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Durability and Fire Performance of Charred Wood Siding (Shou Sugi Ban)

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Abstract: Shou sugi ban, also known as yakisugi, or just sugi ban, is an aesthetic wood surface treatment that involves charring the surface of dimensional lumber, such as exterior cladding. The goal of this research is to examine the effect of shou sugi ban on the flammability and decay resistance of wood. Several species and variants of commercially available sugi ban were tested. The flammability was examined from the heat release rate curves using the oxygen consumption method and cone calorimeter. Durability was examined with a soil block assay for one white-rot fungus and one brown-rot fungus. The testing showed that the shou sugi ban process did not systematically improve the flammability or durability of the siding.

Keywords: shou sugi ban; charred wood; flammability; decay resistance; soil bottle testing; yakisugi

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1. Introduction

Charring wood is an ancient technique for preserving wood and protecting it from fire [1,2]. Called "shou sugi ban", "sugi ban", or "yakisugi", this technique is often applied to siding materials (traditionally *Cryptomeria japonica*, also known as Japanese cedar or sugi cedar). Sugi ban is thought to have originated in the 1600s in the Edo region of Japan (now known as Tokyo) and was originally developed to fire-harden wooden homes in the densely populated cities in growing urban areas that frequently encountered catastrophic structural fires [3]. This primitive approach to fire protection is also thought to improve biological resistance of materials to mold and decay fungi. Charring the bottoms of fence-posts has been used in the United States to prolong their surface life and has been studied since at least 1927 as a method of wood protection [4].

The yakisugi process is thought to increase durability by: (1) removing surface carbohydrates; (2) producing a hydrophobic surface char layer; (3) infusing the remaining wood with smoke from the charring process as volatiles released in the smoke that may have fungistatic properties. From the standpoint of fire performance, char provides a passive insulating layer that retards further degradation of the wood below the char [5]. The development of char and temperature profiles in charred wood have been well-studied for structural fire protection engineering applications [6–14].

Recently, charred wood has exhibited a resurgence in popularity on internet forums and social media. It is now commercially available within the United States and is being marketed for siding and other outdoor uses. This rise in popularity can be partially attributed to aesthetics. Charred wood siding has a unique and desirable appearance [15]. The aesthetics can be further enhanced by partially removing the char or adding coatings, and these enhanced products are also commercially available. Charred wood products from both naturally durable and non-durable wood species are available. Additionally, it is also possible to purchase chemically modified wood (namely acetylated and furfurylated wood) that has been subsequently charred.

It is important to highlight the differences of charred wood (sugi ban) and thermally modified wood. Thermally modified wood refers to wood whose properties are changed by exposing wood to elevated temperatures (160–220 °C), typically in an inert environment (such as water vapor or nitrogen) [16]. Although a complete review of this technology is outside the scope of the paper, several excellent reviews have been published [17]. Thermal modification increases dimensional stability while reducing hygroscopicity [18]. In addition, thermal modifications have been shown to result in a limited increase in the durability of wood; however, biodeterioration data on modified wood are often inconclusive [19].

In contrast, the yakisugi process exposes wood to flaming combustion, forming a layer of char on the surface of the wood. Charring is a thermochemical process of incomplete combustion of solid matter. Char formation in wood occurs when wood is subjected to a high heat flux that removes water vapor and organic constituents, leaving behind mostly carbon [9]. Since char is largely devoid of carbohydrates, in theory, it should be resistant to wood-decay fungi and less flammable. Therefore, the yakisugi process would provide a protective shell of char around the underlying wood. Additional wood protection may be imparted through pyrolysis reactions beneath the char. However, unlike traditional thermal modifications, the yakisugi process is unlikely to modify the entire piece of lumber, but rather only 2–3 mm of the surface [20].

Compared to thermally modified wood, very few data exist on the durability of charred wood. Much of the published literature has focused on the effect of sugi ban on water absorption. Kymäläinen et al. [21] found that charred wood absorbed less moisture at a given relative humidity in the absence of liquid water. For liquid water absorption, Kymäläinen et al. [22] found that charring made the wood more hydrophobic by changing its liquid water contact angle but found mixed results in liquid water uptake. However, Čermák et al. [20] consistently found that charring lowered the rate of liquid water absorption. In the hygroscopic moisture regime, outdoor weathering of shou sugi ban siding was also examined in a field test [23]. These studies were focused on characterizing the interactions of water and charred wood; only one study discussed whether charred wood was more resistant to decay fungi. Machová et al. modified one surface of beech (*Fagus sylvatica*) with a hot plate and ran standard decay tests. In some cases, the average weight loss caused by decay was slightly lower, although no statistical analyses were applied to the data [24].

Similarly, few data exist on whether sugi ban-treated wood is effective at fire-hardening wood. Akizuki et al. found that charring was effective in slowing the spread of fire along the surface of cedar shakes used in traditional soil walls [25]. Machová et al. examined the mass loss of samples exposed to a Bunsen burner for five minutes [24]. In some cases, the charred wood had a lower mass loss, but in others the mass loss of charred specimens was almost double that of untreated wood.

