

Compressive Strength parallel to grains of Charred Paulownia Wood

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Abstract. Wood is a common flammable in the building fire and the dominant fuel in the wildland fire. In this study, the surface of wood specimens has been pre-heated by various radiative heat fluxes and heating times to achieve varying char layer thicknesses. The compressive strength parallel to grains versus various charring thicknesses has been obtained by an electronic universal testing machine (WDW-20). Experimental results demonstrate that a higher heat flux and longer heating times promote the formation of the char layer, but the compressive strength versus the charring thickness first decreases to its minimum value and subsequently remains stable. For the 7 kW/m² case, there is a rapid decrease in compressive strength for the 5-7 heating period. For example, the compressive strength is 31.7 MPa after the initial 5-minute period, and 3.69 MPa after the initial 7-minute period. For the radiative heat fluxes from 7 kW/m² to 10 kW/m², the reduction rate of compressive strength will increase from 1.32 MPa/min to 3.75 MPa/min for the initial 5-minute period, and increase from 4.95 MPa/min to 5.34 MPa/min for the initial 7-minute heating period. This study helps us understand the influence of charring processes on the mechanical properties of wood and the failure of timber structures.

Keywords: radiative heat flux; char layer; compressive strength parallel to grain; heating time

1. Introduction

Wood is a sustainable and environmentally friendly material, which is extensively utilized in construction across various countries. Notable examples include the Mjøstårnet in Norway, currently the tallest wooden structure in the world, and the HoHo building in Austria (Fig. 1 a-b). However, wood undergoes thermal decomposition into char and combustible gases at high temperatures, which can lead to structural damage [1]. Therefore, when wood materials are employed in construction, special attention must be paid to their combustibility and mechanical performance.



Figure 1. (a) the wooden building of Mijosa Tower in Norway (credit: Mjøstårnet Mjøsa), (b) the wooden building of HoHo Tower in Austria (credit: HoHo Wien, Austria), and (c) the fire of Notre Dame Cathedral in Paris(credit: (Notre Dame Cathedral in Paris))

Wooden architecture and timber structures have a rich historical background. However, in modern times, materials such as steel, concrete, and glass have dominated the construction industry. In comparison to contemporary building materials like steel, concrete, and glass, the production process of natural and engineered wood products exhibits lower energy consumption and generates fewer carbon emissions [2]. Nevertheless, despite advancements in flame retardants and active fire protection methods, fire remains a significant concern due to the combustibility of wood materials –

as exemplified by the Notre-Dame Cathedral fire in Paris (Fig. 1c). Consequently, stringent fire safety measures and robust mechanical performance are essential for wooden structures to ensure both property and occupant safety while also increasing timber construction costs [3–5].

Charring was an ancient method to generate a protective layer, which was resisted biochemical impacts [6]. Recently, several studies have been performed to investigate the material characteristics of charred wood, including adsorption capacity, roughness, and thermal conductivity [7–9]. Most studies have investigated the impact of charring under radiant heating conditions or constant temperatures [10]. Research has shown that the pre-charred wood was used to enhance fire performance, which significantly reduced fire hazard by producing a weaker, thinner, and bluer flame compared to the original wood [11]. The influence of temperature on the load-bearing performance of wooden columns was investigated [12], but the effects of charring and heat flux on mechanical properties were not considered. Therefore, the understanding of the char layer and mechanical performance during fires remains limited, indicating a need for further fundamental research and quantitative analysis.

The study employed a heating plate to generate controlled and uniform char layers on the wood surface under relatively low heat radiation (10 kW/m² and 7 kW/m²). The thickness of the char layer was regulated by adjusting the radiation intensity and duration of irradiation (5–12 minutes). Utilizing low radiation intensity in this experiment effectively simulates the initial stage of a real fire scenario. Char layer thickness and compressive strength parallel to the grain are tested to evaluate the material properties of Paulownia wood.

2. Experimental design

2.1 Wood sample

The Paulownia wood is selected in this study, with a density of approximately 260 ± 16 kg/m³. The specimens were cut into cubes with the size of 30 mm × 20 mm × 20 mm and the length aligned parallel to the grain direction. The Paulownia blocks were dried in a 90 °C oven for 6 h to control the initial moisture content at $5 \pm 1\%$. All dried wood samples were sealed and stored in the temperature and humidity chamber.

