Biological durability of preservative treated cross-laminated timber (CLT) made with southern pine lumber

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Abstract: Cross-laminated timber (CLT) is an engineered wood product that is being increasingly utilized in structural applications. However, its susceptibility to fungal decay and termite attack raises concerns about long-term durability, particularly in high-moisture and insect-prone environments. This study evaluates the biological durability of CLT fabricated with southern pine and treated post-layup with two copper-based preservatives: copper azole (CA-C) and micronized copper azole (MCA) under laboratory conditions. Fungal decay resistance was assessed using brown-rot (*Serpula lacrymans*) and white-rot (*Irpex lacteus*) fungi, while termite resistance was evaluated through exposure to *Reticulitermes* spp. Results showed that preservative treatments significantly reduced fungal decay and termite damage compared to untreated controls, although treatment effectiveness varied with CLT configuration (3-ply or 5-ply). While both preservatives effectively mitigated decay in 3-ply panels, treated 5-ply panels exhibited comparable mass loss to untreated counterparts. Termite resistance tests demonstrated that MCA and CA-C treated CLT samples exhibited significantly lower mass loss and higher termite mortality compared to the untreated controls, with both preservatives providing comparable protection.

Keywords: Copper-based preservatives; Mass timber; Termites, Wood decay.

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Introduction

Decay fungi and termite activity present severe hazards that can cause structural weakness in wood materials and ultimately jeopardize the integrity of wooden structures (DeGroot 1976; Garbacz et al. 2020). In response to these issues, many wood preservation technologies have been developed to increase durability against biological deterioration and the service life of timber products (Loferski 1999; Archer and Lebow 2006; Calovi et al. 2024; Ong et al. 2025). Chemical treatment with preservatives like copper azole (CA-C) and micronized copper azole (MCA) are widely utilized for wood used in ground contact due to their effectiveness in preventing fungal degradation and termite attack (Verma et al. 2009; Schultz and Nicholas 2010). Copper-based preservatives protect wood by disrupting cellular processes (i.e., enzyme inhibition, nutrient transport interruption, protein denaturation, etc.) in addition to acting as a toxic deterrent to termite feeding (Civardi et al. 2015; Ohno et al. 2020).

While the efficacy of CA-C and MCA treatments has been widely researched within the context of traditional lumber, their effectiveness when applied to engineered wood products, such as cross-laminated timber (CLT), is in early stages of development and requires more investigation (Lim et al. 2020; Taylor et al. 2023; Ayanleye et al. 2023; Quin et al. 2024, 2025). This is in part because CLT presents added difficulties for applying available wood preservation strategies due to its large size, laminated structure, and adhesive bonds (Lim et al. 2020). Additionally, the penetration depths required to adequately protect CLT from biological agents are not well defined (Wang et al. 2018). The timing of preservative treatment—whether applied before or after panel assembly—is a critical factor influencing the durability, adhesive performance, and treatment penetration of CLT. Pre-treating individual laminates before bonding allows for deeper preservative penetration and more uniform distribution, enhancing resistance to decay fungi and termites (VanAcker et al. 2023). This approach aligns with traditional wood preservation practices, where pressure treatment effectively protects solid wood products. However, pretreatment can interfere with adhesive bonding by introducing chemical residues or altering surface wettability (Lorenz and Frihart 2006). Pre-treatment also generates more preservative-treated waste, as panels typically require additional sawing and sanding post layup. Post-assembly treatment ensures optimal bonding conditions before preservative application, reducing adhesive compatibility issues. However, this method often results in limited preservative penetration, especially in thicker panels, such as 5-ply vs. 3-ply (Ayanleye et al. 2023). Additionally, preservative retention may be inconsistent, with outer layers receiving greater protection than interior sections (Walker et al. 2006).

Biological durability is a key factor influencing the performance, longevity, and useful service-life of wood products, including engineered wood systems like CLT. Cross-laminated timber has gained widespread adoption due to its strength, versatility, and sustainability (Syahirah et al., 2025). However, its vulnerability to degradation by fungi and termites can limit its application in environments with high moisture or pest exposure. This study evaluates the biological durability of southern pine CLT treated with CA-C and MCA post-layup against the white-rot fungus *Irpex lacteus* (Fr.) and the brown-rot fungus *Serpula lacrymans* (Wulf. ex Fr.). *Irpex lacteus*, a white-rot fungus, is known for its ability to degrade both lignin and cellulose, causing significant structural damage, while *S. lacrymans* is a highly destructive brown-rot fungus with documented tolerance to copper-based preservatives and is commonly found in indoor environments (Capelari and Zadrazil 1997; Hastrup et al. 2005; Novotný et al. 2009; Watkinson and Eastwood 2012; Akgul and Akgul 2018). In addition to evaluating durability of treated CLT to fungal colonization, this study also investigates the resistance of treated CLT to subterranean termites (*Reticulitermes* spp.), which are among the most economically significant wood-destroying insects in North America (Shelton and Grace 2003). Research has demonstrated that copper-based preservatives are effective against *Reticulitermes* (Freeman and McIntyre 2008; Lin et al. 2009; Kim et al. 2010; Khademibami and Bobadilha 2022), but their performance in multi-layered engineered wood products like CLT is less understood.