If shou sugi ban-treated wood does indeed provide protection against fire and decay, it could represent an environmentally friendly comprehensive solution to wood protection. Most wood preservatives used in the United States are registered pesticides [26]. Likewise, fire-hardening wood typically involves the use of fire-retardants, intumescent coatings, or the addition of gypsum wallboard, depending on the code requirements of the application [27].

The goal of this work is to examine the effectiveness of the yakisugi process at protecting wood from fire and wood-decay fungi. We examined commercially available charred wood products of several species and test them with standard laboratory test methods for flammability and resistance to wood-decay fungi.

2. Materials and Methods

2.1. Materials

All samples were purchased from a commercial manufacturer of shou sugi ban siding and flooring. In total, 28 different combinations of species, char, and finishes were tested (Figure 1). Six different species groups, as specified by the manufacturer, were tested: cypress, hemlock, white oak, black walnut, acetylated wood, and furfurylated wood. Four different levels of char were examined: no char, light, medium, and heavy. The char levels were based on visual cues and were not specified by the manufacturer. Both a sealant coating, supplied by the manufacturer, and uncoated materials were also tested. The species, char levels, and sealants represent nearly every combination available from the manufacturer and cover nearly all commercially available yakisugi-treated species in the United States. Table 1 summarizes the different combinations of wood species, char, and surface treatments that were examined in the study.

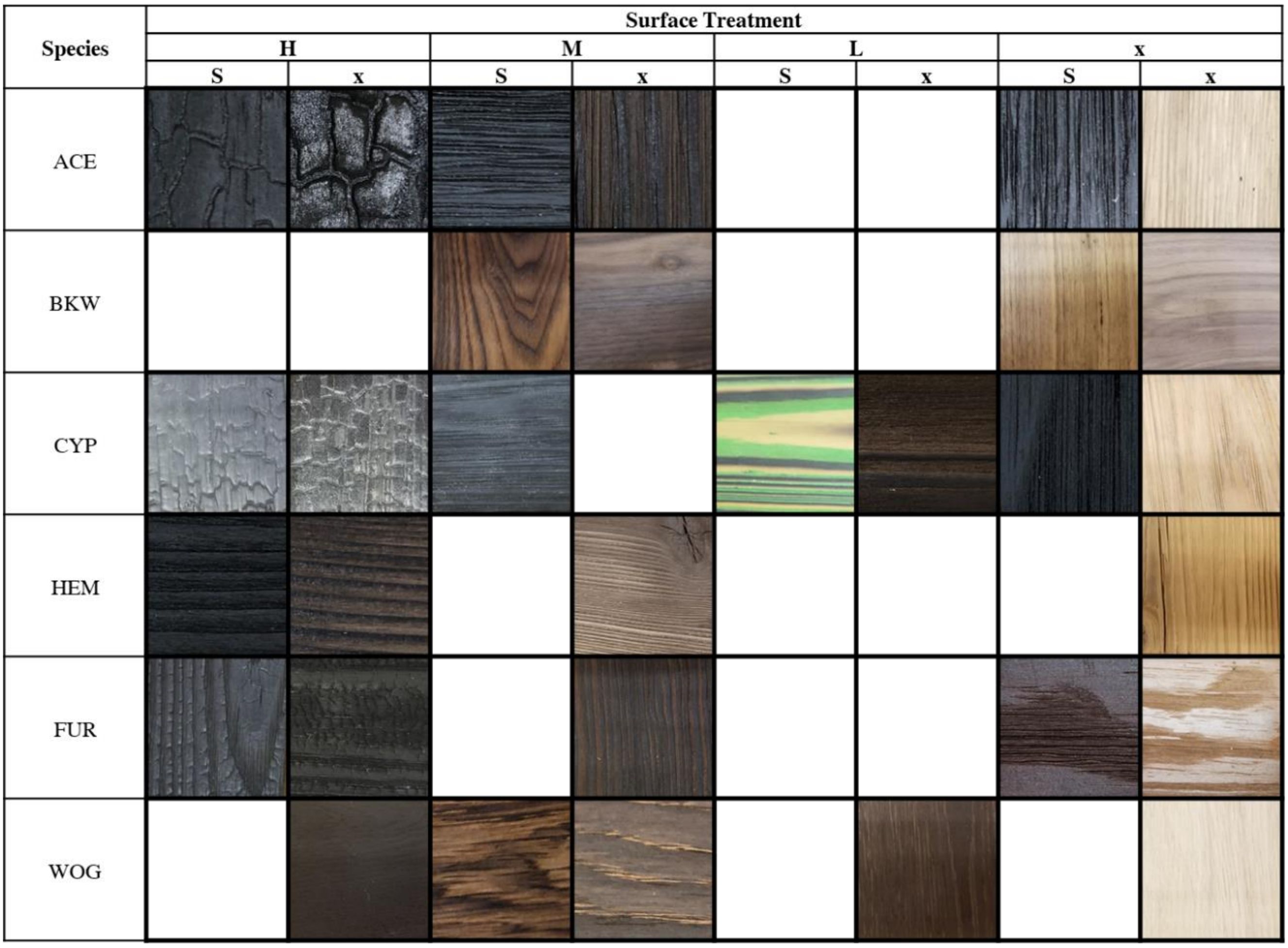

Figure 1. Surface images of the 31 specimens tested. Species group abbreviations are given in Table 1.

