EVALUATION OF DECAY RESISTANCE FOR STEAM-HEAT-TREATED WOOD

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The objective of this research was to evaluate the influence of steam-heat treatment on the decay resistance of Chinese white poplar and Chinese fir wood against the wood-rotting fungi *Gloeophyllum trabeum* (Pers.:Fr.) Murrill. The Chinese white poplar and Chinese fir specimens were obtained from Shandong and Hunan provinces, respectively. They were steam-heat-treated at 170, 185, 200, 215, or 230 ^{o}C with time duration of 1, 2, 3, 4, and 5 hrs in an air-tight chamber that comprised less than 2 per cent oxygen. According to the standard GB/T 13942.1-92, the decay resistance experiments were completed with the wood-rotting fungi *G. trabeum* on an agar block test with 12-week incubation. The results of steam-heat treatment indicated that, compared to a weight loss of 56% for untreated samples, a weight loss of 45% decreased to just 2% for Chinese white poplar with an increase in temperature from 170 to 230℃. No weight loss was observed in the steam-heat-treated China-fir heartwood, sapwood, and untreated sapwood specimens, while only a weight loss of 4.739% in untreated China-fir heartwood specimens was found.

Keywords: Steam-heated wood; Cunninghamia lanceolata (Lamb.) Hook; Populous tomentosa Carr.; Gloeophyllum trabeum; Decay resistance; Agar block test

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INTRODUCTION

The biological durability of wood plays a critical role in its service life. The use of traditional wood preservatives has been restricted due to environmental concerns. Much effort has been concentrated on finding a non-chemical and environmentally-friendly alternative. As a future-oriented technology, thermal treatment is one way to improve fungal and insect resistance in wood, thus increasing its service life. As a result, the use of thermal treatment to increase the biological durability of wood is considered to be preferable over other methods (Homan et al. 2000). There are currently five heat (thermal) treatment processes commonly used at an industrial scale. They are the ThermoWood process in Finland (Syrjänen 2001; Jämsä and Viitaniemi 2001), the Oil-heat treatment in Germany (Rapp and Sailer 2001), the Plato process in Netherlands (Militz and Tjeerdsma 2001), and the Le Bois Perdure process and Retification processes in France (Vernois 2001).

As a biological material, wood provides abundant nutrition to most inquilinous fungi, such as phosphorus, potassium, sulphur, magnesium, and a small amount of iron, zinc, copper, manganese, and molybdenum (Li 2002), which is attributed to inorganic materials in wood. Although the amount is very tiny, the thiamine in the wood is one of the essential nutrients for most wood-rot fungi. The wood would have been free of decay if the thiamine had been extracted from it (Shen 1993).

Generally speaking, the decay resistance of thermal-treated wood depends on the wood species and thermal treatment conditions. The ThermoWood process improves the biological resistance of wood at the temperatures higher than 220℃ and longer than 3 hrs, which was attributed to the chemical degradation in wood and formation of new compounds (Jämsä and Viitaniemi 2001). Kamdem et al. (2002) reported that, compared to a weight loss of 47% in the control Southern pine, a weight loss of 16% in the heat-treated poplar due to the wood-rotting fungi *G. Trabeum* after 8 weeks of incubation in an agar plate block test was found. Furthermore, it was also reported that a weight loss of 7% in the heat-treated pine compared to a weight loss of 19% in the untreated pine. On the other hand, the Plato process also imparted improved durability against decay fungi, especially against brown rot fungi (Tjeerdsma et al. 2000; Militz and Tjeerdsma 2001).

Chinese white poplar and Chinese fir are the most commonly planted tree species in China. The decay resistance of these species plays a critical role in the service life of the products. Thus, there is a need to evaluate the effect of various temperatures and time duration of the steam-heat treatment on the decay resistance of Chinese white poplar and Chinese fir to wood-rotting fungi *G. trabeum*.