Materials and methods

Cross-laminated timber fabrication

Cross-laminated timber panels were assembled using visually graded Select Structural (SS) southern pine (*Pinus* spp.) lumber (38.1 × 139.7 × 2438.4 mm) which was supplied by a local sawmill located in Mississippi, USA. The average specific gravity of the laminates for the panels was 0.49, with an average moisture content (MC) of 12%. The laminates were conditioned to the desired MC indoors under a controlled environment. A single-component polyurethane adhesive (LOCTITE PUR HB X602) was supplied by Henkel Corporation (Düsseldorf, Germany) and used in this study. Ten minutes prior to applying the adhesive, a wood primer (LOCTITE PR 3105) was sprayed onto the surface of the wood at a spreading rate of 20 g/m^2. Once the primer was cured (after 10 min), the adhesive was applied at a spreading rate of 180 g/m^2 according to adhesive manufacturer specifications, at ambient temperature (21°C) and approximately 65% relative humidity (RH), with 1 h for pressing and curing.

Given the prevalence of 3-ply, 5-ply, and 7-ply CLT configurations in North America, we selected only 3-ply and 5-ply panels for this study due to manufacturing constraints associated with 7-ply panels. The final dimensions of the panels were 404 × 676 × 104 mm and 404 × 676 × 175 mm for the 3-ply and 5-ply panels, respectively. A computerized Dieffenbacher laboratory hydraulic hot press equipped with PressMan industrial programmable logic controllers (Dieffenbacher North America Inc., Windsor, Canada) was used to manufacture the panels (Figure 1). The press featured 86.36 × 86.36 cm platens, capable of applying a maximum pressure of 5.02 MPa. Panels were pressed at ambient temperature (21°C), and the applied pressing pressure was 0.689 MPa (100 psi), with press time of 3 h. After fabrication, the panels were stored indoors at an average temperature and relative humidity (RH) of 21°C and 65%, respectively. For more details on CLT fabrication see Quin (2023).

After gluing, CLT panels were separated into three groups: untreated controls, pressure-treated with copper azole (CA-C) or pressure-treated with micronized copper azole (MCA).

Commercially available formulations of CA-C and MCA were used as preservative treatments in this study due to their proven effectiveness against termites and decay fungi and their widespread application in the wood protection industry. The panels that received CA-C treatment were treated by Deforest Wood Preserving (Bolton, Mississippi, USA). The composition of the CA-C treating solution on a 100% active basis was as follows: 96.1% copper, 1.95% propiconazole and 1.95% tebuconazole. The panels that were impregnated with MCA were treated at Koppers Performance Chemicals (Griffin, Georgia, USA). The composition of the MCA treating solution on a 100% active basis consists of 96.1% copper and 3.9% azoles as tebuconazole (AWPA 2023a). Both sets of panels were treated with a target retention of 2.4 kg/m^3, which is the retention level specified by AWPA U1-23 for UC4A

Figure 1. Panels in Dieffenbacher laboratory hydraulic press.

(ground contact or freshwater) applications (AWPA 2023b). Both facilities confirmed that the target retention was achieved. After treatment, CLT panels were cut into test specimen sizes of 5.08 × 2.54 cm (W × T) samples for both 3-ply and 5-ply configurations. The test specimens were then conditioned (4 weeks) to equilibrium moisture content (~17%) before testing.

Fungal Decay Resistance

Modifications to the AWPA E10-22 (AWPA 2023c) standard soil block test method were made to accommodate the larger sample sizes in this study. The modifications on the soil block test included larger container size, greater amounts of water and soil added to each container and longer exposure time to accommodate the larger specimen size utilized in this test. Soil used in this study was collected from John W. Starr Memorial Forest (Starkville, Mississippi, USA) prior to being sifted. The 2-L containers were filled with 480 g of sieved soil and 275 mL of deionized (DI) water based on a water-holding capacity (WHC) test (AWPA 2023c). The 8-L containers were filled with 1.44 kg of sieved soil and 600 mL of water based on the WHC. The results of this test indicated that the soil had a water hold capacity of 38.9% and a pH of 5.14. Ten feeder strips (6.35 × 1.27 cm) were then added to each 2-L container and 12 feeder strips of the same dimensions were added to each 8-L container. Southern pine (*Pinus* spp.) feeder strips were used for the containers to which the brown-rot fungus was introduced, and quaking aspen (*Populus tremuloides* Michx.) feeder strips were used for the containers to which the white-rot fungus was introduced. The containers and lids were covered with aluminum foil then autoclaved at 20.7 kPa and 150°C for 45 min.

