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Research Article

Wood Deterioration of Cooling Tower Structure at Geothermal Power Plant

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Abstract

Background and Objectives: Wooden cooling tower structure in Star Energy Geothermal (Wayang Windu) Ltd's Power Plant was built in 1998 and it is operating since 2000. The wood is exposed to wet and hot environment during cooling tower operation, thus the physical and chemical degradation should be evaluated. **Materials and Methods:** Wood were taken from mainframe component of cooling tower, which represented the exposed to sunlight and the shadowed one. The density and chemical content degradation were measured to estimate the deterioration rate of the component. **Results:** Two species are used for cooling tower mainframe and non-mainframe component, namely redwood (*Sequoia sempervirens*) and douglas fir (*Pseudotsuga menziesii*). Since the impact of water sprinkle and water flow friction to the wood member, the wood density has degraded. In combination with ultraviolet sunray radiation and eroding wind, it significantly pawed the surface so that douglas fir and redwood density has been decreasing until 2.5 and 2.0 mm depth, respectively, for 15 years cooling tower operation. Extractives in the cell wall is leaching so that the extractive content in outer layer is less than in the center of wood. Extractive content in surface layer of redwood (0-2 mm depth) and douglas fir (0-6 mm) are significantly less than control. The cell wall in the surface has chemically deteriorated because of weathering so it was more easily diluted in NaOH 1%, especially in the first layer (0-2 mm depth). Lignin content in the first layer of all samples are less than in the center. The preservative retention was also measured for each depth and it is found that CCB is bounded well to the cell wall. The preservative concentration in the first layer is still higher than the center. **Conclusion:** After 15 years exposed to cooling tower environment, physical and chemical properties of mainframe component of wooden cooling tower in geothermal power plants are degraded.

Key words: Cooling tower, extreme environment, long term weathering, physical and chemical properties of wood, wood degradation, wood weathering, deterioration

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Wood has been utilized for structural member of the cooling tower since the structure was built for the first time. Certified wood is highly recommended for green construction materials because of its advantages: High strength compared to its low density, high dimensional stability, small dimensional changes due to temperature changes, relatively easy to maintain, highly aesthetics, available in nature and its resource is renewable. Morrison¹ reported that wood is the most economical material for longer service lifetime cooling towers compared to other materials. Unlike concrete, wood is less eroded by hot water and it is not corrosive to metal. However, as a natural material, wood is vulnerable to wood attacking organism and it can be degraded due to weathering.

As described in Cooling Tower Institution (CTI) standard (CTI STD-114)², douglas fir cooling tower is designed for 50 years old service life, thus it receives long term loading. Huge fan near the top of structure rotates in certain cycles per minutes (cpm), thus the dynamic load applied to the structure. The wood member in cooling tower structure is poured with hot water, receiving direct sunlight and resisting to erodical wind. Various studies show that the wood structure deteriorate when receiving long term load and it is exposed by extreme environment during cooling tower operation. Bahtiar *et al.*³ studied the degradation of wood member of cooling tower at PT Indonesia Power's Geothermal Power Plant in Kamojang Garut, West Java and reported that the redwood has degraded until 2.95 mm depth after 23 years of usage. The defects were deeper than Sudiyani *et al.*⁴ report which proved a significant reduction in lignin content of wood cell wall at a depth of 0.5 mm on outdoor environment conditions.

To avoid organism attacks, all of mainframe and non-mainframe component of douglas fir cooling tower must be treated by preservative as designated by CTI STD²-114. The preservative treatment procedure is regulated in CTI-STD⁵ 112. It is important to study whether the preservative active component is still bound well in the cell wall or it has been leaching after 15 years cooling tower operation. Bahtiar⁶ identified that there are copper and boron active preservative ingredient in wood bracing of cooling tower at Star Energy Geothermal (Wayang Windu) Ltd. Unfortunately, Bahtiar⁶ did not measure the retention and penetration, thus the leaching depth had not been estimated.

