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# A comparative study on brown-rot fungus decay and subterranean termite resistance of thermally-modified and ACQ-C-treated wood

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**Abstract** The resistance of thermally-modified and Alkaline Copper Quaternary type C (ACQ-C) treated aspen (*Populus tremuloides* Michx), jack pine (*Pinus banksiana* Lamb.), yellow-poplar (*Liriodendron tulipifera* L.), and Scots pine (*Pinus sylvestris* L.) against the brown-rot fungus (*Gloeophyllum trabeum*) and Eastern U.S. subterranean termite (*Reticulitermes flavipes*) was studied. Wood materials were thermally-modified at a temperature of 210 °C for 15 min. ACQ-C was impregnated into yellow-poplar and jack pine wood at three different retention levels and at each level both leaching and non-leaching procedures were conducted. Results indicate that ACQ-C-treated yellow-poplar and jack pine became significantly more resistant to the brown-rot fungus compared to the thermally-modified wood and the untreated control. Thermally-modified yellow-poplar and jack pine were more resistant to this fungus than untreated wood. For aspen and Scots pine, the resistance to *G. trabeum* was improved after the thermal modification, but it remained susceptible to this brown-rot fungus decay. Termite susceptibility of thermally-modified aspen, jack pine, and yellow-poplar was comparable to that of untreated controls. Significantly greater termite attack occurred on thermally-modified Scots pine wood than it did on untreated wood. This likely is attributed to some compounds contained in Scots pine wood that inhibited termite attack.

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## Vergleichende Untersuchung des Braunfäulebefalls und der Bodentermitenresistenz von wärmebehandeltem und mit ACQ-C behandeltem Holz

**Zusammenfassung** Die Resistenz von wärmebehandelter sowie mit ACQ-C (Alkalisch-Kupfer-Quaternäre- Verbindung) behandelter Aspe (*Populus tremuloides* Michx), Jack Pine (*Pinus banksiana* Lamb.), Gelbpappel (*Liriodendron tulipifera* L.) und Kiefer (*Pinus sylvestris* L.) gegen den Braunfäulepilz *Gloeophyllum trabeum* und gegen die ostamerikanische Bodentermite *Reticulitermes flavipes* wurde untersucht. Die Holzproben wurden bei einer Temperatur von 210 °C über eine Dauer von 15 min wärmebehandelt. Gelbpappel- und Jack Pine Proben wurden mit jeweils 3 unterschiedlichen Einbringmengen von ACQ-C imprägniert und dann sowohl ausgewaschen als auch nicht ausgewaschen geprüft. Die Ergebnisse zeigen, dass das mit ACQ-C behandelte Holz der Gelbpappel und Jack Pine im Vergleich zu wärmebehandeltem und unbehandeltem Holz gegen den Braunfäulepilz deutlich resistenter war. Wärmebehandelte Gelbpappel und Jack Pine waren gegen diesen Braunfäulepilz resistenter als unbehandeltes Holz. Die Resistenz von Aspe und Kiefer gegen den Braunfäulepilz war nach Wärmebehandlung zwar verbessert, jedoch waren diese Holzarten auch weiterhin für diese Pilzart anfällig. Die Termitenanfälligkeit von wärmebehandelter Aspe, Jack Pine und Gelbpappel war gegenüber unbehandelten Kontrollproben nicht erkennbar verbessert. Bei wärmebehandeltem Kiefernholz war ein signifikant höherer Termitenbefall als bei unbehandeltem Holz zu verzeichnen. Grund dafür könnte sein, dass in unbehandeltem Kiefernholz einige den Termitenbefall hemmende Verbindungen vorhanden sind.