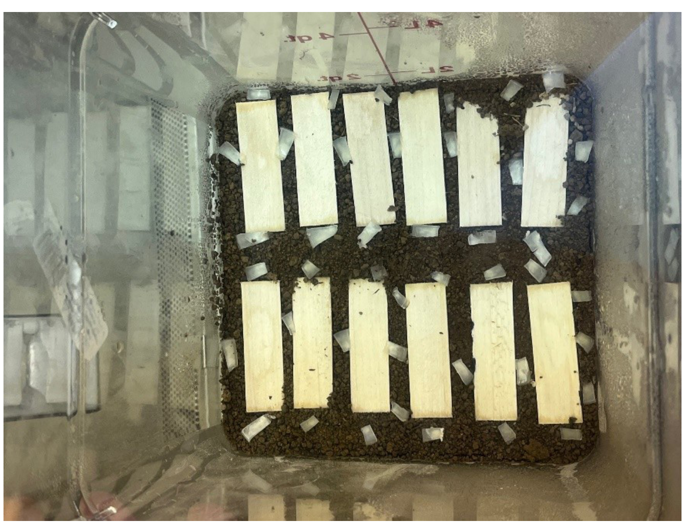

Figure 2. An 8-L soil block container with 12 aspen feeder strips inoculated with mycelial plugs of the white-rot fungus, *Irpex lacteus*.

Mycelial plugs of *Serpula lacrymans,* Wulf ex Fr., ATCC 36335 and *Irpex lacteus* (Fr.) Fr., ATCC 11245 were inoculated into their respective containers as illustrated in Figure 2 and left to grow until full colonization of the feeder strips (~2 weeks). *Serpula lacrymans* was selected for this study because of its demonstrated tolerance to copper-based preservatives, such as those evaluated in the present study. Test samples were autoclaved at 20.7 kPa and 121°C for 45 min, and two samples of the same treatment group were added to each of their respective containers. There were 16 replicates for each fungus, treatment, and layout combination, totaling 192 samples, and exposed in order of treatment. Normally, the standard is based on 10 mm or 19 mm wood cubes, which are deliberately exposed to a test fungus for 8 or 12 weeks, respectively (Figure 4). In this study, 2-L and 8-L polycarbonate containers were used for the 3-ply and 5-ply panels, respectively. Due to the larger size of the samples, the test was conducted for 24 weeks in a Luanaire environmental chamber (Thermal Products Solutions, White Deer, Pennsylvania, USA) maintained at 28°C. During this period, the containers were monitored daily and weighed weekly to ensure that they contained adequate moisture to promote fungal growth. If containers lost weight, sterile water was added to ensure proper conditions for fungal growth. At the end of the test, the samples were removed and oven dried at 35°C until constant weight was obtained to calculate mass losses.

Termite Resistance

Reticulitermes spp. were collected from John W. Starr Memorial Forest (Starkville, Mississippi, USA) and separated from debris as described in AWPA E1-23 (AWPA 2023d). The termites were then counted to determine the weight of three replicate sets of 1000 individuals. This number of termites used for these large-scale tests was based on the findings of França et al. (2022). In addition to the number of termites used, Table 1 summarizes the other parameters of the AWPA E1 standard (AWPA 2023d) that were also modified in this study. Samples were exposed for a total of 28 days. At the end of the test, samples were removed from the containers, cleaned gently with a small brush, and termite mortality (%) was estimated. Termite mortality was assessed visually as prescribed in Clausen et al. (2011). The clean samples were then reconditioned to a constant weight in an oven at 35°C and 65% RH for approximately 2 weeks, before being weighed and subsequently visually assessed, based on Table 2.

Statistical analyses

The data was analyzed as a three-way cross-classification of effects because this analysis allows for the examination of

Table 1. Modifications to the AWPA E1 termite testing standard for evaluation of cross-laminated timber.

Testing conditions	AWPA standard	Modification for CLT samples
Oven drying temp	40°C ± 2 or 103°C ± 2 until constant weight is achieved	60 °C ± 2 until constant weight is achieved
Wood sample size(s)	2.5 × 2.5 × 0.6 cm	10 × 5 × 2.5 cm and 17.5 × 5 × 2.5 cm
Test container(s)	80 × 100 mm glass screw-top jars	2L and 8L
Sand and water	150 g/27 mL	400 g/ 117 mL and 1.4 kg/ 400 mL
Number of termites	400	1000

interactions among multiple factors—configuration (3-ply vs. 5-ply), preservative type (untreated, CA-C, or MCA), and fungus (*S. lacrymans* or *I. lacteus*). This method is important, as the biological durability of timber is influenced not only by individual factors but also by how they interact with one another.