2.2 Pretreatment of the test sample

The charring process was performed using a precisely controlled heating plate. The voltage of the heating plate was adjusted to achieve varying radiation intensities, and the radiation intensities were accurately measured and calibrated by a radiometer. The heating plate provides a relatively constant irradiation to the sample area, thus ensuring that the whole exposed surface of the wood sample receives uniform irradiation. The periphery of the wood sample was wrapped by 1-cm-thickness asbestos, which reduced lateral heat losses and ensured a stable one-dimensional charring process perpendicular to the top surface. At an ambient temperature of 28 ± 3 °C and relative humidity of 40 ± 5 %, the charring radiation was subjected to a low level of 7 kW/m² and 10 kW/m² which was measured by the radiometer. Subsequently, radiation was shielded, and the wood sample was positioned beneath the heating plate. The top unwrapped surface was exposed to the heating plate. After the shield was removed, the radiation was directly applied to the exposed wood surface. To achieve char layers with varying thicknesses, the durations of heating lasted 5 min, 7 min, 10 min, and 12 min, respectively. After heating, some shallow was observed on the charred surface, and a uniform char layer was observed on the cross-section of the wood samples. (refer to Fig. 3).

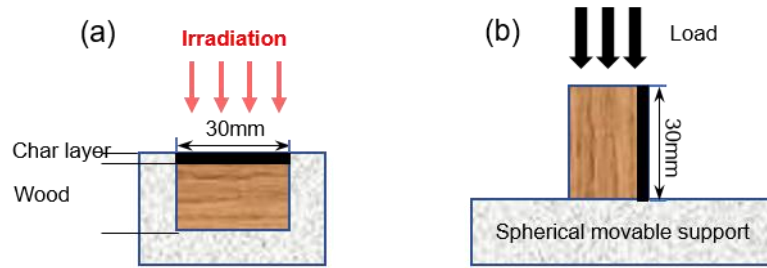
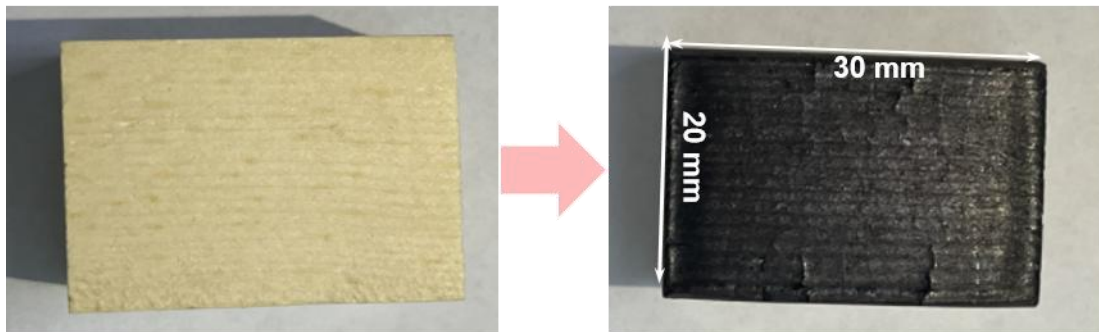


Figure 2. (a) radiative heat flow treatment process (b) Schematic diagram of the experimental device for compressive strength parallel to grain test

2.3 Determination of ultimate stress in compression parallel to grain

Following GB/T 1927.11-2022 Test methods for physical and mechanical properties of small clear specimens - Part 11: Determination of ultimate stress in compression parallel to grain [13], static compression tests were conducted to ascertain the material's mechanical properties on standardized specimens measuring 30 mm \times 20 mm \times 20 mm using a WDW-20 microcomputer-controlled electronic universal testing machine. The specimens were centrally positioned on the spherical movable support of the testing machine, and a uniform load was steadily applied along the length (parallel to the grain) until failure occurred. It can indicate the reduction in load magnitude of the charring sample. To ensure experimental repeatability, three replicate tests were performed for each given condition (refer to Fig. 2b).

