Effects of solid carbon dioxide on thermal conductivity of four common construction timber species in Japan with a special reference to drywood termite control

by

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Abstract

In order to evaluate the thermal conductivity value (^{O}C) of solid carbon dioxide for remedial termite control, tests were conducted using four common construction timbers (D-fir, Sitka spruce, Japanese cedar, and Japanese cypress).

The results bring us to the conclusion that wood species, grain direction, density, and proportion of heartwood are not the main influences on thermal conductivity of $CO_{2\ (s)}$. Instead of these, moisture content has a bigger influence on thermal conductivity. In comparison to thermal conductivity values, there is no significant difference within same region for the timber sources (Japan: Japanese cedar and Japanese cypress, North America: Douglas-fir and Sitka spruce). The amount of 1,300g of $CO_{2\ (s)}$ delivered the required target temperature (-21.3 ^{O}C) to achieve 100% mortality of drywood termites in all wood species.

***Keywords*: Solid carbon dioxide, thermal conductivity, drywood termite, construction timbers**

Introduction

The drywood termites are one of the most destructive groups of termites for construction materials in the southwestern United States. The damage caused by drywood termites has an important economic effect. Scheffrahn et al. (1997) estimated that drywood termites' economic impact and cost of control costs varied from 5 to 20 percent of the total ($1.5 to $5 billion) spent on wood-destroying insect control each year in the United States. The invasion of the western drywood termite "*Incisitermes minor* (Hagen)", native to the southern United States, has started in the East Asia. The first infestation of *I.minor* was spotted in Tokyo in 1976 (Mori, 1976) and it was spread throughout the western part of

Japan. Now *I. minor* is a dominant drywood termite species from Kanagawa to Okinawa. The evidence of *I. minor* infestation was revealed in South Korea in recent years in residential wooden houses. However, due to the early infestation no official survey has been conducted to assess the distribution of *I. minor* throughout that nation.

Thermal control is one of the options available for termite management. The fundamental theory of thermal control is to use the thermal conductivity of heat, either hot or cold, to create unfavorable conditions for wood-destroying insects. Wood is known to be a good insulation material with low thermal conductivity, moderate heat capacity, and consequently low thermal diffusivity (Dupleix et al. 2012). However, thermal conductivity of wood can be increased based on wood density (Yu et al. 2011), direction of heat flow (anisotropy), inclination of grain, the relation of volume or thickness of the sample to moisture content (Suleiman et al. 1999), density and proportion of springwood and summerwood in the timber (MacLean, 1941). Hunt et al. (2008) summarized the thermal conductivity values of materials in the cell wall, which are listed in Table 1 below. Based on those values, the thermal conductivity of bound water in cell walls and free water in the cell lumen are higher than that of air. Therefore, wood conductivity increased in green wood compared to seasoned wood.

Table 1. The thermal conductivity values of materials in cell wall (Hunt et al. 2008)

Material	**Thermal conductivity (W/m.K)**
Cell wall substance	0.410
Air in the lumen	0.026
Bound water in cell wall	0.680
Saturated cell wall (FSP)	0.489
Water vapor in cell lumen	0.018
Free water in cell lumen	0.610

Forbes and Ebeling (1986) were the first to recommend spot-applications with excessive cold from liquid nitrogen (-180 ^{o}C) in wall voids for controlling drywood termites. Based on their published report, 100% mortality of *I. minor* individuals was achieved within 5 mins at temperatures between -18.5 and -19.5 ^{o}C. Rust et al. (1995) investigated the effects of rate of temperature decrease on the thermal tolerance of *I. minor*. They achieved a complete mortality of *I. minor* (workers, and nymphs) at temperatures as low as -21.4 ^{o}C. Several studies on low temperature treatment for drywood termites, indicate the dimensions of timber and physical structure affected the mortality of termites, because wood itself has poor thermal conductivity. Therefore, the dimensions of timber affected the mortality of termites.

We hypothesized that thermal conductivity of $CO_{2\,(s)}$ would increase with higher density of timber due to the higher fibril existence, which is more conductive than air. $CO_{2\,(s)}$ would also be able to create a low enough temperature to reach the critical thermal minima (CT_{min}) (-21.3 ^{O}C) for *I. minor*.

