# Strandboard Made from Soy-Based Adhesive with High Soy Content

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## Abstract

A novel green adhesive with high soy content has recently been developed (13) with a process that denatures soy flour, modifies resulting protein with formaldehyde, and uses suitable phenolic crosslinking agents for co-polymerization. Compared with mechanical and physical performances of oriented strandboard, the new adhesive showed promise for improving panel performances and lowering costs. We studied the effects of four variables (face-resin content, face-furnish moisture content [MC], density of the panels, and press time) on panel performances and identified possible interactions with each variable. The results indicated that increasing face-resin content and density would improve mechanical bending performance. This soy-based phenol-formaldehyde (PF) also somewhat reduced the thickness swelling and water soak absorption. Face-furnish MC had no effect on tested properties, but it significantly enhanced heat transfer (core temperature and internal steam pressure) during the press process. Under a press temperature of 215°C, a closed press time of 150 seconds was not sufficient to fully cure the new soy-PF face resin, and further investigation is recommended to optimize press process (press time and face-furnish MC) and resin performance.

## Introduction

Soy flour, the residue remaining after removing the oil from the soybean, contains a high percentage of protein that can be used as a base material for adhesives. Soybean-derived protein-based adhesives were regularly used in the wood products industry early in the 20th century (8). The early soy-based adhesives were made of a mixture of denaturized soy protein with a caustic solution (8,12). These adhesives were limited in their industrial applications because of their short pot lives, long press times, low solid contents, and limited water resistance (13). Because of their cost and poor wet-bond performance, the soybean-based adhesives were soon replaced by less expensive, better performing synthetic resins in the middle of the 20th century (7). Recently, however, environmental concerns and the high cost of petroleum-based resins have resulted in a dramatically increased interest in soybean-derived protein-based adhesives. Renewed efforts have recently improved the water resistance and stability of soybean-derived protein-based adhesives (4-6,9,10,13). A novel adhesive with high soy content has recently been developed (13). This new green resin system is based on denaturation of soy flour, modification of soy-based protein with formaldehyde, and co-polymerization with suitable phenolic crosslinking agents. The preliminary results show the possibility of making soybean flour adhesives with water resistance comparable to commercial phenol-formaldehyde (PF) resin (13). In addition, the new technology could provide an opportunity for wood panel manufacturers to reduce the cost of face resin by 30 to 40 percent by replacing PF resin with environmentally friendly soybean flour (13). Before new soybean-derived protein-based ad-

hesives are successfully applied in the wood composite industry, an extensive laboratory investigation is needed to fully examine the performance of oriented strandboard (OSB) made from the new resin system. Lab studies with no orientation are helpful for scaling up and developing process parameters. As an initial study in a series of the extensive investigations, the objective was to identify the importance of various processing variables and their individual and interactive effects on the performance of flakeboard made with the new resin. The results will provide guidance to design more specific studies.

## Materials and Method

Southern pine (plantation-grown loblolly pine) wood flakes were provided from a commercial oriented strandboard (OSB) mill in Georgia. The flakes with nominal dimensions of 0.025 inch (0.64 mm) thick, 4.5 inches (114 mm) long, and 1.5 inches (38 mm) wide were conditioned at two different moisture content (MC) levels, 4 percent and 8 percent, before blending with resin. The face and core ratio was 55 to 45 percent. Face resin was a soy-based resin (S4065) with 40 percent solids content provided by Heartland Resource Technologies (Pasadena, CA). The core resin used in this study was a typical OSB phenol-formaldehyde (PF) resin with 43.6 percent solids supplied from a commercial vender. Constant resin content of 3.89 percent based on ovendried furnish was applied for the core layer for all panels made in this experiment. Wax with 53.2 percent solids from a commercial supplier was used for both face and core layers at about a 1.4 percent level.

