Effect of Wood Surface Treatment on Fungal Decay and Termite Resistance

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Surface treatments, such as immersion, brushing, spraying, dipping, and steeping have been extensively used to treat wood for use in low hazard class areas or as an on-site remedial/supplemental treatment of in-service wooden structures to extend their service life. In the present study the wood was subjected to steeping with three preservative formulations, *i.e.*, copper azole type C (CA-C), alkaline copper quat type C (ACQ-C), and tebuconazole-propiconazole combo (TP), and the effect of surface treatment on fungal decay and termite resistance was evaluated. The results showed that the depth of chemical penetration into the wood and the surface absorption primarily depends on the permeability of the wood species. The efficacy of decay and termite resistance was determined by surface retention per unit area of the surface-treated wood. The surface treatment with CA-C, ACQ-C, and TP significantly enhanced the decay and termite resistances of the wood. But for low-permeability wood species such as *Picea asperata*, a higher concentration of preservatives or periodic re-surface-treatment is necessary to maintain resistance to decay and to termites.

Keywords: Surface treatment; Depth of penetration; Surface retention; *Fungal decay resistance; Termite resistance*

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INTRODUCTION

Wood bio-deterioration and bio-degradation are mainly affected by decay fungi and termites (Zabel and Morrell 1992). Chemical treatment is one of the most effective ways to reduce wood deterioration (Schmidt 2006). Waterborne wood preservative systems, such as alkaline copper quaternary (ACQ) and copper azole (CA), have been widely used in improving the biological durability of wood and have substituted for CCA, following its withdrawal from the market (Smith and Wu 2005; Lorenz and Frihart 2006; Goodell *et al*. 2007; Gaspar *et al*. 2010; Tascioglu and Tsunoda 2010). The solvent-borne preservatives tebuconazole and propiconazole combination (TP) are also highly effective against brown-rot and white-rot fungi. In addition, solvent-borne TP is relatively environmentally friendly, leach resistant, and biodegradable in soil, making it attractive as a wood preservative (Buschhaus and Valcke 1995; Valcke 1995; Tolley *et al*. 1998).

There are several different methods of applying preservative chemicals to wood. Preservative treatment with vacuum-pressure equipment is usually required for refractory wood species when used in an environment with a high risk of biological attack by fungi, insects, or marine borers (Islam *et al.* 2008). However, in remedial situations where the need to treat timber *in situ* precludes the use of pressure equipment methods, surface treatments are generally used. For instance, for purposes of on-site conservation and

maintenance of ancient historical constructions in China, surface methods, such as brushing and steeping have been used extensively (Ma *et al.* 2011b). In addition, surface treatments have been used to treat wood for use in low biological hazard service conditions (class III or lower) such as interior construction or above-ground furnishings. Kamdem *et al.* (1996) showed that dipping treatment with copper based formulations exhibited sufficient protection against wood decay fungi. It is important to match the preservative applied method to the use of the wood and the environmental conditions where the wood is used. This will ensure a longer, more useful wood service life, promote wood conservation, and reduce unnecessary waste (Ma *et al*. 2011a).

Surface treatments, including brushing, spraying, or steeping rely on capillary action to allow the preservative to penetrate into the wood. Penetration of the preservative into the surface can be thought of as a three-stage process: rapid initial absorption by the wood surface, slower capillary penetration, and secondary penetration as the timber dries. Three main factors, the permeability of the wood surface, the properties of the preservative solution, and the contact time, determine the chemical absorption and penetration into the wood through the surface treatment (Morgan and Purslow 1973). Mori *et al*. (2007) reported that surface treatment of wood with SF1083 in the early stages of decay caused by *Serpula lacrymans* suppressed progression of the decay on both treated portions and areas surrounding them. Norton and Francis (2008) also reported that a brush coat of water-repellent preservative inside the joints of simulated timber joinery often extended service life. For dipping method, the most important parameter influences the quality is dipping time. So, Humar and Lesar (2009) studied the influence of dipping time on uptake of preservative solution, adsorption, penetration and fixation of copper-ethanolamine based wood preservatives. However, little information is available and reported on the quality control parameters of surface treatment and its influence on the fungal decay and termite resistance.

