# Evaluating Physical Property Changes for Small-Diameter, Plantation-Grown Southern Pine after In Situ Polymerization of an Acrylic Monomer

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**Abstract**

Because of the large percentage of juvenile wood in small-diameter southern pine, this material has lower strength properties compared with the historic published values in the ASTM Standard D2555. Finding new, simple, and inexpensive ways of increasing these strength properties would increase the use of this material for residential construction. For this study, we chose in situ polymerization using the monomer 1,6-hexanediol dimethacrylate to enhance bending strength and stiffness. After determining the lower range of density, modulus of rupture (MOR), and modulus of elasticity (MOE) of juvenile wood from small southern pine logs, southern pine specimens were polymerized using both a vacuum-impregnation and a surface-application approach. The results showed some significant physical property increases for the fully impregnated material that used a large amount of monomer. Although the surface-application approach used less monomer, the physical properties of the juvenile wood did not increase as expected. Only the 1-minute dip treatment showed a significant increase in both bending stiffness and strength, with a weight gain of 11.9 percent. For the surface-application approach, monomer moving to the wood surface during polymerization reduced their effectiveness in increasing MOR and MOE to the expected levels. Therefore, the challenge is finding a method that maintains polymer loading inside the wood structure during the curing process.

Southern pine accounts for approximately 25 percent of the North American softwood lumber production (US Census Bureau 2008, Western Wood Products Association 2008). Because of increasing raw material costs and low lumber prices, lumber manufacturers are installing or evaluating high-speed mills that will process small logs economically with one machine. This would allow manufacturers to purchase less expensive raw material, including small-diameter southern pine that traditionally has been used for pulpwood (J.D., unpublished data, June 2008).

The small-diameter, fast-grown stems processed in these machines usually have an exceedingly high percentage of juvenile wood (Kellison et al. 1984, Larson et al. 2001). The scientific community has long recognized that juvenile wood would present challenges in terms of processing and utilization. With utilization, the strength properties of the juvenile wood are the greatest concern.

Major producers of southern pine timber have recognized the possibility that the current growing stock in many plantations is deficient in bending stiffness, which precludes it from major use in housing construction (Biblis 2006). This fast-grown material is reaching merchantable age and will soon be on the market in increasing volumes. Thus, new uses for products from new pine forests are critical to maintaining a viable market for southern pine in housing.

Researchers have discovered many ways to modify wood and improve material properties (Choong and Barnes 1969,

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Meyer 1981, Schneider 1994, Schneider and Witt 2004, Rowell 2005, Hill 2006). Wood treatment research has found phenol-formaldehyde resins (Stamm and Seborg 1951, 1962) and furfuryl alcohol (Goldstein 1955) to be effective wood treatments, and research continues (Deka and Saikia 2000, Westin et al. 2003). The Indurite™ Process from New Zealand is another treatment for wood hardening (Singh et al. 1999, Franich 2007).

Vinyl monomers, such as methyl methacrylate, styrene, acrylonitrile, and acrylamide, can improve material properties. Solid wood and polymer composites (WPCs) can also improve various physical properties, such as surface hardness, water repellency, dimensional stability, abrasion resistance, and fire resistance (Adams et al. 1970, Rowell 1987, Ibach and Ellis 2005). To fill the voids or lumens, wood is vacuum-impregnated with liquid monomers and then polymerized in situ by gamma radiation or chemical catalyst–heat systems. Improvements in the physical properties of WPCs relate to polymer loading, which depends upon the permeability of the wood species and particular pieces of wood (Rowell 1999). For most species, sapwood usually is more easily filled than heartwood. Compared to other species, southern pine ranks high in permeability (Erickson 1970).

In 2005, the US Department of Agriculture Forest Service Forest Products Laboratory and North Carolina State University began a cooperative project that explored in situ polymerization of monomers of fast-grown southern pine to improve the strength characteristics of the juvenile wood. Past research indicated that specimens impregnated with the monomer 1,6-hexanediol dimethacrylate (HDDMA) showed higher strength and stiffness on average than the control group. Therefore, we selected HDDMA for this study (Ibach and Rule 2001).

The overall objective of this cooperative project was to study the strength properties of in situ polymerized southern pine juvenile wood. Results will assist the forest products industry in determining viable options for enhancing wood properties for the residential housing market.

## Materials and Methods

A series of experiments evaluated the strength properties of juvenile wood from small-diameter southern pine logs to test if vacuum impregnation and surface application of acrylic monomers that were polymerized in situ could improve strength properties. Data were analyzed by analysis of variance (ANOVA) and by pairwise *t* tests between groups using an alpha level of 0.05 for significance. All specimens were loaded on a tangential face closest to the pith as per ASTM Standard D143 (ASTM International 2007).

