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Improved Durability of Wood Strand-Based Panels Using Guayule

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Abstract: In this study, the most effective application method of guayule resin and its effects on termite and fungal decay biological performances of wood strand-based (WSB) panels were explored. Southern yellow pine (*Pinus* spp. L.) wood strands were mixed with phenol formaldehyde (PF) resin to a target resin content of 5.00% and hot-pressed to manufacture the control WSB panels. For the in-situ process, a guayule resin solution was prepared and sprayed on the wood strands immediately after spraying the PF resin to a target content of 5.00%. For brushing and spraying methods, a sub-set of the control panel specimens were further brushed or sprayed with guayule resin solution on all surfaces. To understand the effects of guayule on durability, specimens cut from control and treated panels were subjected to termite resistance and fungal degradation soil block tests. The in-situ specimens with 5.00% guayule were subjected to tensile, internal bond, water absorption, and thickness swelling tests to find out whether guayule affects the mechanical performance of WSB panels. The results showed that in-situ treatment resulted in a significant reduction in the mechanical properties of wood stand-based panels. The sprayed technique resulted in more durable panels, as the mass loss was 2.21% for termites and 3.24% for fungi specimens, which decreased by 76.66% and 80.86%, respectively, when compared to the WSB controls.

Keywords: internal bond (IB); water absorption and thickness swelling; tensile; fungal decay resistance; termite resistance; guayule resin; southern yellow pine (SYP); wood strand-based (WSB) product

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1. Introduction

In recent years, natural renewable resources of wood and wood-based products have been growing in consumption and demand [1–3]. This is due to severe climate changes and the ability of trees to capture and lock carbon within their cells to improve carbon sequestration and reduce global warming effects [1–3]. The exchange of carbon dioxide (CO_2) between forests and the atmosphere is complicated, yet living and dead trees can store >60% of the carbon stock in forest ecosystems [1–3]. Thus, trees can be used to develop different wood and wood composite products such as mass timber, dimensional lumber, cross-laminated timber (CLT), glulam beams, plywood, laminated veneer lumber (LVL), oriented strand boards (OSBs), particleboards, medium-density fiberboard (MDF), and many other engineered wood products [4].

Unprotected wood-based products can slowly be degraded by termites and fungi under certain environmental conditions [5]. Over the years, many chemical preservatives such as creosote, pentachlorophenol (Penta/PCP), and chromated copper arsenate (CCA) have been used in the industry to enhance the durability of wood and forest products, especially in outdoor applications [6–10]. There is always a pressing need to develop applicable natural alternatives, bio-based, environmentally safe, wood-based additives and preservatives with reduced toxicity and low environmental impacts.

Guayule (*Parthenium argentatum* A. Gray), pronounced wy-oo-lee, is a low perennial desert shrub, native throughout the Chihuahuan Desert Ecoregion in Arizona, New Mexico, Texas, and northern Mexico in North America [11,12]. The shrub has large amounts of natural latex rubber in its stems, and cultivated fields have been established with genetically diverse seeds that have been harvested mechanically for rubber production since the before the early 1900s [11–13]. The harvested materials are ground into bagasse and the natural latex rubber is chemically extracted from its cells [13]. After the latex rubber is extracted, a viscous resin byproduct is left over called guayule resin [14,15]. U.S. tire producers such as Firestone, Bridgestone, Cooper Tires, and Goodyear companies are currently the main sources of the available byproducts of guayule resin [16] within the U.S. market. Guayule comes from a mature and established industry, as the United States was able to process guayule to produce over 13.60 metric tons (15.00 U.S. tons) of natural rubber daily during the 1940s [12]. However, such production was replaced with synthetic rubber post-War World II [12]. From 2012 to present day, Bridgestone has opened a Biorubber Processing and Research Center in Arizona, USA, to develop natural rubber from guayule [16]. The guayule resin byproduct has the potential to act as a low-toxicity component of coatings, tackifiers, adhesives, composite components, emulsifiers, bio-control agents, insecticides, anti-microbials, and anti-fungals [17–19]. Guayule resin is an effective natural biocide with termiticidal and fungicidal properties that may have uses in lumber and engineered wood products to provide longevity and protection for many years to come [19–25].

In our previous research (Entsminger et al. [19]), wood strand-based (WSB) panels were fabricated and treated up to the target PF resin content of 5.00% and guayule resin contents of 0.50% and 1.00% to determine the effects of guayule resin on the durability and mechanical performance of such panels. However, due to the low percentage of guayule, it was difficult to make a clear conclusion. In this novel study, our objectives were to explore and use different methods (e.g., spraying, brushing) to apply and treat the WSB specimens with guayule resin, and a higher guayule content of 5.00% of the oven-dry weight of the pine wood strands within the manufacturing process was also explored.

