full-scale production monitoring of the density profile immediately after pressing has been developed (Dueholm 1996).

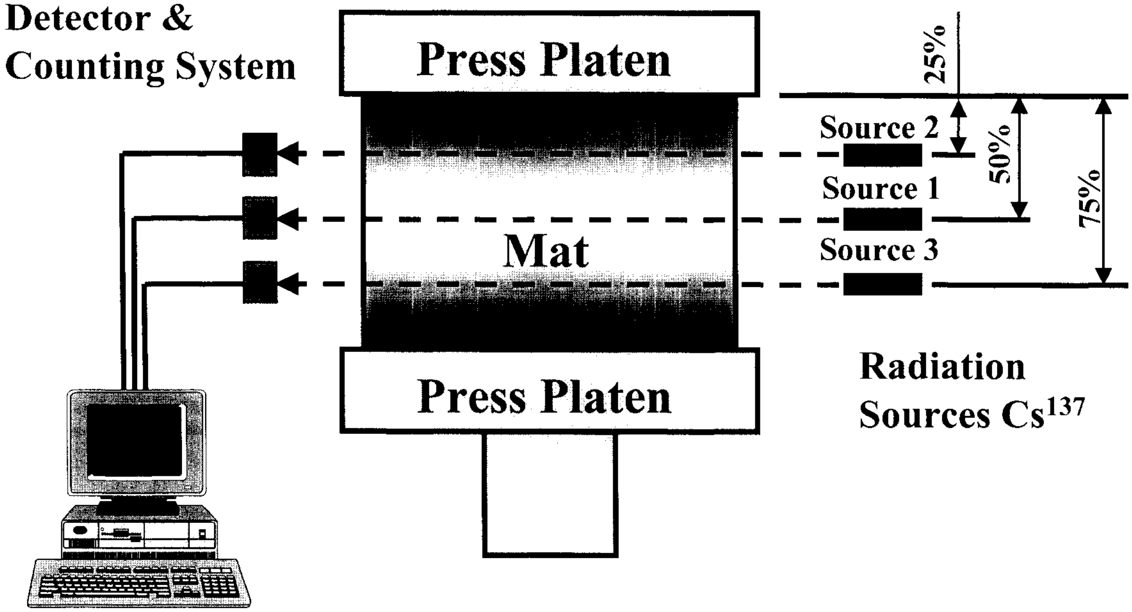

FIG. 2. A schematic representation of the *in-situ* density monitoring system.

This paper presents a description of an *in-situ* density monitoring system and results of laboratory studies to measure system variation and the effect of moisture migration on *in-situ* density monitoring during pressing.

IN-SITU DENSITY MONITORING SYSTEM

Development of the in-press system for real-time density measurement

The in-press radiation system utilizes nuclear sources and electronic detection equipment to measure the relative amount of radiation passing through three horizontal planes in the wood mat as a measure of mat density. The system consists of a mechanical device mounted on the 700-mm by 700-mm laboratory hydraulic hot-press to translate the nuclear sources and detection equipment in concert with the up-acting lower press platen. The mechanical device consists of three yokes, each guided by two linear bearings mounted on the top of the press and driven through a series of racks and gears attached to a plate on each side of the press. The yokes position the sources and detectors at the three fixed positions of 25%, 50%, and 75% of the press opening distance, at anytime during the press cycle (Fig. 2). The three yokes are attached to the up-acting lower platen and move to maintain the fixed source and detector positions. These three fixed monitoring positions can only be slightly adjusted by changing the thickness of the caul plates used during pressing. Regardless of the caul plate thickness, the middle detection system still registers at 50% of mat height. The face detectors can be positioned to within approximately 10% of either face by using thicker caul plates, before there is interaction of the radiation beam with the press platens. A collimated beam of radiation is transmitted in a horizontal plane from a source, through the mat, to the detector on the opposite side of the press. A mass-based density measurement is recorded during the press cycle.

Description of the density measuring system

The density measurements taken during pressing are based on a determination of the radiation attenuation of a collimated beam of gamma rays as they are passed through the wood mat. A photo scintillation counting system was selected for radiation measurement. The complete measurement system consists of a NaI detector crystal that converts gamma ray photons to light photons, a photomultiplier tube that converts the light photons to electrical pulses, a high voltage power supply for the photomultiplier tubes, a preamplifier, a TTL pulse generator, a counter-timer board in the computer, and software to perform the data collection and display functions.