This study is conducted to measure the physical and chemical degradation of wood member after exposed by high temperature and moisture content during cooling tower operation for 15 years. The samples were taken from cooling tower at Star Energy Geothermal (Wayang Windu) Ltd's Power

Plant which was built in 1998 and began operating in 2000. It is reported that the performance of cooling tower is decreasing which is proved by the increasing frequency of its vibration. The vibration of the structure arisen in 9, 12 and 16 Hz in the current year. About 12 Hz frequency is dominant recently. It is higher frequency compared to the 9 Hz frequency (the only one) when measured 5 years ago, even more horrific compared to no vibration when first operated 15 years ago as reported by cooling tower owner. Because of that phenomenon, it is wondered to study the physical and chemical degradation of wood member of cooling tower structure. The measurements were density, solubility in ethanol-benzene, solubility in NaOH 1%, lignin content and preservative active ingredients concentration. The measurements were conducted on several layers from surface and the center. The center of each wood were chosen as control because outer layer protected it and assumed it had not degraded yet.

MATERIALS AND METHODS

The research activities carried out at the Forest Products Department, Faculty of Forestry, Bogor Agricultural University. The samples were taken from the original mainframe component, which never replaced since the first operation of the cooling tower.

Materials: The investigated materials were redwood (sample L and M) and douglas fir (samples J and P) timber, which were taken from mainframe components of Star Energy Geothermal (Wayang Windu) Ltd's cooling tower at Pengalengan Bandung, West Java. Redwood samples were taken from component above fill: Sample M were exposed to direct sunlight during cooling tower operation, while sample L was protected from direct sunlight by other component's shadow. Douglas fir samples were taken from mainframe component below fill: Sample P was exposed by direct sunlight and sample J was not exposed.

Density degradation: The samples were dried in $103 \pm 2^\circ\text{C}$ oven for 2-4 days until constant weight, then they were shaved. Each shaving depth was 0.5 mm. The weight and dimension of wood before and after each shaving were measured to calculate the density of outer shaved layer (surface density). The weight and dimension of timber were measured in oven dry condition before and after shaving. The density of each layer were calculated^{3,7} by Eq. 1:

$$\rho_i = \frac{W_i - W_{i+1}}{V_i - V_{i+1}} \quad (1)$$

where, ρ_i is the density at i-th depth, W_i is the weight before the i-th shaving, W_{i+1} is the weight after the i-th shaving, V_i is the volume before the i-th shaving and V_{i+1} is the volume after the i-th shaving.

The wood was degraded in such depth when the density was lower than control, which would be shown in a graph. The rate of degradation was calculated as the degradation depth divided by 15 years duration of cooling tower operation.

Sample preparation for chemical test: The powder were collected for each 4 times shaving so the chemical tests were conducted for 5 layers of wood depth: First layer (0-2 mm depth), second layer (2-4 mm depth), third layer (4-6 mm depth), fourth layer (6-8 mm depth) and control (center of the timber). The powder from each subsequent test samples were grinded by Wiley mill and screened to obtain fine powder (40-60 mesh size).

Soluble ethanol-benzene extractive: Soluble ethanol-benzene extractive was measured according to ASTM⁸ D1105-96. Amount of 2 ± 0.1 g water-free powder (A) was extracted by soxhletation in 300 mL ethanol-benzene solvent mixture (1:2) for 4-6 h until the solvent in colorless soxlet (clear). Then the solvent was extracted using ethanol for 4 h, followed by hot water for 3 h. The test sample was washed with 500 mL hot distilled water to remove the solvent. Then the free extractive powder dried in the oven at $103 \pm 2^\circ\text{C}$ to constant weight (B). The extractive content was calculated by Eq. 2:

$$\text{Extractive content (\%)} = \frac{A-B}{B} \times 100 \quad (2)$$

Where:

A = Weight of water-free powder before extraction

B = Weight of the powder after extraction

Solute concentration in NaOH 1%: Solute concentration of wood cell wall component in NaOH 1% was measured according to ASTM⁹ D1109. Amount of 2 ± 0.1 g dry powder (A) was placed in 200 mL beaker glass and then added by 100 mL of NaOH 1%. The solution was stirred until the solution mixed well and then heated in a water bath. The solution was stirred 3 times at 10, 15 and 25 min and then kept motionless in the water bath for an hour to cool down. The powder was rinsed with 100 mL of hot water until it had a clear color and then 20 mL of 10% acetic acid was added. The powder is rinsed again with hot water until the powder is free from acid. The powder was dried in an oven at a temperature

of $100-105^\circ\text{C}$ to gain a constant weight. Then powder was placed in a desiccator and was weighed (B). Solute concentration of wood cell wall in NaOH 1% was calculated by the Eq. 3:

$$\text{Solute concentration (\%)} = \frac{A-B}{B} \times 100 \quad (3)$$

Where:

