Factors Influencing the Charring Rate of Chinese Wood by using the Cone Calorimeter

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Wood has better load-bearing capacity following the formation of a char layer when exposed to fire. The charring rate is the most important property of wood with respect to its fire resistance and fire integrity. The objectives of this study were to determine the effects of factors, including density, gas permeability, ring width, grain orientation, and heat flux, on the charring rate. The charring rates of six Chinese woods were tested with a cone calorimeter with densities of 0.35 to 0.69 g/cm^3 and moisture contents of approximately 12%. The results indicated that density, gas permeability, and heat flux, but not the grain orientation, significantly affected the charring rate. There was a positive, linear correlation between the heat flux and the charring rate. The density was nearly linearly related to the charring rate for either softwood or hardwood; the correlation was not found for all woods. The positive, linear correlation between the gas permeability and the charring rate was only found along the grain.

Keywords: Charring rate; Density; Gas permeability; Cone Calorimeter

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INTRODUCTION

Wood is widely used as a building material because of its excellent properties, especially its good load-bearing capacity under fire impact. When exposed to fire, a charred layer is formed on the surface of wood, which can separate the underlying wood from the flame and hinder heat propagation. The uncharred, virgin wood maintains certain loading capacity. Consequently, the charring rate is the most important property of wood with respect to its fire resistance and fire integrity. Numerous investigations on the charring rate of wood have been carried out during the past decade. Various methods have been used to test the charring rate. Charring rates of 0.34 to 0.8 mm/min have been recommended for use in Japan, North America, Europe, and Australia, according to the standard temperature curves of furnaces (JIS A1301 1999; ISO 834 2012; EC5 2004; ASTM E119 2012; AS 1720.4 2006).

The cone calorimeter has also been used to study wood's burning behavior and charring rate because of its easy operation and the associated material savings (Mikkola 1990; Spearpoint and Quintiere 2000; Moss *et al.* 2009; Friquin *et al.* 2010). The charring rate determined by the cone calorimeter is slightly higher than that achieved using the furnace method but could be equal to the furnace method value by considering the heat flux. It is widely accepted that parameters such as the density, moisture content, wood anatomy, and heat flux affect the charring rate to some extent. A positive, linear correlation between the density and the charring rate was found in softwood (0.384 to 0.697 g/cm^3) and hardwood (0.5 to 1.0 g/cm^3) (Schaffer 1967; Njankouo *et al.* 2005). In addition, the charring rate decreases with increasing moisture content (Schaffer 1967; EC5 2004).

However, some literature holds that there is no significant correlation between the charring rate and the density when the density is between 0.35 and 0.75 g/cm^3 and the moisture content is 8% to 15% (Frangi and Fontana 2003; Lingens *et al.* 2005; Hugi *et al.* 2007; Hugi and Weber 2012). Many investigations involving different wood species showed that the charring rate was strongly affected by the wood's anatomy, such as the gas permeability, fiber direction, and percent heartwood (Bhagat 1980; Parker 1986; Hugi *et al.* 2007, 2012). Furthermore, Hugi *et al.* (2007, 2012) state that the gas permeability exhibits a positive, linear correlation with the charring rate. Literature discussing heat flux indicates that the charring rate increases with increasing heat flux (Janssens 2004; Kučera *et al.* 2014). The above studies indirectly indicate that the charring rate has species-dependency. It is thought that Chinese species have a different charring rate as compared with the wood of Europe or North America. Limited studies on the charring rates of wood species in China exist. The recommended charring rate of relevant criteria in China originated from foreign species, and its applicability to Chinese species is in question.

There is a need to study the charring rate of Chinese wood species. In this study, the charring rates of Chinese wood species, including both softwood and hardwood, were studied using a cone calorimeter to determine the recommended charring rate for Chinese wood species.

EXPERIMENTAL

Materials

Six Chinese wood species were selected as the specimens for use in this study; detailed information is shown in Table 1. The samples at the longitudinal section and the transversal section were cut almost entirely from the sapwood portion, as shown in Fig. 1. They were nominally 40 mm thick by 100 mm^2. The heartwood proportion of each specimen was recorded. Samples were stored at room temperature (20 °C) and 65% relative humidity until their moisture content was approximately 12%.