## 1 Introduction

Thermal modification of wood at a temperature of 180 °C to 260 °C leads to degradation of hemicelluloses and lignin (Feist and Sell 1987, Tjeerdsma et al. 1998, Alén et al. 2002, Tjeerdsma and Militz 2005). Although several processes (e.g. Plato-Process, Bois Perdure, OHT-Process, ThermoWood Process, etc.) exist due to the type and condition of the medium used for heat conduction, the basic concept is common, which is to modify wood chemical structure at a certain temperature in inert atmosphere (Militz 2002). The process results in changes in wood chemical composition and reduction in wood hygroscopicity (Hillis and Rozsa 1985, Mitchell 1988, Tjeerdsma and Militz 2005, Boonstra and Tjeerdsma 2006). Thus, thermally-modified wood tends to be more dimensionally stable than non-modified wood of the same species (Stamm and Hansen 1937, Stamm et al. 1946, Hillis and Rozsa 1985). Studies also showed that the resistance of wood against decay fungal attack can be improved efficiently with thermal modification (Dirol and Guyonnet 1993, Tjeerdsma et al. 2000, Jämsä and Viitaniemi 2001). The magnitude of such improvement depends mostly on the maximum temperature applied to wood, the duration at that temperature, wood species to be treated, and some other possible factors (Vernois 2001). However, it was found that mechanical properties, especially bending strength decreased in thermally-modified wood (Bengtsson et al. 2002, Chanrion and Schreiber 2002, Santos 2000, Yildiz et al. 2002).

Alkaline copper quaternary (ACQ) is a wood chemical preservative that currently is being used to replace chromated copper arsenate (CCA) for residential use; both ACQ and CCA are copper-based water-borne preservatives. Thermal modification and ACQ impregnation are two approaches to wood decay prevention. The two methods differ in their processes; the protection is based on different mechanisms as well. Thermal treatment leads to the modification of wood chemical structure, which results in lower water uptake. Chemical treatment with ACQ means impregnation of wood with a biocide, an active ingredient. For fungal attack to occur on wood, it is essential that the substrate can be metabolized by the fungi and contains sufficient water. That is to say, the moisture content has to reach a certain point (20%) (Zabel and Morrell 1992). The reduction of hygroscopicity due to thermal modification helps to prevent diffusion of the low molecular weight depolymerising agents into wood cell wall, thus decay protection occurs (Murmamis et al. 1987, Green and Highley 1997).

In this study, wood materials were thermally-modified in an experimental furnace under the atmosphere of hot combustion gases and steam which is generated from the water remained in wood (Vernois 2001). Data is limited with regard to decay and termite resistance of thermally-modified and ACQ-C-treated wood. This study examined the resistance of four thermally-modified and ACQ-C-treated Canadian hardwood and coniferous species to a brown-rot fungus (*Gloeophyllum trabeum*) (Pers.) Fr. Murr. and to the Eastern U.S. subterranean termite (*Reticulitermes flavipes* Kollar).

## 2 Materials and methods

### 2.1 Materials and preparation

The materials for this study were aspen (*Populus tremuloides* Michx), jack pine (*Pinus banksiana* Lamb.), yellow-poplar (*Liriodendron tulipifera* L.), and Scots pine (*Pinus sylvestris* L.). The kiln-dried boards ($5 \times 10 \times 200\ cm^3$) of the four species were purchased from a local store in Québec, Canada. The boards were then thermally-modified in an experimental furnace in different batches.

During the thermal treatment process, it was assumed that there was no oxygen present in the furnace. The temperature applied to treat the wood was 210 °C and the boards were kept at this temperature for 15 min. Before the temperature reached the treatment temperature (210 °C), the warming up, pre-drying, and drying phases took place. Following the high temperature modification phase, the boards were cooled and conditioned using water spray system. The boards were taken out from the furnace when the temperature dropped to 140 °C and then air dried. The equilibrium moisture content of the treated wood was measured to be 2%–3%.

Sapwood specimen blocks ($19 \times 19 \times 19\ mm^3$) were then cut from full-size thermally-modified and non-modified boards in Canada, and later sent to Mississippi State University Forest Products Laboratory for brown-rot fungus decay and termite resistance evaluation (AWPA 2005a, AWPA 2005b).

### 2.2 Experimental design

Six blocks of thermally-modified aspen, jack pine, yellow-poplar, and Scots pine were tested for evaluation of the resistance to a decay fungus *G. trabeum*. For yellow-poplar and jack pine, the resistance to *G. trabeum* was also measured on leached and non-leached specimens after ACQ-C (provided by Merichem with a concentration of 13.8%) treatment at three retention levels ($1.6\ kg/m^3$, $3.2\ kg/m^3$, and $6.4\ kg/m^3$). The resistance of untreated specimens to *G. trabeum* was examined as positive control. The experiment can be found in Table 1. The weight loss of the blocks before and after decay test was used as the index of decay.