2. Materials and Methodology

2.1. Materials

The commercial southern yellow pine (SYP; *Pinus* spp. L.) wood strands used in this study were obtained from West Fraser (Guntown, MS, USA). We chose SYP based on many factors; for example, it is the most abundant, rapidly renewable softwood species resource in the southeastern United States and throughout the entirety of North America, and it has been used as a major construction material due to its high strength per unit weight, anatomical structure, workability, relatively low cost, high-energy content, aesthetic value, and sustainability overall [5]. The pine wood strands were 10.16 cm long and 2.54 to 5.08 cm wide with an average thickness of 0.0715 cm. Previously reported works stated that the content of this type of wood was rich in lignin (27.50% to 32.39% in mature pine) in comparison to other wood species [26]. The industrial wood composite adhesive used in this study was phenol formaldehyde (PF) resin, from Hexion Inc. (Columbus, OH, USA). The pine wood strands were dried in a high-temperature oven at 88 °C for at least 24 h to reach an average moisture content (MC) of 3.00% and then mixed with PF resin in a drum blender to a target resin content of 5.00% of the oven-dry weight of the pine wood strands. The wood strands' MC was determined to be at 3.00% by using a scientific halogen moisture biomass analyzer and balance equipment.

The guayule resin was provided by the United States Department of Agriculture (USDA) Agriculture Research Service (ARS) for research purposes, and we discovered that this product is extremely difficult to work with as it is a hard solid at room temperature (see Figure 1a in Entsminger et al. [19]). Therefore, to reduce the viscosity of the guayule, it was kept in a laboratory conventional oven above 70 °C as stated by Bultman et al. [27] and Schloman and Wagner [28]. To further decrease its viscosity and improve the workability, a guayule–acetone solution was prepared by mixing guayule resin with pure acetone

($(CH_3)_2CO$) at a 1:1 weight ratio [19,29,30]. The solid content of guayule resin was 100.00%, whereas the guayule–acetone solution had a solid content of ~57.00%.

2.2. Manufacturing Process

Figure 1 shows the schematic diagram of our manufacturing process. To manufacture the WSB control panels, the oven-dry pine wood strands were mixed with PF resin and then oriented uniaxially and immediately hot-pressed to the desired target thickness of 1.27 cm and target density of 672.78 kg/m^3 (Figure 1, Steps 1–4). A Dieffenbacher Hydraulic Hot Press, with PressMAN Press industrial Programmable Logic Controllers (PLCs; Windsor, ON, Canada) was used to hot-press the pine WSB panels for 5 min at 176.67 °C temperature and an average pressure of 0.76 MPa. Each WSB panel was 86.36 × 81.28 × 1.27 cm^3 in size, which was based on the target density, platen size, and applied pressure of the hot-press machine. The average dimensions and number of specimens of the manufactured panels in each treatment group can be found in Table 1. As OSB and WSB products were introduced into the market around the 1980s, many scientists have explored different aspects of processing, pressing, resin, moisture content, and mechanical properties of OSB panels; therefore, our pressing design was the same as conventional OSB manufacturing processes. No commercial WSB products were used other than the commercial SYP wood strands and the industrial PF resin to fabricate WSB panels. During the manufacturing process, the acetone solvent in the guayule-acetone mixture off-gases and evaporates very quickly once exposed to the air; therefore, the guayule resin product is leftover to adhere to the wood strands and, in turn, to the WSB products.

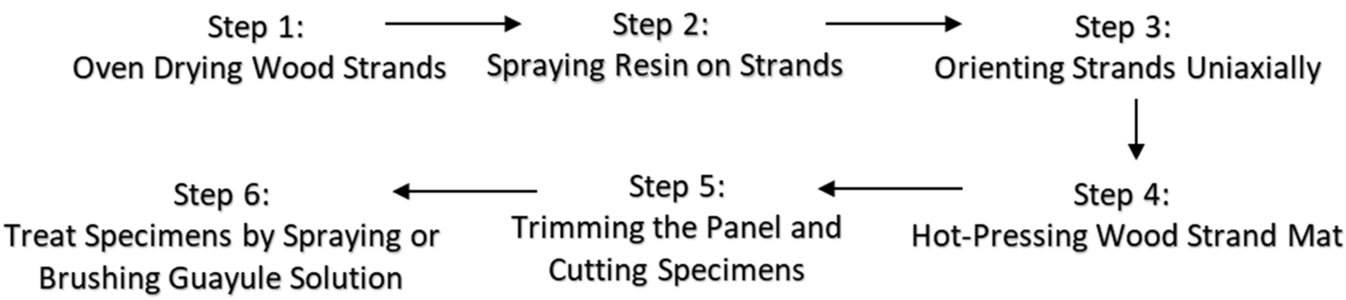

Figure 1. Schematic diagram of our manufacturing process and methodology steps for treating wood strand-based (WSB) specimens with guayule solution.

