Probing the Effects of Density on Combustion Performance of Cement-bonded Particleboard Produced from Wood Processing Residues

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Abstract

The purpose of this study was to provide insights into deeper understanding of the combustion performance of cement-bonded particleboards. Cement-bonded particleboard produced from Chinese fir processing residues is fabricated and its combustion performance is further evaluated by cone calorimeter analysis. Obtained results revealed that combustion performance of cement-bonded particleboard positively depends on the density of which, and higher density imparts corresponding particleboards reduction in heat release rate, total heat release, and mass loss rate, along with elevated time to ignition. With the density of particleboard increasing from 0.7 to 1.0 g/cm³, peak and average heat release rate, total heat release and average mass loss rate of specimens were decreased by 55.9, 73.4, 77.8 and 60.3%, respectively. Furthermore, time to ignition of particleboard increased by more than 20 times as the density increasing. Residual mass of specimens was also remarkably elevated along with higher yields of CO and CO₂ as the density of particleboard increasing. We believe that proposed investigation is beneficial for the value-added utilization of wood processing residues and further developing products fabricated by wood processing residues.

1. Introduction

It has been reported that about 41.8 million tons of wood processing residues are generated each year in China. As compared with other countries (57% in Japan and 68% in Germany), the recycle-utilization rate of wood processing residues in China (30%) is limited (Xu et al. 2015). The further and value-added recycle-utilization of wood processing residues plays an important role in wood processing industry. Traditional recycle of wood processing residues is the feedback of biomass fuel (Kong et al. 2016), activated carbon (López et al. 2013) and wood-based composite (Nazerian et al. 2011; Kula et al. 2016; Souza et al. 2018). Previous research has pinpointed that wood-processing residues are suitable for preparation of cement-bonded particleboards (CBPBs). Potential wood processing residues include rattan furniture waste (Olorunisola and Adejisan 2002), Bagasse particles (Nazerian and Eghbal 2013), construction waste wood (Wang et al. 2016; AtoyeBia et al. 2018), recycling waste wood (Hossain et al. 2018) and Teak (Tectona grandis) wood sawdust (Nta and Olorunisola 2016). Applying wood-processing residues for preparation of CBPBs caves a sustainable and comprehensive way to recycle-utilization of large quantities of wood waste (Od-eyemi et al. 2020). However, the application of wood processing residues on the fabrication of CBPBs and the properties of as-fabricated CBPBs have hardly been investigated.

CBPBs have gained high levels of public interest due to its excellent mechanical property (Raúl and Cloutier 2011; Yel et al. 2020), dimensional stability (Sarkar et al. 2012; Nasser et al. 2014), weather resistance (Okino et al. 2005; Papadopoulos 2008), fire retardancy (Wi-nandy et al. 2008; Pedieu et al. 2012) and low cost (Yilmaz et al. 2016). Nevertheless, most of the previous research focused on the mechanical properties (Gong and Harischandran 2012; Nasser et al. 2014), decay resistance (Esmeralda et al. 2005; Frybort et al. 2008) and dimensional stability of CBPBs (Tabarsa and Ashori 2011). Limited information was available in the term of combustion performance of CBPBs and it further hinders successful its engineering applications of CBPBs (Wang et al. 2008; Yu et al. 2016). Hou et al. (2017) investigated the combustion performance of wood-aluminum composites made from oriented strand board (OSB) and aluminum alloy sheets using cone calorimetry tests. The results revealed that the application of aluminum alloy sheets to wood-based composites is an effective method for improving the combustion performance of wood-aluminum composites. Previous research pinpointed that heat release rate, total heat release and efficient heat combustion of FRW fire-retardant particleboard were obviously reduced as compared with ordinary par-
particleboard, while the char-forming rate of which increased (Liu 2011). It was also reported that fire performance of CBPBs made from Chinese fir processing residues of highly depended on cement-wood ratios, and higher cement-wood ratios imparted CBPBs better flame retardancy (Yu et al. 2016). Due to the restricting in the obliged provision of fire-retardant rating for the materials in the public places (PRC 2008), improvement of combustion performance for CBPB plays a growingly important role in its future application. Hence, it is necessary to further investigate the combustion characteristics and explore the combustion mechanism of CBPBs, which is also beneficial for promoting its application throughout the world for furniture manufacturing and civil construction.