A = Weight of dry powder before dissolved in NaOH 1%

B = Weight of dry insoluble powder after measurement procedure conducted

Lignin content: Lignin content was measured according to ASTM¹⁰ D1106 procedure with some modification as follow: A number of 0.5 g of dry and free extractive sawdust (B) was put into the beaker, then 72% sulfuric acid was added gradually until the solution volume become 5 mL. During this sulfuric acid addition, the solution was stirred slowly and the temperature was kept constant in $2 \pm 1^\circ\text{C}$. The solution was kept at $20 \pm 1^\circ\text{C}$ for 3 h and stirred gently every 15 min. After 3 h, 191 mL of distilled water was added so that the sulfuric acid concentration become 3%. Hydrolysis was done using autoclave at 121°C for 30 min. Lignin was washed with hot distilled water to neutralize the acid and then filtered. Lignin was dried in the oven at $103 \pm 2^\circ\text{C}$ until its weight is constant (A). The lignin content in the cell wall was calculated using Eq. 4:

$$\text{Lignin content (\%)} = \frac{A}{B} \times 100 \quad (4)$$

Where:

A = Weight of dry lignin

B = Weight of dry and free extractive powder (0.5 g)

Active ingredients of preservative: The method used to determine the concentration of preservative active ingredient was conducted by wet ashing method. A total of 0.5 g of the sample was put in digestion tube and 5 mL HNO_3 p.a. and 0.5 mL HClO_4 p.a. were added and then cooled down for 24 h. After 24 h cooled down, the solution was heated in digestions block at 100°C for 1 h, then the temperature was increased become 150°C . After the yellow steam exhausted, block digestion temperature was increased become 200°C . The process finished after white smoke extract vaporized and the remaining approximately 0.5 mL. The tube was removed and cooled down. The extract was diluted with deionized water until the volume become 50 mL and then shaken in a shaker

tube to gain the homogenous solution. Copper and chromium content of the extract samples were measured using Atomic Absorption Spectrophotometry (AAS) with the respective standard series as a comparison using a mixture of air-acetylene flame. Boron measurement was conducted by spectrophotometer. Each 4 mL extract sample and boron standard series were put into a test tube and then 1 mL buffering solution was added and whipped. The solution was added with 1 mL azomethine-H, whipped and kept motionless for 1 h. The boron concentration was measured by spectrophotometer at 430 nm wavelength. Then the active ingredient of preservative content (Cu, Cr and B) calculated by Eq. 5:

$$\begin{aligned} \text{Cu/Cr/B content (ppm)} &= \text{ppm curve} \times \frac{\text{Vol extract (mL)}}{1.000 \text{ mL}} \times \frac{1000 \text{ g}}{\text{Sample weight (g)}} \text{fk} \\ &= \text{ppm curve} \times \frac{50 \text{ mL}}{1.000 \text{ mL}} \times \frac{1000 \text{ g}}{0.5 \text{ g}} \text{fk} \\ &= \text{ppm curve} \times 100 \times \text{fk} \end{aligned} \tag{5}$$

RESULTS AND DISCUSSION

Wood density degradation: The wood density measurements show an interesting phenomenon. The surface

density of wood, which directly exposed to sunlight (M and P) were much lower than the control (Fig. 1b, d). The degradation of wood density occurred from the surface until 2 mm depth, similar depth for redwood and douglas fir that exposed to direct sunlight. Sunlight UV radiation sparks free radical forming which degrading the polymer of wood¹¹. Since the surface shadowed the inner parts, sunlight UV may degrade only a thin film layer of wood. Bahtiar *et al.*³ noted that the combination of sunlight UV and surface erosion caused by water flow and wind might cause deeper degradation. The UV radiation change the wood color become greyist brown. Figure 1a and c also show no surface density degradation in wood that protected from direct sunlight. The surface density of both samples have similar values compared to control, especially for redwood (L). The density degradation of douglas fir (J) was not happened in the first two layers (0-1 mm) but deeper (1-2.5 mm) (Fig. 1c). It indicates that the degradation may be caused by hot water that generate chemical decomposition. These results were consistent with Quarles *et al.*¹² report that old growth redwood has high natural resistant against wet condition, while douglas fir is moderately resistant. Redwood contain oil that repel insects and prevent rot. The oil in redwood give it natural weather resistance and it lasts two or three times as long as douglas fir outdoors. Figure 1 shows that the maximum