The objective of this study was to evaluate the biological effectiveness of surface treatment with various preservatives and propose a guideline for modern wooden building design, as well as conservation and maintenance for ancient historical wood structures. Three wood species, *Pinus radiata*, *Cunninghamia lanceolata* (Lamb.) Hook., and the China ancient wood species Chinese Spruce (*Picea asperata*) were treated by steeping process with three preservative formulations in this study. Then the effects of surface treatment on fungal decay and termite resistance were evaluated. The fungal decay tests were conducted according to Chinese standard LY/T 1283 (2011), and the termite test according to American Wood Protection Association standard AWPA E1 (2011).

EXPERIMENTAL

Wood Specimen Preparation

Three softwood species of wood were used: *Pinus radiata*, *Cunninghamia lanceolata*, and *Picea asperata* (Chinese Spruce). *P. asperata* was the species of wood used for components of ancient buildings in Gansu province, China. *P. radiata* and *C. lanceolata* were dried, sawed wood.

The specimens for surface treatment were prepared to a size of 60 × 20 × 20 mm (longitudinal × radial × tangential) with sapwood, and each treatment contained 12 replicates. In order to prevent longitudinal solution absorption and ensure lateral absorp-

tion using the steeping method, the longitudinal ends were sealed with 502-glue (Fig. 1). If not, the small samples would be filled with preservatives by longitudinal solution absorption, which wouldn't reflect the true surface treatment results.

The ends glue-sealed samples were weighed, and the surface retention was calculated after steeping in preservatives. Then the samples were sawed into three equal parts for measurement of the penetration. After that, each part was further cut into two equal parts; one was evaluated for decay resistance, and another was evaluated for termite resistance. The incisions were brushed with preservatives. The size of the specimens for decay and termite testing was 20 × 20 × 10 mm (radial × tangential × longitudinal). There were 12 replicates for each treatment (Fig. 1).

Preservative Preparation

Three preservatives ACQ-C, CA-C, and TP were used in this test. Deltamethrin was used for a reference in the test of termite resistance. The active ingredients of the preservatives and the treating solution concentrations are listed in Table 1. The reagents basic copper carbonate, BAC (Cas number: 139-07-1), tebuconazole, propiconazole, and deltamethrin were used.

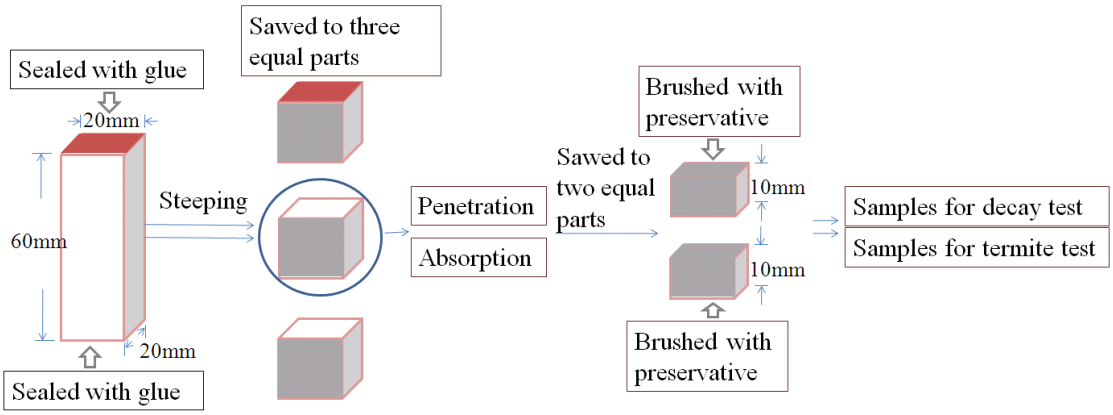

Fig. 1. Diagram of the experiment for evaluating the efficacy of surface-treated wood subjected to decay fungi and termites

Table 1. The Active Ingredients of the Preservative Formulations and the Treating Solution Concentration

