Thermal Insulation Boards from Bamboo Paper Sludge

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This study was conducted to evaluate the properties of insulation boards made from bamboo paper sludge and fly ash floating beads. An orthogonal test design was applied to study the effects of certain factors on the properties of the insulation boards. The results indicated that the sequence of significant effect of factors on the properties of the composite boards was particle size of bamboo paper sludge, thickness of boards, and weight ratio of sludge to fly ash floating beads. The verified optimal conditions were confirmed to be 20 to 40 mesh, 80:20, and 14 mm, representing the particle size of bamboo paper sludge, weight ratio of sludge:fly ash floating beads, and thickness of boards, respectively. The thermal conductivity of the bamboo paper sludge and fly ash floating beads insulation boards was measured and suggested that both insulation boards had thermal conductivity values ranging from 0.12 to 0.165 W/mK, which is close to the conventional insulation material lightweight concrete.

Keywords: Bamboo paper sludge; Fly ash floating beads; Insulation boards; Thermal conductivity

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INTRODUCTION

The forest products industry relies heavily on natural forests, but the pressure to reduce forest harvesting is forcing the industry to look for alternative fiber resources (Geng *et al.* 2007). To a certain extent, the utilization of bamboo can ease the shortage of wood resources. Bamboo plants are a plentifully available resource and play a large role in socio-economic development (Yeasmin *et al.* 2015). There are around 1200 to 1500 bamboo species, under 60 to 70 genera, all over the world (Alam *et al.* 2015). Bamboo is fast-growing and a high-yield renewable resource. It has slender fibers, which can be as important a raw material as wood in the pulp and paper industry. However, like wood, it produces large amounts of solid waste materials. Paper mill sludge is a waste residue from pulp and paper processing, or paper recycling. Sludge can cause serious pollution problems when it is not appropriately treated and disposed of. Traditionally, paper mill sludge has been disposed of by means of land filling, land spreading, composting, incorporation into cement, and incineration (Hamzeh *et al.* 2011; Huber *et al.* 2014). No matter which treatment is adopted, there remain the issues of secondary pollution and energy consumption. Therefore, methods to dispose of, or make use of, sludge have been a challenge for the pulp and paper industry.

Research papers published in recent years have depicted multiple uses for paper mill sludge, including as a material in medium density fibreboards (MDF) (Migneault *et al.* 2011a,b) and particleboards (Taramian *et al.* 2007); incorporated in building materials such as cement (Naik *et al.* 2004), brick (Andreola *et al.* 2005), ceramic (Wiegand and Unwin 1994), and concrete (Chun and Naik 2005); and converted into ethanol (Prasetyo *et al.* 2011). Although authors have often reported some difficulties in areas such as panel product properties, the results have generally been promising.

Fly ash floating beads are bead-like particles that are emitted as waste with coal ash water. These beads are light and have excellent insulation, high temperature resistance, wear resistance, water resistance, and many other advantages. Fly ash floating beads are a new type of functional material and have shown broad application prospects in building materials, plastics, rubber, paint, chemicals, metallurgy, marine engineering equipment, aerospace, and other fields (Du *et al*. 2014). However, no study has yet focused on the possibility of using a mixture of bamboo paper sludge and fly ash floating beads as materials for new thermal insulation boards. This application is interesting because paper sludge and fly ash floating beads are wastes from paper and electric power industries.

In this study, the possibility of using sludge from bamboo paper manufacturing and fly ash floating beads as materials for the production of new thermal insulation boards was examined. The effects of process conditions on thermal conductivity, blending strength, and thickness swelling properties of composite boards made from the mixture of sludge and floating beads using urea formaldehyde resin as a composite binder were also evaluated.

EXPERIMENTAL

Materials

Bamboo (*Neosinocalamus affinis*) paper secondary sludge (SS) (Fig. 1) was collected from the Guizhou Chitianhua Paper Co., Ltd. (Guizhou, China). Fly ash floating beads, power plant emissions of fly ash from waste residue, were purchased from Hefei Power Station (Hefei, Anhui, China) (Fig. 2). The characteristics of the fly ash floating beads used are given in Table 1. The commercial urea formaldehyde (UF) resin in this study was supplied by the Guangda Wood-Based Panel Co., Ltd. (Hefei, Anhui, China). The resin was water dispersed with a solid content of 50%, viscosity of 50 cP, and pH of 6.62. Ammonium chloride (NH_4Cl) was added to urea-formaldehyde adhesive as a hardener at a level of 1% (dry resin basis).