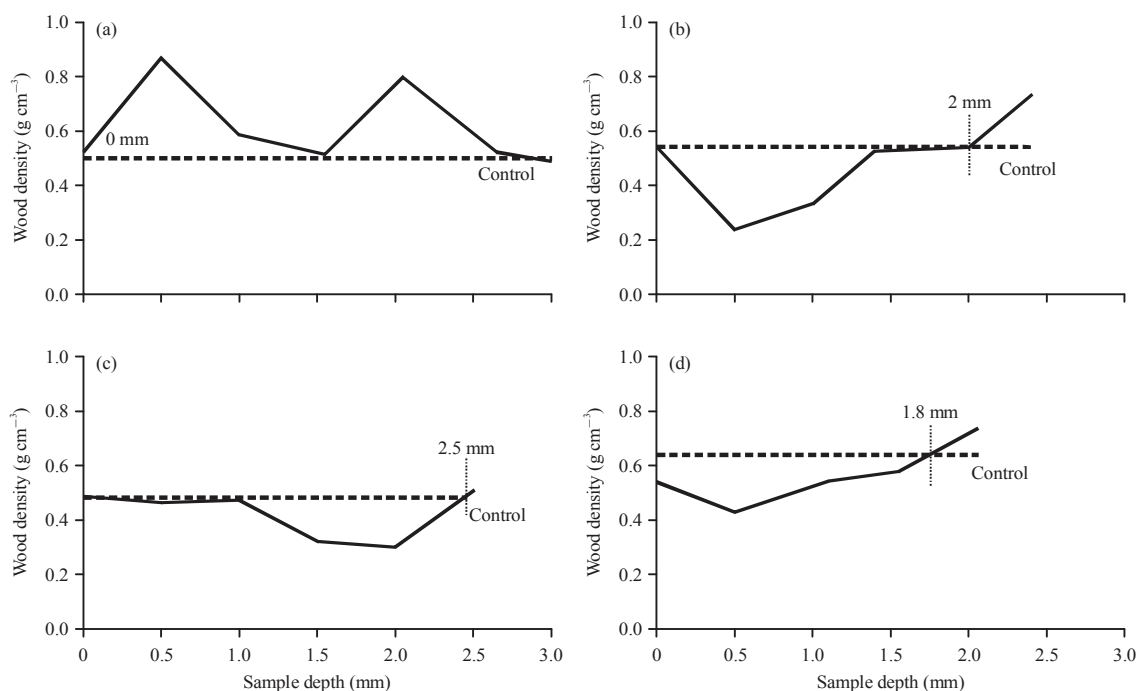


Fig. 1(a-d): Density at various depth of wooden mainframe component of cooling tower after 15 years, (a) Redwood protected from direct sunlight (L), (b) Redwood exposed to direct sunlight (M), (c) Douglas fir protected from direct sunlight (J) and (d) Douglas fir exposed to direct sunlight (P)

density degradation for redwood and douglas fir were 2 and 2.5 mm depth, thus the degradation rates are 0.13 and 0.17 mm year⁻¹, respectively.

Soluble ethanol-benzene extractive: Redwood is very resistant to wood rot fungi attack compared to other temperate wood because it has high extractive content¹³. Most extractive in redwood is bound tightly in the cell wall, so it is leached in slower rate compared to the douglas fir. The soluble ethanol-benzene extractive of redwood in 0-8 mm depth is 7-74% lower than control after 15 years exposed to wet and hot environment during cooling tower operation, while it is 31-78% for douglas fir. Since redwood contain oil, which inhibit extractive leaching, redwood have higher durability in wet condition than douglas fir. The extractive content of redwood and douglas fir in various depth are reported at Fig. 2. The wood extractive substance that soluble in ethanol-benzene are grease, resin and oil compound.