(a) Top view before and after charring



(b) Side view before and after charring

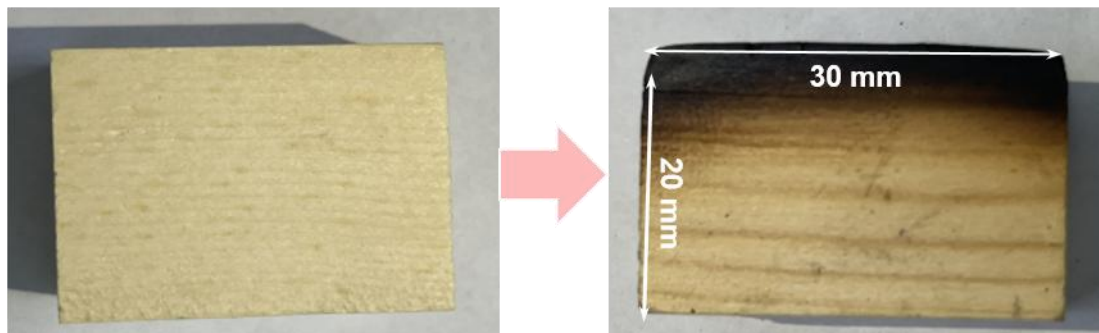


Figure 3. (a) Top view before and after charring; (b) side view before and after charring

3. Experimental results and analysis

3.1 Experimental phenomenon

Figure 4 illustrates the experimental phenomena of wood samples under radiative heat fluxes of 7 kW/m² and 10 kW/m². As shown in Fig. 4, when the radiative heat flux was applied to the top unwrapped surface of the wood, the appearance of white smoke was observed, which could be a mixture of pyrolysis gases and condensed water vapour [4, 14].

Under the radiative heat flux of 10 kW/m², the white smoke was observed after a heating period of 5 seconds. However, the appearance of white smoke was delayed by 93 seconds under the radiative heat flux of 7 kW/m². Moreover, gradual darkening of the wood sample surface was observed due to the char formation. The initial colour change was observed 80 seconds later under a radiative heat flux of 7 kW/m² compared to that under a radiative heat flux of 10 kW/m². Both colour deepening and char layer augmentation were noted. The surface colour of the wood sample eventually changes to pure black. The appearance of pure black was delayed by 123 seconds under the radiative heat flux of 7 kW/m² compared to that of 10 kW/m². Finally, no combustion occurred throughout the entire process under the radiative heat flux of 7 kW/m². The flame point was observed after 570 seconds under the radiative heat flux of 10 kW/m².

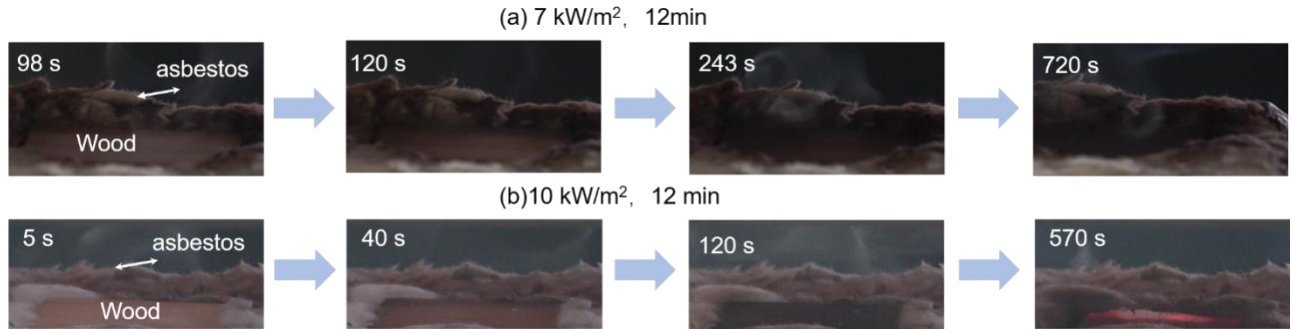
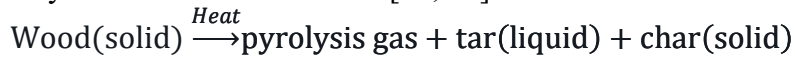


Figure 4. Heating treatment of wood with different constant heat flows

3.2 Thickness of the char layer

Figure 5 presents the char layer thickness of wood samples versus different heating times under radiative heat fluxes of 7 kW/m² and 10 kW/m². The charring of wood is attributed to the pyrolysis heterogeneous reaction of wood [1]. The pyrolysis process does not require the involvement of oxygen and is generally an endothermic reaction [15, 16]:



Under the radiative heat flux of 10 kW/m², the wood sample will be completely charred at 12 minutes, thereby establishing this condition as the final experimental condition. As depicted in Fig. 5, the char layer thickness curve exhibits a nearly linear increase up to 10 minutes under a radiative heat flux of 7 kW/m². However, the slope of the charring curve between 7 and 10 minutes is less steep compared to that between 5 and 7 minutes. This trend is more pronounced under a radiative heat flux of 10 kW/m², the slope of the charring curve between 7 and 10 minutes significantly decreases compared to that between 5 and 7 minutes. It can be attributed that the surface char layer is an effective thermal insulation layer, which delays the temperature increase and pyrolysis of the original wood. Under the radiative heat flux of 7 kW/m² and 10 kW/m², the slope of the charring curve experiences a sudden increase after 10 minutes. The pyrolysis front gradually deepens by continuing to heat the sample beyond 10 minutes, which approaches the top of the insulated bottom part, thereby reducing the wood's internal heat conduction. It leads to an increase in the internal temperature of the wood sample, accelerating the pyrolysis and charring process, the phenomena are more evident under higher radiative heat fluxes [4].

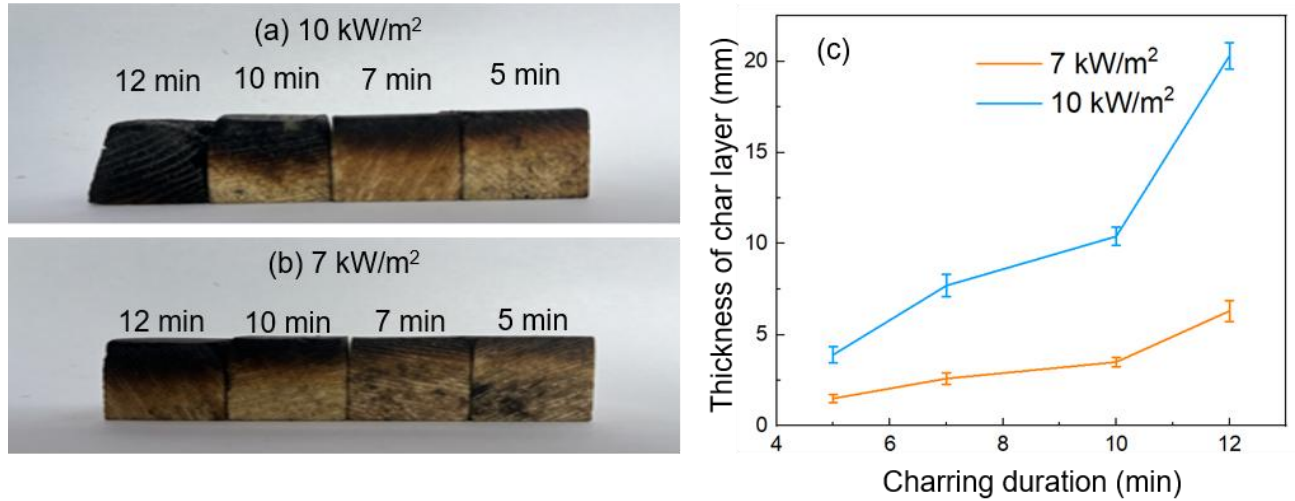


Figure 5. Thickness of the char layer under different radiative heat flow and heating time

3.3 Compressive strength parallel to grain and the rate of change in compressive strength parallel to grain

The calculation of the compressive strength parallel to the grain of the wood should be performed according to Equation (1) [13], with the results reported to an accuracy of 0.001 MPa.

$$\sigma_w = \frac{P_{max}}{bt} \quad \# \quad (1)$$

where σ_w represents the compressive strength parallel to the grain of the samples, which is measured in MPa. P_{max} is the maximum load at failure (N), b is the width of the specimen (mm), and t is the thickness of the specimen (mm).