Table 1. Summary of the species groups, char levels, and coatings tested.

Title 1	Char Levels (1)	Coatings (2)
Acetylated (ACE)	x, M, H	x, S
Black Walnut (BKW)	x, M	x, S
Cypress (CYP)	x, L, M, H	x, S
Hemlock (HEM)	x, H	x, S
Furfurylated (FUR)	x, M, H	x, S
White Oak (WOG)	x, M	x, S

(1) x—no char, L—low char, M—medium char, H—high char; (2) x—no coating, S—sealer (example: BKW-x-S refers to a black walnut sample with no char and a sealer).

2.2. Durability Tests

The AWPA E-10 soil block assay is the industry standard for laboratory testing the efficacy of wood preservatives against wood-decay fungi [28]. It presents a test block to an actively growing fungal strain with documented abilities to degrade wood and often even preservative-treated wood. The exposure is conducted in a glass bottle with presterilized soil and inoculated with a single culture of wood-decay fungi. Two different fungi were used: *Gloeophyllum trabeum* MAD-617-R (Pers.) Murrill, a brown-rot fungus, and *Trametes versicolor* MAD-697 (L.) Lloyd, a white-rot fungus. The ability of these fungi to degrade untreated wood are well-documented [29].

The tests were carried out by placing a wood "feeder-strip", southern pine for *G. trabeum* and maple for *T. versicolor*, on top of the soil. The fungus colonized the feeder strip for 3 weeks. After the fungus was established on the feeder strips, pre-weighed charred wood cubes (19mm on each side, conditioned at 30 °C and 30% RH) were sterilized in an autoclave and placed on top of the feeder strip for 12 weeks. The soil bottles were maintained in an incubator at 30 °C and 70% relative humidity for the duration of the test. Each test combination was replicated 3 times for each fungus (n = 3). The wood blocks were removed from the test after the growth period and brushed free of mycelium. Growth was stopped by placing them in a 60 °C oven overnight, then conditioned, as before, to a constant weight. The mass loss (caused by decay) of the charred wood samples was calculated from:

$$ML = 100 \times \left(\frac{m_{final} - m_{initial}}{m_{initial}} \right). \tag{1}$$

2.3. Flammability Tests

The flammability of the charred wood siding was tested using a cone calorimeter (FTT iCone Mini, East Grinstead, West Sussex, UK) according to ASTM E1354 [30]. Samples were cut from the charred wood to the standard size of 100 by 100 mm. The thickness of the wood depended on the wood species and char treatment; specimens arrived from the factory with thicknesses between 18 and 22 mm. Prior to testing, the samples were stored in a room at 50% relative humidity and 21 °C for over 30 days.

All samples were subjected to irradiance at 35 kW/m^2 in a horizontal orientation with the charred and/or sealed surface exposed to the conical radiant heater. The optional retainer frame was used to hold the specimens during the test and, as specified in ASTM E1354, the sides and bottom of the specimens were wrapped in aluminum foil and the specimen rested on a ceramic fiber blanket. The tests were terminated two minutes after flaming stopped. Each material was tested in triplicate for a total of 84 cone calorimeter specimens and the data were evaluated using the decreased surface area, due to the retainer frame of the sample (88.36 cm^2).

The heat release of the sample was calculated using the oxygen consumption method [31] by measuring the amounts of O_2, CO, and CO_2 in the effluent, and the mass loss of the specimen was also measured. Key flammability parameters such as the time to ignition, heat release rate, and peak heat release rate were tabulated for all treatments.

3. Results and Discussion

3.1. Durability Tests

The mass loss caused by decay fungi is summarized in Figure 2. In this figure, the mass loss of the control, uncharred specimen is plotted on the x-axis, and the mass loss of the charred specimens of the same species are plotted on the y-axis. Separate subplots show the behavior of both the sealed and uncoated specimens for the two fungi tested. Additionally, a solid line is plotted with a slope of 1:1; this solid line represents the null hypothesis that charring does not affect durability of wood.

It is clear from Figure 2 that the yakisugi process does not systematically protect wood from decay. Looking at the sample means, there were more cases where the data fell above the 1:1 sample line than fell below the line. In other words, charring was just as likely to increase the amount of decay as it was to protect it from decay. However, some trends can be observed upon closer examination of the data.

The yakisugi process did not cause large changes to the mass loss for any species group outside of cypress. Most samples in these species groups were not significantly different (at the p = 0.05 level) with the exception of the WOG-H-x (both fungi), HEM-M-x

(*G. trabeum*), and FUR-H-s (*G. trabeum*). These three samples exhibited significantly *higher* amounts of decay than their uncharred counterparts.