Table 1. Average dimensions and number of test specimens per treatment for each test.

Experiment	Treatment Group [a]	Sample Number	Length (cm)	Width (cm)	Thickness (cm)
Internal Bond (IB)	In-situ	15	5.08	5.08	1.34
Water Absorption and Thickness Swelling	In-situ	9	15.24	15.24	1.34
Tensile	In-situ	10	25.40	3.81	1.34
Termite Resistance	Ctrl, In-situ, BRSH, SPRY	7	2.54	2.54	1.46
Fungal Decay Resistance	Ctrl, In-situ, BRSH, SPRY	5	2.54	2.54	1.46

[a] Footnote: In-situ = 5.00% guayule sprayed after 5.00% phenol formaldehyde (PF) resin during manufacturing process; Ctrl = control/no treatment/5.00% PF resin; BRSH = brushed treatment method; and SPRY = sprayed treatment method.

2.3. Treatment Process

As previously stated, one of the main objectives of this research was to find the most efficient and effective methods of applying guayule to WSB products. Therefore, after the WSB panels were manufactured and cut to specimen size, uniform brushing or spraying techniques were used to apply the guayule treatment on these test specimens (Figure 1, Steps 5 and 6). Each WSB specimen had smooth external block side, top, and bottom surfaces from using a very fine-toothed sawblade to process the specimens.

2.3.1. In-Situ Treatment

In this study, treatment of the panels during the manufacturing process is referred to as in-situ treatment. The guayule–acetone solution was immediately sprayed on the pine wood strands right after the PF resin was applied using the same gravity feed air spray gun used for PF resin during the manufacturing process within the drum blender. In our previous research (Entsminger et al. [19]), in-situ treatment using guayule solution to target contents of 0.50% and 1.00% of the oven-dry weight of pine wood strands was used. However, in this study, a higher guayule content of 5.00% of the oven-dry weight of pine wood strands was applied during the manufacturing process for a better understanding of the effects of guayule resin on the durability of the WSB panels.

2.3.2. Brushing/Spraying

Figure 2 shows uniform brushing (the image on the left), using a 2.54 cm wide paint brush, and uniform spraying (the image on the right), using a gravity feed air spray gun with guayule–acetone solution to treat WSB panels. Brushing or spraying guayule–acetone solution on control specimens is referred to as brushing or spraying treatment, respectively. Termite and fungus test specimens had an average length and width of 2.54 cm (an average standard deviation (S.D.) of 0.01 cm) and average thickness of 1.27 cm (an average standard deviation (S.D.) of 0.04 cm), which was the target thickness of the fabricated panels, and were sprayed or brushed only one time on all six sides with an even uniform coating of guayule–acetone solution to better emulate industrial practices and procedures. One uniform coating, with an average application of 1.36 g of guayule solution, was used to brush each termite and fungus specimen on all six sides. Likewise, one uniform coating, with an average application of 3.76 g of guayule solution, was used to treat fungus and termite specimens on all six sides using the spraying technique. Overall, the spraying methodology was a faster procedure, but it used approximately 2.76 times more guayule solution compared to the brushing technique. After the specimens were brushed or sprayed, they were left under a fume hood to off-gas the acetone and then were conditioned for at least 14 days before conducting termite and fungus tests according to American Wood Protection Association (AWPA) E1-23 and AWPA E10-22 protocol standards [31,32].

Figure 2. Brushing (left image), using a 2.54 cm wide paint brush, versus spraying (right image), using a gravity feed air spray gun, techniques with a uniform guayule–acetone solution to treat wood strand-based (WSB) panel specimens prior to testing.

2.4. Testing of the Specimens

Different physical bonding, mechanical, and biological experimental testing properties were conducted to understand the effects of guayule resin on the WSB panels such as tensile, internal bond (IB), water absorption (WA), thickness swelling (TS), and termite and fungal decay resistance. As the guayule solution was applied on wood strands during the manufacturing process for in-situ specimens, it could affect the bonding and, in turn, the mechanical performance of WSB panels. Therefore, in-situ specimens were submitted to tensile, internal bond (IB), water absorption (WA), and thickness swelling (TS) tests following sections 10, 11, and 23 of ASTM D1037 [33]. The tensile specimens were dog-bone-shaped, and detailed dimensions can be found in ASTM D1037, section 10 [33]. The results of these tests were compared to those of control specimens that were submitted to the same tests in our previous research [18]. For brushing and spraying techniques, guayule was applied on the fabricated WSB specimens in a thin coating; therefore, the IB and tensile tests were not conducted on these two treatments, since guayule, as a thin coating, does not affect the mechanical properties of these treated WSB specimens.

To evaluate the effect of guayule treatment on the biological degradation performance of the pine WSB panels, which was the main objective of this study, AWPA E1-23 and AWPA E10-22 were followed [31,32]. The average dimensions and number of specimens per treatment group can be found in Table 1. All specimens were conditioned for a minimum of 4 weeks at approximately 25 °C with a relative humidity of 65% before testing.