MATERIALS AND METHODS

Materials

Fifteen 20-year old Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook) trees were randomly selected and fresh cut from a planted forest in Hunan Province, China. The specimens were cut from annual rings between 11 to 18. Fifteen 40-year old Chinese white poplar (*Populous tomentosa* Carr.) trees were randomly selected and fresh cut from a planted forest in Shandong Province, China. After chopping the trees into logs with a length from 1.3 to 4.5 m, forty boards with a dimension of 500 × 50 × 25 mm (longitudinal × radial × tangential) were cut from each log. The heartwood and sapwood specimens were cut from annual rings between 18 to 22 and between 27 to 34, respect-tively.

Steam-heat Treatment of Boards

The Random Complete Block Design (RCBD) was used to design the experiments in this study. The specimens were dried to an initial moisture content of around 8 % in a high-frequency vacuum dryer. The steam-heat treatment was conducted at temperatures of 170, 185, 200, 215, and 230 ^{o}C and time durations of 1, 2, 3, 4, and 5 hours in an air-tight chamber with less than 2 per cent oxygen. Steam was used as a heating medium and a shielding gas. The moisture content of the steam-heat-treated boards was around 4%.

Specimen Preparation and Agar Block Tests

The specimens with a dimension of 20 × 20 × 10 mm (longitudinal × radial × tangential) for the decay resistance testing were cut from steam-heat-treated and untreated boards. All specimens were sterilized at 138 ^{o}C for 2 hrs in a closed chamber prior to the agar block test. With 12 replicates for each specimen, the resistance against the decay fungi was examined in an agar block test according to Chinese standard GB/T 13942.1-92 (1992). Wood-rotting fungus, *Gloeophyllum trabeum* (Pers.:Fr.) Murrill. was used instead of *Poria plaoenta* (Fr.) Cooke, which is used for testing the decay resistance of softwood, and *Coriolus versicolor* (L. ex Fr.) Quél, which is used for testing the decay resistance of hardwood, to treat all specimens in this study. In order to investigate the effect of steam-heat treatment on decay resistance of the wood, the weight loss of the wood samples was measured after 12-week incubation. The decay resistance was determined according to weight loss rates of the samples after the agar block test. There are four classes for evaluating the decay resistance of wood against the wood-rotting fungi *G. trabeum*. They are highly resistant (0 - 10%), resistant (11 - 24%), moderately resistant (25 - 44%), and nonresistant (> 45%).

RESULTS AND DISCUSSION

The weight loss data for Chinese white poplar, Chinese fir heartwood and sapwood by the action of decay fungi *G. trabeum* in the agar block test with 12-week incubation are presented in Table 1. The results of analysis of variance (ANOVA) on weight loss in steam-heat-treated wood are shown in Table 2, and the multi-comparison analysis of steam-heat parameters results are shown in Table 3, respectively.

According to GBT standard 13942.1-92 (1992), untreated Chinese white poplar with a weight loss of 56% was classified as non-resistant because the weight loss was over 45%. Untreated Chinese fir heartwood with a weight loss of 5% and sapwood with no weight loss were both classified as highly resistant because their weight losses were less than 10%. Most Chinese fir specimens had slight weight gain instead of weight loss after steam-heat treatment. This result indicated that perhaps the wood-rotting fungus *G. trabeum* had no effect on the decay resistance of Chinese fir wood.

The effect of steam-heat treatment on the decay resistance of wood was also evaluated in this study. Figure 1 shows that less hyphae grew on the surface of the wood specimens when the higher temperatures were used to treat the wood specimens. Only a small amount of hyphae was observed on the surface of wood specimens when they were treated at a temperature of 230 ^{o}C for 5 hrs. Table 1 indicates that the weight loss of steam-heat-treated Chinese white poplar decreased with an increase in temperature and time during steam-heat treatment. Using the steam-heat treatment, the decay resistance of Chinese white poplar wood was increased from the class of non-resistant to highly resistant. Table 1 also shows that the decay resistance was easily improved to the class of moderately resistant under a temperature of 170℃ for 1 hour, in which the weight loss was between 25% to 44%. Once the treatment temperature reached 200 ^{o}C with a longer time duration, the decay resistance was further improved to the class of resistant, in which the weight loss was between 11% and 24%. Finally, it could be further enhanced

to the class of highly resistant when a temperature of 230 °C and a time duration more than 1 hour were used.