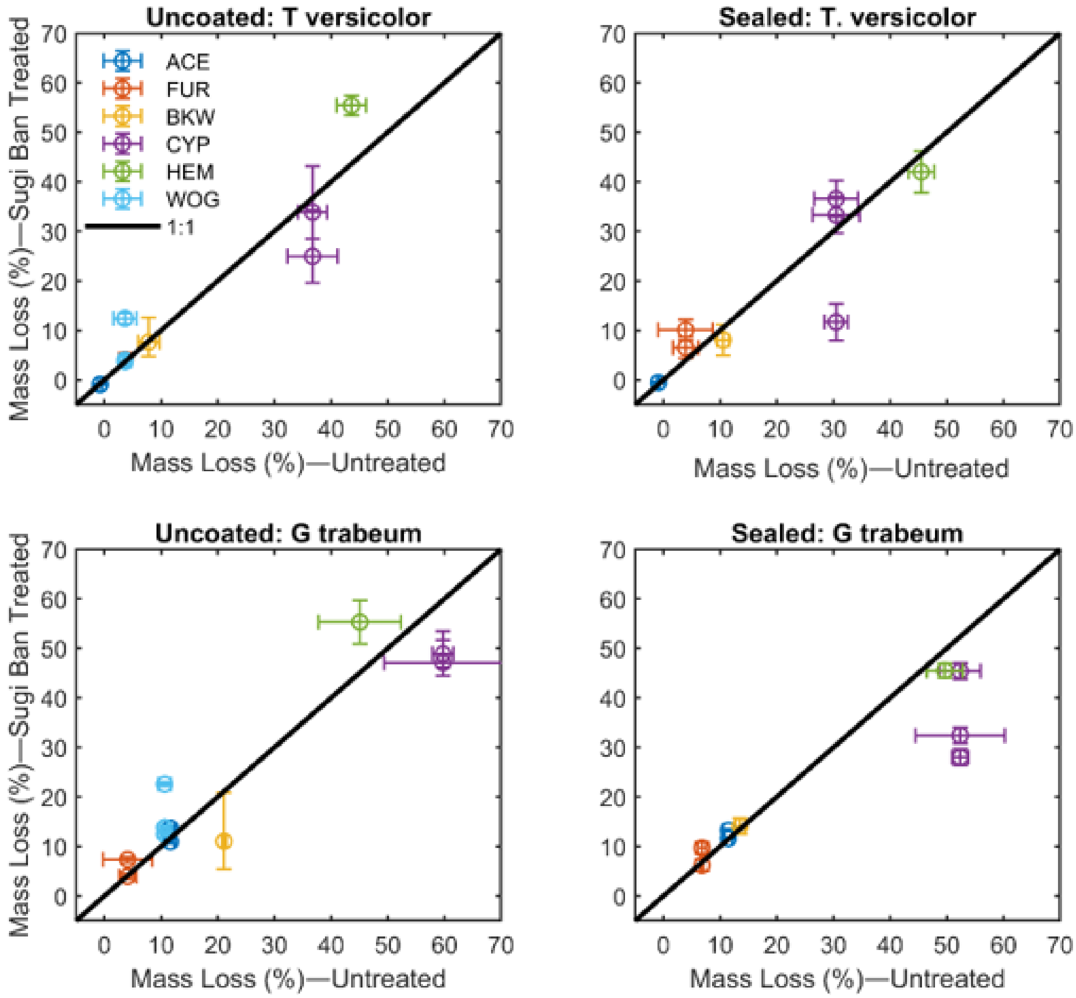

Figure 2. Mass loss caused by decay fungi measured in the soil bottle tests. The error bars represent the standard deviation.

The only species group that exhibited some improvement with charring was the cypress. For the uncoated specimens, the cypress exhibited significantly lower amounts of decay for both *G. trabeum* and *T. versicolor* at the low level of char (CYP-L-x); however, differences between CYP-H-x and the control were not significant. For the sealed specimens, all differences were significant at the $p = 0.05$ level with the exception of CYP-M-s for *T. versicolor* and CYP-H-s for *G. trabeum*. Of the six combinations of char level and fungal strain for the cypress samples, three exhibited significantly less decay, two exhibited no significant changes, and one exhibited significantly higher decay.

Differences in natural durability between wood species are greatly influenced by the extractives [32]. It is unknown how the charring process modifies wood extractives and whether this creates synergistic effects in certain wood species. Understanding durability differences across species for charred wood requires further study. Unfortunately, we were unable to examine *Cryptomeria japonica.* It could be that this species is especially receptive to improvements through charring.

It should be noted that although the yakisugi process appeared to decrease the amount of decay in many of the cypress samples, the samples still exhibited a high amount of mass loss in the 12-week decay test; the average across all charred specimens and fungi was 34% mass loss. It is important to compare potential improvements caused by charring to other methods of wood protection. Chemical wood preservatives have been repeatedly demonstrated to impart long service life in wood used outdoors [33–35]. Likewise, wood modified by acetylation, furfurylation, and thermal modification all improve decay resistance more than charring [36–41]. The small changes in mass loss observed in this study cannot match the performance of these established methods of wood protection.

It can be concluded that the yakisugi process does not provide universal wood protection. It appears that whether charring increases the durability of wood is strongly dependent on the wood species. These results suggest that charring may provide limited improvement to decay fungi for cypress and provide little or no improvements in other wood species. However, more data are needed to understand the other conditions which will allow charring to provide protection against decay fungi.