The objective of this study was to evaluate attaining the CT_{min} using the thermal conductivity properties of solid carbon dioxide applied in the transverse direction (both radial and tangential directions to the annual rings) on four common construction timbers, Douglas fir, Sitka spruce, Japanese cedar, and Japanese cypress.

Materials and Methods

Preparation of wood sample

Four species of softwoods, the most commonly used structural timbers in Japan, were selected for this study. Douglas fir (*Pseudoitsuga menziesil*) and Sitka spruce (*Picea sitchensis*), origin from the United States, were purchased in 2005 and kept in the timber storage area until 2013. Japanese cedar/Sugi (*Crytomeria japonica*) and Japanese cypress/Hinoki (*Chamaecyparis obtusa*), of Japanese origin, were purchased from a local timber distributor. Detailed measurements of the wood samples are shown in Table 2.

Table 2: Detailed measurements by wood species

Wood species	Direction	Size (mm)	Density* (kg/m3)	Annual ring width* (mm)	MC* (%)	Remark (Heartwood %)
Douglas fir	Radial	85 x 135 x 200	634.2	2.97	15.3	100 %
	Tangential		545.4	4.37	18.5	100 %
Sitka spruce	Radial		433.7	2.16	16.3	> 65%
	Tangential		432.5	2.13	18.1	> 35%
Japanese cedar “Sugi”	Radial	85 x 115 x 200	352.1	3.90	19.8	> 70% with knots
	Tangential		464.0	4.17	18.7	> 90% with knots
Japanese cypress “Hinoki”	Radial		533.3	1.30	18.9	> 75% with knots
	Tangential		506.6	1.91	17.2	> 75% with knots

*average value

The sandwiched samples were constructed from untreated 8.5 by 13.5-cm (nominal 4 by 6-in) Douglas-fir and Sitka spruce. For the Japanese wood species, commonly used structural timber sizes (8.5 by 11.5-cm) were used. The length of each timber was 20-cm long. Ten replicates of each wood species and grain direction were prepared. Two 30-cm^3 galleries (2 by 2 by 7.5 cm) were chiseled out of the center of the upper surface of the larger (bottom) timber. In each bottom timber, two 3.5-mm-diameter holes were drilled in each cut edge for thermocouple insertion inside of the galleries (Figure. 1). Wood samples were conditioned at 20 ± 3°C and 65 ± 5% relative humidity for 7 weeks in a conditioning room to stabilize moisture content of the timber. Prior to exposure to solid carbon dioxide ($CO_{2\,(s)}$), silicon weather stripping (0.50-cm thick) was used to form an airtight seal between the sandwiched timber samples (Figure. 1).