This study results that there has been significant degradation of extractives substance in the cell wall of douglas fir at deeper layer than 8 mm depth (Fig. 2c, d). The most severe degradation was in the first layer (0-2 mm depth).

The similar phenomenon is reported by Ahmad *et al.*¹⁴ that the weathering severely cause wood surface damage at the 0-2 mm depth and will tend toward a constant value above 7-10 mm depth. Meanwhile redwood show more high-level resistance against extractive leaching. The extractive leaching of redwood that exposed to direct sunlight occurred in 0-2 mm depth and the extractive in protective redwood is not significantly leaching (Fig. 2a, b).

Solute concentration in NaOH 1%: The soluble substances in NaOH 1% of wood cell wall component are vary from 10.7-19.3% (Fig. 3). The soluble substance content in the first layer (0-2 mm) is significantly higher than control. It indicates the severe degradation of cellulose and hemicellulose. Because of significantly higher substance content dissolved in NaOH 1%, it is expected that several amount of cellulose and hemicellulose in the first layer have been degraded become shorter degree of polymerization. Bierman¹⁵ reported that degraded wood layers generally produce high alkali solubility. The UV radiation detruncates cellulose fraction become shorter polymerization degree in the first layer of wood. This convinces the weathering occurred in the first layer of all wood samples after 15 years exposed to wet and hot environment.

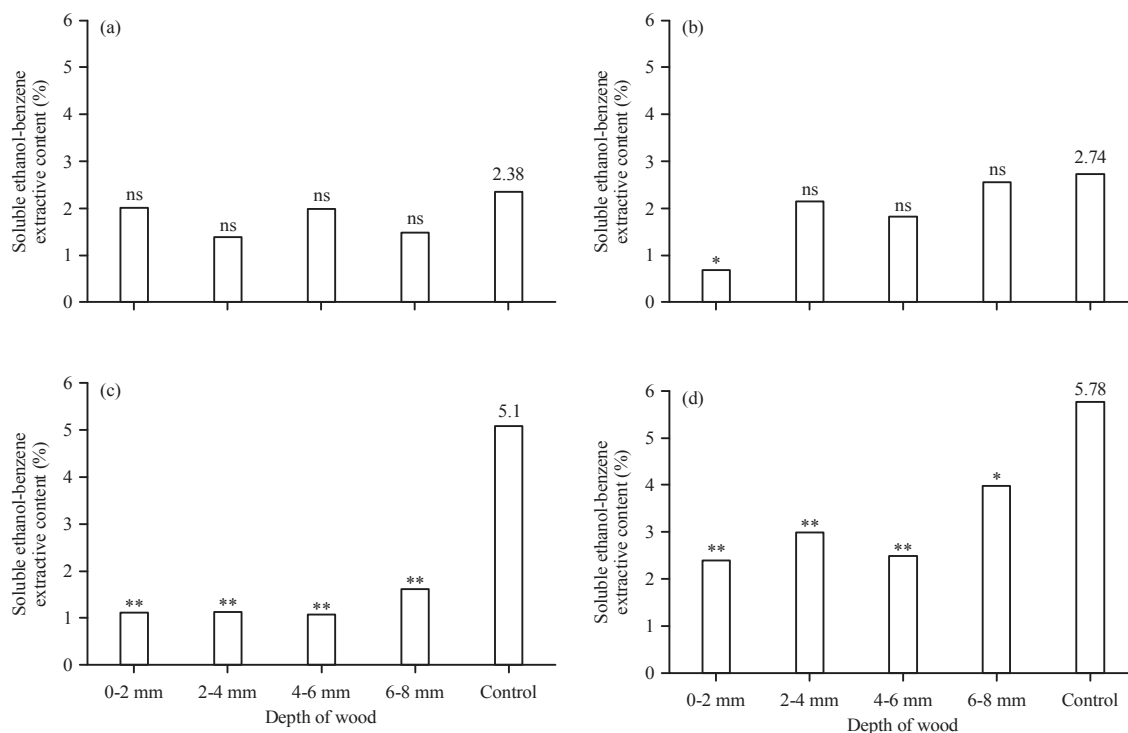


Fig. 2(a-d): Soluble ethanol-benzene extractive content at various depth of wooden mainframe component of cooling tower after 15 years, (a) Redwood protected from sunlight (L), (b) Redwood exposed to direct sunlight (M), (c) Douglas fir protected from direct sunlight (J) and (d) Douglas fir exposed to direct sunlight (P), ns: Not significantly, *Significantly and **Very significantly different compared to control according to Dunnet test