Among the factors that were considered in the overall design of the system were the safe loading and use of the press, protection of the radiation detection system from heat and vapors from the press, and the accuracy and repeatability of the resulting density determination.

Radiation sources

Initial experiments were conducted to determine the best geometry and required amount of radiation for the density determination. Based on some experimental work and published mass attenuation coefficients for wood, the 663 keV gamma ray from Cs^{137} was selected as the radiation source.

An initial experiment was conducted with Cs^{137} to determine the proper geometry, the optimum detector size, and the minimum source size required. It was determined that a collimated beam width of 0.16 cm, and sources of approximately ⅓ curie would be required to produce density measurements at the desired rate (4 or more per second) and desired accuracy.

Based on preliminary experimental work, Cs^{137} sources of approximately 0.30 curies sealed in a standard X8 stainless steel capsule were chosen. Cs^{137} has a half-life of 37 years and emits gamma rays at 663 keV and 1.17 MeV. Because of the large amount of Cs^{137} required for the system (1 curie total) and the penetrating nature of the high-energy gamma emitted, special source holders had to be designed to protect the capsules in case of fire or a crushing accident in the press, and to allow the sources to be safely loaded and unloaded from the press.

The material chosen for the source holders and collimators was 17 alloy tungsten radiation shielding material. This sintered tungsten shielding material is very dense, has a good gamma ray absorption coefficient, has good strength and heat resistance properties, and does not deform when machined to accurate shapes.

The source holders emit radiation of approximately 100 mR/h at their surface. Additional shielding is required on the press to reduce this radiation to acceptable levels and to eliminate radiation that is scattered from the samples and detectors. A lead-shielded frame was constructed around the sources on the press. A sliding shutter assembly with three tungsten plugs in front of the sources blocks the radiation beams while the press is being loaded. An interlock with the press hydraulic system is used to prevent closing the press with the shutter in place.

Radiation detection system

A NaI crystal detector 5.08 cm in diameter and 7.62 cm long was chosen for the detection system. The 5.08-cm diameter allows the radiation beam to be large in the horizontal direction to increase counts, and the 7.62-cm length is required to efficiently collect the high energy radiation from the Cs^{137} sources. A 5.08-cm-diameter photomultiplier tube is used to detect the photons from the NaI crystal. The NaI crystal, the photomultiplier tube and tube base, and the preamplifier are mounted in a 5.08-cm-square aluminum tube with a thin aluminum window for the gamma rays to enter. The NaI crystal and the photomultiplier are optically coupled and sealed together with optical grease. A tungsten collimator 8.89 cm long is mounted in front of the detector tube. This detector collimator limits the entrance radiation beam to 0.16 cm in the vertical direction and 4.45 cm in the horizontal direction. All three detector assemblies are enclosed in a lead-lined chamber to reduce scattered radiation levels in the laboratory.

Counting system

The custom radiation counting system consists of three adjustable high voltage modules to supply the photomultiplier tubes, three custom-built preamplifiers to allow transmission of the signal, and three custom-built TTL pulse generators. All parts are mounted in a single chassis with a 15-volt power supply. A Keithley Instruments, Inc. CTM-05 multifunction counter-timer board is used in the computer to time and count the three separate channels of radiation data. The system had to be carefully set up using an oscilloscope to adjust the high voltage to the photomultiplier and the amplifier gain to assure that all three systems respond primarily to the 663 keV gamma from the sources rather than to low energy, scattered, or background radiation.

Keithley Instruments, Inc. Viewdac© is used as a programming platform to perform the counting and timing functions, to record and display count data, and to record and display corresponding position and time data from the press. The program was written to be time-efficient in data collection to maximize the number of measurements that can be taken while the press is moving. Eight data points per second are collected. Each data point represents total counts over a time of approximately 80 milliseconds. Press position and time are monitored and recorded simultaneously with the radiation data. The three channels of radiation count data, press position, and time are displayed in pseudo real time. All data are saved in ASCII format. Microsoft™ Excel© is ultimately used to smooth the data, to convert the counter data into density values, and to report the results.