The data analysis was conducted using SAS® software, Version 9.4 of the SAS System for Windows. Prior to analysis, the data was evaluated for conformity with the assumptions of homogeneity of variance (HOV) and normality at the 0.01 significance level using Levene's and Shapiro-Wilk tests, respectively. The models for the fungal decay and termite resistance test are presented in Tables 3 and 4, respectively. If the data met the assumptions, an ANOVA was performed, followed by post-hoc comparisons using LSMEANS in PROC GLM. If the assumptions were not met (p-value < 0.01), a non-parametric approach was taken. Specifically, the dependent variable was rank-transformed, and a rank-based non-parametric ANOVA was performed. If the effect(s) being analyzed proved to be significant at α = 0.01, then mean rank separation was done using a Wilcoxon rank pairwise test adjusted by the Bonferroni correction. Termite mortality percentages were arcsine square root transformed to stabilize variance and improve normality prior to statistical analysis. The transformed data were analyzed using the PROC GLIMMIX procedure in SAS, incorporating a binomial distribution to appropriately model the response variable. Multiple comparisons were conducted using Tukey's Honestly Significant Difference (HSD) test at a significance level of α = 0.01 to determine statistically significant differences between treatments.

The statistical model in Table 3 represents a three-way cross classification model in which α, β, and γ represent fungus type (*S. lacrymans* or *I. lacteus*), ply configuration (3-ply or 5-ply), and treatment type (CA-C, MCA, untreated control), respectively. The statistical model in Table 4 represents a two-way cross-classification model in which α and β represent treatment type and ply configuration, respectively.

Table 2. AWPA Visual rating system (AWPA 2023d).

Visual Rating	Description *
10	Sound
9.5	Trace
9	Slight attack (up to 3% of CSA affected)
8	Moderate attack (3-10% CSA affected)
7	Moderate/Severe attack (10-30% CSA affected)
6	Severe attack (30-50% CSA affected)
4	Very severe attack (50-75% CSA affected)
0	Failure

* CSA= Cross sectional area.

Table 3. Statistical model and assumptions for termite resistance test.

Model	$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + e_{ijk}$	i =1,2,3 j = 1,2 k = 1…,12
Assumptions	$\sum_{i=1}^{3} \alpha_i = 0$; $\sum_{j=1}^{2} \beta_j = 0$; $\sum_{i=1}^{3} (\alpha\beta)_{ij} = \sum_{j=1}^{2} (\alpha\beta)_{ij} = 0$ $e_{ijk} N(0, \sigma^2), iid$	

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Results and discussion

Fungal decay tests

Average mass loss in CLT specimens exposed to fungal decay are shown in Figure 3.

These data show that untreated southern pine CLT samples did not meet the 40% mass loss threshold typically seen in solid wood after 24 weeks. This is likely due to the larger sample size, which limits fungal access, compared to smaller wood blocks (Figure 4; AWPA 2023c). To account for this, a 24-week exposure period was chosen instead of 12 weeks to increase time for decay, while minimizing contamination risk. Thus, these results suggest that even longer periods of testing may be needed when evaluating fungal resistance of mass timber

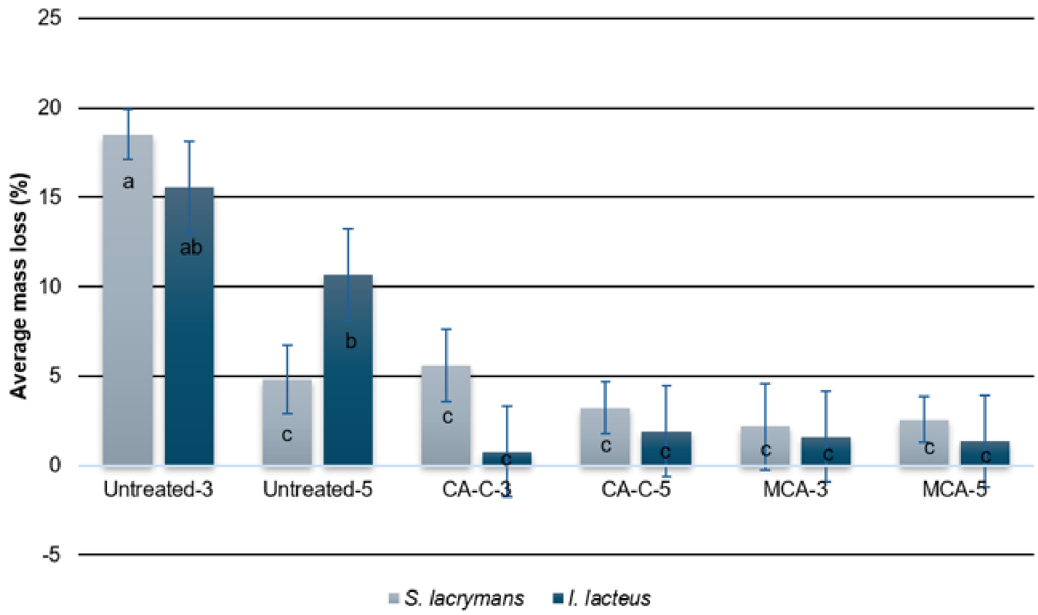

Figure 3. Average mass loss of preservative treated cross-laminated timber samples after 24-week decay tests (3 and 5 represent sample configuration). Bars with the same letter are not significantly different at a 0.01 significance level.