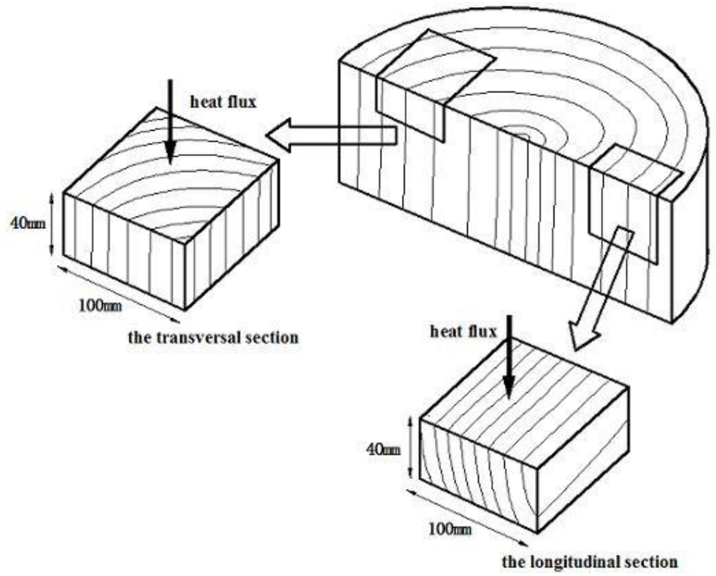

Fig. 1. Sample grain configuration

Table 1. Properties of Six Chinese Wood Species

Species		Density (g/cm^3)		Annual Ring Width (mm)		Latewood Percent (%)		Growth Area
		Mean	COV (%)	Mean	COV (%)	Mean	COV (%)	
Softwood	Chinese fir *(Cunninghamia lanceolata)*	0.36	5.56	4.01	0.75	—	—	Fu'an, Jiangxi Province
	Mongolian pine (*Pinus sylvestris* var. *mongolica* Litv.)	0.47	4.26	1.44	9.72	—	—	Mohe, Heilongjiang Province
	Chinese larch (*Larix gmelinii*)	0.68	4.41	2.01	8.96	—	—	Mohe, Heilongjiang Province
Hardwood	Poplar (*Populus* spp.)	0.43	6.98	12.76	10.82	19.78	6.17	Fangshan District, Beijing
	Cinnamomum camphora (*Cinnamomum camphora* (L.) Presl.)	0.54	3.70	6.01	13.48	26.32	19.91	Guangyuan, Sichuan Province
	Chinquapin (*Castanea henryi* (Skan) Rehd. et Wils.)	0.66	3.03	5.75	16.7	25.8	21.2	Nanning, Guanxi Province

Note: COV represents coefficient of variation

Methods

The charring rates of 42 samples were tested in a cone calorimeter (FTT Ltd., UK) at Northeast Forestry University, according to ISO 5660-1 (2002). Incident heat fluxes of 35, 50, and 75 kW/m^2 were selected for these experiments. Type K thermocouples (Tian Hang Daye Automation Instrumentation Co., Ltd., Beijing) of 2 mm diameter were inserted halfway into the samples through horizontal holes drilled at heights of 10, 20, and 30 mm below the top surface. The holes were with the diameter of 2 mm and the depth 50 mm. The temperatures of the thermocouples were collected by a TDS-530 (Tokyo Sokki Kenkyujo Co., Ltd., Japan) data logger. The charring rate test apparatus is shown in Fig. 2.

Fig. 2. The test apparatus: Cone calorimeter

The char wood was split into three aspects: the char layer, the transition layer, and the virgin wood (Spearpoint and Quintiere 2000). The charring limit was confirmed as the place where the temperature reached 300 °C in the transition layer (White 2000). The charring time was recoded respectively when the temperature of the thermocouple at three places for each sample reached 300 °C. The linear best fit regression line between the char depth and the charring time was built. The charring rate, β, was determined as the slope of the regression line for the charring depth against the charring time (Lane 2005). The charring rates from specimens at the longitudinal section indicate that the charring rates are perpendicular to the grain (CR_p), while the charring rates from specimens at the transverse section indicate the charring rates are along the grain (CR_a).