Principle of density determination

The determination of density from radiation attenuation is based on the basic radiation attenuation equation expressed in the form:

$$I/I_0 = e^{-\mu d t} \qquad (1)$$

where:

I = intensity of the radiation beam after passing through the wood mat (measured in counts/unit time)

I_0 = intensity of the radiation beam in free air (measured in counts/unit time), often referred to as "air counts"

μ = the mass attenuation coefficient of the wood mat (cm^2/gm)

t = the width of the wood mat through which the radiation beam travels (cm), i.e., attentuation distance

d = the wood mat density (g/cm^3)

In practice, μ is a material property of the mat, and may be determined from a "calibration" experiment or from the literature. I and I_0 are determined at each point during the press closing, t is measured, and d, the wood mat density, is calculated using Eq. (1.)

Experimental factors to consider in radiation density determinations

The above basic radiation attenuation equation is for the case of a perfectly collimated monochromatic radiation beam and a perfect radiation measuring system. In practice, before the above equation could be used, it was checked to examine how closely it conforms to the basic attenuation equation. This verification of the system is often referred to as a "linearity" check. When solved for density, the basic radiation attenuation equation becomes:

$$d = (-1/\mu\, t)(\log I/I_0) \qquad (2)$$

The material density is thus a linear function of log (I/I_0). There are a number of factors that can cause a radiation density measuring system to be "nonlinear". Among the more important of these factors are:

1). The radiation used is not actually monochromatic. Cs^{137} has two main emission peaks, and a large amount of low energy, background, and scattered energy is present.

2). There can be built-in nonlinearity in the signal amplifiers and in the photomultiplier tube.

3). The counting system is set up to detect and count individual photons. If the intensity of the radiation beam exceeds the ability of the system to see individual pulses, dead time results, and the overall result will be nonlinear behavior of the system.

4). Beam collimation and alignment are rarely perfect. In this case collimation and alignment have to be maintained while moving both the sources and detectors over 30 cm vertically.

5). The electronics or detector response can drift over the time required for the experiment, for instance because of temperature variation, causing a resulting nonlinearity in the density determination. The detectors for this system are located about 30 cm away from the press platens, which are heated to approximately 400°F.

System performance checks

Performance of the system was tested after the radiation system was installed. The system was evaluated for stability, alignment and collimation, radiation scatter, system translation and air counts, and verification and calibration. Details of these evaluations have already been reported in Winistorfer and Moschler (1996) and are not included here. The most important conclusion from this evaluation process was that the radiation system is linear and accurately measures the density of wood material. The mass attenuation coefficients for 663 keV gamma rays are not particularly material-sensitive and therefore should not vary for most wood species, mat structure, or furnish geometry.

A critical system performance check was to compare density data measured both by the radiation-based system and by the traditional weight-based method. A piece of 12.7-mm-thick OSB, 406 mm wide by 457 mm long was used for comparative measurements. The average density of the OSB was 0.707 g/cm^3 (shown in Table 1). The sample was sawn into 32 narrow strips, each measuring 21.3 mm wide and 406 mm long. Strips were turned by 90° and were bonded face-to-face using a small amount of wood glue on both ends of strip; glue was applied only on the very end of the strips to prevent any adhesive in the area of the specimen where the *in-situ* measurement would be taken. The size of reassembled specimen was 406 mm by 406 mm, 21.3 mm thick. The specimen was inserted into the press without heating the platens, and the density monitoring system was positioned at 10.3%, 50%, and 90.2% of the board thickness. *In-situ* density data were recorded for period of 400 s under no press pressure. The average densities measured by the monitoring system were 0.728 g/cm^3 for position 10.3%, 0.721 g/cm^3 for position 50%, and 0.714 g/cm^3 for position 90.2%, respectively (Table 1). Compared with mean specimen density, the maximum measured difference between two measurement methods was only 2.95%.