The resinated flakes were laid up randomly by hand into a 22- by 22-inch (55.9- by 55.9-cm) mat on a caul plate. A temperature/gas pressure probe was inserted in the middle of the mat to monitor the internal temperature and gas pressure. The mat was compressed and transferred to a 3 by 3 foot (91 by 91 cm) oil-heated press with a computerized control system. The press platen temperature was held constant at 215°C. It took 42 seconds for the press to reach the final target thickness of 7/16 inch (11.1 mm). The panel was then pressed at the target thickness for either 150 or 300 seconds before the press was gradually vented over a 15-second period to release the internal steam pressure. All panels were conditioned at 22°C and 30 percent relative humidity for 3 weeks before samples were cut out and tested according to ASTM D 1037. The density of each sample cut from each panel was individually measured.

Based on the previous studies (3,13), four process variables were identified as being critical for determining their effects on the panel performances and possible interactions. These variables were face-resin content (R), face-furnish moisture content (M), density of the panels (D), and press time at the target thickness (T). Levels of the variables studied were face-resin contents of 3.25 percent

and 6.5 percent; face-furnish moisture content of 4 percent and 8 percent; panel densities of 37, 42, and 47 lb/ft$^3$ (592.7, 672.8, and 752.8 kg/m$^3$); and press times at the target thickness of 150 and 300 seconds. To reduce variability and increase efficiency, we blended enough furnish with resin to make two panels, one with press time of 150 seconds and one for 300 seconds. The resulting split-plot experimental design was based on a factorial experiment using R, M, and D as whole plot treatment factors and with two panels produced at press times of 150 seconds or 300 seconds as a split plot or nested treatment factors. Based on a randomization of the whole plot factors, R, M, and D, two panels, one with a press time of 150 seconds and the other at 300 seconds were produced in random order with the combination of R, M, and D. In our analysis, we assumed that interactions higher than two-factor interactions were random error. Eight 2 by 2 inch (5.1 by 5.1 cm) internal bonding samples, two 3 by 14 inch (7.6 by 35.6 cm) modulus of elasticity/modulus of rupture (MOE/MOR) samples, two 6 by 6 inch (15.2 by 15.2 cm) samples for 24-hour water soak, and two 6 by 6 inch (15.2 by 15.2 cm) samples for 2-hour boil were cut from each 22 by 22 inch (55.9 by 55.9 cm) panel.

For each original panel, the sub sample characteristics were tabulated, including average values and standard deviations (**Table 1**). The average MC of equilibrated samples was 5.1 percent with a coefficient of variation (COV) of 7.6 percent as measured immediately after the mechanical bending test. Analysis of variation (ANOVA) were computed for MOE, MOR, internal bond (IB), and 2-hour boil and 24-hour water soak responses with SAS v8.2 Proc Mixed (11). The MOE, MOR, and IB were analyzed with repeated statements of compound symmetry for type of correlation structure and no degree of freedom adjustments. The boils and soaks were analyzed with random statements and Kenward-Rogers degree of freedom adjustment. The reason for the difference in analytical techniques is that the boil and soak results had positive correlation estimates between errors for the subplots (the two mats with different press times, but same resin, MC, and density), which reduced the available degrees of freedom needed for some comparisons.

## Results and Discussions

The *p*-values from ANOVA are presented in **Table 2**. We found that the two factor interactions among the selected four parameters were very limited. This allowed us to compare the main factors. These results indicated that each of the four selected main factors significantly affected some of the individual performance characteristics of the panels to some extent. We will now individually review these factors.