Formulations	Active Ingredients*	Treating Solution Concentration		
		Test of penetration and absorption	Test of decay resistance	Test of termite resistance
Alkaline copper quaternary (ACQ-C)	Copper as CuO Quat as BAC	/	0.8%, 1.6%, 3.2%	1.6%, 3.2%
Copper azole (CA-C)	Cu tebuconazole propiconazole	0.2%	0.2%, 0.4%, 0.8%	0.4%, 0.8%
Tebuconazole-propiconazole combo (TP)	Tebuconazole propiconazole	0.04%	0.04%, 0.08%, 0.16%	0.08%, 0.16%
Deltamethrin	Deltamethrin	/	/	60, 120 (mg l^{-1})

*Ratios of active ingredients of ACQ-C and CA-C were adopted from American Wood Protection Association standard AWPA P5-10 (2011)

Surface Treatment method

The surface-applied treatment steeping was conducted. The specimens were immersed with formulation in a beaker.

Penetration and Absorption

The specimens were weighed (W_1) prior to treatment. After steeping for 4 h, 8 h, 12 h, 24 h, 48 h, or 72 h with 0.2% CA-C or 0.04% TP, the specimens were weighed again (W_2) and sawed into three equal parts. Specimens will show green when treated with CA-C, and show red when treated with TP and 0.1 g/kg chromogenic agent lycopene. The depth of penetration of the middle cube was measured with micrometer according to the depth of the color. The average the depths from 4 side surfaces (radial and tangential) of each end was recorded. The surface retention was calculated as: Surface retention (%) = $[(W_2 - W_1) \times \text{Solution concentration} \times 10^6 / (4 \times 20 \times 60)] \times 100$.

Decay Resistance Tests

The decay test was conducted according to Chinese standard LY/T 1283 (2011). All specimens were oven-dried at 40 ± 3 °C for 20 h, weighed, and recorded as the initial weight prior to decay test, and further sterilized with steam for 0.5 h at 105 ± 2 °C. Twelve specimens were exposed to a monoculture of either white-rot fungus *Trametes versicolor* (L. ex Fr.) Pilat or brown-rot fungus *Gloeophyllum trabeum* (Pers. ex Fr.) Murr. in a glass jar maintained at 28 ± 1 °C and above 80% RH for 12 weeks in a dark room. The specimens were put into a blast-drying oven at 40 ± 3 °C until a constant mass was reached after cleaning the mycelia and extraneous components on the surfaces when they were taken out of the culture bottles. Each specimen was weighed and recorded to an accuracy of 0.01 g, and the percent mass loss was calculated. Mass losses lower than 3% was considered to be insignificant, and 3% is the efficacy limit.

Termite Resistance Tests

The termite test was conducted according to AWPA standard E1 (2011). All specimens were oven-dried at 40 ± 3 °C for 20 h, and the initial weights were recorded prior to the termite test. They were then sterilized with steam for 0.5 h at 105 ± 2 °C. Six specimens were exposed to a single-choice test of subterranean termites *Coptotermes formosanus* S. A total of 400 termites (the numbers of soldier termites was ≤10% and the number of young termites was ≤5%) were introduced into each test container. The assembled containers were kept at 28 ± 1 °C and above 80% RH for 4 weeks in a dark room. The percent of mass loss of each specimen was calculated from the difference in the oven-dried weights before and after the termite test.

RESULTS AND DISCUSSION

Penetration and Absorption

The penetration depth into the three wood species all increased gradually with the increase of steeping time; penetration leveled off after 48 h in two solutions (Fig. 2, upper). At this moment, the penetration depth was about 2.3/2.4 mm and 2.2/2.3 mm on *P. radiata* and *C. lanceolata* with CA-C/TP, and it was only about 1.9/1.6 on *P. asperata*. The maximum depth of CA-C/TP penetrating into the three wood species was ranked as

P. radiata > *C. lanceolata* > *P. asperata*. These results suggested that *P. asperata* has low lateral permeability, whereas *P. radiata* has high lateral permeability. There was a slight difference between the trends of the penetration depth of same species using two different solutions. The depth of CA-C penetration into wood was slightly deeper than the depth of TP penetration.