TABLE 1. *System performance check using reconstructed OSB specimen.*

Source	Source 1	Source 2	Source 3
Source Position	50.0%	10.3%	90.2%
In-situ measured values (g/cm^3)	0.721	0.729	0.715
Average value by traditional weighted method (g/cm^3)	0.708	0.708	0.708
Difference between above two values (%)	1.93	2.95	1.03

MOISTURE INFLUENCE ON IN-SITU DENSITY MEASUREMENTS DURING PRESSING

Typical in-situ *measurements in pine OSB mats*

In a simple experiment, a pine OSB mat was pressed in the first trials of the *in-situ* density measuring system. Pine industry furnish was procured and conditioned to 6% moisture content. Target panel density was 0.608 kg/cm^3, and a commercial phenol formaldehyde resin was applied at 3% resin solids based on oven-dry wood weight. Wax was not used. Press platen temperature was 204°C, and the total press cycle length was 370 s. The closure rate was 40 s, marked from the time the mat made contact with the upper platen. The density monitoring system was positioned at 10%, 50%, and 90% of the mat thickness. Figure 3

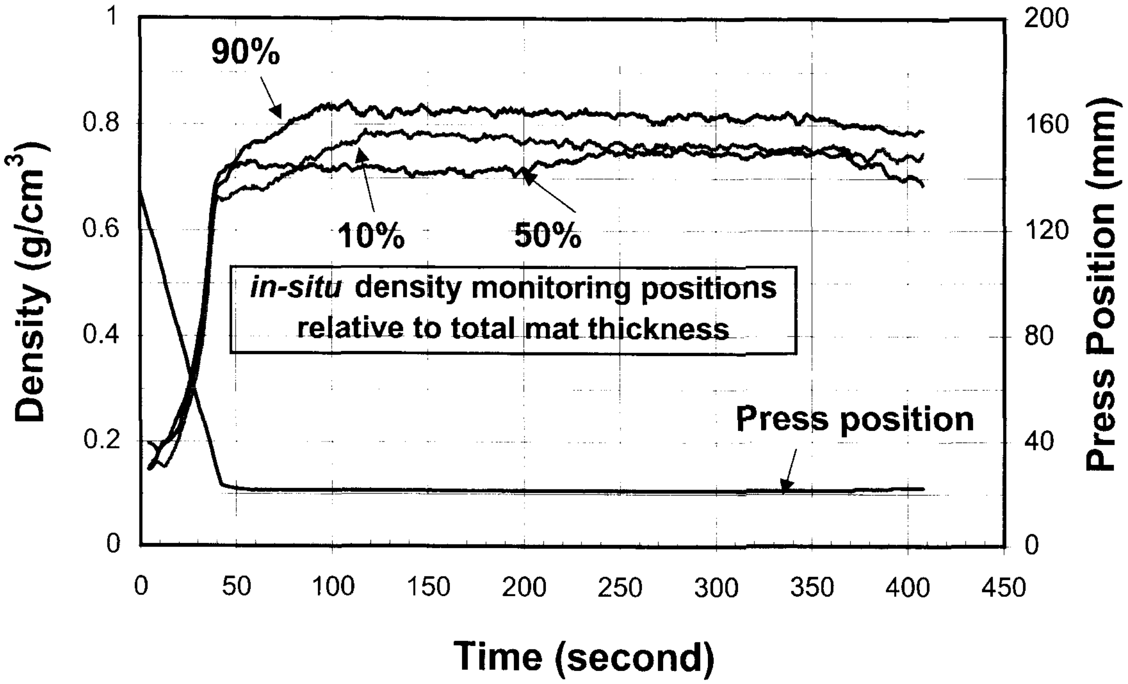

FIG. 3. In-press densities of a pine OSB mat pressed at a 40-s closure rate.