Fig. 1. Bamboo paper sludge

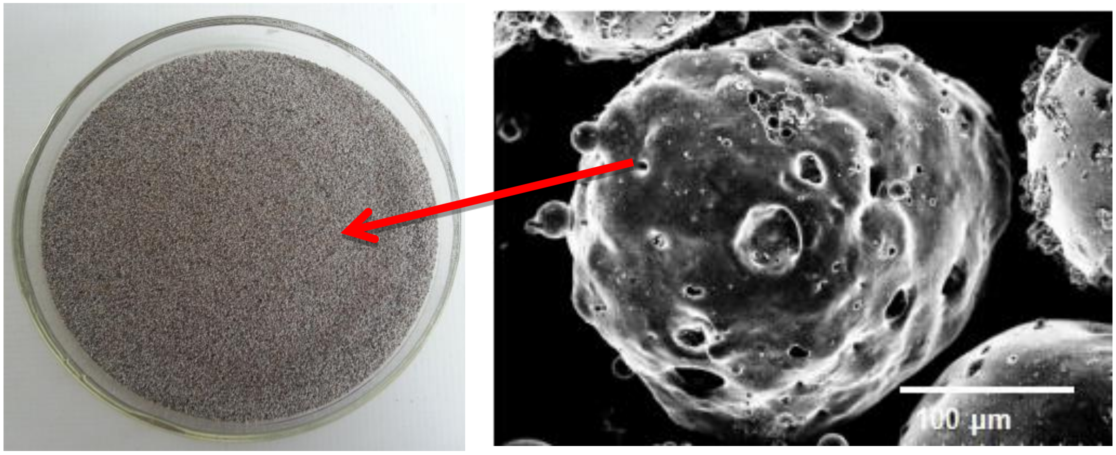

Fig. 2. Scanning electron micrograph of fly ash floating beads

Table 1. Characteristics of Fly Ash Floating Beads (Du *et al.* 2014)

Particle Size (µm)	Bulk Density (g/cm^3)	Melting Point (°C)	Thermal Conductivity (W/mK)
1 to 300	0.20 to 0.35	1400 to 1500	0.85

Methods

Bamboo paper sludge characterization

Bamboo paper sludge, ground to a fine particle size (40 to 60 mesh), was placed in an airtight container to homogenize the moisture content for subsequent chemical analyses. Cellulose content was determined using Kürschner and Hoffer's nitric acid method (Browning 1967). Pentosan content was obtained according to GB/T 2677.9 (1994). Total lignin content was determined using the Klason method according to GB/T 2677.8 (1994; acid-insoluble lignin) and quantified using absorption spectroscopy at 205 nm according to GB/T 10337 (2008; acid-soluble lignin). Extractives contents were determined *via* successive extractions using an organic solvent mixture (ethanol/toluene) according to GB/T 2677.6 (1994). Ash content was obtained according to GB/T 742 (2008). Two replicates were conducted for chemical analysis.

Fiber size and distribution were measured according to the method proposed by Liu *et al.* (2009). Appropriate amounts of distilled water and bamboo paper sludge powders (oven-dried) were mixed in a centrifuge tube. Vials containing solutions were then sealed tightly and vortexed for 1 min, and a drop of the suspension was observed under an optical microscope.

Bamboo paper sludge preparation

Bamboo paper sludge is very sensitive to fungal attack. Therefore, the sludge was immediately dried in an oven at 100 °C for 24 h to adjust it to a specific moisture content (9%). It was then ground using a laboratory mill to obtain the desirable bamboo paper sludge size.

Board preparation

The test boards were processed according to an orthogonal design of three factors and three levels, as shown in Table 2. The boards were made with 20 to 40, 40 to 60, or 60 to 80 mesh for the particle size of bamboo paper sludge. Weight ratios for sludge:fly ash floating beads were 100:0, 90:10, or 80:20. The boards were 14, 16, or 20 mm thick. Urea-formaldehyde resin (UF) (15%, dry-mass resin on dry-mass sludge and floating beads) was mixed with 1% ammonium chloride catalyst (dry-mass catalyst on dry-mass resin). Mats were hand-formed in a 320 × 320 mm mold. The boards' target density was 800 kg/m^3, pressing temperature was 110 °C, and pressing cycle was 12 min (including closing and opening times).

Table 2. Orthogonal Test Design with Three Factors and Three Levels

Level	Particle Size of Bamboo Paper Sludge (mesh)	Weight Ratio for Sludge:Fly Ash Floating Beads	Thickness of Boards (mm)
1	40 to 60	100:0	14
2	60 to 80	90:10	16
3	20 to 40	80:20	20

Board testing

Prior to testing the physical and mechanical properties, the boards were conditioned at 20 ± 5 °C and 65 ± 5% relative humidity (RH) until they reached equilibrium moisture content. The modulus of rupture (MOR), modulus of elasticity (MOE), and thickness swelling (TS) after soaking for 24 h in water were measured according to the Chinese Industrial Standard (GB/T 11718 (2009)).