The face-resin content showed a significant direct effect ($p \leq 0.05$) on the MOE, boil thickness swell (TS), wa-

**Table 1.** ~ *Average properties with standard deviation in parentheses.*

| Run | Face resin | MC | Density | Press time | MOE | MOR | IB | 2-hour boil Thickness swell | 2-hour boil Water aborption | 24-hour soak Thickness swell | 24-hour soak Water absorption |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | - - - - (%) - - - - | | (pcf)[a] | (s) | ($10^6$ psi)[b] | ($10^3$ psi)[b] | (psi)[b] | - - - - - - - - - - - - - - - - - (%) - - - - - - - - - - - - - - - - - | | | |
| 1A | 3.25 | 8 | 47 | 150 | 0.663 (0.065) | 4.59 (0.60) | 85.2 (9.2) | 67.9 (0.2) | 94.0 (6.1) | 37.1 (4.6) | 61.3 (12.0) |
| 1B | 3.25 | 8 | 47 | 300 | 0.781 (0.010) | 4.59 (1.19) | 101.6 (16.6) | 56.7 (2.6) | 78.6 (2.5) | 29.7 (1.8) | 53.9 (7.5) |
| 2A | 3.25 | 4 | 47 | 150 | 0.590 (0.102) | 4.06 (0.49) | 89.0 (11.1) | 63.0 (6.7) | 94.7 (3.8) | 34.2 (13.3) | 57.9 (17.7) |
| 2B | 3.25 | 4 | 47 | 300 | 0.761 (0.045) | 5.04 (0.30) | 106.4 (5.7) | 60.1 (3.3) | 89.3 (5.7) | 29.7 (1.7) | 51.7 (4.1) |
| 3A | 6.5 | 8 | 37 | 150 | 0.573 (0.102) | 3.59 (0.50) | 73.7 (15.7) | 46.8 (2.6) | 96.8 (3.2) | 27.8 (1.3) | 70.9 (4.7) |
| 3B | 6.5 | 8 | 37 | 300 | 0.513 (0.061) | 3.17 (0.29) | 87.3 (10.3) | 34.4 (1.2) | 91.6 (5.3) | 18.9 (3.9) | 55.2 (14.0) |
| 4A | 6.5 | 4 | 37 | 150 | 0.506 (0.058) | 3.28 (0.54) | 78.2 (11.8) | 40.1 (0.9) | 106.0 (1.9) | 28.6 (0.5) | 80.6 (14.2) |
| 4B | 6.5 | 4 | 37 | 300 | 0.548 (0.023) | 3.04 (0.11) | 73.2 (10.8) | 33.9 (1.9) | 96.9 (3.3) | 27.0 (1.2) | 70.9 (8.5) |
| 5A | 6.5 | 8 | 42 | 150 | 0.643 (0.017) | 4.15 (0.12) | 82.7 (7.3) | 46.8 (1.2) | 84.5 (0.9) | 24.5 (5.0) | 56.4 (17.6) |
| 5B | 6.5 | 8 | 42 | 300 | 0.778 (0.054) | 5.44 (0.87) | 97.0 (7.0) | 42.0 (2.7) | 78.4 (9.6) | 23.3 (0.7) | 56.5 (3.3) |
| 6A | 3.25 | 4 | 37 | 150 | 0.436 (0.051) | 2.77 (0.47) | 76.1 (12.0) | 46.4 (3.0) | 100.9 (1.7) | 36.7 (2.5) | 88.3 (4.9) |
| 6B | 3.25 | 4 | 37 | 300 | 0.498 (0.036) | 2.96 (0.22) | 79.9 (8.3) | 44.9 (1.8) | 90.9 (2.1) | 30.7 (5.4) | 84.0 (1.3) |
| 7A | 6.5 | 8 | 47 | 150 | 0.695 (0.161) | 4.22 (1.13) | 66.8 (11.8) | 54.8 (1.4) | 71.0 (5.4) | 18.1 (4.6) | 43.2 (9.0) |
| 7B | 6.5 | 8 | 47 | 300 | 0.798 (0.090) | 4.73 (0.59) | 97.5 (9.6) | 42.5 (1.0) | 65.2 (8.6) | 15.0 (11.9) | 37.9 (22.6) |
| 8A | 6.5 | 4 | 42 | 150 | 0.602 (0.055) | 3.90 (0.72) | 93.9 (13.3) | 48.6 (2.0) | 80.3 (1.1) | 27.2 (3.2) | 62.4 (17.9) |
| 8B | 6.5 | 4 | 42 | 300 | 0.633 (0.128) | 3.65 (1.15) | 98.4 (13.7) | 45.8 (4.6) | 78.0 (4.7) | 27.1 (7.8) | 58.6 (16.1) |
| 9A | 3.25 | 8 | 37 | 150 | 0.608 (0.082) | 3.57 (0.19) | 79.63 (10.2) | 49.9 (2.6) | 120.7 (0.8) | 38.4 (0.2) | 79.1 (10.4) |
| 9B | 3.25 | 8 | 37 | 300 | 0.480 (0.008) | 2.88 (0.63) | 79.0 (7.2) | 40.3 (5.8) | 109.9 (7.6) | 28.9 (4.5) | 87.8 (9.4) |
| 10A | 3.25 | 4 | 42 | 150 | 0.544 (0.039) | 3.56 (0.01) | 83.5 (17.9) | 52.4 (0.9) | 103.0 (0.2) | 36.2 (3.8) | 79.8 (10.8) |
| 10B | 3.25 | 4 | 42 | 300 | 0.571 (0.017) | 2.70 (0.31) | 82.8 (8.1) | 52.3 (2.0) | 87.1 (4.9) | 35.5 (0.6) | 73.7 (2.3) |
| 11A | 3.25 | 8 | 42 | 150 | 0.569 (0.147) | 3.12 (1.16) | 79.0 (6.8) | 62.9 (3.6) | 94.1 (3.0) | 33.2 (8.1) | 64.4 (24.8) |
| 11B | 3.25 | 8 | 42 | 300 | 0.734 (0.112) | 4.55 (0.97) | 78.5 (5.6) | 54.0 (8.5) | 91.7 (11.0) | 32.7 (4.9) | 68.7 (20.4) |
| 12A | 6.5 | 4 | 47 | 150 | 0.730 (0.079) | 4.37 (0.25) | 78.2 (6.1) | 50.8 (2.9) | 74.6 (3.3) | 17.7 (10.9) | 38.5 (14.7) |
| 12B | 6.5 | 4 | 47 | 300 | 0.822 (0.067) | 5.49 (0.66) | 85.1 (8.1) | 47.9 (0.8) | 69.9 (11.4) | 15.9 (3.0) | 38.1 (4.3) |