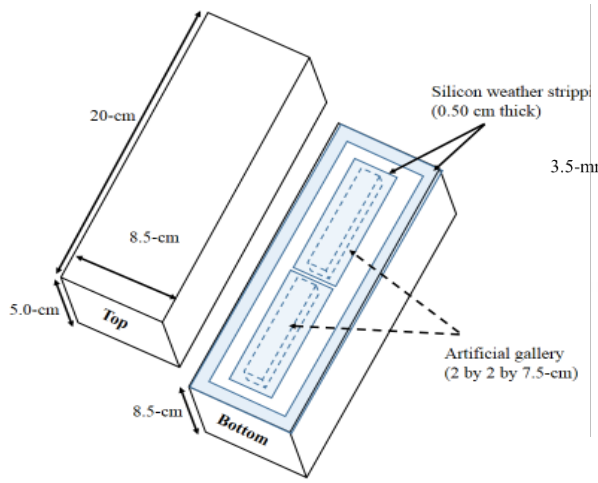

Fig. 1 The sandwiched sample

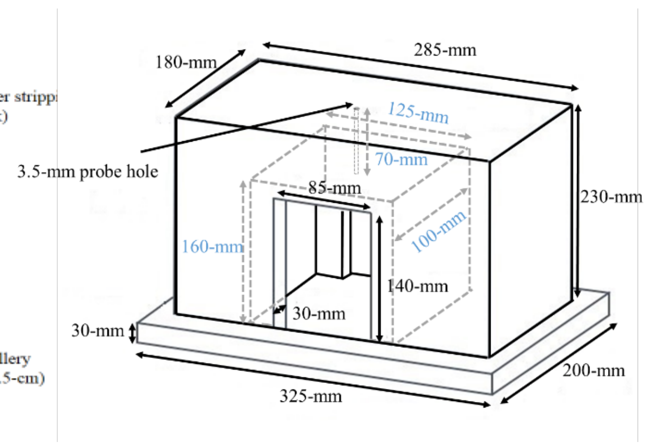

Fig. 2 The polystyrene foam test chamber

Thermal conductivity and CT_{min} measurement

In order to enhance the thermal conductivity of $CO_{2\,(s)}$, Polystyrene foam (JIS A-9511) was used for this study as an insulation chamber (Figure. 2). The void area inside of the chamber after placing the sandwiched sample had a total volume of 810 cm^3, which is indicated with the grey outlined dash in Figure 2. 1,300g ± 3% of $CO_{2(s)}$, purity of 99.5%, were used for the study. Each well-sandwiched sample was placed into the insulation chamber. Afterward, assigned amounts of $CO_{2\,(s)}$ were placed on the surface of the sandwiched sample and tightly sealed. To reduce the loss of temperature from the longitudinal direction, a vinyl bag was used to wrap the insulation chamber. The temperature inside of the chamber and the artificial galleries were monitored with three thermocouples (10-cm long) connected to a computer via a thermocouple interface and SoftThermo E830 software for 20 hours at 15 min intervals. All CT_{min} measurements were conducted in a room with controlled temperature (26 ^{O}C) and relative humidity (65%).

Statistical analysis

Statistical analysis was carried out using the SAS software program, JMP 9.0.2, at a 95% confidence level. Grouping was made between wood species using the Tukey honestly significant difference (HSD) test.

Results and discussions

Thermal conductivity patterns of $CO_{2\,(s)}$

Prior to the study, an experiment on the thermal conductivity patterns of $CO_{2\,(s)}$ was conducted on Sitka spruce. Figure.3 shows the thermal conductivity patterns of 1,300g $CO_{2\,(s)}$ on Sitka spruce. The quickest conductivity and lowest temperature reading was recorded from the surface due to direct contact with $CO_{2\,(s)}$, followed by the 2.5-cm distance from the bottom of the exposure surface, 2.5-cm distance from top of the exposure surface, and then in the artificial gallery, which was located 4.25-cm from both exposure surfaces. The graph in figure 3 explains the physical properties of $CO_{2\,(g)}$. Because the density of $CO_{2\,(g)}$ is heavier than air, the cold air moves down to the lowest void inside the insulation chamber, which creates temperature gradient into the upper void area. Therefore, a higher thermal conductivity and thermal diffusivity was created at the 2.5-cm distance from the bottom of the timber. On average, after 270 minutes, the temperature in the artificial gallery had reached the lowest (thermal diffusivity) and remained at the lowest temperature for 60 ± 15 minutes (heat capacity) after placement of $CO_{2\,(s)}$ on the surface of the wood sample.