2.4.1. Termite Methodology

The laboratory methods for evaluating the termite resistance of wood-based materials followed the AWPA standard E1-23 Laboratory Methods for Evaluating the Termite Resistance of Wood-Based Materials [31]. This standard was followed for evaluating the termite resistance of treated and untreated WSB panels. A total of seven (7) specimens per treatment plus one additional specimen for operational mass loss were used. Additionally, eight (8) SYP softwood thin-wafer specimens were used as the test control for the termite resistance test, and these specimens had an average dimension size of 2.54 × 2.54 × 0.635 cm^3. There were two different control groups within this test—SYP softwood thin-wafer control specimens and WSB control specimens—that we manufactured as stated earlier in this manuscript. Overall, there were 40 specimens (32 pine WSB specimens and 8 pine control specimens). Before starting the termite tests, all pine WSB and control specimens were oven dried at 40 °C for 7–10 days until a constant weight was achieved to obtain the initial oven-dry weights. Each individual test specimen was placed into sterilized glass jar containing 150.00 g of oven-dry sterilized sand and 30.00 milliliters (mL) of deionized water, and then inoculated with 1.00 g of termites (~400 termites). A single-choice (no-choice) test procedure was used. Overall, approximately 35.00 g of native eastern subterranean termites (*Reticulitermes flavipes*) from a single colony was obtained from Dorman Lake Field Test Plots, Starkville, MS, USA. All jars were placed in a Blue M Dry Type Bacteriological Incubator (Blue M Electric Company, Blue Island, IL and New Columbia, PA, USA) set at 28 °C and monitored for four weeks (28 days). The mass of each pine WSB specimen and pine control specimen was taken before and after termite exposure to obtain mass loss values in oven-dry conditions.

After the final weights were recorded, four (4) different people conducted visual rating scores on all specimens as part of the analysis. In the AWPA E1-23 [31] standard, section 7 requires that each specimen block is examined and visually rated using their rating system of the following values: 10 = sound, 9.5 = trace, surface nibbles, 9 = slight attack up to 3%, 8 = moderate attack (3–10%), 7 = moderate to severe attack (10–30%), 6 = severe attack (30–50%), 4 = very severe attack (50–75%), and 0 = complete failure (100%) [31].

2.4.2. Fungus Methodology

The laboratory method for evaluating the decay resistance of WSB materials was performed according to AWPA standard E10-22 Laboratory Method for Evaluating the

Decay Resistance of Wood-Based Materials Against Pure Basidiomycete Cultures [32]. Five blocks of each treatment were conditioned, based on the standard, to a constant weight at the recommended conditions between 20° and 30 °C and between 25% and 75% relative humidity. Five (5) wooden blocks of untreated SYP (1.905 × 1.905 × 1.905 cm^3) remained untreated as control specimens. The brown-rot decay fungus *Gloeophyllum trabeum* was introduced into sterilized jars of soil with deionized water, in which an SYP untreated wafer (feeder strip) was placed. We chose this type of brown-rot fungus based on the AWPA E10-22 professional standard for this type of wood-based material and that brown-rot fungi are more typically associated with softwood species compared to white-rot fungi, which are typically associated with hardwood species [32]. The fungi were allowed to grow on the feeder strips, which were maintained in an incubator set at 27 °C, with no internal light, for approximately two weeks. Once the fungi matured on the feeder strip, each treated or untreated wood block was introduced into individual jars and maintained in the same incubator. Based on recommendations in the AWPA E10-22 standard, since the material was a WSB composite, a minimum of 12 weeks was allotted for the test [32].

2.5. Statistical Analysis

The results and effects of guayule on WSB panels' physical bonding performance (water absorption and thickness swelling), mechanical properties (IB and tensile strengths), and durability (termite and fungal decay resistances) are discussed in the following sections. Robust statistical analysis programs such as Microsoft Office Excel and SAS 9.4 software were used to conduct mean value comparisons, a *t*-Test, a least significant difference (LSD) test, and an analysis of variance (ANOVA) to determine if statistical differences among treatments were detected. The *t*-Test and ANOVA test also assume the validity of homogeneity of variances and normal distributions of the data. Statistical analyses were performed at $p < 0.05$ at an α level of 0.05 [34].

3. Results and Discussion

3.1. Physical and Mechanical Properties

To understand the effect of guayule on the physical and mechanical bonding performance of wood strands, in-situ specimens with 5.00% guayule were submitted to IB and tensile tests. In Figure 3, the results of these tests are compared to that of control specimens that were submitted to the same test in our previous research [19]. The IB and tensile strengths of in-situ specimens were 55.00% and 26.00% lower than those of control specimens, respectively. As mentioned previously, sprayed and brushed specimens were not subjected to IB and tensile testing as they have the same mechanical properties as WSB controls, since a thin coat of guayule does not affect these properties.