Herein, CBPBs with different densities as fabricated by Chinese fir processing residues, Portland cement and CaCl₂ were prepared. We further conducted an investigation into the combustion performance of CBPBs based on cone calorimeter analysis. Important parameters including time to ignition (TTI), fire performance index (FPI), heat release rate (HRR), effective heat of combustion (EHC), total heat release (THR), mass loss rate (MLR), residual mass, CO yield (COY) and CO₂ yield (CO₂Y) were measured. The effect of density of CBPBs on the corresponding combustion performance was analyzed. Our work herein can facilitate the concept of the circular economy by upcycling the wood processing residues into CBPBs with excellent flame retardancy performance.

### 2. Materials and methods

#### 2.1 Materials

As illustrated in Fig. 1(a), Chinese fir (Cunninghama lanceolata) processing residues were collected from Lin’an lumber market in Hangzhou, China. The Chinese fir processing residues were processed into Chinese fir particles by a hydraulic shaving machine (YM-145, Zhengzhou Yamei Machinery Manufacturing Co., Ltd. China) with a particle length of 6 cm [Fig. 1(b)]. Chinese fir particles for the production of CBPB were adjusted to a moisture content (MC) of 12±1.0% in an oven (DKN611, Yamato Company, Japan) at the temperature of 103±2°C. Portland cement applied in this study was produced by Shanggan cement plant of Lin’an, Zhejiang Province, China, with its chemical compositions and mineral compositions cited by Wang et al. (2012), Yu et al. (2016) and Dong et al. (2016). CaCl₂, purchased from Hangzhou Gaojing Fine Chemical Co., Ltd, Hangzhou, China, was used as the cement curing accelerator.

| Preset density g/cm³ | Dimensions of CBPBs mm (L)×mm (W)×mm (T) | Weight of material* g | Actual oven-dried density g/cm³ | Final MC % |
|----------------------|-------------------------------------------|------------------------|----------------------------------|------------|
| 0.7                  | 300×300×10                                | 630                    | 0.74±0.04                        | 12.0±0.3   |
| 0.8                  | 300×300×10                                | 720                    | 0.84±0.09                        | 11.9±0.5   |
| 0.9                  | 300×300×10                                | 810                    | 0.97±0.07                        | 12.5±0.3   |
| 1.0                  | 300×300×10                                | 900                    | 1.12±0.05                        | 11.1±1.3   |

*Total weight of oven-dried Chinese fir particles and Portland cement for the fabrication of CBPBs under different preset oven-dried density conditions.

Fig. 1 Wood processing residues (a) and wood particles (b) of Chinese fir.
shown in Table 1. The corresponding homogenized Chinese fir particles-Portland cement mixture was placed in a 300 mm×300 mm wooden mold to provide an oven-dried density as uniform as possible. Then the mixture was cold-pressed by a press (XLB-D500×500, Huzhou Dongfang Machinery Co., Ltd. China) at a pressure of 10 MPa for 24 hours with a preset thickness of 10 mm.

2.3 Final MC and actual oven-dried density measurement of the CBPBs
The prepared CBPBs were cut into square specimens with dimensions of 100 mm (L)×100 mm (W)×10 mm (T) to obtain the final MC and actual oven-dried density. These specimens were dried in an oven at the temperature of 103±2°C until constant mass was reached. 18 replications corresponding to each level of particleboard density were measured for the final MC and actual oven-dried density (Table 1). Final MC of CBPBs was calculated according to the specimen oven-dried weight ($M_o$) and initial weight ($M_i$) according to Eq. (1).

$$MC_F = \frac{M_i - M_o}{M_o} \times 100\%$$

where, $MC_F$ is the final MC of specimens; $M_o$ is oven-dried weight of specimens; $M_i$ is initial weight of specimens.

Actual oven-dried density of CBPBs was calculated according to the specimen oven-dried weight ($M_o$) and dimensional parameters as shown in Eq. (2).

$$\rho_o = \frac{M_o}{L_o \times W_o \times T_o}$$

where, $\rho_o$ is oven-dried density of specimens; $M_o$ is oven-dried weight of specimens; $L_o$, $W_o$, and $T_o$ are length, width and thickness of specimens under oven-dried condition, respectively.