[a] 1 lb/ft$^3$ = 16 kg/m$^3$
[b] 1 lb/in$^2$ = 6895 Pa

**Table 2.** ~ *Results and associated levels of significance (p-value) for each main factor and the second-order interactions. The p-values less or equal to 0.05 are show in* **bold**.

| Effect | MOE | MOR | IB | *p*-value Boil thickness swell | Boil water absorption | Soak thickness swell | Soak water absorption |
|---|---|---|---|---|---|---|---|
| Resin content (R) | **0.048** | 0.081 | 0.587 | **0.036** | 0.113 | **0.003** | **0.023** |
| MC (M) | **0.050** | 0.115 | 0.305 | 0.629 | 0.942 | 0.118 | 0.222 |
| Density (D) | **0.009** | **0.019** | **0.027** | 0.055 | 0.128 | **0.029** | **0.019** |
| R × M | 0.183 | 0.694 | 0.403 | 0.639 | 0.560 | 0.213 | 0.784 |
| R × D | 0.542 | 0.238 | **0.020** | 0.515 | 0.702 | 0.053 | 0.833 |
| M × D | 0.178 | 0.126 | 0.157 | 0.929 | 0.709 | 0.222 | 0.333 |
| Press time (T) | **0.025** | 0.324 | **0.005** | **0.000** | **0.001** | **0.000** | 0.103 |
| R × T | 0.795 | 0.749 | 0.279 | 0.343 | 0.150 | 0.106 | 0.363 |
| M × T | 0.740 | 0.695 | 0.109 | **0.001** | 0.921 | **0.043** | 0.554 |
| D × T | 0.078 | 0.313 | **0.045** | 0.097 | 0.827 | **0.008** | 0.708 |