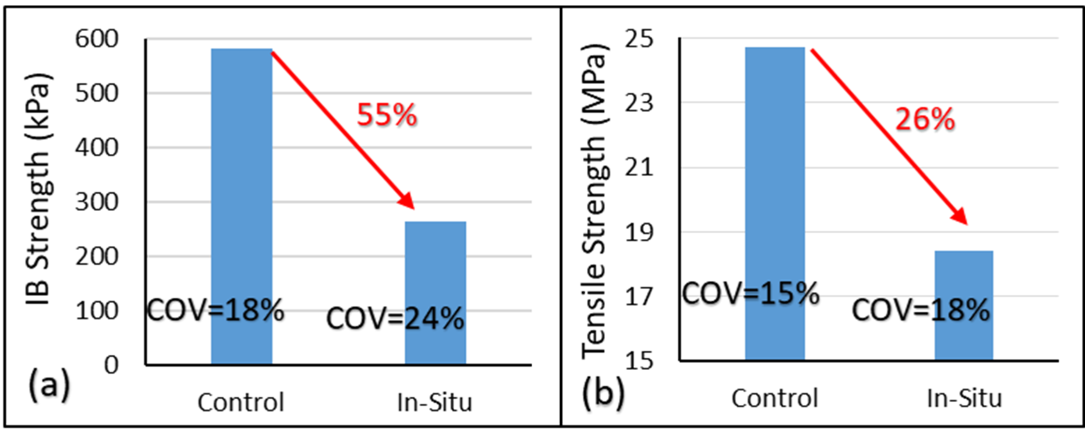

Figure 3. Comparison between (**a**) internal bond (IB) and (**b**) tensile strengths of wood strand-based (WSB) control and WSB in-situ specimens. COV = coefficient of variation, which is equal to the ratio between the standard deviation and the mean.

Water absorption and thickness swelling test results are given in Figure 4. In the first two hours, both water absorption and thickness swelling results of the in-situ specimens were lower than those of control specimens. However, after 24 h and 72 h immersion in the water, the in-situ specimens showed higher water absorption and thickness swelling compared to the control specimens.

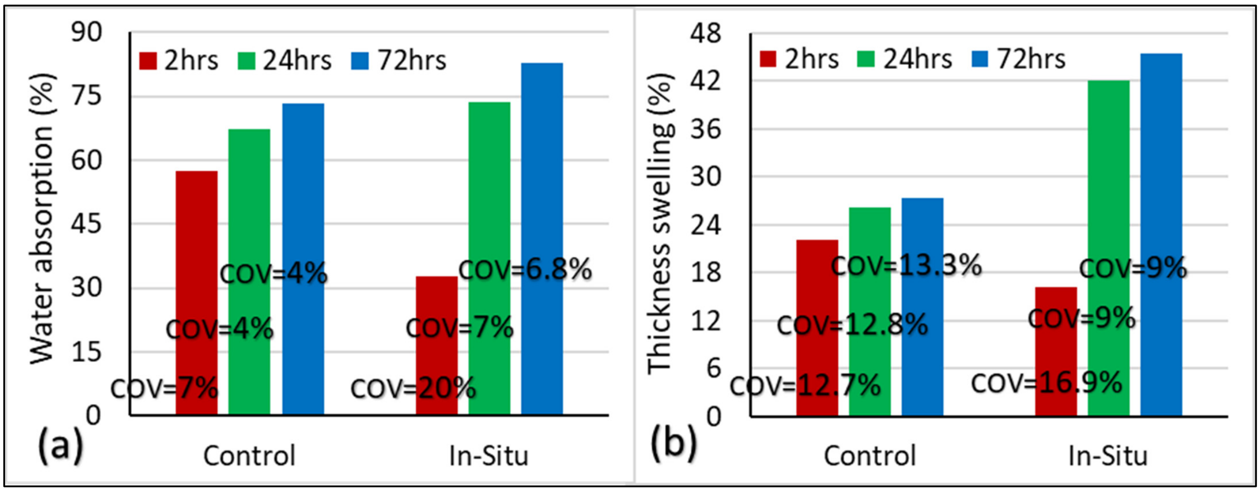

Figure 4. Comparison between (**a**) water absorption and (**b**) thickness swelling of wood strand-based (WSB) control and WSB in-situ specimens being submerged in water during 2 h, 24 h, and 72 h test period. COV = coefficient of variation, which is equal to the ratio between the standard deviation and the mean.

The results of IB strength, tensile strength, water absorption, and thickness swelling tests of in-situ specimens revealed that adding guayule during the manufacturing process along with PF resin has a negative effect on the bonding performance of wood strands, and in turn reduces the IB and tensile strength and increase the WA and TS of the panel. Considering such negative effects on the structural performance of WSB panels, adding guayule as a treatment during the manufacturing process is not recommended.