2.4 Cone calorimeter analysis of CBPB
The combustion performance of CBPB was measured by cone calorimeter (Fire Testing Technology LTD., UK) in accordance with the ISO Standard 5660-1 (ISO 2015). In prior to the cone calorimeter testing, CBPB specimens were conditioned to equilibrium moisture content (EMC) at a controlled environment (23°C and 50% relative humidity) in a humidity conditioner (EL-10KA, Espec Corporation. USA) until constant mass was reached. The square specimens with dimensions of 100 mm (L)×100 mm (W)×10 mm (T) was irradiated with an incident heat flux of 50 kW (Yu et al. 2016; Hou et al. 2017).

Experimental data of heat release rate (HRR), time to ignition (TTI), fire performance index (FPI), total heat release (THR), mass loss rate (MLR), residual mass, CO yield (COY) and CO$_2$ yield (CO$_2$Y) were analyzed with a one-way ANOVA. The effect of different densities on aforementioned combustion performance was also investigated at a level of 0.05.

3. Results and discussion
3.1 Actual oven-dried density of CBPBs
Actual oven-dried density of CBPBs with different preset oven-dried densities is presented in Table 1. A slight increase of actual oven-dried density was observed as compared with preset oven-dried density. The corresponding increase rate was 5.7, 5.0, 7.8 and 12.0% at the preset oven-dried density of 0.7, 0.8, 0.9 and 1.0 g/cm$^3$, respectively. This is mainly due to the hydration of Portland cement in the mixing process of Portland cement.

3.2 Heat release rate (HRR)
Figure 2 illustrates the HRR curves of CBPBs with different densities. Peak heat release rate (PHRR) and average HRR (AHRR) of CBPB are shown in Fig. 3. A typical curve for prepared CBPB was observed to occur to the CBPB with a density of 0.7 g/cm$^3$ and the second PHRR exhibited a greater value than the first one. Besides, the HRR curve that corresponds to CBPB with the
density of 0.8 g/cm³ exhibited only one PHRR, indicating the suppression effect on combustion of Chinese fir particles. Furthermore, the same conclusion can be drawn for CBPBs with densities of 0.9 and 1.0 g/cm³. It can be attributed to the fact that Portland cement as binder was relatively evenly distributed on the surface of wood particles, and pores between Chinese fir particles decreased with the increasing density (Fan et al. 2000). Decrease of porosity leads to the improvement in fire-retardant performance of CBPBs. Our previous research reveals that combustion of Chinese fir particles can be effectively prevented by cement hydrate layer due to increasing particleboard density (Yu et al. 2016). As seen in Figs. 2 and 3, increasing in the density of CBPBs decreased the PHRR. The time to PHRR was also significantly extended from 150 s to 680 s when the density of CBPBs increased from 0.8 to 0.9 g/cm³, and the corresponding time slightly prolonged to 685 s with further increase in density to 1.0 g/cm³. Aforementioned analyses strongly suggest a lower flammability of CBPBs with higher density. Meanwhile, decrement of PHRR and AHRR of CBPBs was as much as 56.88% and 73.42% with density increasing from 0.7 to 0.8 g/cm³. Further increasing in the density of CBPBs brings no further decrement in PHRR and AHRR. It can be attributed to the fact that compaction rate of Chinese fir particles increased with increasing density values.

The thickness of cement hydrate layer on the surface of Chinese fir particles also increased with increasing density, which can effectively prevent Chinese fir particles from sharply combusting during cone calorimeter measurement. Therefore, HRR declines sharply with increase in incomplete combustion of prepared CBPBs. Values of variance analysis on HRR of CBPBs at different densities are shown in Table 2. It indicated that the effect of density on PHRR of CBPB was significant at 0.05 level. However, that the effect of density on AHRR of CBPBs was not significant at 0.05 level. This may be due to the fact that increasing in density of CBPBs resulted in the reduction of porosity, further leading to the significant decrease in HRR of CBPBs during cone calorimeter measurement.

### 3.3 Time to ignition (TTI) and fire performance index (FPI)

TTI and FPI of CBPBs are shown in Fig. 4. Values of variance analysis on TTI and FPI of CBPBs with different densities are shown in Table 3. It should be noted that the effect of density on TTI and FPI of CBPBs were significant at 0.05 level. It can be attributed to the fact that...
that the compactness of CBPBs was increased with density increasing, further leading to a reduction in the thermal decomposition rate of CBPBs and prolong in TTI as expected.