### Experiment 1: Determining density, modulus of resistance, and modulus of elasticity of plantation-grown southern pine

This test evaluated juvenile wood from small log material at the various density levels and established the lower range of physical properties to determine the best approach for Experiment 2.

Kiln-dried southern pine test lumber was collected from a small log mill in Effingham, South Carolina (Fig. 1). The 200-mm (8-in.) logs were butt logs taken from the first thinnings of a southern pine plantation that were processed by the mill into 32 by 150-mm (5/4 by 6-in.) decking material. The Effingham mill processes only this size material, and all material tested originated from this mill. Specimens were selected from 2-foot end-trims of this decking material and were processed into 25 by 25 by 400-mm (1 by 1 by 16-in.) specimens, which is the secondary recommended method for static bending of small, clear specimens (ASTM Standard D143; ASTM 2007). The classification of the specimens is similar to those found in the Standard Grading Rules for southern pine lumber (Southern Pine Inspection Bureau 2002). All material tested was from this same original stock of 5/4-inch decking.

Specimens were categorized into three different density levels: low, medium, and high. Low-density specimens were defined as those that contained less than 15 percent latewood regardless of rings per inch. Medium-density specimens were defined as specimens with approximately four or more annual rings per inch on either end. Specimens averaging less than four rings per inch were accepted as medium density if they averaged 1/3 or more latewood. High-density specimens were defined as having six or more annual rings per inch and 1/3 latewood on either end. Specimens averaging four or more annual rings per inch were accepted as high density if they averaged 1/2 or more latewood. The unmodified specimens of small plantation-grown southern pine were equilibrated at 70°F and 50 percent relative humidity (RH) and evaluated for modulus of rupture (MOR) and modulus of elasticity (MOE) according to ASTM Standard D143 (ASTM 2007) and specific gravity (SG) according to ASTM Standard D2395 Method A (ASTM 2002). Density was calculated as weight per volume of the conditioned specimens (i.e., 14% moisture content [MC]). Bending strength and stiffness values were corrected to 14 percent MC using the following equation from Chapter 4 of the Wood Handbook (Green et al. 1999):

$$P = P_{12}\left(\frac{P_{12}}{Pg}\right)^{(12-M/M_P-12)} \quad (1)$$

where

$P$ = the property at M percent MC,

$P_{12}$ = the same property at 12 percent MC,

$P_g$ = the same property for green wood, and

$M_p$ = 21 for southern pine.

### Experiment 2: Vacuum impregnation (full coverage) for low-density material

Small specimens of approximately 6 by 6 by 150 mm (1/4 by 1/4 by 6 in.), cut from low-density, 5/4-inch decking material collected from the Effingham mill, were selected to ensure full impregnation. Material used for testing was not from the boards that were classified as low-density material in Experiment 1. Each specimen set consisted of end-matched specimens, one serving as the control and the other impregnated. Specimens were soaked for three different lengths of time to obtain different levels of weight gain: (1) 0 minute, (2) 10 minutes, and (3) 30 minutes. Controls were kept in the conditioning room during the treatment.

A forced-draft oven dried the southern pine specimens at 105°C for 24 hours to remove moisture, after which samples were cooled for 1 hour at room temperature in a glass