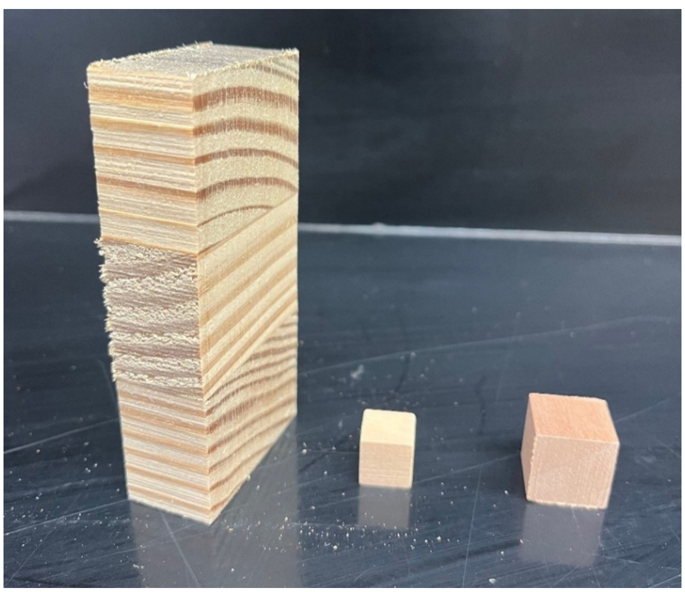

Figure 4. Size comparison of the 3-ply sample used in this study (left) compared to the AWPA E10 standard-recommended sample sizes.

materials. Additionally, the test specimens used in this study were southern pine, which is a softwood, and as a result may have contributed to the lower mass loss observed for *I. lacteus*, as this fungus preferentially attacks hardwood species.

The data was analyzed with a three-way cross-classification to examine the effects interactions among multiple factors—configuration (3-ply vs. 5-ply), preservative type (untreated, CA-C, or MCA), and fungus (*S. lacrymans* or *I. lacteus*). This analysis captures the full complexity of the system, helping to identify specific combinations that may lead to higher mass loss or greater durability. Statistical analysis revealed a statistically significant three-factor interaction ($p = 0.0014$, $\alpha = 0.01$) between number of laminates, treatment, and fungal species, indicating a complex relationship among these factors affecting the mass loss of wood samples.

Untreated CLT samples exposed to *I. lacteus* exhibited significantly greater mass loss after 24 weeks than samples treated with either MCA or CA-C. These findings align with previous research on the effectiveness of copper-based preservatives against *I. lacteus*, although variations in wood species, preservative formulations, and exposure durations can influence decay performance (Freeman and McIntyre 2008). Decay from *Serpula lacrymans* was significantly greater on untreated 3-ply CLT than on 5-ply CLT and treated CLT. Additionally, copper-tolerance by *S. lacrymans* was not observed in this study, as both MCA and CA-C seemed to effectively deter fungal growth for all ply configurations. In general, *S. lacrymans* is a dry-rot fungus and has a lower optimal growth range temperature (22°C) than traditional brown-rot fungi (28°C) (Sienkiewicz et al. 1997; Schmidt 2006), which could explain why tolerance was not observed in this study.

Representative images of CLT samples after the 24-week exposure period (Figure 5) visually illustrate the extent of decay in both untreated and treated samples. Degradation was observed across all laminates in untreated samples, suggesting uniform fungal colonization. In contrast, decay of preservative-treated samples was primarily localized to middle laminates, despite equal exposure on the feeder strips. This pattern may be attributed, in part, to challenges in preservative penetration. As chemical treatment occurred after CLT fabrication, it is possible that the middle laminates were not as well treated as the outer laminates. In CLT, the adhesive layers can obstruct preservative diffusion (Tascioglu et al. 2003), resulting in an "envelope protection" where the outer laminates receive higher copper penetration and retention compared to the inner layers. Ayanleye et al. (2023) showed that samples taken from the center laminate exhibited reduced copper retention, likely due to limited exposure to the preservative and restricted diffusion across adhesive layers.