ter soak TS, and water absorption (WA), but showed only a marginal effect ($0.05 < p \le 0.10$) on the MOR and undetectable overall effect ($p > 0.10$) on IB (**Table 2**). **Figure 1** shows the main effects plots for the resin, MC, density, and press time factors for each of the tested properties. In-

creasing the face-resin content will improve the mechanical bending performance and reduce TS and water soak absorption. As expected, increasing face resin did not affect IB values, which are usually related to core resin performance.

Face-furnish MC had no detectable overall effect on any of the tested properties except for MOE, but it did have a significant effect on TS when interacting with press time (**Table 2**).

Increasing panel density showed significant direct effects on the mechanical properties, improved 24-hour water soak performance, and marginal effect on the boil TS. The improvement in the mechanical performance and resistance to TS related to increasing panel density was not unexpected based on previous research studies (2).

Increased press time significantly affected the MOE, IB, and 2-hour boil and water soak performances (**Table 2**). The difference in IB performance of panels made with the two press times (**Table 1**) indicates that while a 150-second press time did not seem long enough to completely cure the resins inside the panels, the longer 300-second press time improved the cure of both the surface and core resin. This was shown by increased stiffness and IB and decreased the 2-hour TS and WA. Why the longer press time did not improve MOR values is unclear, but it could be related to the small size of the experimental design. Future studies will be needed to further investigate the resin performance under different press times to optimize the press process.

To better understand the thermal and physical conditions within the consolidating mat controlled by pressing processes, a probe was inserted into the unpressed mat and its multiple sensors continuously recorded mat pressure, core temperature, and internal stream pressure. The maximum mat pressures generated during hot pressing are illustrated in **Figure 2** for different mat MCs and press times. The maximum mat pressure is usually related to the press capacity and pressing speed, and mat MC and density are usually considered as two additional major parameters that affect maximum mat pressure. With a higher mat MC, it is easier for the mat to be compressed because of increased wood plasticity (less stiffness). Our result indicates that the increased wood plasticity related to changing the MC of face layers from 4 to 8 percent did not practically change the maximum mat pressure (differences ranging from 1.6% to 2.7%). We also found that the press time did not affect the maximum mat pressure (**Fig. 2**).

Core temperature of the mat during hot pressing is the key indication of heat transfer and its potential influence on the resin curing process. The maximum core temperature (MCT) and the time to reach MCT (started from the time when the mat reached the initial designated thickness) are important parameters that need to be understood for optimizing the OSB manufacturing processes. **Figures 3 to 5** show the MCT, time to reach MCT, and the rate of core temperature rise from 40° to 100°C, respectively. Mat MC is widely believed to have an influence on transferring heat from the faces to the core. Usually, the higher mat MC will increase the heat conductivity, which