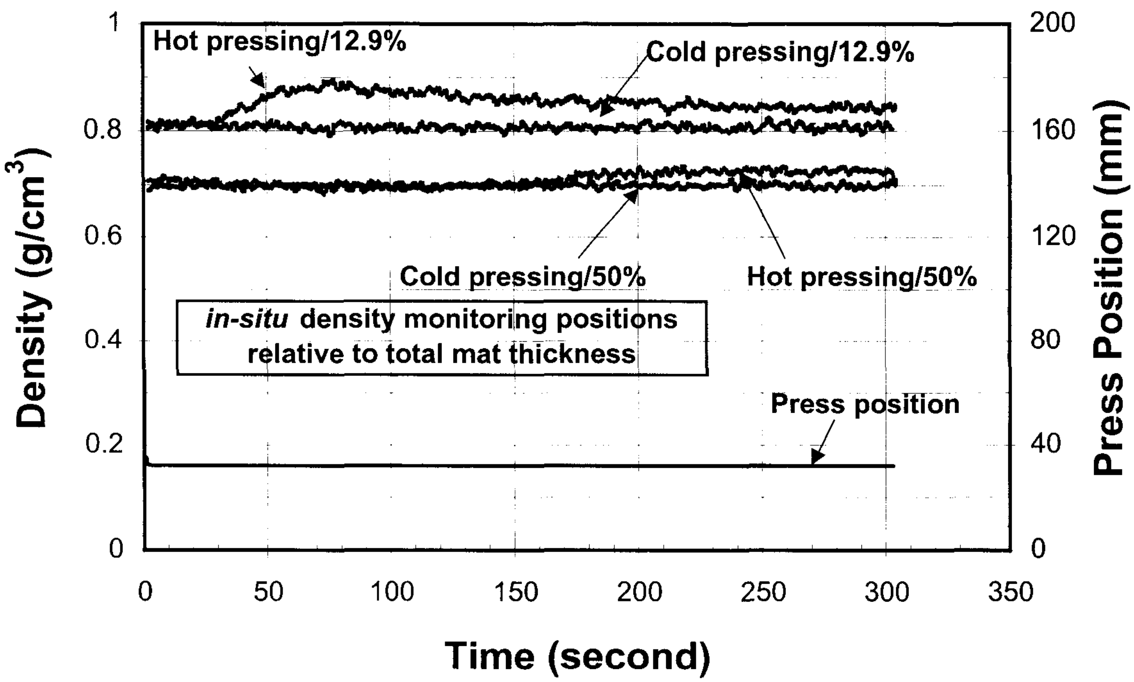

FIG. 4. A comparison of density changes in a 25.4-mm-thick MDF panel when pressed hot and when pressed cold.

shows the *in-situ* density data for the 40 s press closure rate treatment. Press position is also shown in Fig. 3 where final closure is reached at 40 s. During the first 40 s of the cycle, all three density monitoring positions reflect the rapidly increasing density of the compacting mat. The three locations of the mat achieve the same dynamic density during this initial compaction period leading up to final closure position. Immediately upon reaching final closure position, there is a marked change in the mat density at the three monitoring locations. It is important to note that mat density continues to change after the press has reached final position. Measurements made with this *in-situ* system are the first to document that mat density continues to change after the initial consolidation period to final thickness position. Both face monitoring detectors reflect increasing density up to about 100–120 s in the cycle and then show a continual gradual decrease during the remainder of the cycle. The core density shows an initial slight decrease during the period from 60 s to about 200 s, and then steadily rises until the culmination of the press cycle. The relative change in the face layer densities is about 22% from the initial measurement at final press position at 40 s to the peak density at about 110 s.

It is known that moisture migrates in a composite mat during hot-pressing, both from the hot platens to the mat center and from the mat center to the mat edges (Humphrey and Bolton 1989). A logical question about our data is whether the entire magnitude of the recorded density change after the press has reached final closure position is due to the migration of moisture from the panel surface layers into the core. Recognition of moisture movement in the mat and relative measures of the impact of moisture movement on measured density is important to understanding of the consolidation process.

Effects of moisture migration in the panel on density measurement

In order to understand the influence of moisture and moisture migration in the mat during pressing and its relation to the *in-situ* density measuring system, we experimented with a commercially produced piece of MDF that had been conditioned to different moisture content levels. Commercial MDF 12.7 mm thick and 25.4 mm thick were procured from a mill. The panels were trimmed into samples measuring 457 mm by 406 mm. The samples were equilibrated at 25°C and 92% humidity; the resulting moisture content was 8.36% for the 25.4-mm-thick panel and 7.4% for the 12.7-mm-thick panel.