It is worth noting that during this study, we did observe occasional negative mass loss (0.01%–2.6%) in some preservative-treated samples, particularly those exposed to *I. lacteus*. This phenomenon is likely attributed to moisture uptake during fungal exposure, where water absorption outweighed degradation-induced mass loss. This is supported by several published studies. For example, Palanti et al. (2012) observed that *Pinus sylvestris* L. treated with a copper complex grafted to amino-functionalized silica gel showed negative mass loss when exposed to *Coniophora puteana* (Fr.) Karst., likely due to hydrolyzed water absorption. Likewise, Meyer and Brischke (2015) reported negative mass loss in Douglas fir (*Pseudotsuga menziesii* (Mirbel) Franco) samples during a pile test with *C. puteana*, which they attributed to internal mycelium growth with minimal wood metabolization. In the present study, preservative treatments may have altered the hygroscopic properties of the wood, enhancing moisture absorption during fungal exposure, as noted by Brischke and Alfredsen (2020). In addition to the effects of preservative treatments, the presence of several adhesive layers comprising the CLT panel may have also contributed to moisture retention by hindering drying, particularly within inner plies. These types of moisture dynamics should be evaluated further in future studies.

Overall, results from the fungal durability tests highlight the effectiveness of a chemical treatment utilized to protect the wood against decay fungi. It is clearly shown that both MCA and CA-C are hindering growth of both *I. lacteus* and *S. lacrymans* for 3-ply and 5-ply CLT layups. Future research should aim to evaluate additional chemical treatments against common decay fungi. While this study was able to ascertain

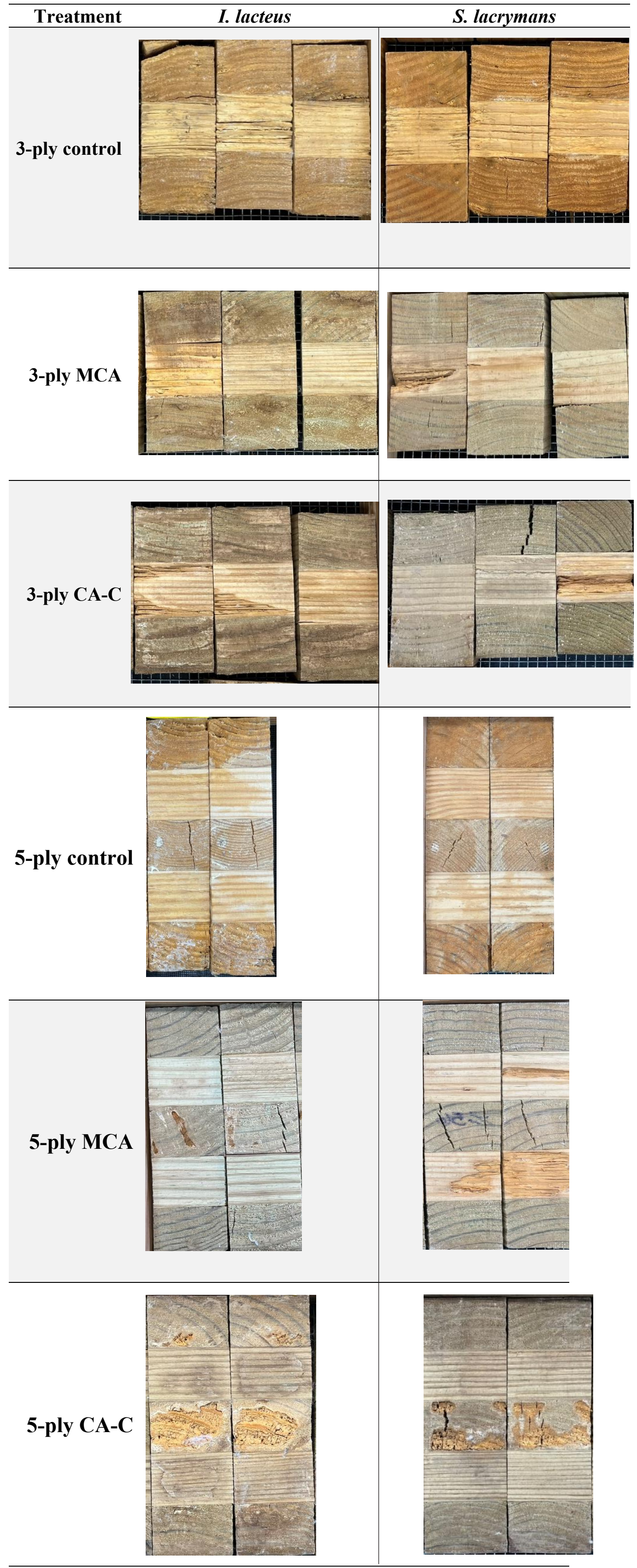

Figure 5. Cross-laminated timber 3-ply and 5-ply samples after 24 weeks of fungal exposure to *I. lacteus* and *S. lacrymans* for control, MCA-treated, and CA-C-treated samples.

useful information on the durability of treated 3-ply and 5-ply southern pine CLT, additional research is needed to understand the treatability and durability of softwood and hardwood mass timber products. Additionally, exploring interactions between panel configuration, environmental variables, and fungal physiology could lead to more accurate assessments of mass timber durability.