3.2. Durability and Degradation

3.2.1. Termite Resistance Percent Mass Loss

Figure 5 shows the average percent mass loss and average termite visual rating assessment damage for the different treatments tested. Following the AWPA E1-23 [31] standard, the percent mass loss for specimens sprayed with guayule had an overall average mass loss of 2.21%, therefore having a 76.66% lower mass loss than the WSB control specimens. The specimens brushed with guayule resin had an overall average mass loss of 2.36%, therefore having a 75.08% lower mass loss than the WSB control specimens. The in-situ specimens had an overall average mass loss of 4.98%, therefore having a 47.41% lower mass loss than the WSB control specimens. The WSB control specimens had an overall average mass loss of 9.47%, which was 75.82% lower than that of the SYP control specimens. The SYP untreated control pine wafer specimens had an overall average mass loss of 39.17%. There were no statistical differences ($p > 0.05$) between the specimens brushed and specimens sprayed with guayule for mass loss as represented by the letter D (Figure 5). However, there were statistical differences ($p \leq 0.0001$) between the specimens of the SYP wafer control untreated specimens, WSB controls, and in-situ specimens for mass loss as represented by the letters A, B, and C, respectively (Figure 5).

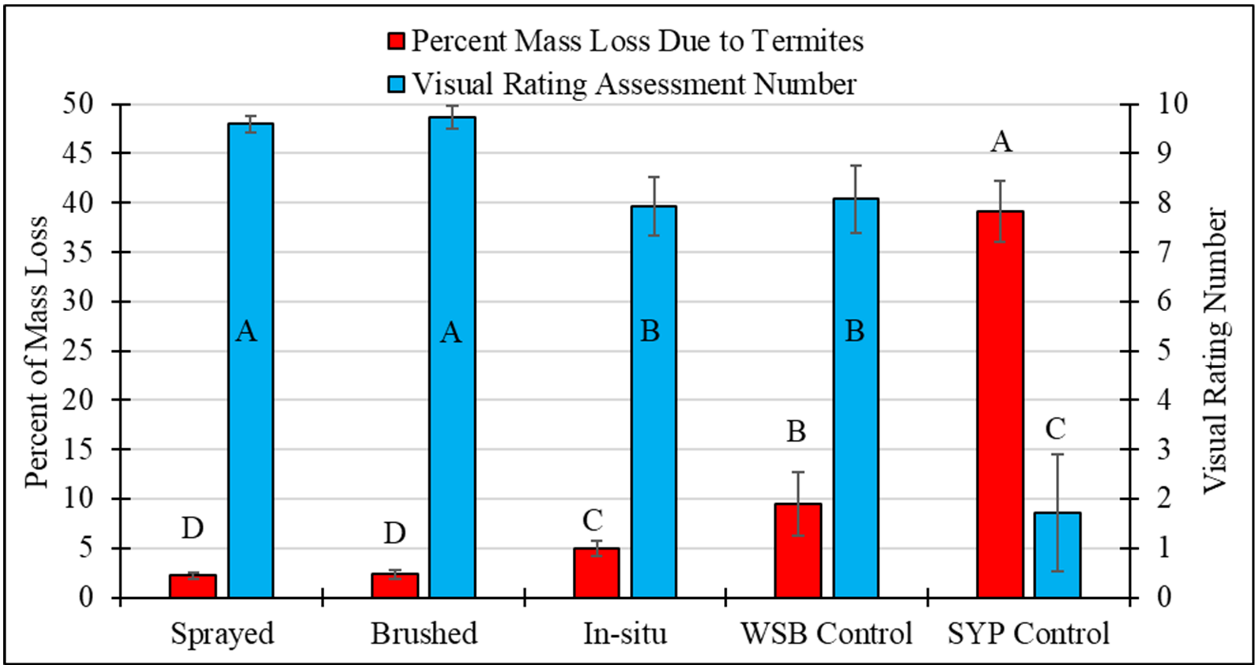

Figure 5. Average percent mass loss (in red) and average termite visual rating assessment damage (in blue) for different treatments. The letters A, B, C, and D represent statistically significant differences between treatments, whereas the same letters (i.e., letter D) represent no statistical differences from treatments performed similarly. The bars represent standard deviation (S.D.) of the means. WSB Control = wood strand-based control specimens; SYP Control = southern yellow pine control specimens.