Besides, TTI values of CBPBs are noticeably prolonged with increasing density (from 20 s to 404 s). This was due to the presence of cement hydrate layer on Chinese fir particles exhibits excellent fire-retardant property. Thickness of cement hydrate layer increased with increasing density of CBPBs, which can effectively prevent Chinese fir particles from sharply combusting. Therefore, CBPBs with higher density needs remarkably longer time to ignite than those with lower density. It can also be found that FPI of CBPBs significantly increased from 0.14 to 6.23 s/(kW/m²) when the density of CBPBs increased. The reason underlying the aforementioned phenomenon was that the increasing in density of CBPBs significantly elevated corresponding TTI (Fig. 4). Also, the decrements of PHRR of CBPBs as displayed in Fig. 3 contributes to the elevated FPI of CBPBs.

3.4 Effective heat of combustion (EHC) and Total heat release (THR)

EHC and THR curves of CBPBs as a function of time are showed in Figs. 5 and 6. Obtained results revealed that peak EHC (PEHC) and average EHC (AEHC) of CBPBs declined with density of CBPBs increasing. The CBPB with a density of 0.7 g/cm³ exhibited the largest values of EHC during the initial 500 s as illustrated in Fig. 6. After an ignition time of 700 s, EHC emitted from CBPB increased significantly due to sharply combustion of charred Chinese fir particles. A dramatic increase in EHC of CBPB was found to occur near the time to PHRR (Figs. 4 and 6) which is due to the sharply combustion of Chinese fir particles and an obvious release of heat. A gradual decrease of AEHC was observed with density of CBPBs increasing from 0.7 to 0.9 g/cm³. The same conclusion was also obtained for PHRR of all CBPBs. The EHC of CBPBs slightly increased from 7.62 to 8.07 MJ/kg with density of CBPBs increasing to 1.0 g/cm³.

As seen in Fig. 6, obvious decrease was observed as occur to THR of CBPBs with density increasing from 0.7 to 1.0 g/cm³ (from 110.1 to 24.4 MJ/m²). It can also be found that the THR of CBPBs with a density of 0.7 g/cm³ was more than 100 MJ/m², indicating the high fire hazard level of combustion. The THR of CBPB with a density of 0.8 g/cm³ was observed to reach the scale of intermediate fire hazard level (Yu et al., 2016). As described in the analysis of HRR of CBPBs, pyrolysis and charring of Chinese fir particles were noticeably inhibited due to the poor thermal conductivity of cement hydrate layer and Chinese fir particles. Incomplete combustion of CBPBs decreased with the density increasing (Hou et al., 2017). Cement hydrate layer on Chinese fir particle surface was thick enough to remain intact, thus preventing Chinese fir particles from further combusting in the combustion process (Figs. 4 and 5). However, content of combustibles (Chinese fir particles) increased with increasing density of CBPBs. Therefore, a slight increase in THR of CBPB was observed with further increase of density to 1.0 g/cm³. Results of variance analysis on THR of CBPBs with different densities are shown in Table 2. It was found that the effect of density on THR of CBPB were not significant at 0.05 level. The reason was that the THR of CBPBs obvious decreased with density increasing from 0.7 to 0.8 g/cm³, and slightly decreased when further increasing in density of CBPBs. In summary, combustion of Chinese fir particles resulted in slight increase in EHC and THR of CBPBs when further increasing in density of CBPBs.

3.5 Mass loss rate (MLR) and residual mass

MLR and residual mass of CBPBs are presented in Figs. 7 and 8, respectively. MLR and residual mass of CBPB, values of variance analysis on MLR and residual mass of CBPBs with different densities are shown in Tables 4 and 5, respectively. It can be found that values of peak MLR (PMLR) and average MLR (AMLR) decreased with density of CBPBs increasing. MLR of CBPBs significantly decreased with the increase in density from 0.7 to 0.8 g/cm³ and decreased with further increase in density. It should be also noted that the effect of density on PMLR and AMLR was significant at 0.05 level, which is due to the fact that the presence of cement hydrate layer
of low-flammability prohibits degradation of Chinese fir particles, and it further causes remarkable reduction in MLR. It is well consistent to the reduction in both PHRR and THR as displayed in Figs. 3 and 6, respectively. As similar as the trend of HRR, EHC and THR of CBPBs, increasing the concentration of Chinese fir particles leads to a slight increase in PMLR.

