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Influence of particle size and addition of recycling phenolic foam on mechanical and flame retardant properties of wood-phenolic composites

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HIGHLIGHTS

- Recycling PF particles can be reused with wood fibers for flame retardant panels.
- A striking decline in thickness swelling was noted after adding PF particles.
- Mechanical and thermal properties were affected by size and ratio of PF particles.
- Optimal particle size and addition amount were 80–120 mesh and wt 30%, respectively.

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ABSTRACT

To recycle the thermoset phenolic foam (PF) wastes, a new flame-retardant panel was developed using milled PF particles and natural wood fibers (WB). PF particles were smashed into three particle size, pre-modified and blended with the sizing fibers in five wt% contents (0, 10, 20, 30, 40%). Each type of mixtures was hot-pressed at same temperature. Physical, mechanical and flame-retardant properties of WB-PF composites were investigated. The mechanical properties of WB-PF composites were found to be rapidly declined with the increasing proportion and size of PF particles. There was also a progressive decrease in thickness swelling for the boards with increasing addition of PF particles. The ultimate fire-retardant property of the boards was remarkably enhanced with more addition and smaller size of PF particles. Among the WB-PF composites, panel with 30 wt% of PF particles had optimum results. The final board with good physical-mechanical and fire-retardant properties can find application in fields like muti-functional furniture, construction, house ware, etc.

1. Introduction

Thermosetting composites are widely used in a range of applications such as vehicles, ships and constructions [1]. With the wider application and green energy concept deeply rooted in the public, their recycles are becoming increasingly important and seen as a hot topic for both the government and businesses [2]. Phenolic foam (PF) panel as a thermoset composite, with excellent properties, e.g. light weight, fire-proof, good mechanical strength [3], thermal and acoustic insulation, especially the non-burning as well as less smoke during combustion [4], has been favored and admired by the China government as foam core materials in the thermal insulation of sandwich constructional structure in recent 10 years. Generally, these kinds of sandwich panels were constructed with a thick foam core and two thin boards as the face sheets. The foam core used in thermal insulation buildings was with the common foam thickness between 30 mm and 100 mm [5] and its mean mass density commonly 40.0 kg/m^3 to 80.0 kg/m^3 [6].

However, a large amount of chunks and scrap wastes of PF panels were generated during the process of sizing production, transportation and manual handing. As a thermosetting material, in the past years, the PF chunks were be incinerated for energy recovery or be disposed of in landfill, which would produce lots of harmful gases or result in environmental pollution problems. With economic development, the way of recycling process could be fundamentally divided into two categories: One was mechanical grinding to reduce the particle sizes as fillers or as component of composite products; and the other was thermal processes to break the crushed aggregates into lower molecular weight organic substances (liquids and gases) and potentially to be used as a raw material for further chemical processing [7–10]. However, the pyrolysis processes were generally more complicated and would

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need further processing for the organic mixtures to be purified and refined in successive procedures, which seemed relatively complex and likely to result in the final products with high costs.

Therefore, the method of mechanical grinding was feasible and relatively efficient to reuse the PF wastes as fillers. In fact, the low density PF chunks were generally smashed into particles and reused in the production for same kinds of PF panels, or as a filler of lightweight concrete according to certain proportions, which did not fully take advantage of its material properties. China patents [11,12] disclosed a method for PF scraps to produce new kinds of PF panels. Particles as fillers were added into the process of preparation of composites along with other modifiers. The highest addition ratio of the PF particles was less than wt 5% of the preparation system in order to ensure an appropriate mixture viscosity, in that the thermoset particles would absorb more liquid resin and so increase the viscosity of the molding compound. Therefore, the biggest shortcoming of this method was that the addition proportion of PF particles was relatively small and a set of mixing equipment for the slurry and particles was needed to ensure uniformity.

Phenol-formaldehyde thermosetting foam materials commonly contained a large number of hindered phenolic sites, flame retardants, char-forming agents and synergistic agents, which ensured the materials relatively high temperature resistance properties [13,14]. Typically the finer graded fractions were particles and contained a higher proportion of filler and polymers that same as the original composites. Those wastes in the form of fine powders can be reused as functional filler additives when the cured material had good strength [15,16]. Wood fibers (WB) are a kind of natural cellulose resources which are widely used in the modern composite industry for their specific characteristics [17]. However, as wood fibers were polar, hydrophilic and flammable [18], while plastic particles were relatively non-polar and hydrophobic, the incompatibility and uniformity of wood fibers and plastics were difficult to reach without surface modification of the thermoset plastic particles. Furthermore, more PF particles were expected to incorporation into wood fiber matrix in order to make maximum use of the thermoset plastics, which would decrease the combination between PF particles and wood fibers, and thus further reduced the mechanical properties of composite panels significantly. More recent studies have shown that grafting and coupling agent modification treatment of the raw materials can increase the bonding and thereby improve the mechanical properties of the final composites [19,20].