3.2.2. Termite Visual Rating Assessment

The visual rating assessment of the WSB termite specimens given in Figure 5 showed that the specimens sprayed with guayule resin had an overall rating of 9.74 out of 10. Similarly, the specimens brushed with guayule resin had an overall rating of 9.60 out of 10. These specimens, either sprayed or brushed, had mostly 9.5 visual ratings with a few having a score of 10 (Figure 5). However, many of these treated specimens exhibited delamination failure during this 28-day-long test. The in-situ specimens had an overall visual rating of 7.93 out of 10, whereas the WSB control specimens had an overall visual rating of 8.07 out of 10. Over 89% of the in-situ and WSB control specimens scores were between seven and nine; >50% of the visual ratings were eight, listed as moderate (3–10%) termite attack and damage. In-situ WSB and WSB control specimens with slight damage and solid SYP control specimens that were completely destroyed by the subterranean termites are shown in Figure 6. The SYP wafer control untreated specimens had very severe termite attacks of 50–75% failure and up to 100% complete failure due to termite attack in the cross-sectional area that was affected, with an average visual rating assessment of 1.71 out of 10 (Figure 5). In >90% of the brushed, sprayed, and in-situ specimens, failure was not due to termite attack, but instead it was mostly due to water intrusion causing delamination of the WSB specimens. Wood is moisture-sensitive, as failure and swelling are common when this material is exposed to high relative humidity values [7,8]. The WSB control specimens exhibited little delamination overall. Each of the operational mass loss specimens from each treatment had a 10 out of 10 visual rating assessment (Figure 5).

Figure 6. Photos of in-situ wood strand-based (WSB) specimen (far left) with slight to moderate damage; WSB control specimen (middle image) with slight to moderate damage; and solid southern yellow pine (SYP) wood control specimens (far right) with very severe 50–75% and up to 100% complete failure of termite attack by subterranean termites (*Reticulitermes flavipes*) during a 28-day-long American Wood Protection Association (AWPA) E1-23 termite test.

3.2.3. Termite Resistance Summary

It should be highlighted that within 7 days of the start of this test, it was found that all the termites died in all the brushed, sprayed, and in-situ treatment specimens. However, the WSB control jars had slow termite die-offs during weeks 2, 3, and 4, with complete termite mortality by the end of the four-week test period. The termites in each of the untreated SYP control specimen jars had lots of tunnels and vigorously ate the wood; the specimens were each covered with sand, and the termites were active, as shown by the >39.00% average mass loss of the pine control specimens and 100% wood failure on the visual rating scores.

3.2.4. Fungal Decay Resistance Percent Mass Loss

The average fungal decay test specimen results are shown in Figure 7. The SYP control specimens had a mass loss range of 34.02% to 57.89% with an average mass loss of 45.45%. *G. trabeum* (brown-rot fungus) should cause weight loss of 40.00% or greater on SYP wood blocks in 12 weeks based on AWPA E10-16, section 18.3 [35]. The control test specimens had >45.00% average mass loss, indicating that the decay fungi were actively degrading the control blocks, showing a valid test. The WSB control specimens had an average mass loss of 16.93%, which was 62.75% lower than that of SYP control specimens. The high temperature during the manufacturing process could be an explanation for such greater mass loss variation in the WSB control specimens. The in-situ specimens had an average mass loss of 6.57%, therefore having a 61.19% lower mass loss compared to the WSB control specimens. However, specimens brushed with guayule resin had an average mass loss of 5.88%, therefore having a 65.27% lower mass loss compared to the WSB control specimens. Specimens sprayed with guayule resin had an average mass loss of 3.24%, which was 80.86% lower than that of the WSB control specimens. There were statistical differences ($p \leq 0.0001$) between the specimens of the SYP control untreated specimens, WSB controls, in-situ specimens, and those sprayed or brushed with guayule resin for fungus decay resistance mass loss, as represented by the letters A, B, and C, respectively (Figure 7). Overall, the best solution was the sprayed guayule resin, as indicated by the lowest average percent mass loss compared to any other treatment, despite there being overlaps with brushed and in-situ specimen ranges (Figure 7).