Gas permeability testing samples with dimensions of 25 mm (diameter) by 40 mm (thickness) were tested according to SY/T 5336 (2006) at the China University of Petroleum (Beijing). The gas permeability index (OPI) is defined as the negative logarithm of the coefficient of permeability,

$$K = \frac{2Q_a P_a \mu L}{A\left(P_1^2 - P_2^2\right)} \times 1000 \tag{1}$$

$$\mathrm{OPI} = -\log_{10}(K) \tag{2}$$

where OPI is the gas permeability index, K is the coefficient of permeability of the test sample (μm^3), Q_a is the gas flux under atmospheric pressure (cm^3/s), P_a is the atmospheric pressure (Pa), μ is the gas viscosity at the given pressure and temperature (mPa·s), L is the sample thickness (cm), A is the sample cross sectional area (cm^2), P_1 is the sample inlet pressure (Pa), and P_2 is the sample exit pressure (Pa).

The graphical analysis was processed with the Origin 9.0 software. The statistical significance analysis with the significance level of 0.05, and multi-linear regression analysis between the factors influencing the charring rate and the charring rate were performed using the Excel 2010.

RESULTS AND DISCUSSION

The gas permeability test results are shown in Table 2. Heating rate curves of thermocouples are shown in Fig. 3. The time for each thermocouple to reach 300 °C was extrapolated for each thermocouple depth and then the char depth plotted against time for samples under various heat fluxes, as shown in Fig. 4. The charring rates determined are shown in Table 3. The charring rate decreased with increasing density and decreasing heat flux for both softwood and hardwood. Moreover, CR_a was observed to be greater than CR_p. The thermal conductivity of the wood across the grain was typically around 2.1 times greater than that along the grain direction (Spearpoint and Quintiere 2000). According to an algorithm found in the literature (Spearpoint and Quintiere 2000), the ignition temperature perpendicular to the grain was greater than that along the grain for any wood species. The heating rate of the inner wood along the grain was also greater than that perpendicular to the grain. Therefore, the charring rates of the six Chinese species along the grain appeared higher than those perpendicular to the grain.

Results of the one-way ANOVA for the charring factors are shown in Table 4. Differences existed in the significance of the factors on the charring rate with $\alpha = 0.05$. When the p-value is less than 0.05 and the F value is greater than the F_{crit} value, the hypothesis is accepted that the factor strongly affects the result. The p-value of the grain orientation was greater than 0.05, which indicated that the grain orientation did not significantly affect the charring rate. This agrees with the findings of Hugi *et al.* (2007). In this study, the results of the one-way ANOVA showed that the density also significantly affected the charring rate of the woods. This was not the same as in the findings of other studies (White 2000; Frangi and Fontana 2003; Lingens *et al.* 2005; Hugi *et al.* 2007; Hugi and Weber 2012) due to the differences of experimental setups, the specimen size, and the calculation method of the charring rate. The furnace method with the standard temperature curves was selected and the test specimens were composite timber or full size structure lumber in those previous researches.

The multi-linear regression analysis results of the charring rate and factors, including the density and gas permeability are shown in Table 5. The values of the significance, F, and R^2 of CR_p indicated that the density and the gas permeability had a co-effect on the charring rate. Furthermore, the p-values of the density, and gas permeability indicated that the gas permeability affected the charring rate to a greater extent than the other factors. The relationships between the density and gas permeability and the charring rate are shown in Figs. 5 and 6, respectively. The correlation coefficient of the density decreased with increasing heat flux for both CR_p and CR_a. The coefficients of determination between the charring rate and the density based on the test data for all tested species were obviously lower than those between the density and the charring rate in the test data of softwood or hardwood only (Fig. 7).

Meanwhile, the coefficient of determination of the gas permeability and CR_p was slightly below 0.70 (Hugi *et al.* 2007) and 0.801 (Hugi and Weber 2012). However, the relationship between the gas permeability and CR_a was not statistically significant. The findings of Hugi *et al.* (2007, 2012) showed that the gas permeability of the fiber orientations 0, 45, and 90° exhibited better correlations with the charring rate. However, a statistically significant relationship was found only between the gas permeability of the fiber orientation 90° and CR_p in this study.

The optimally fitted curves of the heat flux and the charring rate were also built (Fig. 8). The charring rate increased linearly with increasing heat flux. Unfortunately, no obvious correlation between the ring width and the charring rate appeared (Fig. 9).