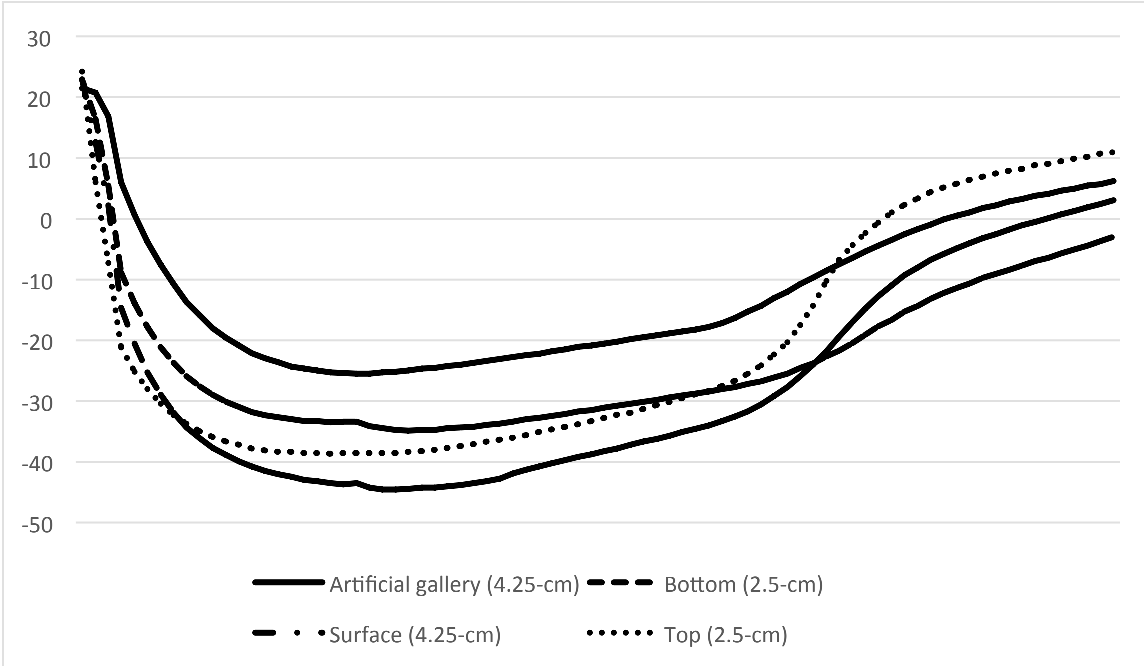

Fig. 3 $CO_{2\ (s)}$ thermal conductivity pattern on Sitka spruce

Thermal property values of $CO_{2\ (s)}$ in the radial and tangential direction

The thermal property values of $CO_{2\ (s)}$ in the radial and tangential directions were evaluated based on three variables; minimum temperature, entry time of CT_{min} (target temperature as -21.3 ^{O}C), and duration of CT_{min} inside the artificial gallery (Table 3). Based on the ANOVA analysis (P=0.05, Tukey-Kramer HSD test) of thermal conductivity values in the radial and tangential direction, the thermal conductivity of $CO_{2\ (s)}$ showed a similar thermal conductivity in the radial and tangential directions in both the US and Japanese wood species. A similar conclusion was found in several studies (Simpson and TenWolde 1999, Suleiman et al. 1999, Hunt et al. 2008, Dupleix et al. 2012) which showed there is no significant difference in conductivity between the radial and tangential directions. For the other two variables, entry time to CT_{min} (Thermal diffusivity) and duration of CT_{min} (Heat capacity), the radial direction shows quicker entry to CT_{min} and a longer duration of CT_{min} than the tangential-apart from Japanese cypress. The result of quicker entry to CT_{min} in all species other than Japanese cypress was due to the proportional relation between thermal conductivity and thermal diffusivity.

Table 3. Thermal property values of three variables by wood species

	Min. temperature (^{O}C)	**Entry to CTmin** (min)	**Duration in CTmin** (min)
Japanese cedar-T	-24.06 ± 1.64	206.67 ± 27.58	351.25 ± 27.58
Japanese cedar-R	-24.97 ± 2.08	196.25 ± 31.63	420.00 ± 27.58
Japanese cypress-T	-23.53 ± 0.82	200.42 ± 18.40*	232.92 ± 80.07
Japanese cypress-R	-24.45 ± 1.40	223.75 ± 20.79*	307.92 ± 112.08
Douglas fir-T	-23.38 ± 1.47	278.00 ± 47.03	295.50 ± 90.57
Douglas fir-R	-22.14 ± 1.44	270.00 ± 48.99	312.00 ± 65.12
Sitka spruce-T	-23.67 ± 0.93	214.50 ± 10.12	337.50 ± 88.67
Sitka spruce-R	-23.51 ± 1.31	222.00 ± 9.49	338.50 ± 99.81

*Significant difference

Thermal conductivity values (^{O}C) in selected wood species

The results of thermal conductivity values on Japanese cedar, Japanese cypress, Douglas fir, and Sitka spruce are presented in Figure 4.