Figure 6 presents the compressive strength parallel to the grain and the rate of change in compressive strength parallel to the grain of wood samples with different char layer thicknesses. The compressive strength decreases as the heating time for wood samples increases. The significant changes in compressive strength parallel to the grain mainly are observed before 7 minutes, and the rate of change in compressive strength parallel to the grain slows down after 7 minutes. When the radiative heat flux increases, the compressive strength parallel to the grain of the wood samples decreases. The weakening of the mechanical properties is primarily attributed to the char layer and the loss of strength of the original wood. The compressive strength parallel to the grain of wood is also related to the softening of chemical components and thermal degradation [17, 18].

It can be observed that the compressive strength parallel to the grain of the complete char layer is close to zero in Fig. 6a. The thickness of the char layer affects the variation in compressive strength parallel to the grain of the wood. To analyze the relationship between the char layer thickness and compressive strength parallel to the grain, a nonlinear fitting method using a Gaussian function is employed. The fitted regression curves are shown in Figs. 6c and 6d, indicating a direct relationship between the char layer thickness and the compressive strength parallel to the grain. Additionally, the compressive strength parallel to the grain of the wood sample also depends on the weakening of its strength of the uncharred part. Therefore, the char layer thickness is one of the contributing factors to the reduction in compressive strength parallel to the grain, while pyrolysis is the fundamental cause of the decrease in high-temperature compressive strength parallel to the grain of the wood, consistent with the results analyzed from a chemical composition perspective in the literature [19].

Figure 6b illustrates the rate of change in compressive strength parallel to the grain of wood samples under radiative heat fluxes of 7 kW/m² and 10 kW/m². The compressive strength parallel to the grain is influenced by both the radiative heat flux and the heating time. The average compressive strength parallel to the grain of the original sample was determined to be 38.306 MPa. The calculation of the rate of change in compressive strength parallel to the grain is shown below:

$$\text{the change rate of compressive strength} = 1 - \frac{\sigma_w}{38.306} \# \quad (2)$$

It can be observed that the influence of heat flux and time on compressive strength parallel to grain gradually diminishes for each time interval in Fig. 6 and Table 1, such as 0-5 min, and 5-7 min. After 7 minutes, the overall rate of change in compressive strength parallel to grain approaches zero. Comparing the rate of change in compressive strength parallel to grain between the 7-10 min and 10-12 min intervals under the same radiative heat flux, it can be observed that the effect of heating time is similar for the two stages. When the radiative heat flux is increased, its influence on the compressive strength parallel to the grain of the wood samples is mainly concentrated before 5 minutes. The combined effect of heat flux and time is primarily observed before 7 minutes. In the 0-7 min interval, the rate of change in compressive strength parallel to grain under radiative heat fluxes of 7 kW/m² and 10 kW/m² is 0.903 and 0.975, respectively. Increasing the heat flux accelerates the decrease in compressive strength parallel to the grain during the 0-5 min interval. However, the rate of change in compressive strength parallel to grain decreases as the radiative heat flux increases during the 5-7 min, 7-10 min, and 10-12 min intervals due to the inhibitory effect of the char layer.