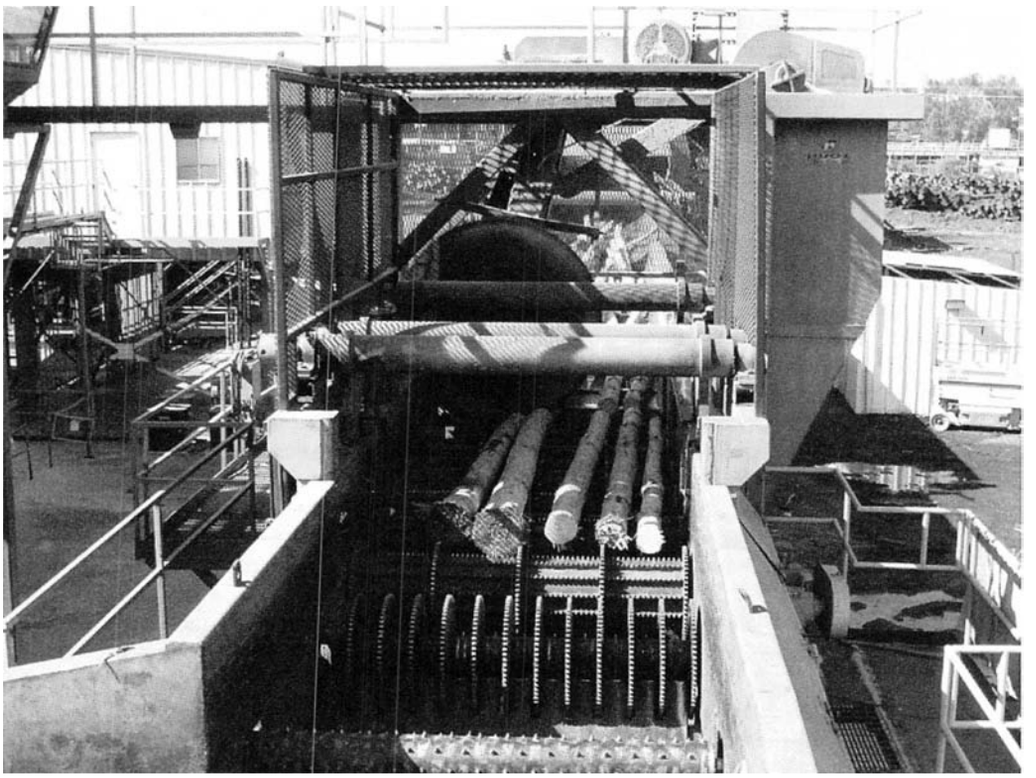

*Figure 1.—Southern pine log from a small-diameter tree ready for processing into lumber.*

desiccator and then weighed. Next, specimens were placed in a glass desiccator, and the system was evacuated for 30 minutes with a water aspirator (28 mm Hg). The 99.5 percent HDDMA solution (Sartomer Company, Inc., West Chester, Pennsylvania) with 0.5 percent Vazo 67 (2,2′-azobis(2-methylbutyronitrile; Du Pont, Wilmington, Delaware) was admitted into the treating chamber until the solution covered all the specimens and then held for 5 minutes. A glass weight held specimens in place to prevent floating. The vacuum was released, and the chamber was brought to atmospheric pressure. The specimens soaked for either 0, 10, or 30 minutes in the solution and were then removed, wiped of excess solution, wrapped immediately in aluminum foil, and placed in a 105°C oven for 18 hours to polymerize. The foil was removed, specimens weighed, and percentage weight gain calculated. The fully impregnated specimens were equilibrated at 70°F and 50 percent RH and evaluated for MOR, MOE, and SG according to ASTM Standard D143 (ASTM 2007). Density was calculated as weight per volume of the conditioned specimens (i.e., 11.3% MC for controls and 2.4% MC for treated specimens). Material was tested, and results were reported at these expected in-use MC.

## Experiment 3: Surface application (less coverage) for low-density material

This experiment examined different methods involving surface application of monomer. After reviewing the results from Experiment 2, we hypothesized that more monomer than necessary had been used to produce the increase in desired properties. Therefore, we expected a 15 percent increase in physical properties from a 60 percent monomer addition into the wood structure using a surface treatment. These approaches allowed the potential of a lower overall weight gain while improving physical properties to historical levels. Specimens 25 by 25 by 300 mm (1 by 1 by 12 in.) cut from $^{5}/_{4}$-inch decking material from the Effingham mill were larger than those used in the second experiment to help lower the variation. Material used for testing was not from the boards that were classified as low-density material in Experiment 1. Each specimen set consisted of end-matched specimens, one serving as the control and the other treated. Controls were kept in the conditioning room during the treatment. All specimens were visually inspected for strength-reducing defects, such as knots and slope of grain.

A forced-draft oven dried the southern pine specimens at 105°C for 24 hours to remove moisture, after which specimens were cooled for 1 hour at room temperature in a glass desiccator and then weighed. Specimens were modified in one of five different ways:

1. Both flat-sawn surfaces were coated with monomer solution (25 mL/side) applied with a paintbrush (not wiped).
2. Both quarter-sawn surfaces were coated with monomer solution (25 mL/side) applied with a paintbrush (not wiped).
3. The whole specimen was dip treated for 1 minute in monomer solution.
4. The whole specimen was dip treated for 10 minutes in monomer solution.
5. The whole specimen was dip treated for 100 minutes in monomer solution.