Six blocks of thermally-modified aspen, jack pine, yellow-polar, and Scots pine were exposed to subterranean termite *R. flavipes* for termite resistance test while using

**Table 1** Experiment for brown-rot fungus decay and subterranean termite resistance tests
**Tabelle 1** Versuchsplan zur Prüfung der Resistenz gegen Braunfäule und Bodentermiten

| Treatment | | | Yellow poplar | | Jack pine | | Aspen | | Scots pine | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Decay | Termite | Decay | Termite | Decay | Termite | Decay | Termite |
| Thermally-modified | | | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |
| ACQ-C-treated | Retention | Leached | 6 | – | 6 | – | – | – | – | – |
| | level 1 | Non-leached | 6 | – | 6 | – | – | – | – | – |
| | Retention | Leached | 6 | – | 6 | – | – | – | – | – |
| | level 2 | Non-leached | 6 | – | 6 | – | – | – | – | – |
| | Retention | Leached | 6 | – | 6 | – | – | – | – | – |
| | level 3 | Non-leached | 6 | – | 6 | – | – | – | – | – |
| Untreated control | | | 6 | 6 | 6 | 6 | 6 | 6 | 6 | 6 |

Notes: The values shown in the Table were the number of specimens prepared for the tests. 'Leached' means at each retention level the ACQ-C-treated blocks went through a leaching procedure. 'Non-leached' means the blocks were only ACQ-C-treated

non-modified specimens as controls. Visual rating scale and weight loss were two measures of termite resistance.

The Duncan's Multiple-Range Test was performed to examine the significance of difference in decay and termite resistance of thermally-modified and ACQ-C-treated aspen, yellow-poplar, jack pine, and Scots pine. Statistical Analysis System (SAS) software (1990) as an analytical tool was used to conduct the Duncan Test.

### 2.3 Test procedures

Impregnation of ACQ-C into the specimen blocks of yellow-poplar and jack pine was conducted in vacuum/pressure equipment. Six intact wood blocks were impregnation treated in one container and three retentions were applied to the blocks in different containers. Leaching of ACQ-C-treated blocks and decay resistance test were conducted according to the procedures given in AWPA Standard E10-01 (2005b). The test blocks were conditioned at 50 °C and the weight was taken, then they were sterilized at 100 °C for 20 min, cooled, and placed in bottles inoculated with *G. trabeum*. After twelve weeks of incubation in a room controlled at 27 °C and 80% relative humidity (RH), the blocks were removed from the culture bottles. Again, the blocks were conditioned at 50 °C and weighed. The weight loss can be obtained from the weight of the blocks before and after decay test using Eq. 1.

Test to determine the resistance of thermally-modified and non-modified blocks to the subterranean termite was conducted in accordance with the procedures described in AWPA Standard E1-97 (2005a). Eastern U.S. subterranean termites (*R. flavipes*) were collected near Starkville, Mississippi, USA. A single-choice procedure was followed meaning that the test block was placed on the surface of the sand with no alternative food source for termite feeding. The test blocks were conditioned at 50 °C before they were placed into the bottles and weighed. After four weeks, the blocks were taken out of the bottles and visually rated using the following rating system.

10 sound, surface nibbles permitted;
9 light attack;
7 moderate attack, penetration;
4 heavy attack;
0 failure.

The weight of the blocks was also taken after conditioning at 50 °C. The weight loss of the blocks after four weeks of exposure to termites can be calculated using Eq. 1.

$$\text{weight loss}(\%) = 100(M_1 - M_2)/M_1\,, \quad (1)$$

where: $M_1$ is the weight of the conditioned block before decay or termite test;

$M_2$ is the weight of the conditioned block after decay or termite test.

## 3 Results and discussion

### 3.1 Decay resistance

Table 2 presents the average weight loss as of thermally-modified and ACQ-C-treated yellow-poplar, jack pine, aspen, and Scots pine after twelve weeks of exposure to the fungus *G. trabeum*. The average weight loss of thermally-modified yellow-poplar was 17.8% and significantly less than the untreated controls. An average weight loss of 25%–44% can be classified as moderately resistant to decay fungi and the weight loss higher than 45% is considered to be slightly resistant or non-resistant (Kartal and Ayrilmis 2005). Thus, yellow-poplar can be concluded as a non-resistant species against the brown-rot fungus *G. trabeum* since the average weight loss after twelve weeks of incubation reached 68.5% (Table 2). In general, yellow-poplar treated with ACQ-C at the three retention levels was significantly more resistant to this brown-rot fungus than both thermally-modified and untreated wood. Obviously, the higher retention of ACQ-C resulted in less weight loss and the weight loss of the leached specimens was more than