The surface retention gradually increased with the increase of steeping time, and leveled off after 48 h, except for *P. asperata* treated with CA-C and *P. radiata* treated with CA-C (Fig. 2, lower). The surface retention per unit area of *P. radiata* could reach 4.3/2.58 g m^{-2} with CA-C/TP and *P. asperata* about 2.58/0.18 g m^{-2}, but *C. lanceolata* only about 1.4/0.4 g m^{-2} after 48 h steeping. The absorption of CA-C was higher than the absorption of TP for the same wood species. The CA-C surface retention of three wood species after 48 h steeping was ranked as *P. radiata* > *P. asperata* > *C. lanceolata*. After 48 h steeping in CA-C, the decreasing surface retention of *P. radiata* suggested that *P. radiata* had already reached saturation. But specimen of ancient wood species *P. asperata* could still absorb the solution. It is thought that ancient wood has bigger cell interspaces due to weathering away of material for a long time. Consequently, such samples more easily absorb solutions, although *P. asperata* has low lateral permeability. For the ancient wood, steeping time should be prolonged to ensure the absorbability of enough chemicals.

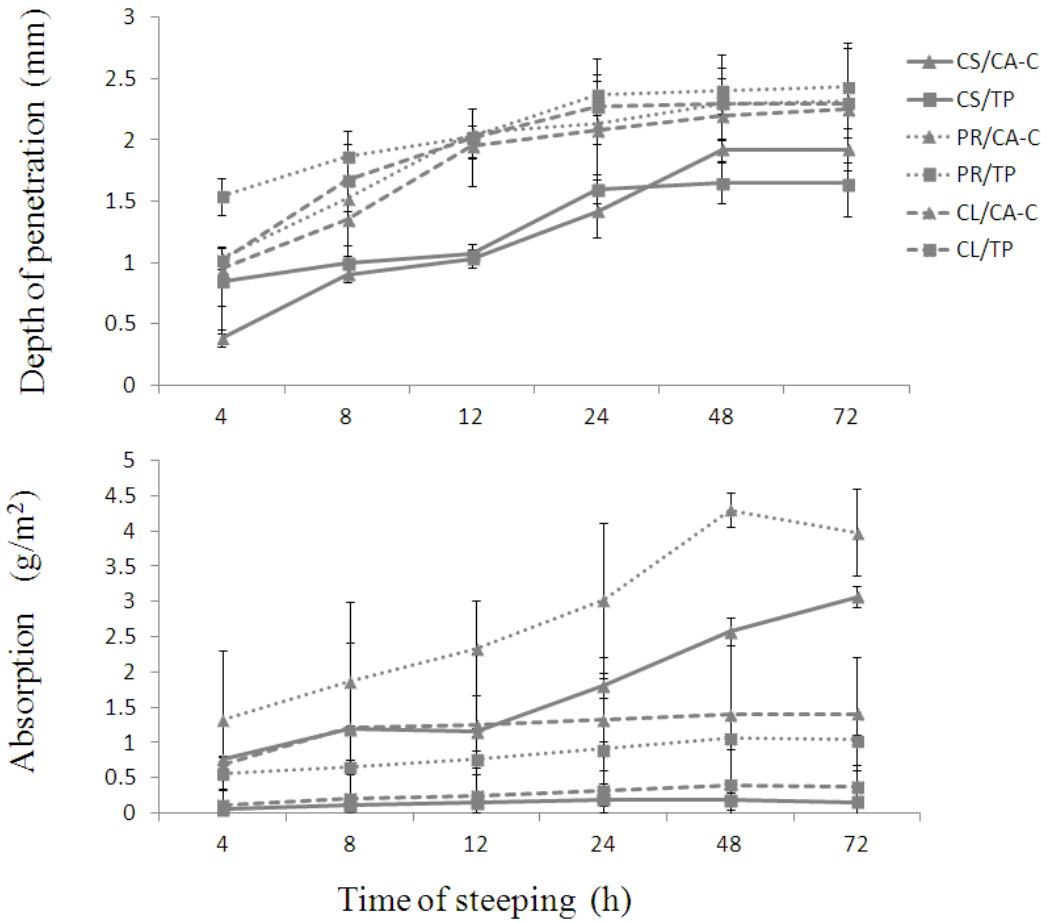

Fig. 2. Lateral absorption and penetration of surface-treated wood by steeping CS: Chinese Spruce (*Picea asperata*); CL: *Cunninghamia lanceolata;* PR: *Pinus radiata;* CA: copper azole-C C; TP: tebuconazole & propiconazole combo