Only specimens from dip treatments were wiped of excess solution, wrapped immediately in aluminum foil, and placed in a 105°C oven for 18 hours to polymerize. The foil was then removed, the specimens weighed, and the percent weight gain calculated. The surface-applied specimens were equilibrated at 70°F and 50 percent RH and evaluated for MOR, MOE, and SG according to ASTM Standard D143 (ASTM 2007). Density was calculated as weight per volume of the conditioned specimens (i.e., 14.4% MC for controls and 12.9% MC for treated specimens). Material was tested, and results were reported at the expected in-use MC (14%).

Scanning electron microscopy (SEM) analyzed the polymer penetration of the wood surface. To analyze the polymer penetration of the wood surface, the transverse surfaces of 1 by 1-cm wood blocks microtomed from the specimens were examined and photographed in a LEO EVO40 scanning electron microscope (Carl Zeiss SMT, Inc., Thornwood, New York) at a working distance of 10 mm at 15 kV. The blocks were mounted on aluminum stubs using silver paste and coated with gold using a Denton Desk-1 sputter coater (Cherry Hill, New Jersey). The specimens were cut from 3 to 4% inches from the numbered end of the specimen. The total length of the specimen was 12 inches. One quarter of the specimen was sectioned from this, which included the comer two surfaces down to the center of the specimen.

Vacuum impregnation may cause uneven polymer loading. Therefore, SEM was also conducted on a treated specimen along the length at two spots, on the end and 1.5 inches from the end, to determine if any differences in polymer loading could be seen, particularly at the end.

Surface coverage of the specimens after treatment was determined as well. Level of surface coverage may show how effective treatment was regarding polymer penetration into the wood structure. The surface coverage of the polymer was rated from 0 to 4 as follows: 0 = 0 percent (none), 1 = >0 to ≤25 percent, 2 = >25 to ≤50 percent, 3 = >50 to 575 percent, 4 = >75 to 100 percent.

## Results and Discussion

A series of experiments evaluated strength properties of wood from small-diameter southern pine logs to see if in situ polymerization could improve the strength properties.

### Experiment I: Determining density, MOR, and MOE of plantation-grown southern pine

In this experiment, physical properties of density, MOR, and MOE were evaluated in three different categories of visual density (Table 1). As expected, the densities of all three groups of specimens (low-, medium-, and high-density specimens) were significantly different.

Regarding MOR, the low-density material was significantly weaker than the medium- and high-density specimens. The medium- and high-density materials were similar in MOR strength. The results were the same for MOE: The low-density material had significantly lower stiffness than the medium- and high-density specimens, and the medium- and high-density materials were similar in terms of MOE.

The density, MOR, and MOE for the tested samples were compared with values given in ASTM D2555-06 (ASTM 2006). All values were adjusted to 14 percent MC.

The average density of the low-density specimens was significantly lower (at the 0.05 probability level) than the published density in ASTM D2555-06 adjusted to 14 percent MC of 0.54 ± 0.06 g/cm³ (mean ± SD), whereas the high-density specimens were significantly higher than this published value. The average MOR values for the low-density specimens were significantly lower than the published MOR value in ASTM D2555-06 adjusted to 14 percent MC of 77.8 ± 12.8 MPa. We found a significant difference between the MOR value for the high-density specimens and this published value. The average MOE values for all specimens were significantly lower than the published MOE value in ASTM D2555-06 adjusted to 14 percent MC of 11.7 ± 2.7 GPa. Note that even though the high-density specimens had significantly higher density compared with the published data, this higher density did not result in higher MOE properties. This indicates that density, which correlates with strength properties in most situations, does not fully explain the MOE values in the material tested. However, the large percentage of juvenile wood present in this material would explain the low MOE values found.

*Table 1.—Density, MOR, and MOE for small plantation-grown southern pine (no treatment).*[a]

| | Physical properties | | |
|---|---|---|---|
| Type of material | Density (g/cm³) | MOR (MPa)[b] | MOE (GPa)[b] |
| Low ($n$ = 12) | 0.44 ± 0.04 | 59.1 ± 7.3 | 6.28 ± 1.20 |
| Medium ($n$ = 12) | 0.54 ± 0.03 | 79.8 ± 9.0 | 9.59 ± 1.20 |
| High ($n$ = 12) | 0.64 ± 0.07 | 88.1 ± 14.9 | 9.26 ± 3.63 |
| Published values[c] | 0.54 ± 0.06 | 77.8 ± 12.8 | 11.7 ± 2.7 |

[a] Values are means ± standard deviations based on individual values.
[b] Modulus of resistance (MOR) and modulus of elasticity (MOE) pressure conversion: 1 mPa is 145 pounds per square inch (psi); 1 GPa is 145,000 psi.
[c] Published values for loblolly pine found in ASTM D2555-06 (ASTM 2006); adjusted to 14 percent MC.