The 25.4-mm-thick sample was inserted into the press with the press platens at ambient temperature (no heat was applied to the press), and density at the three *in-situ* locations was measured using the in-press system (Fig. 4). There was no external press pressure on any panel during measurement; the press was closed to the position representing the panel thickness. The same sample was then inserted into the press with the press platen temperature at 200°C, and density was measured using the in-press system (Fig. 4). Because the panel density profile is nearly symmetrical, only the core and one face position of the *in-situ* system are shown in Fig. 4. A third trial of this same panel at oven-dry (0% moisture content) was also conducted. The same procedure was repeated for the 12.7-mm-thick panel (Fig. 5).

Because the press was closing on an already manufactured panel, the plot of press position was a constant horizontal line that represents the panel thickness (Figs. 4 and 5). For the 25.4-mm panel, the monitoring positions of 50% (core) and 12.9% (distance from the top surface) are noted on Fig. 4. Core density of this panel at 8.36% moisture content was 0.699 g/cm^3. Density of the face at approximately 12.9% from the top surface was 0.807 g/cm^3. The press time for the cold panel measurement is not important other than to show the stability of the measuring system over the 300-s press cycle. With the press heated to 200°C, the influence of moisture moving in the panel is recorded by the density measuring system. For the surface density, there was an initial period of about 30 s for heat-up of the

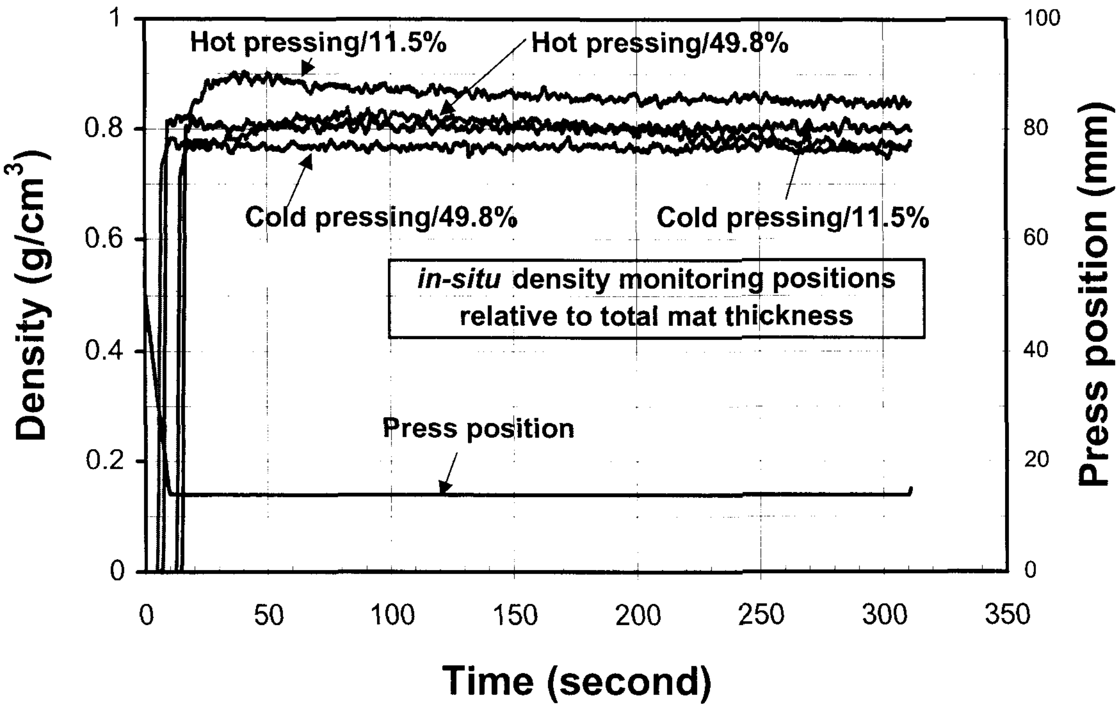

FIG. 5. A comparison of density changes in 12.7-mm thick MDF panel when pressed hot and when pressed cold.