**Figure 1.** ~ *The main effects plots for the percentage resin content, percentage MC level, density (lb/ft³), and press time(s) factors for each of the tested properties.*
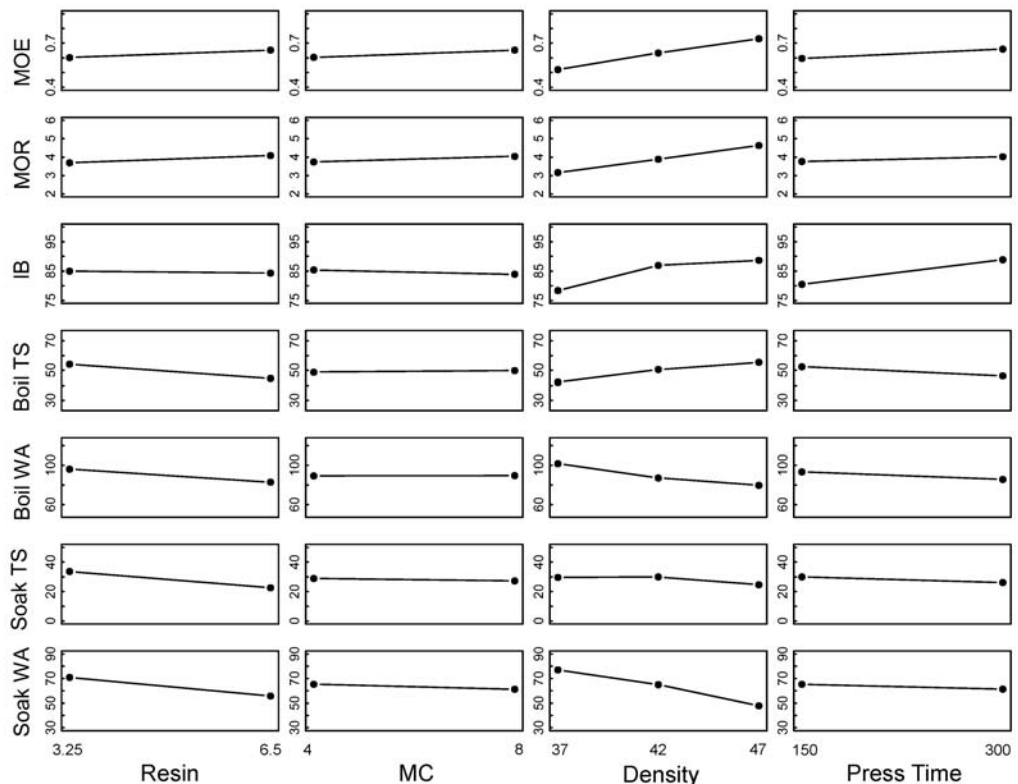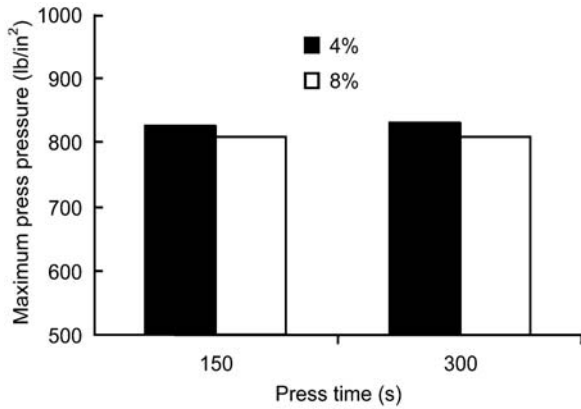
**Figure 2.** ~ *Maximum mat pressure under different face-furnish MC and press time in seconds.*
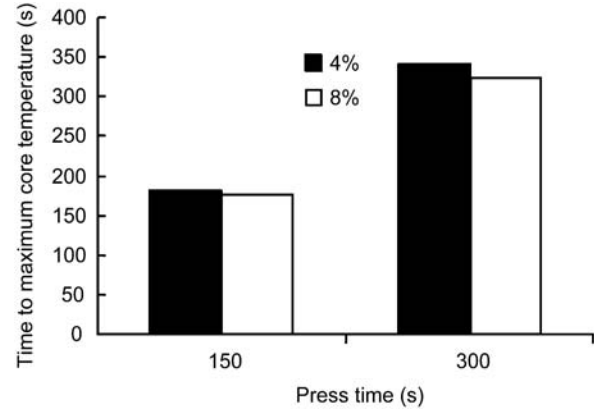