After it reached a plateau, the depth of penetration and the surface retention per unit area did not increase any more. It appears that the maximum penetration and the surface retention were determined by the surface permeability of the wood species. The species *P. radiata* has high lateral permeability and *P. asperata* and *C. lanceolata* have low lateral permeability. Based on the surface retention formula, it could be deduced that the concentration increase of the preservative could increase surface retention per unit area, but the permeability of the wood species surface is the primary factor in the depth of penetration and absorption. The properties of the preservative are secondary factors affecting the penetration depth and solution absorption for the surface treatment process. The depth of CA-C penetration into wood and the surface retention of CA-C were higher than the depth of TP penetration and surface retention from the same wood species in the study. Humar and Lesar (2009) reported that longer dipping times resulted in higher uptake of preservative solution, better penetrations, and lower leaching of copper-ethanolamine based wood preservatives from wood. But with the steeping time long enough, the wood species would reach saturation, and the depth of penetration and the surface retention would not increase with steeping time any longer. It is evident that the penetration depth and the lateral surface retention did not increase for fresh wood *P. radiate* and *C. lanceolata* after 48 h steeping (Fig.2). However, the steeping time may be prolonged in the surface treatment of ancient wood.

Decay Resistance

Table 2 shows the mass losses of surface-treated wood after being subjected to decay fungi. The concentration of CA-C increased from 0.2%, 0.4% to 0.8%, ACQ-C from 0.8%, 1.6% to 3.2%, and TP from 0.04%, 0.08% to 0.16%, respectively. The mass losses of untreated control all exceeded 19% after being subjected to brown-rot fungus, and 30% after being subjected to white-rot fungus. It showed that the sapwood of three species of wood were not durable if they were not treated with preservatives.

The mass losses of surface-treated *C. lanceolata* were all less than 10% after being subjected to brown-rot and white-rot fungi with the lower concentration solution treatment. *C. lanceolata* is considered to be a naturally moderately durable species (Ma *et al*. 2011a; GB/T 13942.2, 2011). Therefore, specimens of lower surface retention had higher decay resistance. Table 2 shows there weren't any significant mass losses of *C. lanceolata* after being subjected to brown-rot fungus at the surface retention 1.24 g m^{-2} CA-C, 4.36 g m^{-2} ACQ-C, and 0.23 g m^{-2} TP. The mass loss of *C. lanceolata* was less than 3% after being subjected to white-rot fungus at the surface retention 1.24 g m^{-2} CA-C. But the mass loss was more than 3% after being subjected to white-rot fungus at the surface retention 14.36 g m^{-2} ACQ-C, and 0.23 g m^{-2} TP. These results suggest that if the surface retention of *C. lanceolata* is more than 4.36 g m^{-2} ACQ-C or 0.23 g m^{-2} TP, the sapwood of *C. lanceolata* could be resistant to white-rot fungi.

The decay resistance of surface-treated *P. radiata* and *P. asperata* increased when the surface retention was raised. When the surface retention of *P. radiata* was 3.08 g m^{-2} with 0.4% CA-C, 9.98 g m^{-2} with 1.6% ACQ-C, and 0.45 g m^{-2} with 0.08% TP, the mass losses were less than 3% after being subjected to decay fungi. When the surface retention of *P. asperata* was 3.28 g m^{-2} with 0.8% CA-C, 10.78 g m^{-2} with 3.2% ACQ-C, the mass losses were less than 3% after being subjected to decay fungi. It is suggested that surface treatment with CA-C, ACQ-C, and TP significantly enhanced the decay resistance of the wood with higher surface retention. The surface retention per unit area increased with the increase of solution concentration.

