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Combustion and charring properties of five common constructional wood species from cone calorimeter tests

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HIGHLIGHTS

- Demonstrates cone calorimeter test for assessment of combustion and charring of timber.
- Investigates combustion and charring properties of five common wood species.
- Behaviour of Douglas Fir, Scots Pine, Shorea and Southern Pine indistinguishable.
- Merbau was most resistant to fire reflecting the fact that it is almost twice as dense.
- European and Australian standards shown to underestimate charring depth.

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ABSTRACT

Cone calorimeter tests conducted at three levels of heat flux, 25, 50 and 75 kW/m^2, were employed to investigate the combustion and charring properties of five common constructional wood species: three softwood species: Douglas fir (*Pseudotsuga menziesii*), Scots Pine (*Pinus sylvestris*) and Southern pine (genus *Pinus*), and two hardwood species: Shorea (genus *Dipterocarpaceae*) and Merbau (*Intsia bijuga*). The ignitability and combustibility parameters of these five species were calculated and the time to ignition, heat release and mass loss rates, specific extinction area, effective heat of combustion, and CO and CO_2 yield compared. The measured charring rates from the cone calorimeter tests were transformed to equivalent charring rates for standard furnace tests and compared with those promulgated by European and Australian standards. It is shown that transforming cone calorimeter data obtained under conditions of 50 kW/m^2 and fire exposure greater than 30 min to equivalent furnace data using the concept of 'local fire intensity' resulted in relative good with standard-promulgated values for charring depths less than 30 mm. Merbau, having a density almost twice the other four species, demonstrated superior fire performance in all parameters considered. The other four species were essentially indistinguishable in terms of their overall performance. Finally, this study demonstrates the utility of the relatively inexpensive cone calorimeter test, for the rapid assessment of combustion and particularly charring performance of timber.

1. Introduction

Timber is widely used throughout the world as the principle structural material for both residential and commercial construction. Emphasising the sustainability of responsibly harvested timber, engineered timber structural elements are becoming increasingly attractive for larger spans and taller buildings. Timber, however, is combustible, providing fuel to a building fire while simultaneously losing structural load carrying capacity as the wood is consumed. When burned, timber produces heat, smoke and toxic gases which affect both occupant casualty and property loss. Thus the study of the combustion properties of constructional timber is critical to the safety of timber building construction.

When exposed to fire, a charring layer develops on the surface of timber members. Although this charring layer does not contribute to the residual capacity of the member, it protects the

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interior of the timber cross-section from heat and, because the thermal conductivity of the charring layer is much lower than that of the unburnt wood, reduces the amount of heat transferred by the surface burning to the unburnt part of the wood section. The reduced cross-section method [1], which is based on the expected charring depth, is often used to calculate the residual capacity of timber members in and after fire events. Thus, the prediction of charring depth or charring rate is crucial to the fire design of timber structures.

1.1. Obtaining combustion properties of timber

Cone calorimeter tests are widely used to measure the combustion characteristics of timber exposed to constant heat flux. The test results from cone calorimeter tests have been shown to correlate with results from full-scale room fires [2–7]. Spearpoint and Quintiere [3] experimentally examined the ignition of 50 mm thick samples of four species of wood using a cone calorimeter. It was shown that the critical heat flux and the thermal inertia can be obtained from the plot of $t_{ign}^{-1/2}$ (t_{ign} is the time to ignition) against incident heat flux. Cone calorimeter tests were to study the flammability properties of wood treated with flame retardant and to assess the efficacy of using flame retardant to improve the overall fire behaviour of particleboard [4]. Cone calorimeter tests were used to extend the methodology developed for the ignition and pyrolysis characteristics of polymeric materials to obtain flammability properties of charring materials [5]. The combustion characteristics, including the heat release rate, total heat release, total smoke release, specific extinction area and flaming time of multiple species of timber [6], wood- and gypsum based panels [7], and wood and PVC flooring [8] have all been experimentally investigated using the cone calorimeter. The thermal degradation, ignitability and combustibility parameters and gaseous emissions of two kinds of plywood were investigated with a cone calorimeter [9] as was the flame heat flux of medium density fibreboard [10]. Despite the many cone calorimeter tests carried out to study the combustion characteristics of wood, there are few results available in the literature for species commonly used for construction and furnishing buildings such as Scots Pine, Southern pine, Shorea and Merbau.