As illustrated in Fig. 8 and Table 4, residual mass of CBPB remarkably increased (from 19.58 to 64.67%) when increasing the density. This was because the cement-wood ratio applied in this study was 1.5 and combustion of Chinese fir particles can be effectively prevented by cement hydrate layer when increasing cement dosage and the density of CBPBs. Cement hydrate layer was thick enough to remain intact and prevents the further combustion of Chinese fir particles during the combustion process (Yu et al. 2016). In addition, the effect of density on residual mass of CBPBs was significant at 0.05 level as listed in Table 5. The reason was that cement as binder relatively evenly distributed on the surface of wood particles, and pore between wood particles reduced with increasing density. Decreasing of porosity of CBPBs leads to improvement in fire-retardant performance. Therefore, the effect of density on residual was significant as expected.

### 3.6 COY and CO$_2$Y

Figures 9 and 10 illustrate CO and CO$_2$ production rate of CBPB with different densities. The gas products released by decomposing CBPB depend on chemical nature of organic constituents, oxygen availability and fire temperature (Babaukas and Parker 1987; Harada 2001; Mouritz et al. 2006; Lee et al. 2011). As illustrated, Chinese fir particles began to undergo pyrolysis and charring, accompanied by a large amount of flammable gas generation once exposed to fire. CO production rate elevated with the further charring of Chinese fir particles until HRR of CBPBs increased to the peak value (Fig. 2). CO$_2$ production rate of CBPBs significantly increased.

### Table 4 Mass loss rate (MLR) and residual mass of CBPBs under different density conditions.

| Preset density (g/cm$^3$) | Peak MLR (g/s) | Average MLR (g/s) | Residual mass (%) |
|---------------------------|---------------|-------------------|------------------|
| 0.7                       | 0.176±0.01    | 0.068±0.008       | 19.58±2.50       |
| 0.8                       | 0.110±0.008   | 0.024±0.007       | 58.40±3.75       |
| 0.9                       | 0.077±0.001   | 0.028±0.005       | 61.51±4.23       |
| 1.0                       | 0.100±0.01    | 0.027±0.004       | 64.67±3.12       |

### Table 5 Values of variance analysis on peak mass loss rate (PMLR), average mass loss rate (AMLR) and residual mass of CBPBs with different densities.

| Parameter         | Source   | SS    | DF  | MS  | F    | P-value | F$_{crit}$ | Sig. |
|-------------------|----------|-------|-----|-----|------|---------|------------|------|
| PMLR              | Interblock | 1.08  | 1   | 11.08 | 116.7 | 3.72×10$^{-5}$ | 5.9874 *  |      |
|                   | Intraclass | 0.06  | 6   | 0.01 | 50.0 | 116.7 | 3.72×10$^{-5}$ | 5.9874 *  |      |
|                   | Sum       | 1.14  | 7   |     |      |         |            |      |
| AMLR              | Interblock | 1.32  | 1   | 1.32 | 154.8 | 1.65×10$^{-5}$ | 5.9874 *  |      |
|                   | Intraclass | 0.05  | 6   | 0.01 | 50.0 | 116.7 | 3.72×10$^{-5}$ | 5.9874 *  |      |
|                   | Sum       | 1.37  | 7   |     |      |         |            |      |
| Residual mass     | Interblock | 5038.1| 1   | 5038.1 | 22.60 | 0.003 | 5.9874 *  |      |
|                   | Intraclass | 1339.3| 6   | 223.2 |      |        |            |      |
|                   | Sum       | 6337.4| 7   |     |      |         |            |      |

Note: * means significant at 0.05 level.
and reached to the peak value in the meantime. CO₂ production rate of CBPBs exhibited the same varying pattern as compared with the HRR curves of CBPBs. On the contrary, CO production rate of CBPBs increased to the peak value in prior to the time to peak HRR and CO₂ production rate. After that, CO production rate of CBPBs decreased to the lowest value when HRR and CO₂ production rate rise to the peak value.