### Experiment 2: Vacuum impregnation (full coverage) for low-density material

Given that the low-density specimens were lower in mechanical properties compared with the medium- and high-density specimens, the second experiment focused on the potential increase in mechanical properties of low-density material when fully impregnated.

The second experiment showed that impregnation could improve strength properties (increasing MOR 39% and MOE 27%) of fast-grown juvenile wood material. However, the density and weight gain values were proportionally higher than the gains in MOR and MOE (Table 2). We grouped all treated specimens together, because the different level of weight gain for the three soaking times was not significant and did not warrant separate categories.

Values of density, MOR, and MOE for the modified group that was impregnated were significantly higher (at the 0.05 probability level) than those for the control group. Values for the control group of low-density specimens were compared with values of low-density specimens in the first experiment. All values of density, MOR, and MOE found in the second experiment were significantly lower than values found in the (untreated) control group from the first experiment. This may have happened because the material for the second experiment was cut from stock material closer to the pith and had below-average physical properties

*Table 2.—Density, MOR, and MOE for small plantation-grown southern pine (fully impregnated).*[a]

| Type of material | PWG | Density (g/cm$^3$) | Change (%) | MOR (MPa)[b] | Change (%) | MOE (GPA)[b] | Change (%) |
|---|---|---|---|---|---|---|---|
| Control ($n$ = 16)[c] | — | 0.36 ± 0.04 | — | 47.9 ± 6.1 | — | 4.00 ± 0.48 | — |
| Modified ($n$ = 16) | 180 ± 33 | 0.93 ± 0.06 | 160 | 65.6 ± 8.9 | 39 | 5.03 ± 0.69 | 27 |
| Published values[d] | — | 0.52 ± 0.06 | — | 93.8 ± 15.4 | — | 15.3 ± 2.9 | — |
| Control (low)[e] | — | 0.44 ± 0.04 | — | 59.1 ± 7.3 | — | 6.28 ± 1.20 | — |

[a] Values for PWG (percent weight gain), density, MOR, and MOE are means ± standard deviations based on individual values.
[b] Modulus of rupture (MOR) and modulus of elasticity (MOE) pressure conversion: 1 mPa is 145 pounds per square inch (psi); 1 GPa is 145,000 psi.
[c] Control specimens from second experiment used for calculating percent change.
[d] Published values for loblolly pine found in ASTM D2555-06 (ASTM 2006); adjusted to 11 percent MC.
[e] Low-density material control group values from first experiment for comparison (Table 1).

or was cut from different heights within the tree than was the other material in Experiment 1 (Baker and Shottafer 1968). Although the SG of 0.36 is low compared with the other control group material, the value did fall within the range of values listed by Zobel et al. (1972) for southern pine juvenile wood.

## Experiment 3: Surface application (less coverage) for low-density material

The third experiment was designed to evaluate if surface application would improve mechanical properties, because full-vacuum impregnation is a rather expensive process in terms of material use and processing time compared with surface application (Table 3).

For all of the different monomer applications, the density was statistically different between the control and treated groups (at the 0.05 probability level). This indicates an uptake of monomer into specimens. Between the control and treated groups, only the material dipped for 1 minute showed a statistically significant difference (at the 0.05 probability level) for MOR and MOE. Material with treatment applied to the tangential surfaces showed a statistically significant difference (at the 0.05 probability level) just for MOE. Results for mechanical properties of MOR and MOE of different methods for surface application were inconsistent and not expected because of weight gain (increase in density).

To explore this inconsistency in weight gain compared with mechanical properties for this part of the study, we evaluated the specimens from each surface application using SEM. Examining the SEM photographs indicated little difference in penetration for each surface application (Fig. 2). To explore this phenomenon further, the depth of polymer coating of the wood surface was determined. On the rating scale of 0 to 4, surface coverage was 1.00 ± 0.58, 1.00 ± 0.00, 1.86 ± 0.90, 2.57 ± 0.53, and 3.57 ± 0.53, respectively, for the five surface treatments. The results indicated that as weight gain from treatment increased, the surface polymer coating depth also increased, although all wood surfaces for the dip treatments were wiped before polymerization. Therefore, higher weight gains for longer dipping times more likely resulted from coating of the surface than from monomer polymerizing in the wood structure.