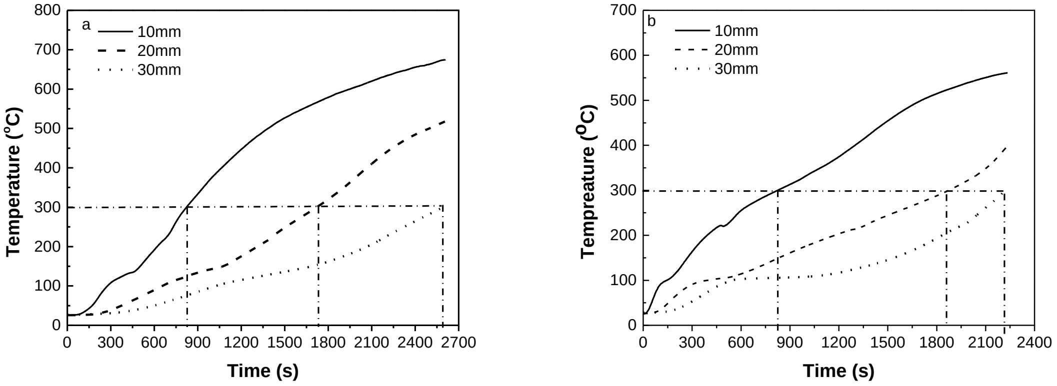

Fig. 3. Heating rate curves of thermocouples at the heat flux 50 kW/m^2 (*Cinnamomum camphora* (L.) Presl.); a: perpendicular to the grain; b: along the grain

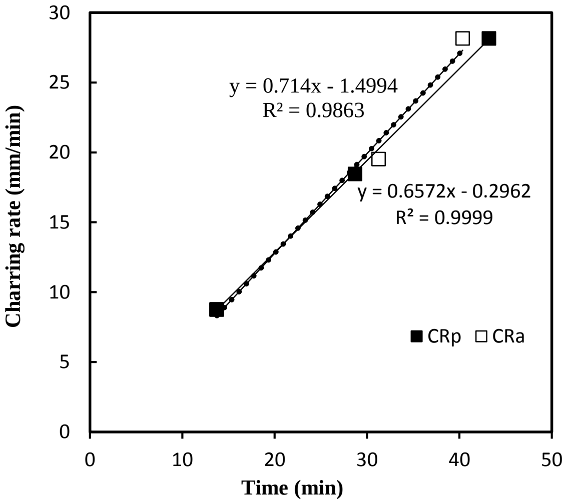

Fig. 4. Curve of the char depth plotted against time at the heat flux 50kW/m^2 (*Cinnamomum camphora* (L.) Presl.)

Table 2. Gas Permeability of Samples

Species		*K* (μm^3)		OPI	
		Along the Grain	Across the Grain	Along the Grain	Across the Grain
Softwood	Chinese Fir	0.26	56.90	3.62	1.24
	Mongolian Pine	0.23	7.46	3.64	2.13
	Chinese Larch	0.16	0.91	3.81	3.04
Hardwood	Poplar	1.34	242.44	2.87	0.62
	Cinnamomum Camphora	0.06	72.86	4.24	1.14
	Chinquapin	0.03	551.09	4.56	0.26

Table 3. Charring Rates of Chinese Wood Species

Species		Charring Rate (mm/min)					
		CR$_p$			CR$_a$		
		75 kw/m^2	50 kw/m^2	35 kw/m^2	75 kw/m^2	50 kw/m^2	35 kw/m^2
Softwood	Chinese Fir	0.805	0.720	0.645	0.884	0.749	0.688
	Mongolian Pine	0.647	0.604	0.496	0.789	0.621	0.512
	Chinese Larch	0.861	0.78	0.705	1.008	0.887	0.738
Hardwood	Poplar	1.275	0.971	0.944	1.289	1.071	0.952
	Cinnamomum Camphora	0.701	0.657	0.543	0.748	0.714	0.626
	Chinquapin	0.753	0.669	0.578	0.945	0.834	0.596

Table 4. One-way ANOVA Results of Char Factors

Factor	F	P-value	F_{crit}
Grain Orientation	1.71	2.14E-01	3.68
Density	127.46	5.70E-10	3.11
Gas Permeability	127.46	5.70E-10	3.11
Heat Flux	50.34	1.78E-04	5.14