3.2. Flammability Tests

The heat release rate curves measured in the cone calorimeter experiments are presented in Figure 3. Each wood species group is presented as its own subfigure. These curves are useful for understanding the general flammability characteristics of the materials. However, comparisons between the materials can be useful by examining specific features of the curve, such as the time to ignition, peak heat release rate, and total heat released (area under the curve).

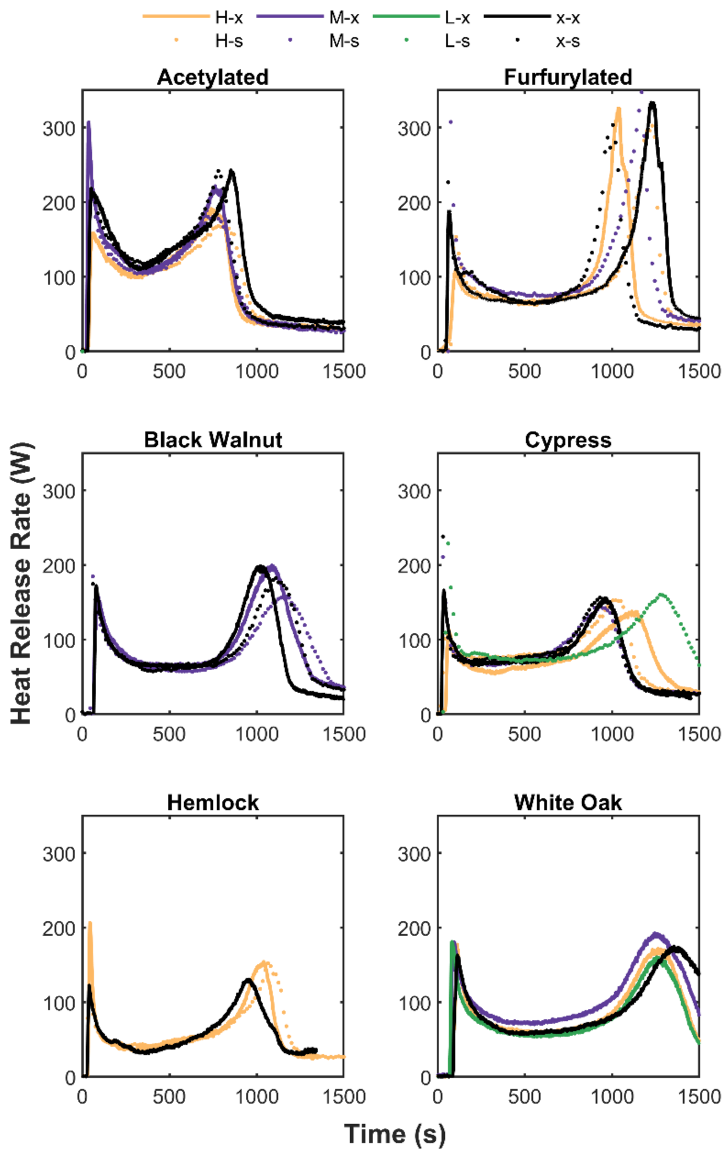

Figure 3. Average heat release rate curves for each material.

The heat release rate curves in Figure 3 exhibit the typical shape expected for wood products. There is an initial increase to a peak, a drop to a steady-state heat release rate after a char layer has formed, then a second peak that corresponds to the increased production of volatiles from the remaining, unburned portion of the specimen [42,43].

Additionally, from Figure 3, it is evident that, although each species group follows the same general shape, differences can be observed with regard to the peak heights, widths, and time at which they occurred. Within a given group, slight differences between the curves can be observed as a result of the yakisugi process and the finishing treatments.

For instance, the furfurylated wood had a higher second peak heat release rate compared to the $pHRR_i$, while the second peaks for the other species groups were either similar or lower than the initial peak.

3.2.1. Time to Ignition

The time to ignition (T_{ig}, s) was visually determined and recorded when a stable diffusion flame was present and not flashing. Average T_{ig} values are presented in Figure 4 for each material; the error bars represent the standard deviation of three replicates.