To examine the gradient of polymer loading, one of the 1-minute dip specimens was sectioned along its length using SEM. For the I-minute dip specimen 19 A, the end SEM photographs (Figs. 3a and 3b) indicated (as expected) higher polymer loading, because most of the lumens were full of polymer. As for the corresponding SEM photograph at 1.5 inches (Figs. 3c and 3d), this showed similar loading, ignoring the latewood band, as the SEM photographs from 3 to 4% inches from the end (Figs. 3e and 3f). Therefore, an end effect is noticed, but the degree of polymer loading appears to level out before 1.5 inches from the end of the specimen. A greater degree of polymer loading because of the end effect does reduce the effectiveness of the treatment; hence, increases in MOE and MOR would not be optimal. Coating the ends before treatment with some inert material could limit monomer penetration through the end.

Another possible influence on the variability of results was caused by the strength-reducing characteristics observed on specimens during visual examination. Five of the 35 treated specimens had flaws: two specimens had small knots, two were slightly crooked, and another had a flaw in the middle. After reevaluating the results without the flawed specimens, we found that the defects had no significant effect on the reported results for MOR and MOE found in Table 3.

An ANOVA test was run to evaluate if different monomer applications produced differences in density, MOR, and MOE. The tests showed no statistically significant difference in density, MOR, and MOE. This is to be expected

*Table 3.—Density, MOR, and MOE for small-diameter plantation-grown southern pine (surface impregnated).*[a]

| | PWG | Density (g/cm$^3$) | | | MOR (MPa) | | | MOE (GPa) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Monomer addition | Modified ($n$ = 7) | Control ($n$ = 7) | Modified ($n$ = 7) | Change (%) | Control ($n$ = 7) | Modified ($n$ = 7) | Change (%) | Control ($n$ = 7) | Modified ($n$ = 7) | Change (%) |
| Applied to both tangential (flat-sawn) surfaces | 7.91–2.50 | 0.424–0.043 | 0.447–0.03 | 5.44 | 50.3–9.0 | 54.0–14 | 7.47 | 4.19–1.70 | 4.70–2.00 | 12.1 |
| Applied to both radial (quarter-sawn) surfaces | 7.01–1.40 | 0.448–0.035 | 0.476–0.036 | 6.14 | 55.3–9.0 | 58.7–10 | 6.21 | 4.76–1.20 | 4.72–1.30 | −0.92 |
| 1-min dip | 11.9–4.0 | 0.407–0.049 | 0.451–0.049 | 10.9 | 48.3–12.0 | 54.1–17 | 12.1 | 3.95–1.30 | 4.51–1.60 | 14.2 |
| 10-min dip | 13.9–5.0 | 0.431–0.040 | 0.487–0.031 | 13.0 | 55.0–11.0 | 55.1–13 | 0.09 | 4.78–1.40 | 4.49–1.50 | −6.04 |
| 100-min dip | 18.5–5.0 | 0.459–0.049 | 0.516–0.038 | 12.6 | 59.5–19.0 | 61.3–16 | 3.01 | 5.18–2.20 | 4.94–1.80 | −3.01 |

[a] Values in modified and control columns are 95 percent confidence intervals. PWG = percent weight gain.