These results are in good agreement with the conclusions from other researchers. Kamdem et al. (2002) reported the weight loss in heat-treated poplar decayed by *G. trabeum* after agar plate block test was 16 ± 5% at temperatures ranging from 200 to 260℃ for 1 to 24 hours. These results are also similar to those reported by Calonego et al. (2010), Metsa-Kortelainen et al. (2005), Alén et al. (2002), Rapp and Sailer (2001) and Homan et al. (2000), who found that the heat treatment of wood at high temperatures enhanced the decay resistance of the wood.

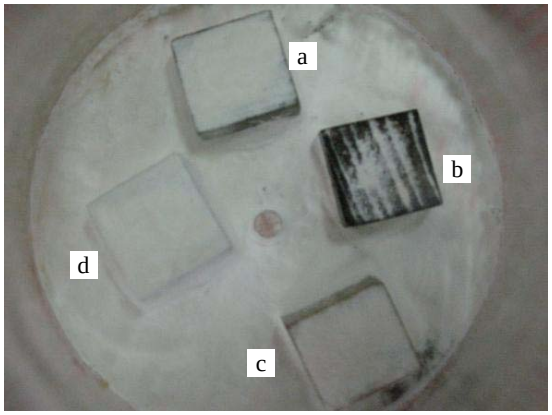

Fig.1. Comparison among different volumes of mycelium on Chinese white poplar specimens a: 5h, 215℃; b: 5h, 230℃; c: 5h, 200℃; d: 5h, 170℃

Table 1. Weight Loss Rates of Steam-heat-treated Wood after Agar Block Test

Species	Time	Weight loss rate (%)					
		Control	170 °C	185 °C	200 °C	215 °C	230 °C
Chinese fir heartwood	1h	4.739	3.108	-	-	-	-
	2h	4.739	-	-	-	-	-
	3h	4.739	-	-	-	-	-
	4h	4.739	1.011	-	-	-	-
	5h	4.739	-	-	-	-	-
Chinese fir sapwood	1, 2, 3, 4, 5h	-	-	-	-	-	-
Chinese white poplar	1h	55.746	44.690	41.726	38.374	26.595	18.648
	2h	55.746	43.423	39.880	34.280	22.504	8.086
	3h	55.746	42.123	36.117	27.829	18.672	7.317
	4h	55.746	39.014	34.450	25.294	16.432	3.157
	5h	55.746	37.612	31.904	21.474	12.073	2.052

"-" means no weight loss.

According to GBT 13942.1-92 (1992), the decay resistances of untreated and steam-heat treated Chinese fir heartwood and sapwood are both classified as highly

resistant after agar block test with 12-week incubation. The weights of the steam-heat-treated Chinese fir heartwood and sapwood were slightly increased compared to the untreated specimens. It was likely that when the hyphae grew into wood cells the wood-rotting fungi died of lacking necessary nutrition. The dead hyphae could not be removed from wood cells, so that the gross weight of the wood specimen finally increased. Therefore, the additional part of weight should be attributed to the weight of dead hyphae. This conclusion is in a good agreement with other reports. Weiland and Guyonnet (2003), Vernois (2001), Jämsä and Viitaniemi (2001) indicated that the heat treatment modified the chemical composition of the wood and cut down the food for fungi. The equilibrium moisture content of the wood was reduced, and new molecules that act as fungicides were formed. It would make it more difficult for fungi to recognize the substrate due to the cross-linking the lignin and the polymer from the thermally degraded cellulose. Kamdem et al. (2000) reported that the improved decay resistance of thermal-treated wood was likely partially due to the formation of some toxic byproducts from heat treatment based on detecting some polyaromatic compounds in the organic extractives from thermal modified wood using GC-Mass and ^{13}C NMR.