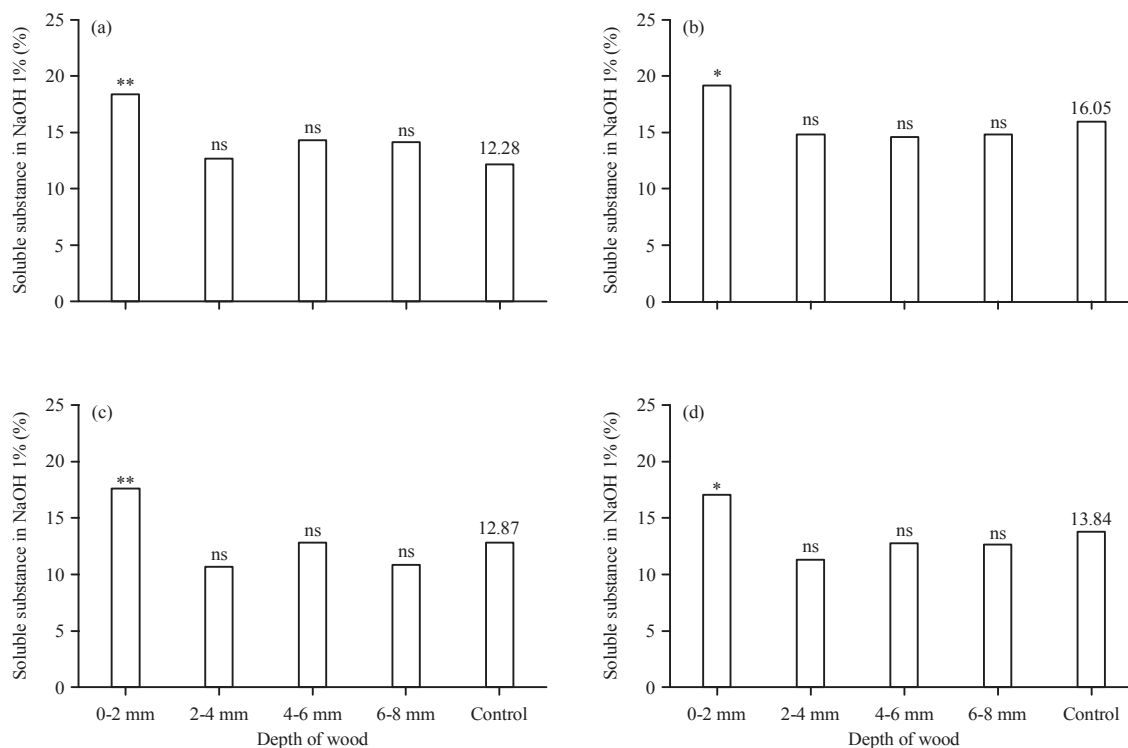


Fig. 3(a-d): Solute concentration in NaOH 1% of wooden mainframe component of cooling tower after 15 years, (a) Redwood protected from direct sunlight (L), (b) Redwood exposed to direct sunlight (M), (c) Douglas fir protected from direct sunlight (J) and (d) Douglas fir exposed to direct sunlight (P), ns: Not significantly, *Significantly and **Very significantly different compared to control according to Dunnet test

Table 1: Lignin content in cell wall of wood mainframe component of 15 years old cooling tower