Termite tests

Results from laboratory termite tests are presented in Table 5, and images of the samples at the end of the test are shown in Figures 6 and 7. Although the mass loss data are presented as percentages for clarity and ease of comparison, all statistical analyses were conducted on the raw mass loss values. This approach ensured that our analyses reflected the actual consumption rates observed in the samples. The analysis revealed that the interaction between treatment and configuration was not significant ($p = 0.7132$), indicating that the combined effects of these factors did not influence termite consumption. Additionally, the main effect of configuration was not significant at the 0.01 significance level ($p = 0.0141$), suggesting that panel thickness (3-ply versus 5-ply) did not markedly affect termite consumption. In contrast, the main effect of treatment was highly significant ($p < 0.0001$). Post hoc comparisons using Tukey's HSD ($\alpha = 0.01$) demonstrated that untreated controls had significantly greater mass loss compared to both CA-C and MCA treated panels, with no significant difference observed between the two preservative treatments.

For termite mortality, least squares means comparisons indicated that both CA-C and MCA treatments resulted in significantly higher termite mortality rates, compared to the untreated controls. Analysis of the termite mortality data confirmed that the effect of treatment was highly significant ($p < 0.0001$). It is important to note that termite mortality was done in a subjective manner in this study, instead of performing direct counts, due to the large numbers of termites. However, these mortality results generally support the conclusion that both treatments were toxic to the termites, which agrees with published literature on similarly treated wood materials.

Similar to decay results, the untreated controls in this study exhibited lower mass loss (3.3% in 3-ply and 1.3% in 5-ply) (Table 5) when compared to results from other published studies. For example, França et al. (2018) reported an average mass loss of 6%, a visual rating of 7.5, and termite mortality ranging from 0–33% in untreated CLT (25.4 mm thick, 101.6 or 50.8 mm wide, 101.6 mm long). In solid untreated southern yellow pine (4–10 mm thick, 40 mm long, and 27 mm wide) Arango et al. (2006) recorded mean mass loss values of 41.3%. However, differences in sample dimensions likely contributed to these discrepancies, as smaller specimens have a higher surface-area-to-volume ratio compared to larger specimens, which can result in higher percent mass losses in the smaller specimens even under identical exposure conditions. Some of the treated specimens even showed slight increases in mass at the end of the test. This can be attributed to several factors, including the absorption of moisture and the accumulation of sand and frass pasted in by the termites. The visual ratings (Table 5, Figure 6 and 7) further reinforce these findings, especially in the 3-ply samples, where there was clear evidence of termite attack, even though percent mass loss values were low.

In aboveground field tests, Mankowski et al. (2022) evaluated soil insecticidal drenches and spray-on insecticide/fungicide treatments for mass timber protection, finding that untreated southern pine CLT had an average termite rating of 8.9 after 2 years. This rating is slightly higher than the untreated control samples in the present study, possibly due to differences in exposure duration and test conditions. Additionally, visual ratings of termite damage are inherently subjective, which may contribute to variations in reported resistance levels across

Table 5. Mass loss, visual ratings and termite mortality data for untreated, CA-C, and MCA treated 3-ply and 5-ply samples.

Configuration	Treatment	Average mass loss (Std. Dev.) (%)	Average visual rating*	Average termite mortality (%)
3-ply	Untreated	3.33 (1.0)	7.0	16.6
	CA-C	0.94 (1.61)	8.1	68.1
	MCA	0.59 (0.94)	8.4	77
5-ply	Untreated	1.28 (0.27)	7.6	22.4
	CA-C	-0.06 (0.40)	8.6	100
	MCA	0.004 (0.32)	8.7	100

* Visual rating based on AWPA E1 (AWPA 2020b).

Figure 6. Cross-laminated timber 3-ply: (a) untreated, (b) MCA-treated, and (c) CA-C-treated samples following exposure to *Reticulitermes* spp. for 4 weeks in a no-choice termite test.

both studies. It is important to note that the Mankowski et al. (2022) study was performed as a field study rather than a controlled laboratory study, therefore termite pressure likely varied compared to that of the present study. However, the consistently high ratings for preservative-treated samples across studies reinforce the effectiveness of copper-based treatments in enhancing termite resistance.