However, the mass loss in the low lateral permeability species *P. asperata* was more than 15% when subjected to the white-rot fungus, the surface retention of which was 0.5 g m^{-2} TP. The results indicated that a higher concentration of preservatives or periodic re-treatment is necessary to maintain the decay resistance of low permeability wood species in case of inadequate surface retention.

Table 2. Mass Losses (%) of Surface-treated Wood after Being Subjected to Decay Fungi

Preservative	Wood species	Concentration	Surface retention (g m^{-2})	Mass loss (%)	
				Gloeophyllum trabeum	*Trametes versicolor*
Untreated control	*Pinus radiata*	/	/	21.1±2.3	37.9±5.7
	Cunninghamia lanceolata	/	/	19.3±4.0	29.8±2.1
	Picea asperata	/	/	29.4±2.0	39.6±3.2
Copper azole type C	*P. radiata*	0.2%	2.21	2.5±1.7	22±2.6
		0.4%	3.08	0	1.3±0.5
		0.8%	5.70	0	0
	C. lanceolata	0.2%	1.24	0	0.6±0.8
	P. asperata	0.2%	1.27	3.3±1.1	16.8±2.7
		0.4%	2.00	0	3.6±1.0
		0.8%	3.28	0	0.2±0.1
ACQ-C	*P. radiata*	0.8%	7.92	3.0±1.2	18.1±3.3
		1.6%	9.98	0	1.3±0.3
		3.2%	19.29	0	0
	C. lanceolata	0.8%	4.36	0	5.8±1.2
	P. asperata	0.8%	5.24	3.6±0.3	31.5±4.2
		1.6%	7.19	0	3.3±1.4
		3.2%	10.78	0	1.7±0.8
Tebuconazole propiconazole combo	*P. radiata*	0.04%	0.26	0	14.1±2.3
		0.08%	0.45	0	0
		0.16%	1.33	0	0
	C. lanceolata	0.04%	0.23	0	7.8±1.7
	P. asperata	0.04%	0.34	2.6±0.5	20.9±3.2
		0.08%	0.18	0	20.3±4.3
		0.16%	0.50	0	15.1±3.5

Termite Resistance

Table 3 shows the mass losses of surface-treated *P. radiata* and *P. asperata* subjected to termites. The mass losses of *P. radiata* and *P. asperata* surface-treated with deltamethrin were less than 10%. The mass losses of *P. radiata* surface-treated with 5.7 g m^{-2} CA-C and 19.29 g m^{-2} ACQ-C were less than 3%. This showed that surface treatment with CA-C and ACQ-C significantly enhanced the termite resistance of the wood with high surface retention (Fig. 3, left).

Although the effect of termite resistance was greater than 80%, the mass losses of *P. asperata* surface-treated with CA-C and ACQ-C were more than 15%, even when the surface retention per unit area was 3.28 g m^{-2} CA-C and 10.78 g m^{-2} ACQ-C (Fig. 3, right). These results indicate that it is necessary to further increase the concentration of preservatives or to periodically re-treat the wood to maintain the termite resistance of low-permeability, ancient wood species in case of inadequate surface retention.

Table 3. Mass Losses (%) of Surface-treated Wood after Being Subjected to Termites

Preservative	Copper azole (0.4%)		Copper azole (0.8%)		ACQ-C (1.6%)		ACQ-C (3.2%)		Deltamethrin (60 mg l^{-1})		Deltamethrin (120 mg l^{-1})		Untreated control
	A	M	A	M	A	M	A	M	A	M	A	M	M
Pinus radiata	3.08	6.6 ±0.5	5.70	2.6 ±0.7	9.98	7.8 ±1.5	19.29	2.1 ±0.3	0.16	6.8 ±1.7	0.31	6.6 ±2.2	92.0 ±2.6
Picea asperata	2.00	23.0 ±1.2	3.28	15.2 ±2.3	7.19	21.8 ±3.1	10.78	16.3 ±2.5	0.12	10.0 ±2.8	0.24	9.5 ±0.9	86.1 ±3.0

A: the surface retention (mass/unit area), g m^{-2}
M: mass loss of specimens (%)