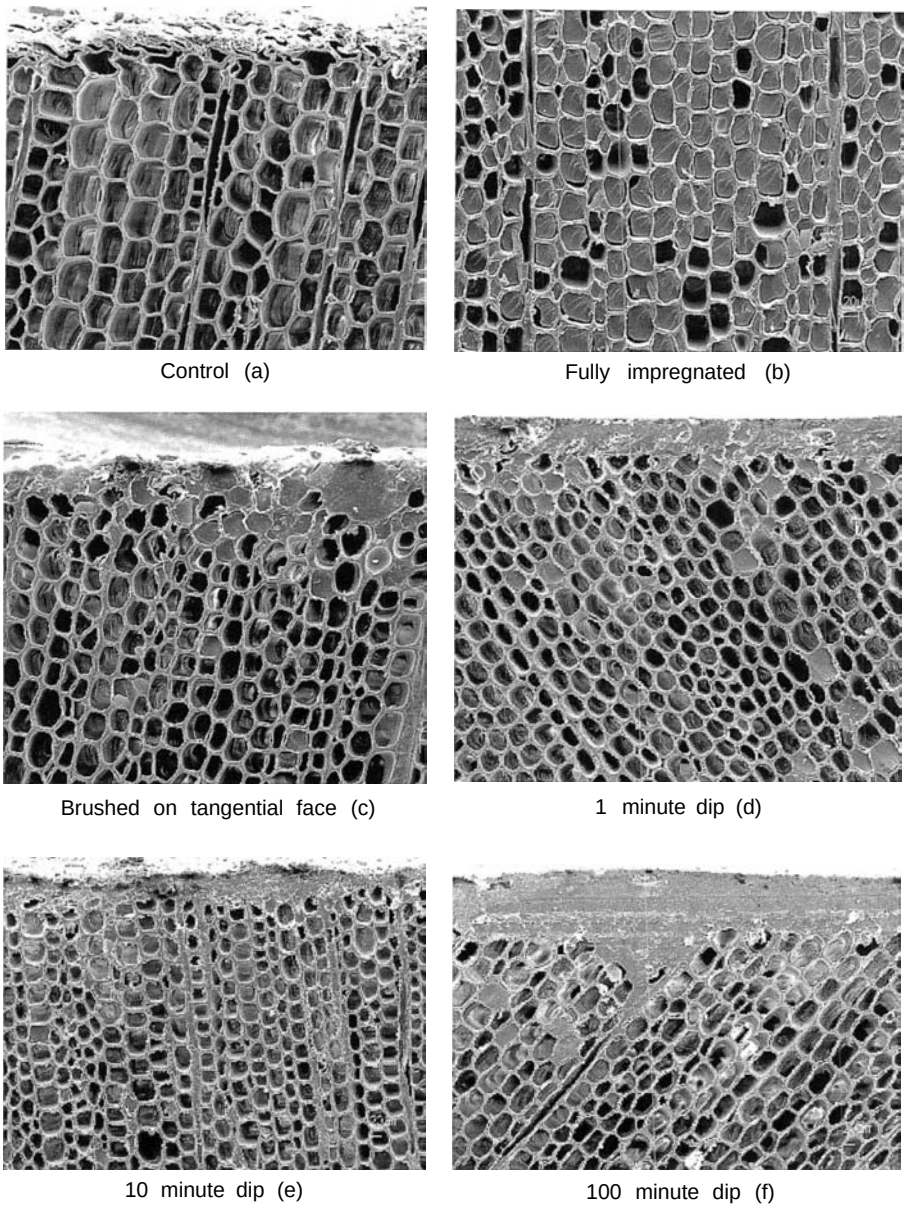


*Figure 2.—Scanning electron microscope photographs of specimens treated for the third experiment: (a) untreated control, (b) vacuum-impregnated with surface wipe (Experiment 2), (c) brushed on tangential surface, (d) I-minute dip with surface wipe, (e) 10-minute dip with surface wipe, and (f) 100-minute dip with surface wipe.*

because of the large variation (SD) for the change in density, MOR, and MOE for each treatment.

In this study, surface treatments did not indicate an effective way of increasing the mechanical properties of the southern pine material for several reasons. These reasons included the large variability in mechanical properties for the material before treatment and the inconsistent effect and uptake of the monomer. This is in contrast to the impregnation treatment (Experiment 2).

## Conclusions

Except for the 1-minute dip approach, the different surface monomer applications did not influence the mechanical properties of wood. Lack of influence on physical properties is largely explained by lack of monomer retention below the wood surface during polymerization. Results from the 1-minute dip approach, however, showed the potential to enhance physical properties of southern pine juvenile wood.

Southern pine lumber produced using plantation-grown, small-diameter logs obtained from the first thinning can be identified visually as low-, medium-, or high-density material. Visually identified low-density lumber correlated with lower measured density and mechanical properties. However, for visually identified and calculated medium- and high-density material, higher density was not an indicator of higher strength. For material graded as high density, this may cause some problems. An example is using the material for structural purposes, where failure may occur because of lower-than-expected physical properties. The lower-than-expected values may be explained by the known properties and characteristics of juvenile wood (wood that grows for 5 to 15 years next to the pith).