Figure 11 shows COY and CO₂Y of CBPBs with different densities. Results of variance analysis on CO and CO₂Y of CBPBs with different densities are shown in Table 6. It indicated that the effect of density on CO and CO₂Y of CBPB were significant at 0.05 level. The reason underlying the phenomena was that increase in density increased the incomplete combustion of CBPBs, further resulting in the increased generation of CO and decreased production in CO₂ during the cone calorimeter test. In addition, the average COY and CO₂Y of CBPBs increased with density increasing from 0.7 to 0.8 g/cm³ and decreased with the further increasing of density to 1.0 g/cm³. Increased COY/CO₂Y also indicated the incomplete combustion of CBPBs with increased density, which can be attributed to the elevated compaction rate of Chinese fir particles in CBPBs with increased density. The mixture made from cement hydrates and Chinese fir particles exhibits a poor thermal conductivity, thus it is hard to transfer heat from heat source in the cone calorimeter at a great lick. On that basis, the pyrolysis and charring of Chinese fir particles were inhibited. Furthermore, cement hydrate layer on the Chinese fir particles was thick enough to effectively prevent Chinese fir particles from sharply combusting at the cement-wood ratio of 1.5 as reported in our previous research (Yu et al. 2016). Elevated density of CBPBs leaded to the incomplete combustion of CBPBs and further resulted into increased the generation of CO.

Additionally, a large amount of CaCO₃ was generated during the hydration of cement (Jorge et al. 2004; Frybort et al. 2008). The decomposition of CaCO₃ occurred when the temperature reaches to 530°C. Therefore, the CO₂ production obviously increased with increasing density of CBPBs from 0.7 to 0.8 g/cm³. However, CO₂Y of CBPBs decreased with further increase in density. It can be attributed to the elevated compaction rate of Chinese fir particles in the CBPBs with high density, which prevents wood particles from sharply combusting.

Fig. 9 CO production rate of CBPBs under different density conditions.

Fig. 10 CO₂ production rate of CBPBs under different density conditions.

Fig. 11 Average COY and CO₂Y of CBPBs under different density conditions.

Table 6 Values of variance analysis on yields of CO (COY) and CO₂ (CO₂Y) of CBPBs with different densities.

| Parameter | Source | SS  | DF | MS  | F    | P-value | F crit. | Sig.  |
|-----------|--------|-----|----|-----|------|---------|---------|-------|
| COY       | Interblock | 1.34 | 1  | 1.34 | 160.6 | 1.48×10⁻¹ | 5.9874  | *     |
|           | Intraclass| 0.05 | 6  | 0.01 |       |         |         |       |
|           | Sum     | 1.39 | 7  |      |       |         |         |       |
| CO₂Y      | Interblock | 0.52 | 1  | 0.52 | 22.0  | 0.003   | 5.9874  | **    |
|           | Intraclass| 0.14 | 6  | 0.02 |       |         |         |       |
|           | Sum     | 0.66 | 7  |      |       |         |         |       |

*means significant at 0.05 level and ** means not significant at 0.05 level.
4. Conclusions

This study investigated the effects of density of CBPBs which were fabricated using Chinese fir particles processing residues on the combustion performance of CBPBs. Combustion characteristics of CBPBs were measured in terms of TTI, HRR, EHC, THR, MLR, and residual mass to evaluate the combustion performance of CBPBs. The experimental results revealed that the TTI of CBPBs was remarkably increased when increasing the density of CBPBs to 1.0 g/cm³. The corresponding FPI increased from 0.14 to 6.23 s/(kW/m²) when the density of CBPBs elevated. Increasing the density of CBPBs from 0.7 to 1.0 g/cm³ further reduced PHRR, AHRR, AEHC and THR of CBPBs, respectively. AMLR of CBPBs with high density was also decreased to 40.9%. Additionally, residual mass of CBPBs was significantly increased when increasing the density. Both COY and CO2Y of CBPBs was increased with elevation in the density. The effect of density of CBPBs on PHRR, TTI, FPI, MLR and yields of CO and CO2 were significant as obtained from ANOVA analysis. This work contributes to in-depth understanding the effect of density of CBPBs on corresponding combustion performance of CBPB, thus providing useful information for the recycling utilization of wood processing residues.

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