**Figure 3.** ~ *Maximum core temperatures for different face-furnish MC and press time in seconds.*



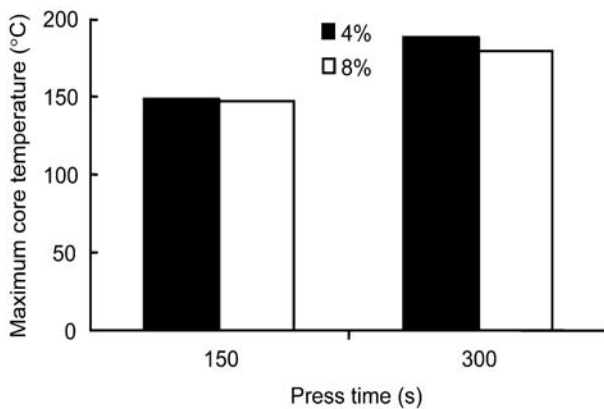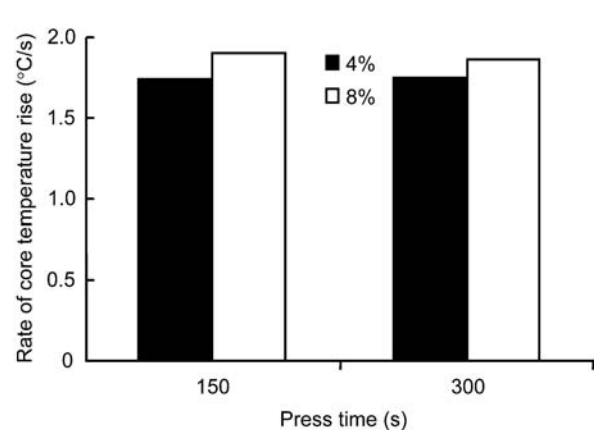**Figure 4.** ~ *Time to reach the maximum core temperature for different face-furnish MC and press time in seconds.*



**Figure 5.** ~ *Rate of temperature rise from 40° to 100°C for different face-furnish MC and press time in seconds.*

will speed the heat transfer into the consolidating mat; however, we found that the time to reach the maximum core temperature was not strongly affected by the face-layer MC of the mat (**Fig. 3**). Rather, it was more strongly related to press time because the temperatures reached their maximum at the end of press cycle (**Fig. 4**). We noted a slight increase in the rate of temperature rise from 1.7° to 1.9°C/s (**Fig. 5**) with face-furnish MC from 4 to 8 percent. Differences within an OSB mat during hot pressing result in differences in mat consolidation and porosity that will affect the steam vapor pressure, water evaporation, lateral steam flow, and dynamic equilibrium of these parameters. In this study, however, we observed that the maximum core temperature did not depend on the mat MC; rather, it was more closely related to press time because MCT increased when the press time increased.

Steam is generated within the consolidating mat when the moisture within the mat surface layers contacts the hot-press plates and migrates toward the cooler mat core. The core steam pressure increases as steam continues to

migrate from the hotter surface layers toward the cooler core. The high core steam pressure then slowly drives the steam outward toward the edge of the mat where it escapes. When the sum of steam generated equals the sum of steam loss because of condensation and edge flow, the core steam pressure will first reach a maximum and then begin to decline. **Figures 6 and 7** show the maximum core steam pressure (MCSP) and the time to reach the MCSP. Unlike the maximum core temperature, MCSP was strongly related to the mat MC, but not the press time (**Fig. 6**). As expected, higher mat MC generated more steam, which in turn resulted in a higher maximum stream pressure within the mat. The mat with initial higher MC also took a little less time to reach its maximum stream pressure (**Fig. 7**).