**Table 2** Summary of the brown-rot fungus decay (*Gloeophyllum trabeum*) resistance test
**Tabelle 2** Braunfäuleresistenz (*Gloeophyllum trabeum*); Versuchsergebnisse

| Treatment | | | Yellow poplar | | Jack pine | | Aspen | | Scots pine | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Weight loss (%) | SD | Weight loss (%) | SD | Weight loss (%) | SD | Weight loss (%) | SD |
| Thermally-modified | | | 17.8B | 1.9 | 9.53B | 1.1 | 40.7B | 4.7 | 8.68B | 0.9 |
| ACQ-C-treated | Retention level 1 | Leached | 11.3C | 1.3 | 1.85C | 0.2 | – | – | – | – |
| | | Non-leached | 4.65D | 0.7 | 0.78C | 0.2 | – | – | – | – |
| | Retention level 2 | Leached | 5.03D | 0.8 | 0.90C | 0.2 | – | – | – | – |
| | | Non-leached | 1.42E | 0.5 | 1.30C | 0.4 | – | – | – | – |
| | Retention level 3 | Leached | 2.55DE | 0.5 | 1.20C | 0.4 | – | – | – | – |
| | | Non-leached | 1.90E | 0.7 | 1.62C | 0.8 | – | – | – | – |
| Untreated control | | | 68.5A | 7.8 | 65.0A | 5.9 | 72.8A | 9.9 | 11.6A | 1.0 |

Note: Values within species followed by the same letter are not significantly different by Duncan's Multiple-Range test at the 0.05 significance level. SD is standard deviation.

those of the non-leached ones. Table 3 shows the average weight loss of ACQ-C-treated yellow-poplar and jack pine blocks after the leaching procedure. An average weight loss of 4.75% after leaching was observed for retention level 1 (1.6 kg/m$^3$), 4.58% for retention level 2 (3.2 kg/m$^3$) and 3.65% for level 3 (6.4 kg/m$^3$). For outdoor applications without ground contact, a retention level of 6.4 kg/m$^3$ may be needed in this species as overall the weight loss at this retention (leached and non-leached) was the smallest compared to that at the other two retentions.

A similar pattern appeared in jack pine. The weight loss of the untreated control was significantly higher than that of thermally-modified and ACQ-C-treated wood (Table 2). No decay occurred on the test blocks treated at the three retentions and there was no significant difference between leached and non-leached specimens. Untreated jack pine had an average weight loss of 65% after twelve weeks of exposure to *G. trabeum* (Table 2). Thus, jack pine can be classified as non-resistant species as well. Thermal modification improved the resistance of jack pine to the brown-rot fungus *G. trabeum* (weight loss 9.53%), but did not prevent decay of this fungus. In addition, in jack pine non-leached/ACQ-C-treated group, higher retention level did not result in lower weight loss (Table 2). This is likely due to the different initial weight of the test blocks. It is more difficult for chemicals to diffuse into denser wood. Thus, after impregnation ACQ-C chemical remaining in denser blocks was fewer causing higher weight loss after twelve weeks of decay test. The average initial weight of the blocks for the three retention levels can be given here with 2.99 g (retention level 1), 3.08 g (retention level 2), and 3.03 (retention level 3). In jack pine, there was no significant difference in weight loss between the blocks (leached and non-leached) impregnated at the three retention levels. Therefore, the retention level of 1.6 kg/m$^3$ may be sufficient for ACQ-C impregnation when the timber is used outdoor without earth contact.

**Table 3** Weight loss of ACQ-C-treated yellow poplar and jack pine blocks after leaching procedure
**Tabelle 3** Masseverlust von mit ACQ-C behandelten, ausgewaschenen Gelbpappel- und Jack Pine-Proben

| ACQ-C treatment | Weight loss (%) | |
|---|---|---|
| | Yellow-poplar | Jack pine |
| Retention level 1 | 4.75 | 2.31 |
| Retention level 2 | 4.58 | 2.22 |
| Retention level 3 | 3.65 | 2.20 |