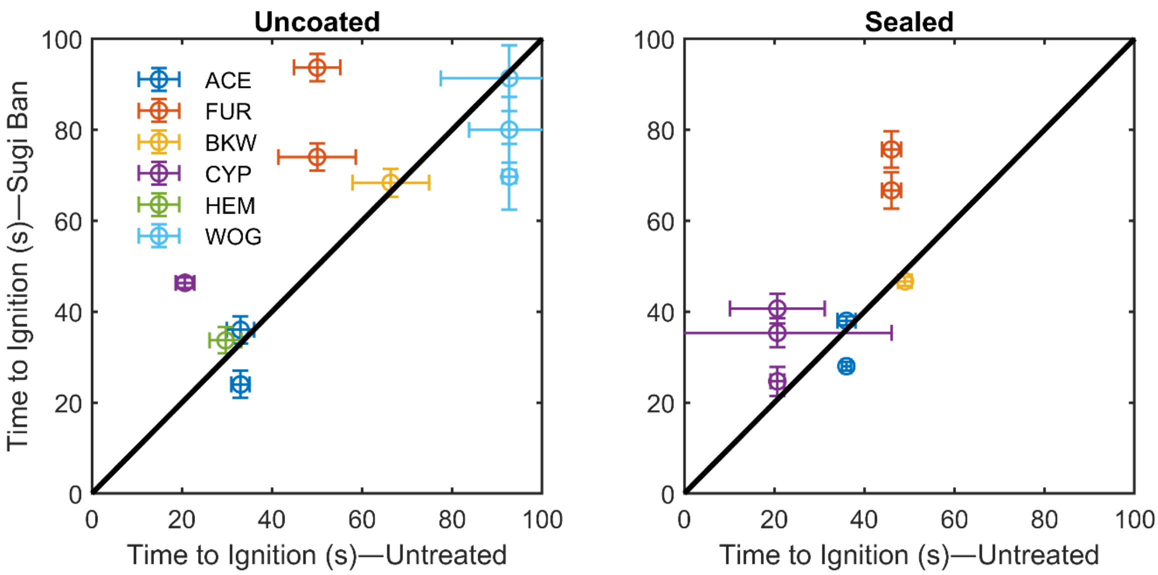

Figure 4. Comparison of the time to ignition (T_{ig}, s) between the untreated and charred wood specimens for both the uncoated and sealed specimens. The error bars represent the standard deviation.

From Figure 4, it can be seen that the wood species affects the time to ignition, with certain wood species, such as white oak, having a much longer time to ignition. However, the effect of the yakisugi process on T_{ig} is less clear. Most of the uncoated sugi ban samples do not exhibit significant changes in T_{ig} from their uncharred, control counterparts. Three samples (CYP-H-x, $p < 0.001$; FUR-M-x, $p < 0.001$, and FUR-H-x, $p = 0.01$) exhibited a significantly higher T_{ig} (better fire performance). On the other hand, two uncoated samples (ACE-M-x, $p = 0.01$; WOG-L-x, $p = 0.006$) also exhibited a lower T_{ig}.

Many of the sealed samples showed an increased time to ignition after the sugi ban process. Both furfurylated samples exhibited a significant ($p < 0.001$) increase in the T_{ig}. While the mean of all of the cypress tests fell above the 1:1 correlation line, only the sample with a low amount of char was significant ($p = 0.03$). In contrast, one sample had a significantly lower T_{ig} (ACE-M-x, $p < 0.001$).

Finally, we can make comparisons for sealed and unsealed samples from the same species group with the same amount of char. These comparisons are given in Figure 5. From the figure, it does not appear that the sealant universally increased or decreased the time to ignition. In most cases, differences between the sealed and uncoated samples were not statistically significant. The most notable exception was that for both black walnut specimens and furfurylated wood with a medium amount of char, the sealant decreased ($p \leq 0.01$) the T_{ig}, although it should be noted that it also increased T_{ig} for the acetylated wood with a medium level of char ($p = 0.034$).

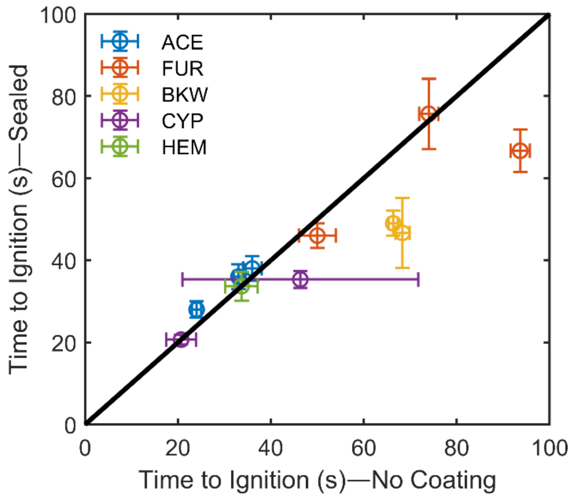

Figure 5. Comparison of the time to ignition (T_{ig}, s) between the coated and uncoated specimens. The error bars represent the standard deviation.

3.2.2. Initial Peak Heat Release Rate

Figure 6 plots the average $pHRR_i$ for the charred wood for each species against its uncharred counterpart; the error bars represent the standard deviation. For this metric, a lower value indicates a less flammable material or an improvement to the untreated case. Similar to the other metrics examined, the yakisugi process does not universally increase or decrease the initial peak heat release rate. Instead, there are approximately an equal number of samples that exhibited an increase in $pHRR_i$ to the number that exhibited a decrease.