An evaluation of certain mechanical and physical properties of OSB from three southern pine mills was conducted in 1989 when OSB panels were replacing plywood panels as major sheathing and subflooring products in housing (1). All boards from the three mills met the re-
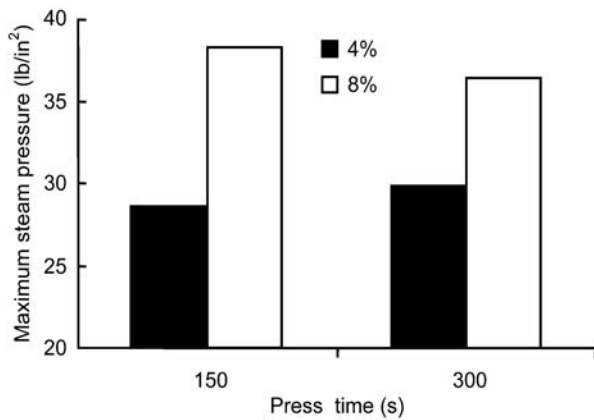
**Figure 6.** ~ *Maximum steam pressures for different face-furnish MC and press time in seconds.*
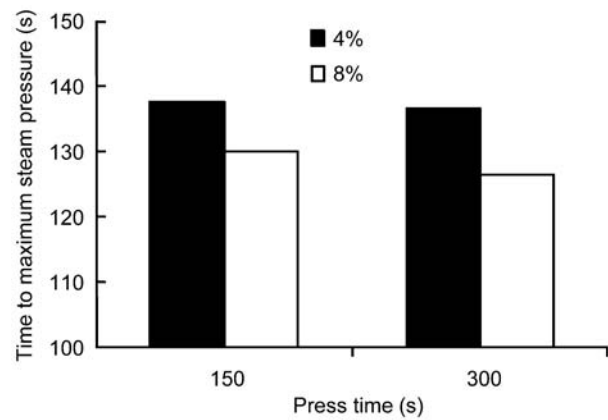


**Figure 7.** ~ *Time to reach maximum steam pressure for different face-furnish MC and press time in seconds.*

quirements of the APA – The Engineered Wood Association standards for sheathing exposure 1. The average density of panels from the three mills was about 45.1 lb/ft$^3$ (722.4 kg/m$^3$). The average MOE and MOR from the commercial OSB panels in parallel to the flake-oriented direction were 722,020 and 3,950 lb/in$^2$ (4.9781 GPa and 27.23 MPa), respectively. The average MOE and MOR in perpendicular to the flake-oriented direction were 419,605 lb/in$^2$ and 3,388 lb/in$^2$ (2.8930 GPa and 23.36 MPa), respectively. The average IB was 57 lb/in$^2$ (3.9 kPa). The average TS and WA were 17.6 percent and 48.7 percent, respectively. Although made in the random flake orientation, the mechanical and physical performances of panels made with the new soy-based resin in this study are very comparable to those of the commercial OSB panels. At the target density of 47 lb/ft$^3$ (752.9 kg/m$^3$), the performances of panels made with the soy-based resin (both at 3.25% and 6.5% levels) are similar and some even exceed the performance of the commercial OSB panels in parallel to the flake-orientation direction. At the target density of 42 lb/ft$^3$ (672.8 kg/m$^3$), only the panels with high face-resin usage (6.5%) exhibit the equivalent performances with the commercial OSB panels. For the low-density panels (at 37%), most of them show more inferior performances than the commercial panels. Note that these comparisons are made without any density and flake-orientation adjustments. With process optimizations (mat MC, flake orientation, press time, panel density, and resin usage), we think that the new soy-based resin system will have a promising future in improving panel performances and lowering costs.

## Conclusions and Recommendations

Four variables (face-resin content, face-furnish moisture content, density of the panels, and press time) were selected to examine their effects on panel performance with a new soy-based resin system. We also studied the possible second-order interactions of these variables with each other. The resulting experimental design was based on a factorial experiment, and ANOVA was used to test the significance of the variables and their interactions. As would be expected with a pure PF resin, results from the soy-based resin indicated that increasing face-resin content and density improved mechanical bending performance and reduced TS and water soak absorption. Face-furnish MC had no effect on the tested mechanical and dimensional properties, but it showed significant effects on the heat transfer (core temperature and internal steam pressure) during the press process. Based on the significant differences in the mechanical and water soak performance between the two press times, we concluded that press time had a significant effect on the relationship between the face (soy/PF) and core (PF) resin curing processes. Therefore, we recommend that future study focuses on the resin performance under different press times and face MCs to optimize the press process for this new resin.

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