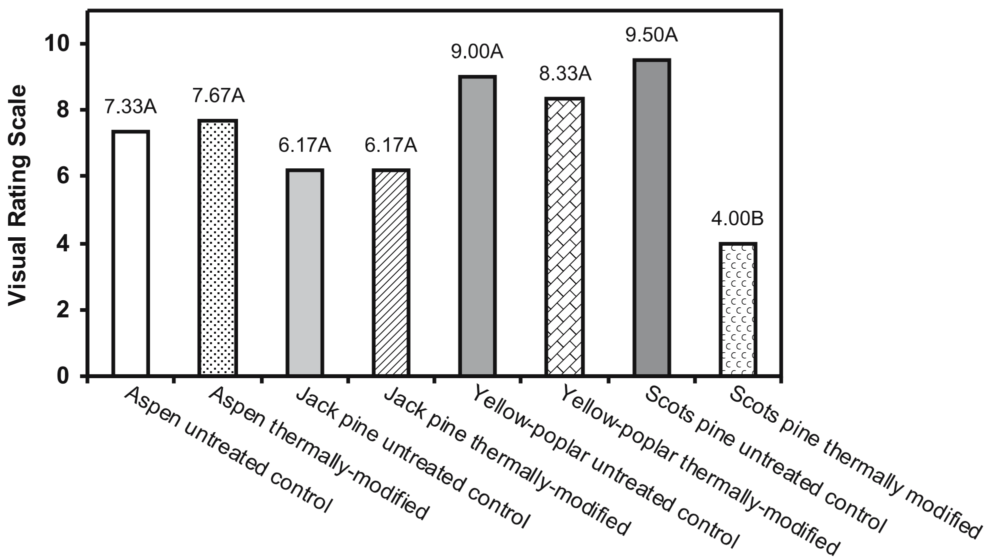
For aspen, the average weight loss of thermally-modified wood (40.7%) was significantly less than that of untreated control (72.8%), but the brown-rot fungus decay was not prevented (Table 2). The thermal modification improved the brown-rot fungus decay resistance of aspen wood; however, aspen heat-treated at this certain condition is still only moderately resistant to *G. trabeum*. In order to become more resistant to the brown-rot fungus, higher temperature and longer duration at this temperature may be needed in the high temperature modification phase. Thermal modification reduced the susceptibility of Scots pine to the brown-rot fungus decay. The values for thermally-modified and untreated Scots pine were fairly low as compared with aspen (Table 2), which indicates either Scots pine untreated or thermally-modified wood were more resistant to *G. trabeum* decay.

It was found that the four species were more resistant to the brown-rot fungus decay after thermal modification at 210 °C for 15 min. The findings are accordant with those from previous studies (Dirol and Guyonnet 1993, Tjeerdsma et al. 2000, Jämsä and Viitaniemi 2001).

## 3.2 Termite resistance

As can be seen in Fig. 1, there was no significant difference in the visual rating scale of thermally-modified aspen compared to untreated control after four weeks of exposure to *R. flavipes*. The mean rating scale for thermally-modified aspen was 7.67, and for the control it was 7.33 (Fig. 1). Ac-

**Fig. 1** Visual rating scale of thermally-modified and untreated aspen, jack pine, yellow poplar, and Scots pine after four weeks of exposure to subterranean termites. Note: Values shown in figure are average rating scales. Values within species followed by the same letter were not significantly different by Duncan's Multiple Range test at the 0.05 significance level
**Abb. 1** Visuell festgestellter Zerstörungsgrad von wärmebehandelter und unbehandelter Aspe, Jack Pine, Gelbpappel und Kiefer nach vierwöchigem Befall mit Bodentermiten