Table 5. Comparison of Multi-Linear Regression Analysis Results of Three Factors Including the Gas Permeability, and the Density

Grain Orientation	Factor	p-value	F	Significance, F	Adjusted R^2
CRp	Gas Permeability	0.0083	30.6627	0.0101	0.9223
	Density	0.2847			
CRa	Gas Permeability	0.1992	1.4740	0.3582	0.1594
	Density	0.3428			

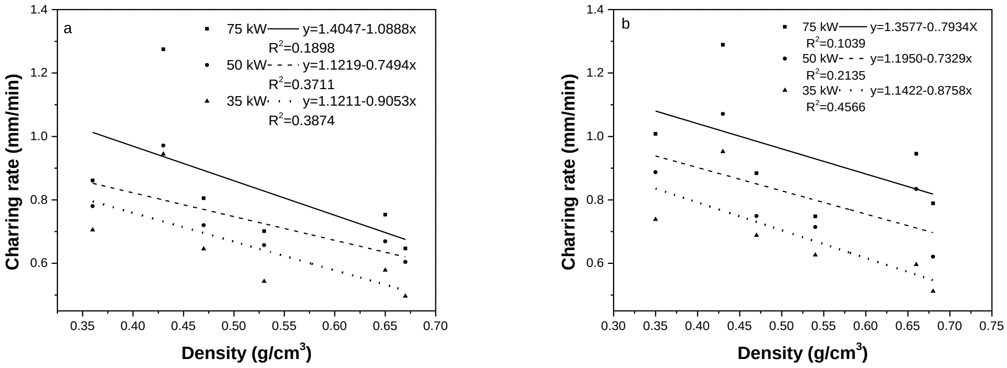

Fig. 5. Relationship between the density and the charring rate for all species at different heat fluxes; a: perpendicular to the grain; b: along the grain

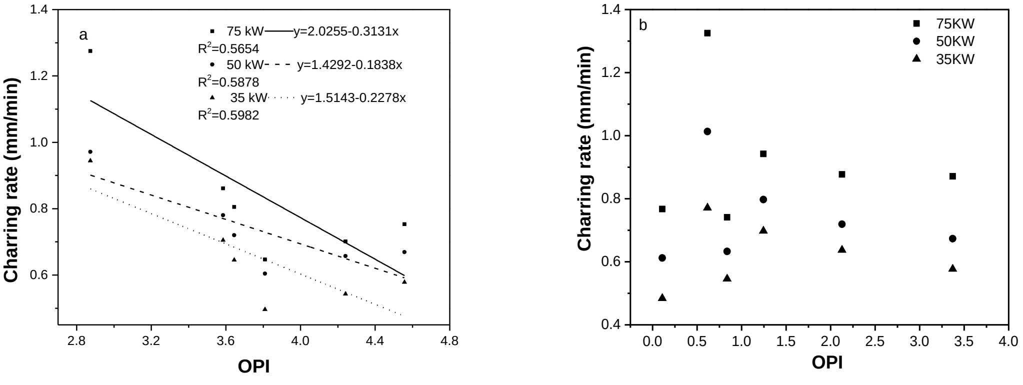

Fig. 6. The relationship between the gas permeability and the charring rate for all species at different heat fluxes; a: perpendicular to the grain; b: along the grain

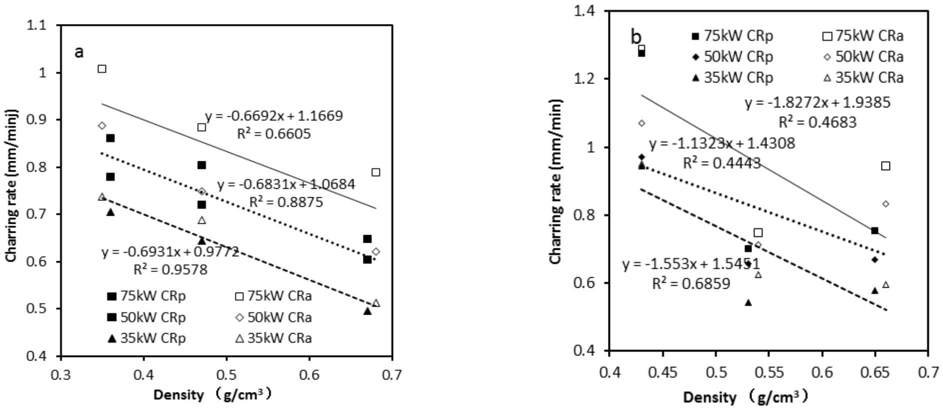

Fig. 7. Relationship between the density and the charring rate for softwood and hardwood at different heat fluxes; a: softwood; b: hardwood