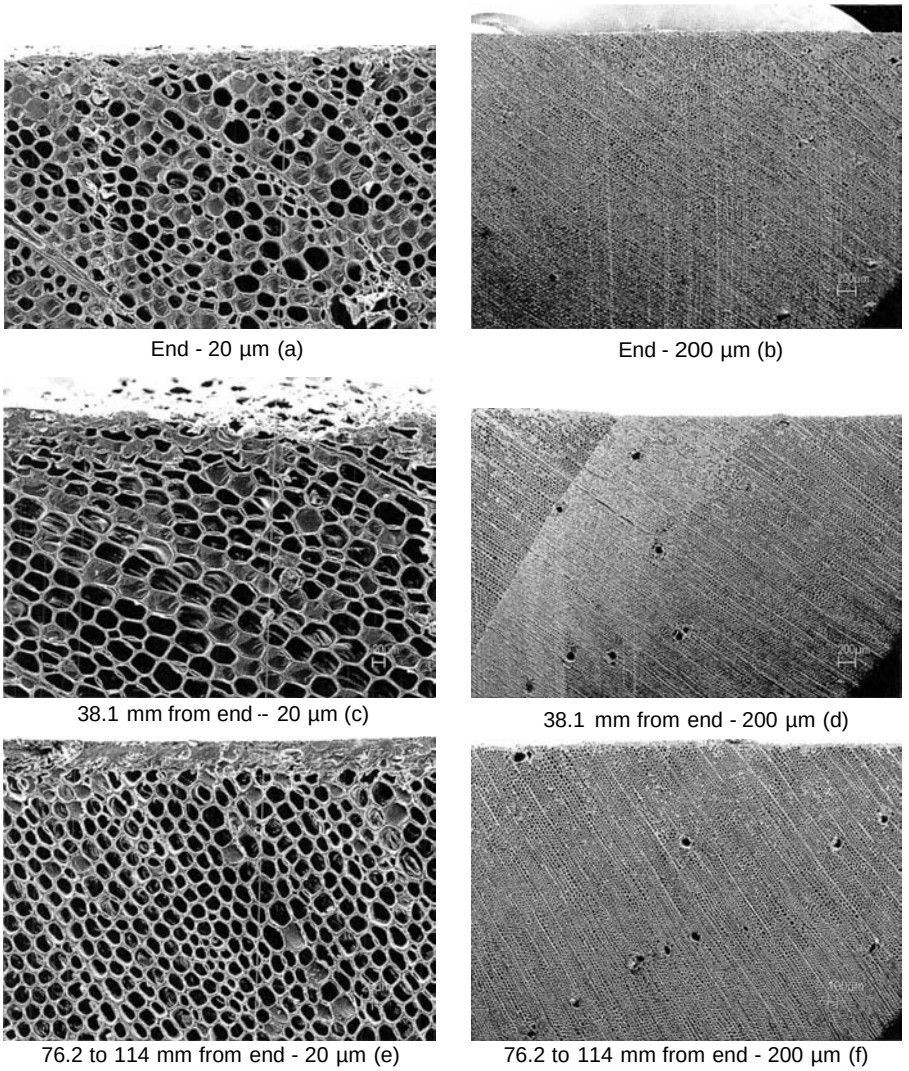


*Figure 3.—Scanning electron microscope photographs of the 1-minute dip specimen 19 A along its length: (a) end, bar = 20 µm, (b) end, bar = 200 µm, (c) 38.1 mm in from end, bar = 20 µm, (d) 38.1 mm in from end, bar = 200 µm, (e) 76.2 to 114 mm from end, bar = 20 µm, and (f) 76.2 to 114 mm from end, bar = 200 µm.*

Vacuum impregnation of the monomer HDDMA followed by in situ polymerization of acrylic monomer was investigated as one technique to improve the strength properties of low-density southern pine juvenile wood. The result was significantly higher density, MOR, and MOE when comparing the treatment to the control group. However, density and weight gain values were proportionally higher than gains in MOR and MOE. Furthermore, the problem created by the small physical size of the specimens was reinforced when comparing the values found in the experiment to the mechanical properties listed in ASTM D2555-06. For density, the value for the control group was significantly lower than the published density of 0.52 g/cm$^3$, whereas density for the modified group, as expected, was significantly higher. This is in contrast to the MOR and MOE values. Both MOR and MOE values for the control and treatment group were significantly lower than published values. This may have been the result of a smaller experimental specimen size, which led to large variability compared with the specimen size used for the reported values.

The large weight gain from the vacuum impregnation did not result in a similarly large increase in MOR and MOE. Therefore, a less costly method was explored using less monomer while maintaining the same proportional increase in MOR and MOE. Samples were either coated or dipped into the monomer before in situ polymerization. In addition, a larger specimen was used in an attempt to mitigate the problem of large variability found in small specimens.

Our overall conclusion from these findings indicates that mechanical properties of small-diameter southern pine logs are different from published values. Using in situ polymerization does significantly increase the physical properties for the full-impregnation method. Although the surface-application approach used less monomer, the physical properties did not increase as expected for all cases. Therefore, further work is needed to identify a different, more effective impregnation method that improves the level of polymer loading in the wood structure during the curing process to enhance physical properties to the desired level.

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