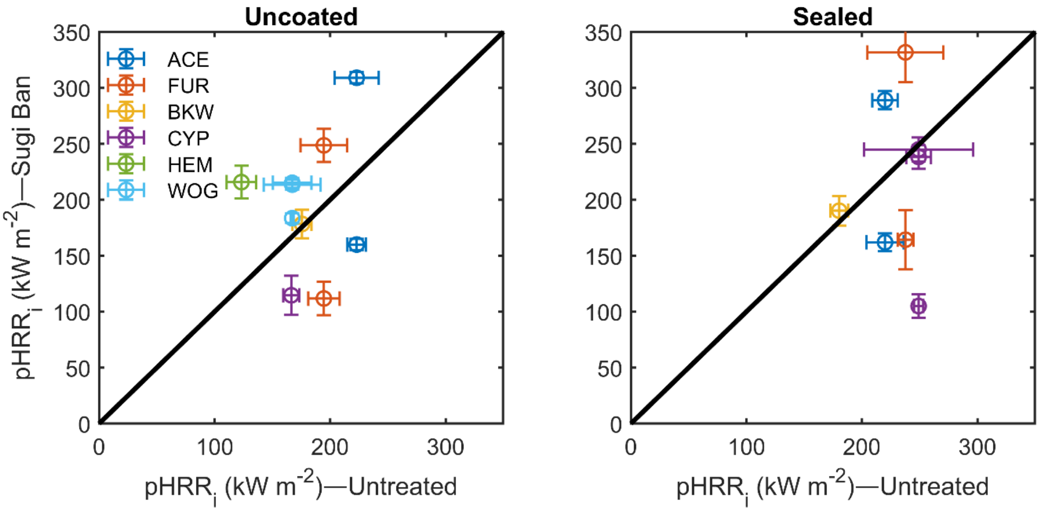

Figure 6. Comparison of the initial peak heat release rate ($pHRR_i$) between the untreated and charred wood specimens for both the uncoated and sealed specimens. The error bars represent the standard deviation.

Specifically, for the uncoated specimens, the white oak and hemlock specimens all exhibited a significant ($p < 0.05$) increase in $pHRR_i$ after the yakisugi process. The cypress samples exhibited a significant ($p < 0.05$) decrease in $pHRR_i$. Interestingly, the acetylated and furfurylated specimens had one sample with a significantly higher $pHRR_i$ (ACE-M-x,

$p = 0.002$, FUR-M-x, $p = 0.03$) and one with a significantly lower one (ACE-H-x, $p < 0.001$, FUR-H-x, $p = 0.002$).

For the sealed specimens, three samples exhibited a lower $pHRR_i$ significant at the $p < 0.05$ level: CYP-H-s, ACE-H-s, and FUR-H-s. However, both the acetylated and furfurylated groups exhibited significantly higher initial peak heat release rates for the samples with a medium level of char.

In comparing the sealed to the unsealed samples (Figure 7), it appears that, in many cases, the sealer does not affect the initial peak heat release rate. In only three cases (CYP-x, $p = 0.002$; FUR-M, $p = 0.02$, and FUR-H, $p = 0.004$) was the pHRRi of the sealed sample significantly different from the control. In both of these cases, the pHRRi increased for the case with the sealant.

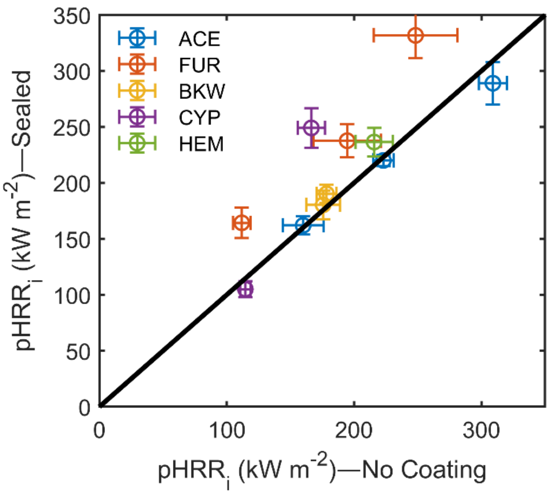

Figure 7. Comparison of the initial peak heat release rate ($pHRR_i$) between the uncoated and sealed specimens. The error bars represent the standard deviation.

3.2.3. Total Heat Release

The total heat release (THR) is the cumulative heat released (the area under the heat release curve) over the duration of the test. Similar to $pHRR_i$, a lower heat release indicates a less flammable material. Figure 8 plots the THR for the charred specimens against the uncharred controls.