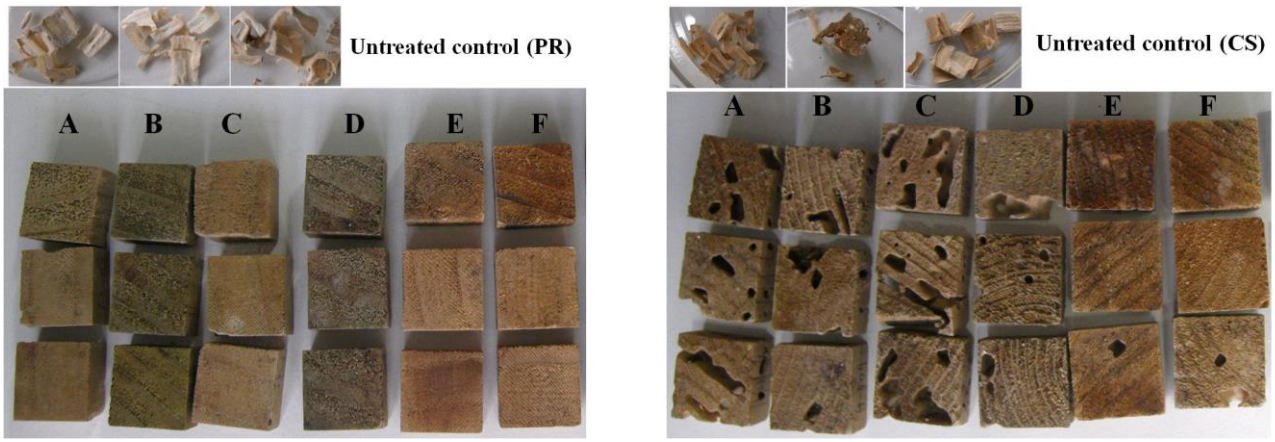

Fig. 3. Surface-treated *Pinus radiata (left)* and *Picea asperata (right)* specimens after termite exposure. A Treated with 0.4% copper azole-C; B treated with 0.8% copper azole-C; C treated with 1.6% ACQ-C; D treated with 3.2% ACQ-C; E treated with 60 mg l^{-1} deltamethrin; F treated with 120 mg L^{-1} deltamethrin

CONCLUSIONS

1. The depth of the preservative penetration into wood and the wood surface absorption by surface treatment mainly depends on the permeability of the wood species.
2. The surface retention per unit area determines the efficacy of decay and termite resistance of the surface-treated wood.
3. The surface treatments with CA-C, ACQ-C, and TP significantly enhanced the fungal decay and termite resistance of the wood.
4. When the surface retention reached 1.24 g m^{-2} for CA-C, over 4.36 g m^{-2} for ACQ-C, and over 0.23 g m^{-2} for TP, the mass loss of *C. lanceolata* was less than 3% against the decay fungi. When the surface retention reached 3.08 g m^{-2} for CA-C, 0.45 g m^{-2}

for TP and 9.98 g m^{-2} for ACQ-C, the mass loss of *P. radiata* was less than 3% against the decay fungi. When the surface retention reached 3.28 g m^{-2} for CA-C and 10.78 g m^{-2} for ACQ-C, the mass loss of *P. asperata* was less than 3% against decay fungi.

5. When the surface retention reached 5.7 g m^{-2} for CA-C and 19.29 g m^{-2} for ACQ-C, the mass loss of *P. radiata* was less than 3% against termites.
6. A higher concentration of formulation could increase the surface retention per unit area, but the maximum surface retention was determined by the permeability of the wood species. Even if the concentration of CA-C reached 0.8% and ACQ-C at 3.2%, the surface retention was only 0.5 g m^{-2} CA-C and 10.78 g m^{-2} ACQ-C. However, *P. asperata* with these surface retentions exhibited over 15% mass loss by termites. When the surface retention was 0.5 g m^{-2} with 0.16% TP, the mass loss of *P. asperata* was over 15% when subjected to the white-rot fungus. So periodic re-treatment is necessary to maintain the decay and termite resistance of the wood species with low permeability in case of inadequate surface retention.

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