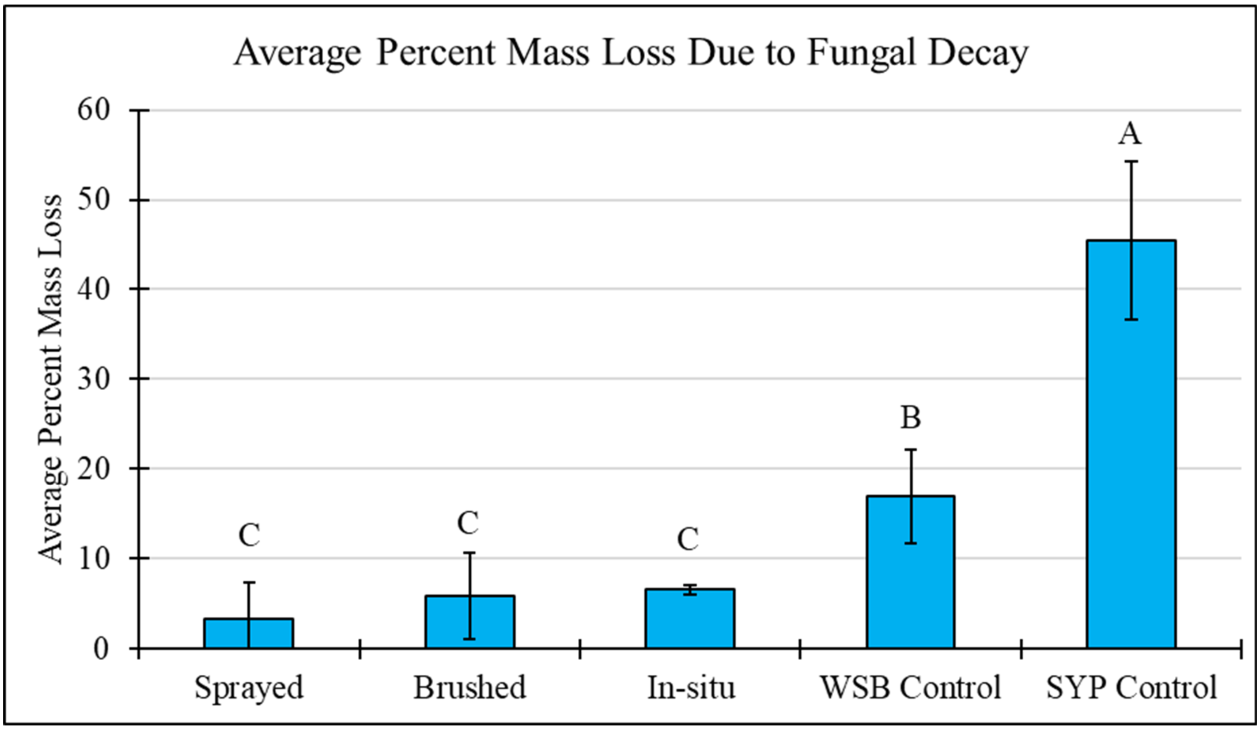

Figure 7. Average percent mass loss due to fungal decay: assessment of damage for different treatments. The letters A, B, and C represent statistically significant differences between treatments, whereas the same letters (i.e., letter C) represent no statistical differences from treatments performed similarly. The bars represent standard deviation (S.D.) of the means. SYP Control = southern yellow pine control specimens; WSB Control = wood strand-based control specimens.

4. Conclusions

- Based on adding 5.00% guayule resin during the manufacturing process along with PF resin, there was a significant reduction in the IB and tensile strength of the WSB panels.
- By adding 5.00% guayule resin during the manufacturing process along with PF resin, the results showed an increase in the WA and TS of the WSB panels.
- Considering the reduction in the structural performance of the WSB panels, treatment of these panels with guayule resin during the manufacturing process is not recommended at this time.
- Fungal decay results also revealed that in-situ treatment had >61% decreased mass loss in durability tests compared to the WSB panels.
- Spraying or brushing guayule resin on specimens significantly decreased the fungal degradation damage of southern yellow pine WSB panels as mass loss decreased by about 81% and >65%, respectively, compared to WSB control specimens.
- In-situ treatment, however, decreased the termite degradation of WSB panels by >47%.
- Treating WSB panels using brushing or spraying techniques was more effective, as termite degradation decreased by more than 75% and about 77%, respectively, compared to control WSB panels.
- The sprayed technique produced the best results regarding degradation resistance, as it had the lowest average percent mass loss of 2.21% for termites and 3.24% for fungus tests compared to WSB control specimens.
- Considering the experimental results and required time to treat panels, which is an important factor in the production process, treating the WSB panels by spraying guayule resin on fabricated WSB panels was the fastest and most effective method of application to improve durability overall.
- As rigorous AWPA and ASTM standards were followed in this study, a larger sample number might have been used to gain a clearer statistical conclusion on the effects of

guayule resin on the structural, physical, water resistance, and biological performance of the WSB products.
- Future works could investigate more physical properties to better understand the guayule resin-modified WSB wood's behavior.

Author Contributions: All authors contributed equally to the study conception, design, testing, and results. Material preparation, data collection, and statistical analysis were performed by E.D.E., M.M., C.E.S. and S.P. The first draft of the manuscript was written by E.D.E., and all authors commented and added detailed information to all sections in previous versions of the manuscript. M.M. and E.D.E. created Figure 1 (schematic diagram of our manufacturing process). M.M. took the photos used in Figure 2. E.D.E. and M.M. created Table 1. M.M. prepared Figures 3 and 4. E.D.E. prepared Figures 5 and 7. E.D.E. took the photos used in Figure 6. E.D.E., M.M. and S.P. conducted mechanical property testing. E.D.E. conducted the termite test. C.E.S. conducted the fungus test. All authors have read and agreed to the published version of the manuscript.

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