Lignin content (%)				
Wood depth (mm)	Redwood protected from direct sunlight (L)	Redwood exposed to direct sunlight (M)	Douglas fir protected from direct sunlight (J)	Douglas fir exposed to direct sunlight (P)
0-2	30.48±0.10*	25.20±0.84**	29.41±0.04*	28.24±0.75*
2-4	34.77±0.17 ^{ns}	33.41±1.98 ^{ns}	31.49±0.92 ^{ns}	28.91±0.73 ^{ns}
4-6	33.73±2.07 ^{ns}	35.18±0.36 ^{ns}	32.61±2.17 ^{ns}	29.95±0.69 ^{ns}
6-8	35.26±0.40 ^{ns}	35.82±0.19 ^{ns}	33.54±1.34 ^{ns}	29.24±1.15 ^{ns}
Control	31.83±0.20	35.67±0.49	30.49±0.64	31.98±0.75

ns: Not significantly, *Significantly and **Very significantly different compared to control according to Dunnet test

Lignin content: Lignin is an important component in determining the chemical properties of wood. Higher lignin contents in cell wall indicate the higher rigidity and firmness of wood. The measured lignin content in wood mainframe component of 15 years old cooling tower is presented in Table 1. Based on the lignin content measurement, the first layer (0-2 mm) of wood is degraded. The lignin content in the first layer is significantly lower than control. The lignin degradation is mainly influenced by sunlight UV radiation. The direct sunlight exposed wood reveal more severe lignin degradation compared to the protected one. Lignin have a major role on the absorption of ultraviolet light, while ultra

violet can decompose lignin until 25-300 μm depth of wood. Therefore, lignin damages occur only on the first layer of wood. Nzokou and Kamdem¹⁶ reported the similar phenomenon at pinewood that the wood surface is degraded after 20 years of usage.

Active ingredients of preservative: Wood component in cooling tower mainframe is wet and susceptible to wood destroying organism, especially wood-rot fungi. The wood must be treated by suitable preservative to overcome those attacks. According to Cooling Tower Institute (CTI) standard (CTISTD-103)¹⁷, the mainframe component of cooling tower