The weight loss of Chinese white poplar decreased gradually with the increase of temperature and time during the steam-heat treatment. The decay resistance of the wood was improved from nonresistant to moderately resistant, and even highly resistant. Figure 2 shows that the untreated Chinese white poplar specimens were damaged severely by the wood-rotting fungi *G. trabeum* after the agar block test, while the other specimens retained their shapes and looked better and better when the treatment temperatures were elevated. In particular, the specimens treated at 230 ^{o}C for 5 hrs retained their original shapes after the agar block test, as shown in Fig. 2. Furthermore, the rate of weight loss in Chinese white poplar was accelerated when the temperature was around or over 200 ^{o}C. This result showed that the temperature had a stronger effect on decay resistance of Chinese white poplar than the time duration.

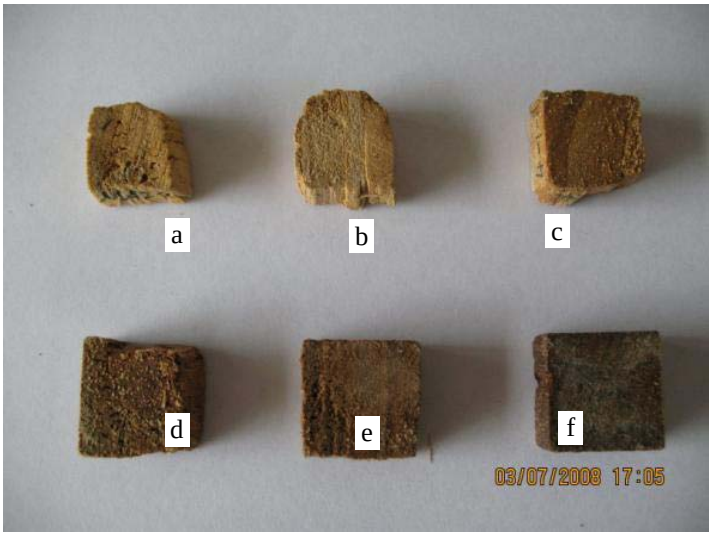

Fig. 2. Comparison among different figures in Chinese white poplar specimens
a: untreated; b: 5h, 170 ^{o}C; c: 5h, 185 ^{o}C; d: 5h, 200 ^{o}C; e: 5h, 215 ^{o}C; f: 5h, 230 ^{o}C

Generally speaking, the decay resistance of steam-heat-treated wood depends on wood species and thermal treatment conditions. Steam-heat treatment usually changes the structures and relative contents of the three main chemical components in wood cell walls, cellulose, hemicellulose, and lignin. Stamm (1964) reported that wood begins to degrade obviously at a temperature of around 165 ^{o}C. Hemicellulose decomposes much faster than cellulose, and cellulose decomposes faster than lignin during the process of heat treatment. When the wood is heated, the first weight loss starts from the loss of water, followed by a variety of chemistries that produce degradation products and volatile gasses (Shafizadeh and Chin 1977). In this study, the contents of cellulose and hemi-cellulose decreased respectively with an increase in temperature and time duration, while the relative content of lignin increased. This result is in good agreement with other reports (Bourgois et al. 1988; Dirol and Guyonnet 1993). In the meantime, thermal treatment reduced the equilibrium moisture content (EMC) of wood by 40 to 60% (Syrjänen and Kangas 2000), which is believed to be closely associated with the decay resistance, since a certain MC of wood is necessary for the growth of fungi (Stamm and Harris 1953; Stamm 1964). All these reactions above-mentioned improved the decay resistance and reduced mass of wood finally.