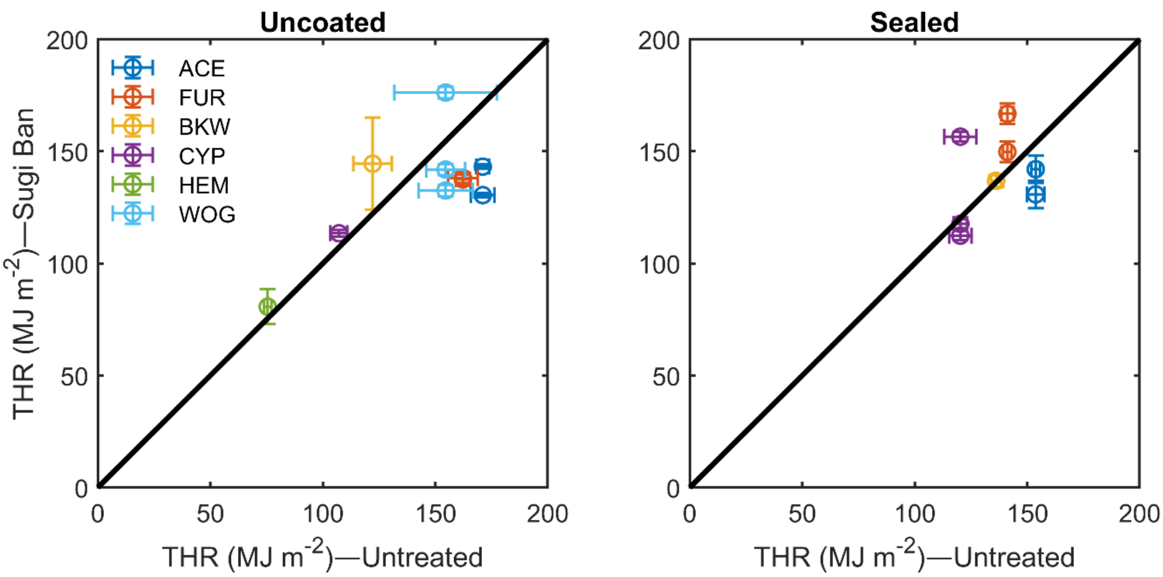

Figure 8. Comparison of the total heat released (THR) between the untreated and charred wood specimens for both the uncoated and sealed specimens. The error bars represent the standard deviation.

For the uncoated specimens, all acetylated and furfurylated samples exhibited a significant ($p < 0.05$) decrease in the THR. Additionally, the white oak specimen with a low level of char exhibited a significant ($p = 0.03$) decrease in THR. No uncoated samples exhibited a significantly ($p < 0.05$) higher level of THR after charring.

In contrast, several sealed, charred samples exhibited a higher THR than the sealed control samples. Both furfurylated samples and the cypress sample with the low amount of char exhibited a significantly higher ($p < 0.05$) THR than the controls. However, both acetylated samples exhibited a significantly lower ($p < 0.05$) THR.

Figure 9 directly compares the THR of the sealed and unsealed samples. From Figure 9, it appears that the sealant does not universally increase or decrease the THR. The sealant caused a significant increase ($p < 0.05$) in the THR for the uncharred cypress, along with the hemlock specimens with a high level of char and furfurylated specimens with medium and high levels of char. At the same time, uncharred furfurylated and acetylated specimens exhibited a significantly lower THR than their unsealed controls ($p < 0.05$).

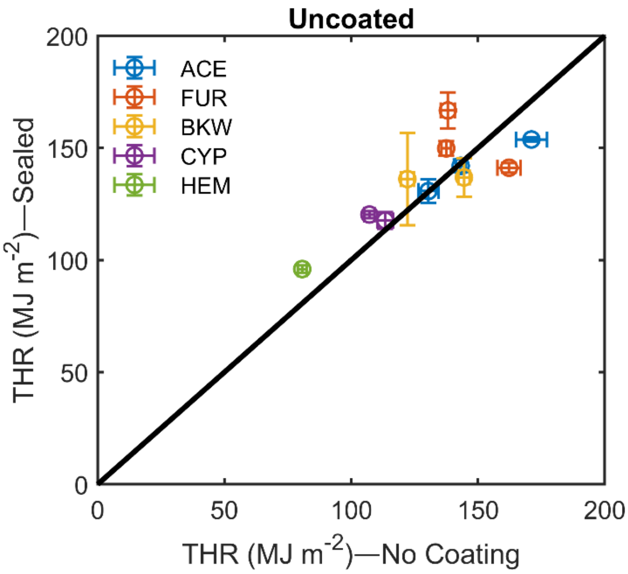

Figure 9. Comparison of the total heat released (THR) between the sealed and uncoated specimens.

3.2.4. Summary of Flammability Tests

The cone calorimeter results showed that, in some cases, charring resulted in a significant difference in flammability parameters. However, these changes were roughly equally distributed between increases and decreases to flammability.

While sugi ban does not appear to impart wood protection universally across wood species, the results for cypress are interesting. Cypress specimens exhibited slight improvements in both the time to ignition and the initial peak heat release rate. It appears that charring may impart a slight improvement in the flammability and decay resistance of cypress. However, in terms of fire-hardening, commercially available fire retardants can improve the flame spread of wood to achieve a Class A flame spread rating [27,44]. Although the yakisugi process undoubtedly produces an aesthetically appealing surface, its effectiveness in terms of fire-hardening cannot compare with more traditionally used technologies.

4. Conclusions

Sugi ban-treated wood of several different wood species and char levels were tested to see if the yakisugi process fire-hardened the wood or provided increased durability. The data on the flammability and decay resistance of shou sugi ban-treated wood were inconclusive.

In many cases, the results were not significantly different from that of untreated wood. For each metric studied, at least one combination of wood species and char exhibited an improvement that was statistically significant. However, with the exception of THR, the converse was also true and there was at least one type of charred wood with a decrease in performance. The sealer applied to the surface of the sugi ban-treated wood does not appear to have a consistent effect on the performance of the wood.

Slight improvements were observed in decay resistance, time to ignition, and the initial peak heat release for cypress. While these improvements in cypress were statistically significant, they were small in magnitude. It must be concluded that sugi ban-treated wood should be thought of as primarily increasing the aesthetics of wood rather than improving the durability or flammability.

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Informed Consent Statement: Not applicable. The study did not involve humans.

Data Availability Statement: Data can be obtained by contacting the corresponding author.

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Conflicts of Interest: The authors declare no conflict of interest.

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