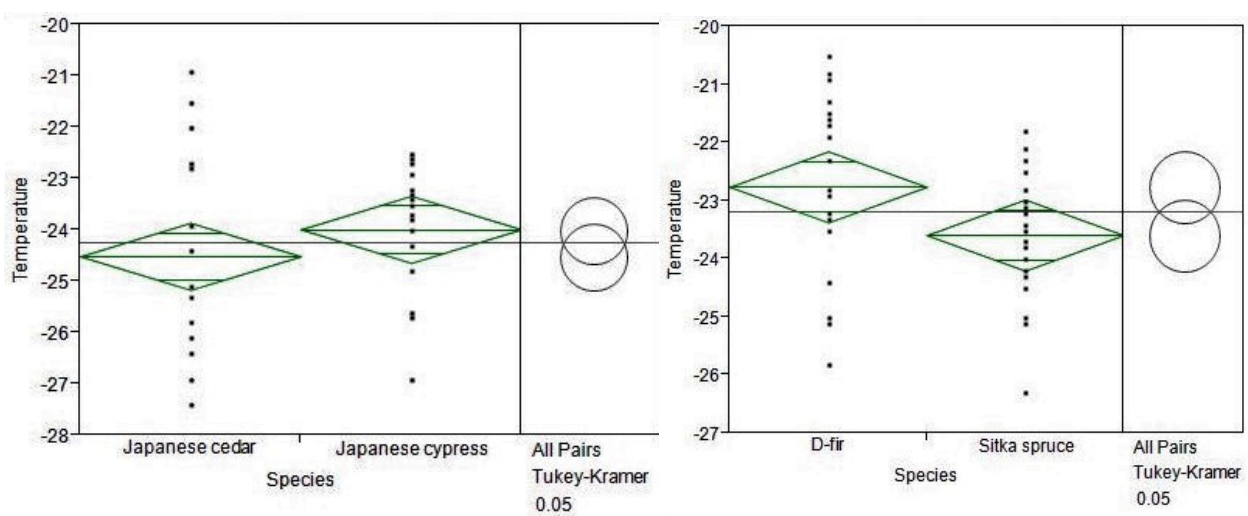

Fig. 4 Thermal conductivity value (^{O}C) of selected wood species

The lowest CT_{min} was recorded in Japanese cedar (-24.51 ^{O}C ± 1.89), Japanese cypress (-23.99 ^{O}C ± 1.22), Sitka spruce (-23.59 ^{O}C ± 1.11), and lastly Douglas fir (-22.76 ^{O}C ± 1.55). The higher CT_{min} in Japanese species was mainly caused by the smaller dimension of timber, which was roughly 15% smaller than the US wood species. However, roughly 4.6% higher thermal conductivity was recorded. Based on the ANOVA, there was no significant difference found within the same region for these wood species. The results show that there is little influence of wood species, density, and proportion of heartwood. Similar conclusions were found in several studies (Wager et al. 1994, Jia et al. 2010, and Sonderegger et al. 2011), which indicate there is no significant different between one species to other. The above studies were conducted with Oak, Maple, Norway spruce, and European beech.

Other factors influencing thermal conductivity have been studied by Vay et al (2013). Their studies reported that the lignin rich middle lamellae reduced thermal conductivity compared to the cell wall, which supports the behavior of an isotropic material. Theoretically, the thermal conductivity should be higher in high density timber, because it contains a greater amount of solid wall material, but less lignin. The result from the thermal conductivity values we obtained with the four selected wood species shows that the highest thermal conductivity was recorded from the lowest density timber (Japanese cedar: Ave. 408 kg/m^3). It seems like the thermal conductivity value overrides the thermal conductivity property against lignin content.

The anisotropic characteristics of wood make it a challenging material for measuring thermal conductivity. The influence of heterogeneities cannot be completely eliminated if the probe location is changed. Further studies concerning thermal transfer in defects and higher moisture content are needed to increase our knowledge of the thermal behaviour of selected timber.

Conclusion

The results bring us to the conclusion that wood species, grain direction, density, and proportion of heartwood are not the main influences on thermal conductivity of $CO_{2\ (s)}$. Instead of these, moisture content has a bigger influence on thermal conductivity of $CO_{2\ (s)}$. The amount of 1,300g of CO2 (s) delivered the temperature required to control drywood termites in all wood species commonly used in Japan for residential structures.

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