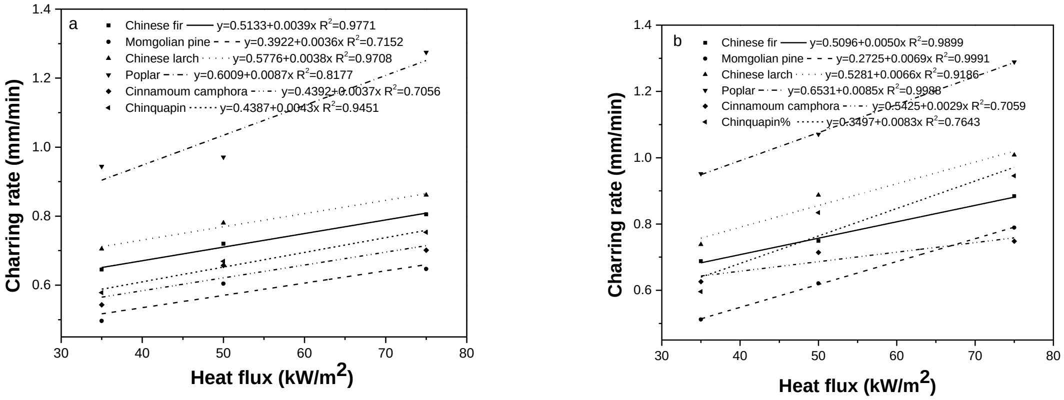

Fig. 8. Relationship between the heat flux and the charring rate for all species; a: perpendicular to the grain; b: along the grain

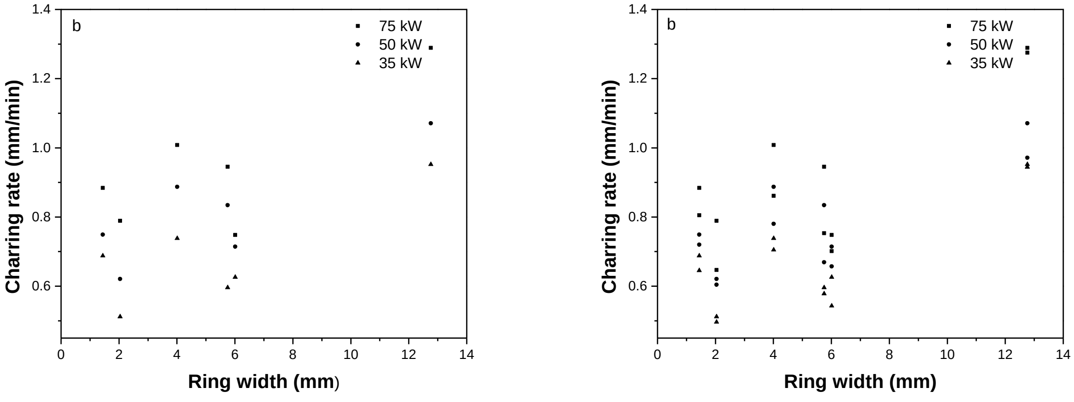

Fig. 9. Relationship between the ring width and the charring rate for all species at different heat fluxes; a: perpendicular to the grain; b: along the grain

CONCLUSIONS

1. The charring rates of six Chinese species perpendicular to the grain were slightly less than those along the grain direction.

2. The grain orientation exhibited no significant correlation with charring rate.
3. The charring rate linearly increased with increasing heat flux.
4. Factors including the density, gas permeability, and heat flux significantly affected the charring rate. The significances of the effects of the ring width and the density were less than that of the gas permeability.
5. The densities of both softwood and hardwood had a positive, linear correlation with the charring rate, although the relationship between density and charring rate was not found for all species. The gas permeability study only had a positive, linear correlation with the charring rate in the longitudinal direction.

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