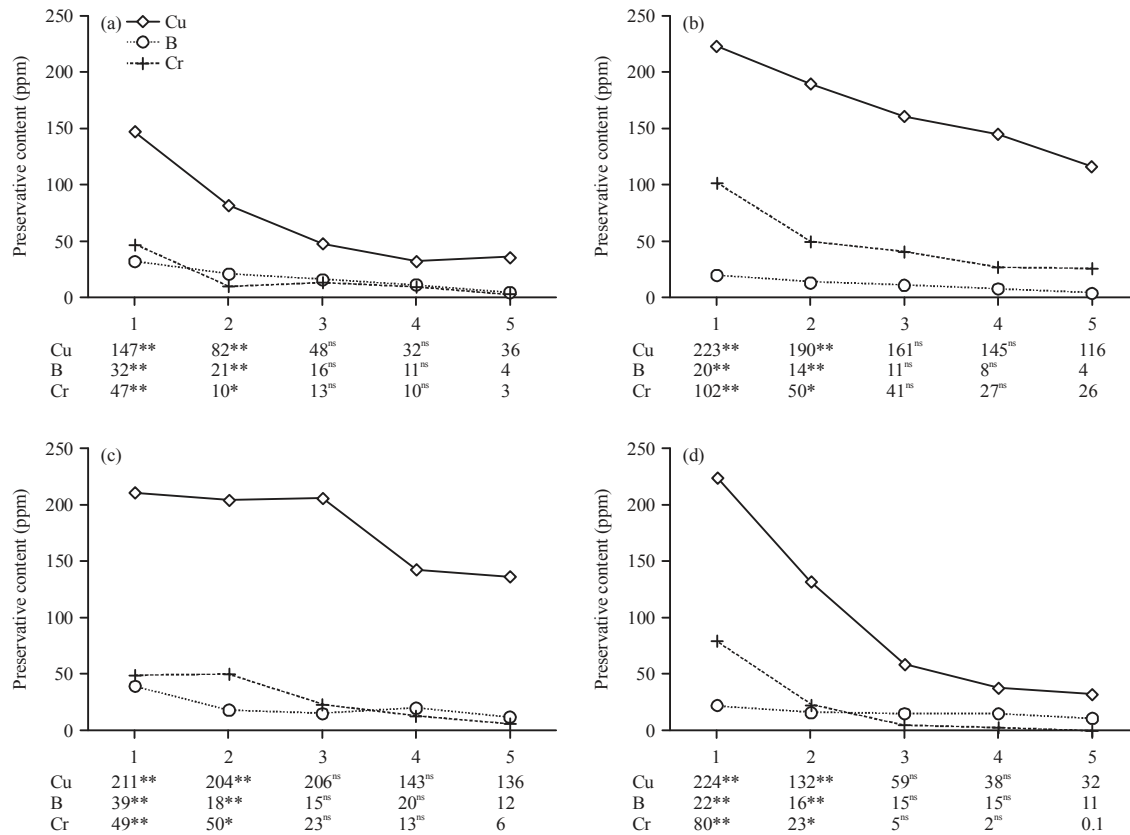


Fig. 4(a-d): Preservative active ingredients (Cu, Cr and B) in several layers of wood, 1: 0-2 mm, 2: 2-4 mm, 3: 4-6 mm, 4: 6-8 mm and 5: Center parts as control of cooling tower mainframe component, (a) Redwood protected from direct sunlight (L), (b) Redwood exposed to direct sunlight (M), (c) Douglas fir protected from direct sunlight (J) and (d) Douglas fir exposed to direct sunlight (P), ns: Not significantly, *Significantly and **Very significantly different compared to control according to Dunnet test

must use preservative treated redwood, while CTI STD-114 regulates that douglas fir for framework and non-framework component of cooling tower must be treated by pressure preservation procedure. Both standards suggest CTI STD-112 as standard procedure for wood preservation. Cooling tower in Star Energy Geothermal (Wayang Windu) Ltd., used CCB treated wood. The active ingredients of CCB are copper (Cu), chromium (Cr) and boron (B). The test results showed that both wood species (redwood and douglas fir) were treated with similar concentration of CCB. The test results are presented in Fig. 4.

As seen on Fig. 4, copper contents in the cell wall of wood surface layer are still in high concentration compared to the control (center of the wood). Copper tightly bound to the cell wall thus it does not leached very much. Ozgenc and Yildiz¹⁸ reported that copper forming a complex compound that significantly reduce the degradation and the delignification during weathering. Copper forms Cu^{2+} ion, which capable to

bind tightly with lignin and cellulose of wood cell wall. In addition, a small portion of copper and chromium tend to form $CuCrO_4$ that chemically bind to lignin. Those reported phenomenon convince this research result that a high concentration of copper is still found in the surface layer of treated redwood and douglas fir exposed in the cooling tower environment for 15 years.

Chromium found in lower concentration compared to copper because only a small portion of it forming chromium complex compound. Temiz *et al.*¹⁹ reported chromium complex compound could bind with guaisil lignin and inhibit discoloration of wood surface. This bound kept the chromium concentration in the wood cell wall, so this study found that chromium content in the surface layer was significantly higher than control. Boron content in the first layer is found in lowest concentration, although the concentration in the deeper layer was similar with chromium. This indicated that boron leached most severely compared to chromium and

copper. Kakaras *et al.*²⁰ reported that boron compound do not bind strongly to wood cell wall which causes boron leached more easily in water flow. Dunnet test showed that all of preservative active ingredient (Cu, Cr and B) in the surface layer were found in higher concentration compared to control (center of wood). It indicated that the wood is still resistance to wood destroying organism attack although it was already used for 15 years in cooling tower environment.

CONCLUSION

After 15 years exposed to cooling tower environment, physical and chemical properties of redwood and douglas fir are degraded. The severe density degradation of redwood and douglas fir are happened in the surface until 2 and 2.5 mm depth, respectively. The extractive contents are leached so that in the surface significantly lower compared to the center parts. The extractive leaching of douglas fir happen in deeper layer (0-8 mm) compared to redwood (0-2 mm) which caused redwood more resistant in wet environment than douglas fir. Cellulose and hemicellulose in the surface layer are estimated to be truncated become shorter polymerization degree so it highly soluble in NaOH 1% solution. Active ingredient of preservative (Cu, Cr and B) are found higher on the surface layer, thus the wood were expected still resistance against wood destroying organism attacks.

SIGNIFICANT STATEMENT

The wood density and its chemical component are deteriorated after exposed to cooling tower environment for 15 years, but the active preservative ingredients did not leach significantly since they are well bonded to the cell wall.

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