panel before moisture migration began to have an effect on the measurement. In the early period of the cycle, moisture began to move away from the face layers, migrating to the core of the panel. The time period from approximately 30 s to 80 s includes the highest level of moisture migration through the system detection location at the 12.9% monitoring position. Measured density during this time reached its highest level of approximately 0.880 g/cm^3 and then continually diminished throughout the remainder of the cycle as moisture migrated further into the panel core, and some escaped from the panel edges. The relative difference between the cold-pressed MDF surface density and the hot-pressed MDF surface density was about 9.0% greater for the hot-press condition, reflecting the additional mass of the water moving through the detection system during early seconds of the cycle. Mean density at the surface detector at the end of press cycle was 0.844 g/cm^3. At the end of the 300-s press cycle, the hot-pressed MDF panel surface density remained greater than the cold-pressed panel surface density. The hot-press condition resulted in a density measurement 4.47% greater than the cold-pressed condition. There remained a greater amount of water that migrated into the 12.9% layer position during the hot-pressed condition than was present at that layer location for the cold-pressed condition. What is evident is that in the core at 150 s into the press cycle, moisture was migrating into the core from the panel surface layers, as evidenced by the increasing density measurement in the core for the hot-pressed condition. The core density was still increasing even at the end of the cycle, where the hot-pressed condition resulted in a measurement 3.85% greater than the core of the cold-pressed MDF. Based on panel weight, the moisture content of the panel after hot-pressing had decreased to about 5.9%, reflecting a loss of about 2.5% water from the original condition. The hot-pressing of this same panel at oven-dry (0% moisture content) showed that there were no significant density changes in the three layers during the 300-s press cycle.

Figure 5 shows comparison of density changes in the 12.7-mm-thick panel when pressed hot versus when pressed cold. There still was significant influence of moisture moving in the 12.7-mm-thick panel on the density measurements. However, the thinner panel showed different trends than the 25.4-mm panel. Moisture began to move away from the face layers, migrating to the core of the panel immediately after the top press platen contacted the top of the panel. Measured density of the face at 11.9% from the top surface reached its highest level of 0.892g/cm^3 after the press had maintained a final position for about 30 s and then continually diminished throughout the remainder of the cycle as moisture migrated farther into the panel core. The relative difference between the cold-pressed MDF surface density and the hot-pressed MDF surface density was about 10.9% greater for the hot-press condition, reflecting the additional mass of the water moving through the detection system during these early seconds of the cycle. At the end of the 300-s press cycle, the hot-pressed MDF panel surface density was 5.69% greater than the cold-pressed panel surface density. Similar density changes were recorded for the core layer as were for the face layer. At only about 30 s into the press cycle, moisture was migrating into the core from the panel surface layers, as evidenced by the increasing density measurement in the core for the hot-pressed condition. Core density then continually diminished throughout the remainder of the cycle as moisture escaped from the panel edges. At the end of the 300-s press cycle, the hot-pressed MDF panel core density remained only 0.496% greater than the cold-pressed panel core density.

We recognize that closing the press on a finished panel and monitoring moisture migration is different than monitoring moisture migration of a compacting mat where the mat may more easily breath during the consolidation process. Moisture migration will be different in a compacting mat of loose particles than in an already-pressed panel. We do not believe that this entire magnitude of density change was due to the migration of moisture from the panel surface layers into the core. The relative change in the face layer densities was about 22% from the initial measurement at final press position and the core density change about 5.01% during the later stages of the cycle (Fig. 3). It is likely that this magnitude of change is also not due simply to the moisture migration into the core, as some of the moisture probably escaped from the mat edges during the press cycle.

CONCLUSIONS

We have designed a radiation-based system for measuring density of wood composite mats during consolidation. The *in-situ* density system provides for density measurement at three horizontal planes in the wood mat, at positions of approximately 25%, 50%, and 75% of the mat thickness at any time during the press cycle. Comparison tests show that there were few differences between the radiation-based density measurement and traditional weight-based measurement.

Moisture migration during hot-pressing resulted in significant density changes measured by the in-press radiation-based measurement. The influence of moisture movement for surface layers happens much earlier in the press cycle than for the core layer. The influence of moisture movement for thin panels is slightly larger than for thick panels.

It is clearly established that the vertical density profile of wood composite panels is formed from a combination of actions that occur both during consolidation and also after the press has reached final position; measurements recorded in the press show that the densification continues after the press has reached final position.

Having the capability to measure the density profile during pressing, coupled with other in-press sensing equipment, should lead to better insight into the consolidation phenomenon of hot-pressed panels with an eye toward improving manufacture and performance of these products.

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