1.2. Obtaining charring properties of timber

Tests methods commonly used to obtain the charring rate of timber include: standard furnace tests with furnace temperatures following the ISO 834 [11] or ASTM 119 [12] curves [13–19]; tests with small-scale samples exposed to constant heat flux such as Cone calorimeter tests [20–24]; and full scale room tests [25,26]. Of these three methods, the imposed heat flux in the first and third method is variable with fire exposure time, while in the second test method, the imposed heat flux is kept constant for the test duration. Many studies have been conducted to correlate the charring rates obtained from these test methods. Principally, it was found that the charring rate measured from the variable heat flux methods can be correlated with the measured charring rate of the constant heat flux through the average heat flux [22,27,28].

Furnace tests based on ASTM E119 [13] and ISO 834 [14,15] have been conducted in which the charring rate is determined from thermocouple measurements of the 300 °C isotherm char front [13,15] or on residual specimen dimension [14]. In these studies, timber density and moisture content are found to greatly influence the measured char rate. Importantly, the charring rate prediction proposed by EC-5 [1] was found to be overly conservative for dense tropical hardwoods while other predictions, including the Australian Timber code [29] and that proposed based on previous experimental data [13] were found to be unsatisfactory [15]. As a result, a model for calculating the char rate (still based on density) of denser species was proposed [15]. Hugi et al. [16], on the other hand, conducted a series of furnace tests on twelve wood species with densities ranging from 350 to 750 kg/m^3 exposed to an ISO 834 fire. No correlation was observed between the charring rate and timber density. Instead, a strong correlation between oxygen permeability perpendicular to the wood fibre direction and charring rate was found.

Cone calorimeter tests are a convenient and less-expensive means of obtaining charring properties of timber [20–22], treated lumber [23] and engineered wood products [24]. Equations for the prediction of charring rate have been proposed based on heat transfer models [24] and heat release rate and mass loss rate recorded in a cone calorimeter test [20]. It has been proposed that the charring depth is linear with fire exposure time and a relationship between the charring depth and imposed heat flux suggested [21].

Correlation between charring properties determined using a cone calorimeter and those obtained in furnace tests have been proposed. The charring rate of spruce was experimentally investigated [22] from which the variation of the ratio between the charring depths obtained from cone calorimeter tests and those obtained from furnace tests with different fire exposure time was developed. It was concluded that the charring depths obtained in cone calorimeter tests at 50 kW/m^2 were similar to those obtained in furnace tests having a duration of 30–40 min [22]. Other correlations between the test approaches propose the concept of local fire intensity to correlate the charring depth measurements from each method [27] or simply using the average heat flux [28]. Most extant study of charring rates focus on North American and European softwoods; there is relatively little data available for hardwoods.

The microstructure of the wood and char was also carefully investigated using scanning electron microscopy (SEM) by Cutter et al. [30] and Zicherman and Williamson [31]. Three distinct zones including (1) a heavily distorted outer char layer, (2) a charred but relatively undistorted inner layer, and (3) whole, nondegraded wood underlying the char were observed. Between the decomposed wood and whole wood was a thin transition layer a few cell rows in thickness. Ragland et al. [32] summarised the physical properties, thermal properties, chemical properties, reaction rates and mineral properties of the wood and char. The density and shrinkage ratio of virgin and charred medium density fireboard was studied by Li et al. [33]. The measured reductions in the vertical and horizontal direction were 40% and 20% respectively. Li et al. [34] also carried out a set of experiments using large-scale compartments made of medium density fireboard to investigate the char pattern and depth at postflashover compartment.

2. Experimental program

In this study, the cone calorimeter test was employed to investigate the combustion and charring properties of five common constructional wood species. The ignitability and combustibility parameters were calculated [3] and the time to ignition, heat release and mass loss rates, specific extinction area, effective heat of combustion, and CO and CO_2 yield of the five species were compared. The measured charring rates were transformed to equivalent charring rates for standard furnace tests [22] and compared with those promulgated in existing design guidelines [1,29]. In this manner the fire performance of these wood species were compared and summarised, to provide reference for fire protection measurement for timber structures and wooden furnishing. This study also demonstrates the utility of the cone calorimeter test, particularly for obtaining charring data.

2.1. Test specimens and test matrix

Specimens from five common constructional wood species were used, three softwood species: Douglas fir (*Pseudotsuga menziesii*), Scots Pine (*Pinus sylvestris*) and Southern pine (genus *Pinus*), and two hardwood species: Shorea (often referred to as Meranti; genus *Dipterocarpaceae*) and Merbau (*Intsia bijuga*). All specimens