These results demonstrate some of the challenges associated with laboratory termite testing of mass timber products, as well as the importance of wood preservatives in enhancing resistance of southern pine CLT against termite attack. However, laboratory tests cannot account for many of the variables that are likely to affect mass timber materials in use. For example, concerns raised by Kirker et al. (2021) regarding moisture absorption in mass timber elements warrants further investigation, particularly to assess the combined effects of termite exposure and moisture on CLT performance over time. This is in part due to the fact that subterranean termites can increase the moisture content of wood if they have contact with soil or some type of building water source (e.g., leaky pipes).

Conclusions

Results from this study highlight the effectiveness of copper azole and micronized copper azole preservative treatments in enhancing the termite and decay resistance of both 3-ply and

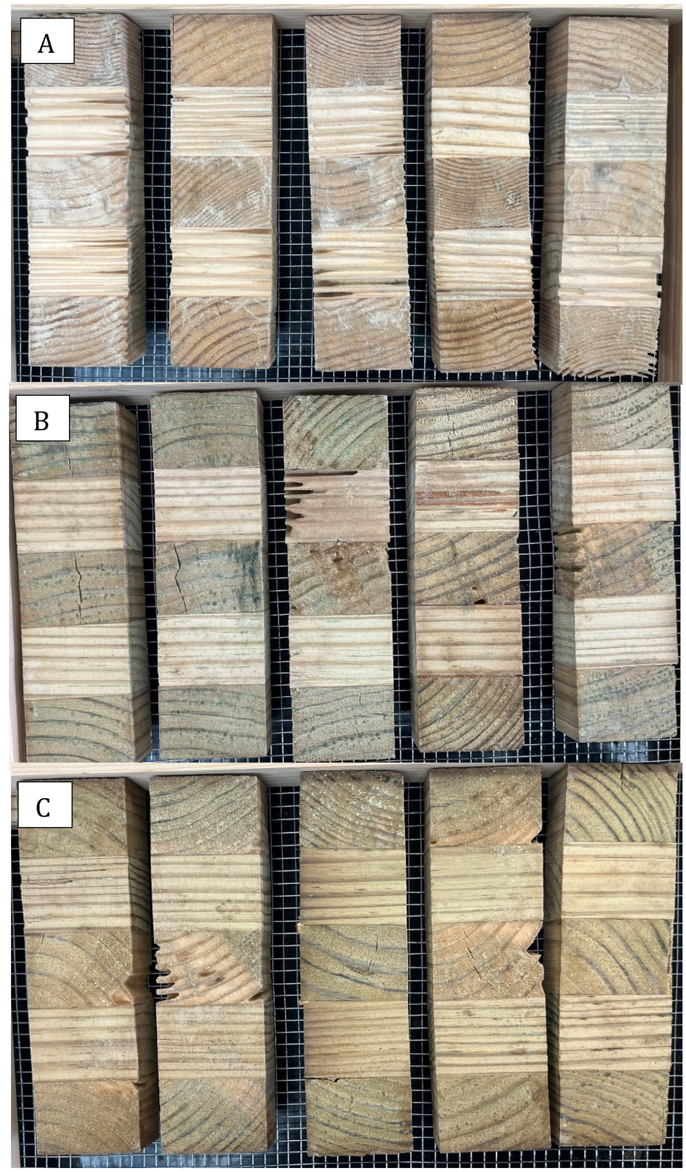

Figure 7. Cross-laminated timber 5-ply samples of (a) untreated, (b) MCA-treated, and (c) CA-C-treated samples following 4-week exposure to *Reticulitermes* spp. in a no-choice termite test.

5-ply cross-laminated timber panels under laboratory conditions, although these findings should be evaluated further in field studies. Fungal decay and termite feeding both lead to mass loss, which directly correlates to reductions in mechanical properties (Curling et al. 2002). Maeda et al. (2015) demonstrated that strength properties of decayed wood can be estimated based on mass loss, reinforcing the relationship between fungal degradation and structural performance. In the current study, preservative-treated samples exhibited lower mass loss from termites or decay, suggesting improved long-term mechanical integrity. However, further research on mass timber should incorporate mechanical testing, such as shear and compression assessments before and after fungal and termite exposure, to quantify strength performance over time. Future research should also explore long-term performance under varying environmental conditions, optimize treatment formulations, and assess potential impacts on structural properties and sustainability.

One important thing to note is that cross-laminated timber samples evaluated here were produced from post-layup treated materials (i.e., panels were fabricated prior to chemical pressure treatment). While the issue of mass timber treatability was not directly examined in this study, treatment timing undoubtedly impacted durability results. Visual observations of treated samples from both decay and termite tests show that damage was primarily to the middle laminates. This suggests that preservatives may not have penetrated past the outer layer during pressure treatment, which may present a substantial challenge for protection of mass timber panels that are treated post-layup. A better understanding of preservative penetration in mass timber materials fabricated pre- and post-layup—particularly across different wood species—is still needed to guide treatment strategies.

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