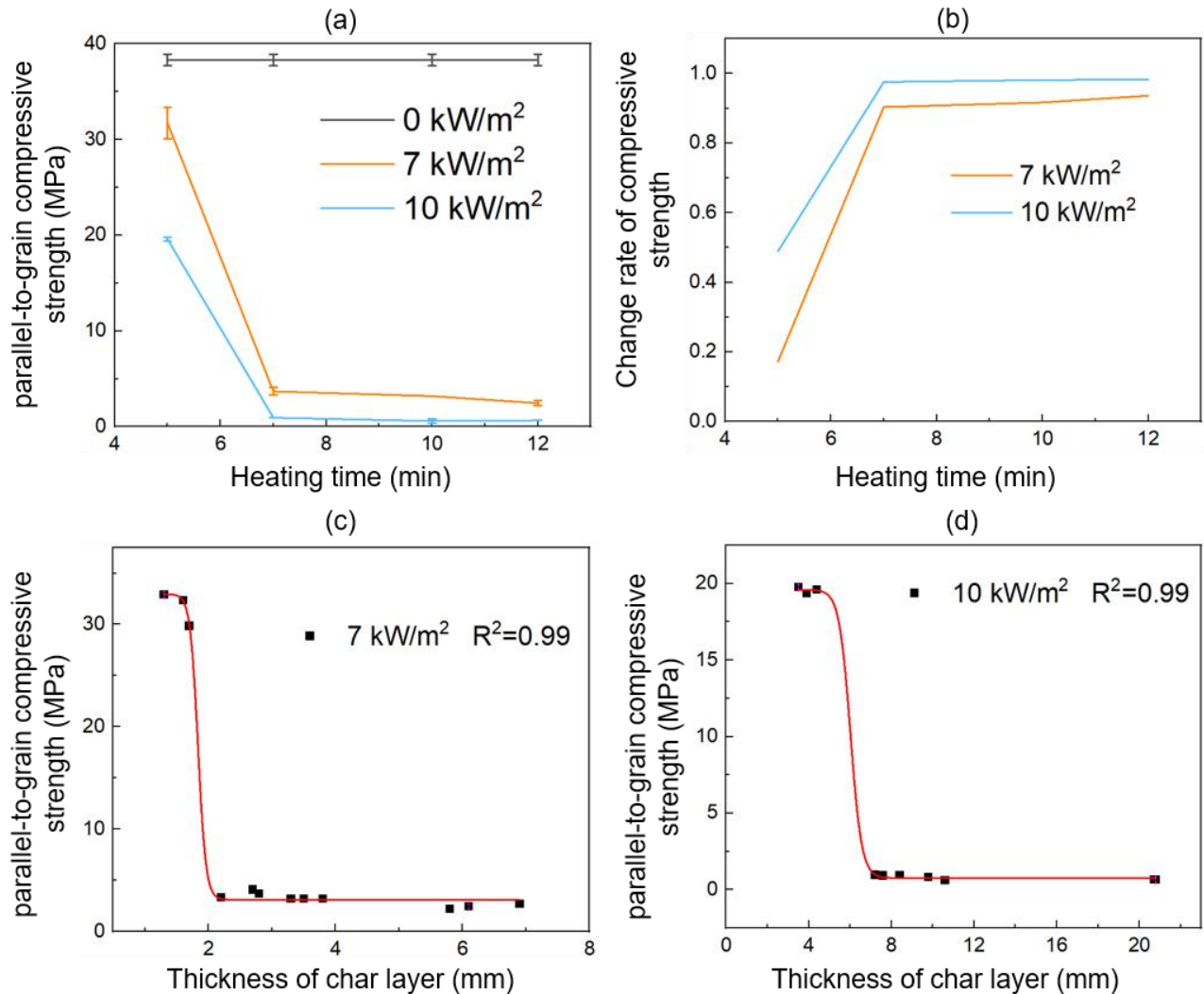


Figure 6. (a) The compressive strength parallel to the grain of wood under low radiation and time (b) the change rate of compressive strength parallel to grain under low radiative heat flow and time (c) (d) the fitting of the thickness of char layer to the compressive strength parallel to the grain

Table 1. The change rate of compressive strength parallel to the grain of constant heat flow at different times

Charring duration (min)	7 kW/m ²	10 kW/m ²
0-5 min	0.172	0.488
5-7 min	0.731	0.486
7-10 min	0.013	0.005
10-12 min	0.019	0.001
0-7 min	0.903	0.975
7-12 min	0.032	0.007
0-12 min	0.935	0.982

4. Summary

In this experiment, the surface of wood specimens has been pre-heated by various radiative heat fluxes (7 kW/m² and 10 kW/m²) and heating times (5-12 min) to achieve varying char layer thicknesses. The compressive strength parallel to grains versus various charring thicknesses has been obtained by an electronic universal testing machine (WDW-20). Experimental results demonstrate that a higher heat flux and longer heating times promote the formation of the char layer, but the compressive strength versus the charring thickness first decreases to its minimum value and subsequently remains stable. For the 7 kW/m² case, there is a rapid decrease in compressive strength for the 5-7 heating period. For example, the compressive strength is 31.7 MPa after the initial 5-minute period, and 3.69 MPa after the initial 7-minute period. For the radiative heat fluxes from 7 kW/m² to 10 kW/m², the reduction rate of compressive strength will increase from 1.32 MPa/min to 3.75 MPa/min for the initial 5-minute period, and increase from 4.95 MPa/min to 5.34 MPa/min for the initial 7-minute heating period. Future work will focus on testing the mechanical properties of wood samples treated under different conditions, such as simulating real fire environments, using different tree species, or using treated wood with preservatives.

Acknowledgements

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