Herein, the main objective of this research is to demonstrate that low density rigid PF wastes can be recycled into manufacturing fire-retardant medium density fiberboard (MDF) as a partly alternative to flame retardants. In order to reduce the potential production costs and obtain excellent physical and fire-retardant properties of the final functional wood-based composite boards, a series of PF particles were modified and reused with different additive amounts in this paper. Further the mechanical and flame retardant properties of the experimental panels were also evaluated.

2. Materials and methods

2.1. Materials

Wood (*Eucalyptus* spp.) fibers were obtained by hot-grinding process from Fenglin Wood Industry Group Co., Ltd, Guangxi, China. The detailed fiber morphology was approximately 2.4–5.6 mm in length and 15–30 μm in width. All the fibers were dried to a moisture content of 4–6% and reserved in a sealed plastic container for manufacturing the WB-PF composite panels. The PF panels in fragment shape, with mean mass density of 58.6 kg/m^3 were recycled from factory of Tengzhou Huahai New Thermal Insulation Material Co., Ltd, Shandong, China. Table 1 shows the material properties of the PF sample panels used for the study. The properties were partly provided by the PF manufacturer and the mechanical properties, limiting oxygen index (LOI) and maximum smoke density (MSD) were obtained according to ISO 1209-2007, ISO 1926-2009 and the Chinese National Standard GB/T 2406.2-2009, GB/T 8627-2007, respectively. Urea-formaldehyde resin adhesive (UF) as the interface adhesion, was supplied by Fenglin Wood Industry Group Co., Ltd, Guangxi, China. The viscosity was 180–200 mPa·s (25 °C), the solid content and pH were 50–52% and 7.6–8.0, respectively. The curing condition included a high temperature of 100 °C and time duration for 60 s. Diphenyl-methane-diisocyanate (MDI, I-BOND® MDF EM 4330) as the PF particles modifier, was provided by Huntsman, Shanghai, China. The density was 1.23 g/cm^3 and the viscosity was 275 cps (25 °C). The resin color was dark brown and its solid content was 100%.

Table 1
Physical and mechanical properties of recycling PF panel in this work.

Sample	Physical properties			Mechanical properties (MPa)	
	ρ (kg/m^3)	LOI (%)	MSD (%)	Flexural strength	Tensile strength
PF	58.6	48.2	2.5	0.42	0.18

2.2. Samples preparation

The PF chunks were douched by tap-water to wash the clay and dirt on the panel surface, after drying at 60 °C for 4 h in a conventional circulating air oven, the chunks were broken to pieces and further smashed into particles in a mechanical hammer mill as shown in Fig. 1. The particles were classified into three categories by passing the sieves as shown in Table 2.

Reference to the current process of flame retardant MDF production [21], urea-formaldehyde resin adhesive (UF) was sprayed to fibers and the adhesive consumption was 16% on account of the oven dry weight of wood fibers, then the glued fibers were carefully dried to remove the moisture in an oven to ensure the moisture content of fibers was 8%–10%. Prior to compounding the PF particles with the glued fibers, the PF particles were modified by the sprayed diphenyl-methane-diisocyanate (MDI), and the additive amount was 2% by oven mass of the PF particles. The specific operation was that a certain mesh size of PF particles was stirred in a mechanical mixer at 75 rev/min, and at the same time MDI modifier was sprayed so that the modifier could fully blended with the PF particles. Lastly, the well-blending mixtures of fibers and PF particles were paved to form a fiber-mat for hot-pressing. WB-PF composite panels with three particle sizes and four wt% contents (10, 20, 30, 40%) were then fabricated by a self-designed mold with a dimension of 350 mm × 350 mm × *h* mm (*h* was the thickness of fiber mat). The hot-press temperature, time and pressure was 180 °C, 5.5 min and 3.5 MPa, respectively. The target density was calculated as 800 kg/m^3 and thickness of 12 mm. The sample design of flat pressed panels with milled PF particles is present in Table 3. All the composites were sanded to remove the pre-cured layers and then cut to standard size prior to testing. The WB-PF composites thus prepared with milled PF particles in different particle sizes and addition proportions are shown in Fig. 2.

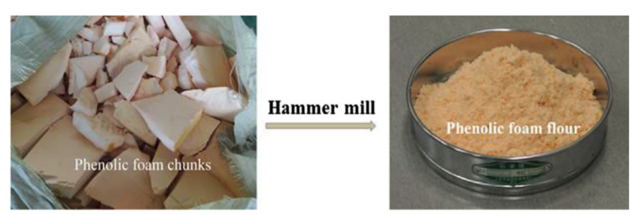

Fig. 1. Phenolic foam chunks and flours.

Table 2
Particles classified into three categories.

Category	Size class interval	
	Mesh	μm
40–60*	40–60	250–380
60–80	60–80	180–250
80–120	80–120	120–180

* 40–60 means that the particles passed the 40 mesh but didn't pass 60 mesh.