With an analysis of variance, Table 2 shows that a significant effect was found for the temperature on the weight loss for Chinese white poplar and Chinese fir heartwood at

Table 2. Repeat Two-way Analysis of Variance (ANOVA) for Weight Loss Rate in Steam-heat-treated Wood with Different Treatment Parameters

Species	Source	df	SS	MS	*F* value	$P_r > F$
Chinese fir heartwood	Block	7	83.41	11.92	0.66	0.7045
	Temp.	4	928.55	232.14	12.89	< .0001
	Time	4	47.92	11.98	0.67	0.6171
	Temp.*Time	16	284.51	17.78	0.99	0.4732
	Model	31	1344.39	43.37	2.41	0.0002
	Error	168	3026.70	18.02		
	Cor. Total	199	4371.09			
Chinese fir sapwood	Block	7	701.92	100.27	1.61	0.1357
	Temp.	4	170.73	42.68	0.69	0.6031
	Time	4	73.68	18.42	0.30	0.8804
	Temp.*Time	16	499.50	31.22	0.50	0.9441
	Model	31	1445.83	46.64	0.75	0.8277
	Error	168	10464.60	62.29		
	Cor. Total	199	11910.44			
Chinese white poplar	Block	4	228.98	57.24	0.50	0.7389
	Temp.	4	17468.07	4367.02	37.81	< 0.0001
	Time	4	1356.79	339.20	2.94	0.0244
	Temp.*Time	16	228.98	57.24	0.50	0.7389
	Model	28	20736.78	740.60	6.41	< 0.0001
	Error	96	11086.71	115.49		

the level of 0.01. However, no effect was found for Chinese fir sapwood. Also, no significant influence was found of the time duration on weight loss for both Chinese white poplar and Chinese fir wood. No significant interaction between the temperature and the time on weight loss was found for the three types of wood specimens.

The multi-comparison analysis of heat treatment temperatures is presented in Table 3. It shows that no significant difference on weight loss among 185 ^{o}C, 200 ^{o}C, 215 ^{o}C, and 230 ^{o}C was found for Chinese fir heartwood. Also no significant difference in weight loss for Chinese fir sapwood among all temperature levels was observed. However, there was a significant difference in weight loss for Chinese white poplar among different temperature levels.

CONCLUSIONS

The decay resistance of Chinese white poplar against the wood-rotting fungi *G. trabeum* was improved remarkably from nonresistant to highly resistant through the steam-heat treatment with different treatment conditions. Compared to the weight loss of 56% in untreated specimens after the agar block test in 12-week incubation, the weight loss of Chinese white poplar was decreased from 45% to 2% at treatment temperatures from 170 ^{o}C to 230 ^{o}C and time duration of 1 to 5 hrs. However, the wood-rotting fungus *G. trabeum* had no effect on the decay resistance of Chinese fir wood due to the fact that no weight loss of wood had been observed after agar block test. In other words, Chinese fir wood has a high decay resistance against the fungus *G. trabeum*. Steam-heat treatment of wood is not only a practical method to extend the service life of wood but also a novel solution to help industries to produce high value-added forest products.

Table 3. Multi-comparison of Steam-heat-treated Parameters on Wood

	Chinese fir heartwood			Chinese fir sapwood			Chinese white poplar		
Factor	Level	Mean	Duncan grouping	Level	Mean	Duncan grouping	Level	Mean	Duncan grouping
Temp.	170℃	0.414	A	170℃	-8.641	A	170℃	41.372	A
	185℃	-3.003	B	215℃	-9.119	A	185℃	36.815	B
	200℃	-4.038	B	185℃	-9.242	A	200℃	29.450	C
	215℃	-4.947	B	230℃	-10.401	A	215℃	19.250	D
	230℃	-4.973	B	200℃	-10.649	A	230℃	7.852	E
Time	1h	-2.638	A	1h	-9.233	A	1h	34.007	A
	5h	-2.839	A	4h	-9.483	A	2h	29.635	B
	4h	-3.402	A	3h	-9.525	A	3h	26.412	C
	2h	-3.702	A	5h	-9.773	A	4h	23.669	D
	3h	-3.965	A	2h	-10.038	A	5h	21.023	D

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