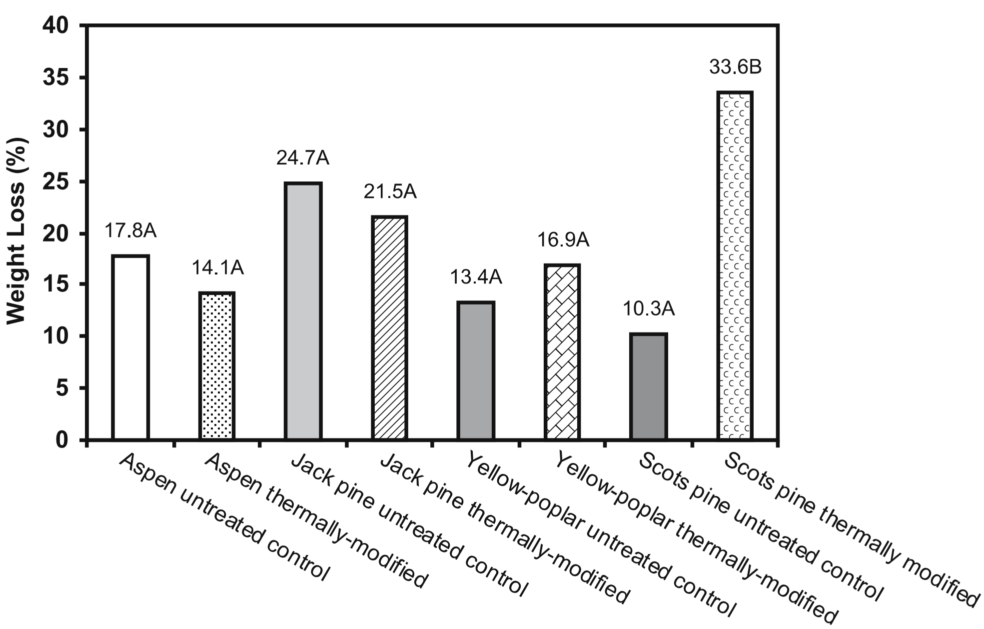

cording to the rating system in AWPA E1-97 (2005a), the attack of termite upon thermally-modified and untreated aspen was on a moderate to light scale. Figure 2 shows the weight loss of thermally-modified aspen compared to its controls after four weeks of exposure to termites (14.1% weight loss in thermally-modified aspen wood versus 17.8% weight loss in untreated aspen).

The termite attack on thermally-modified jack pine and its untreated control was rated to be moderate since the visual rating scale was 6.17 (Fig. 1). No significant difference was found in the visual rating scale between thermally-modified and untreated wood in this species. Exposure to termites resulted in 21.5% weight loss for the thermally-modified wood and 24.7% for the control (Fig. 2).

The visual rating scale and weight loss of thermally-modified yellow poplar and its untreated control were both not significantly different (Figs. 1 and 2). Termites caused light attack on yellow poplar, since the visual rating scale was 8.30 for thermally-modified wood and 9.00 for untreated wood.

In Scots pine, termite attack was rated visually as heavy (4.00) (Fig. 1). However, for the untreated wood, the attack was fairly slight. Only a few surface nibbles were found and the visual rating scale was 9.50. The same phenomenon was also found in weight loss. The weight loss of thermally-

**Fig. 2** Weight loss of thermally-modified and untreated aspen, jack pine, yellow poplar, and Scots pine after four weeks of exposure to subterranean termites. Note: Values shown in figure are average weight loss. Values within species followed by the same letter were not significantly different by Duncan's Multiple Range test at the 0.05 significance level
**Abb. 2** Masseverlust von wärmebehandelter und unbehandelter Aspe, Jack Pine, Gelbpappel und Kiefer nach vierwöchigem Bodentermitenbefall



modified Scots pine reached 33.6%, but its untreated control lost only 10.3% weight after four weeks of termite feeding (Fig. 2). This interesting phenomenon is likely due to some compounds contained in intact wood of Scots pine that prevents termite attack from occurring.

## 4 Conclusions

A comparative study shows that ACQ-C-treated yellow poplar and jack pine were significantly more resistant to the brown-rot fungus *G. trabeum* decay than the same species modified by heat or untreated wood. Thermally-modified yellow poplar and jack pine were less susceptible to the same decay fungus than the untreated wood. In yellow-poplar, higher ACQ-C retention level made the wood more resistant to the brown-rot fungus and such resistance was greater in non-leached than leached specimens. However, retention levels did not make a significant difference in this brown-rot fungus decay resistance for jack pine wood treated with ACQ-C.

Both thermally-modified aspen and Scots pine appeared significantly more resistant to the brown-rot fungus *G. trabeum* when compared to their untreated controls, indicating the resistance of aspen and Scots pine against *G. trabeum* was improved after the thermal modification.

The resistance of thermally-modified aspen, jack pine, and yellow poplar to the Eastern U.S. subterranean termite *Reticulitermes flavipes* was similar to that of untreated controls. There was no significant difference in either visual rating scale or weight loss in the three species between thermally-modified and non-modified wood. With four weeks of exposure to termites, the attack on thermally-modified Scots pine was significantly greater than its untreated control. There are likely compounds contained in Scots pine wood which contributed to inhibition of termite attack.

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