Thermal conductivity was measured at room temperature and normal pressure using the steady-state bi-substrate technique (ASTM C177-13 (2013)). The basic principle of operation was to create a one-dimensional axial heat flow through the sample to utilize the Fourier equation of heat conduction, as seen in Eq. 1,

$$q = -\kappa A \frac{dT}{dx} \tag{1}$$

where q is the steady-state flow (heat flux) (W), κ is the thermal conductivity (W/mK), A is the cross-sectional area of the sample (m^2), and $-dT/dx$ is the temperature gradient (Mamatha *et al.* 2014). A suitable heat flow meter was used for thermal conductivity measurements. The sample, with a cross section of 300 mm × 300 mm, was sandwiched between a hot and a cold metal plate. The hot plate acted as both temperature sensor and heat source. Following the measurements of heat flux and temperature difference across the specimen thickness, thermal conductivity was determined using Eq. (1).

RESULTS AND DISCUSSION

Bamboo Paper Sludge Characteristics

The chemical compositions of SS samples are shown in Table 3. Cellulose and pentosan (part of the hemicelluloses) contents were roughly similar for the three SS samples. Low cellulose and pentosan contents were found in SS. This result was in agreement with previous reports (Pervaiz and Sain 2011; Su *et al.* 2013) and is due to the fact that SS contains few wood fibers. The lignin content was relatively high in SS, particularly in wood pulp TMP SS. This could be explained by the fact that lignin is found not only in fiber cell walls, but also in other chemical by-products, such as polyphenols (Migneault *et al.* 2010, 2011a,b). The bamboo paper kraft SS had the lowest extractives content, and the wood pulp TMP SS sample contained a very high extractives proportion.

Ash in SS comes from non-woody materials rejected in wastewaters at any stage of pulp and paper processing, such as dirt from chip cleaning, papermaking chemicals, papermaking fillers, or rejected inert solids (Jesús 2008). The ash content was higher in the bamboo paper kraft SS and wood pulp kraft SS than in the wood pulp TMP SS. The kraft process uses high quantities of chemicals for pulping, which partly explains its higher ash content in SS. The wood pulp TMP SS had the lowest ash content because no chemicals were used in the pulping process.

Table 3. Chemical Composition of Secondary Sludge (SS) (Oven-Dry Weight Basis)

Parameter	Bamboo Paper Secondary Sludge (BSS) from	Wood Pulp Secondary Sludge (WSS)	
	Kraft	Kraft[a]	TMP[a]
Ash content (%)	36.7	41.3	12
Lignin (%)	28.7	36.4	50.2
Extractives (%)	2.6	7.9	21.5
Pentosans (%)	3.6	3.4	3.0
Cellulose (%)	18.1	18.9	19.7

*Data for wood pulp sludge from kraft[a] and TMP[a] came from Migneault *et al.* (2011a,b)
TMP, thermomechanical pulp

Figure 3 shows the fiber length distribution in the bamboo paper secondary sludge. The fiber average length was 0.21 mm. As illustrated in Fig. 3, the bamboo paper SS contained more short fibers, approximately 74% of which were less than 0.2 mm. In addition, most of the fibers in bamboo paper SS were broken (Fig. 4).

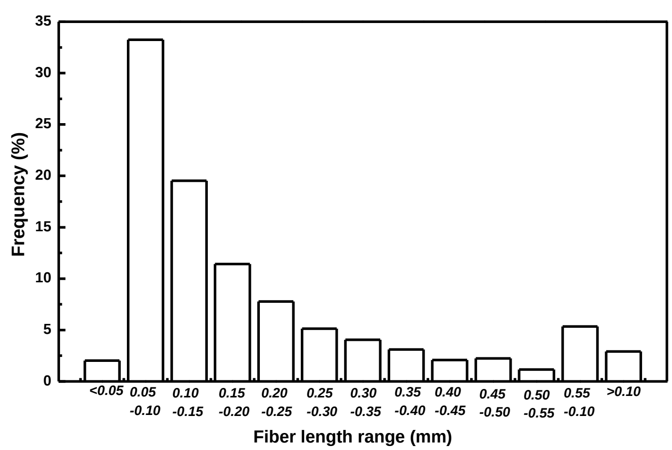

Fig. 3. Length distributions of fibers in bamboo paper secondary sludge

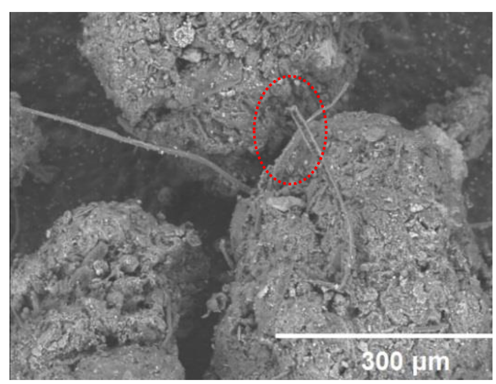

Fig. 4. Scanning electron micrograph of bamboo paper sludge

Optimization of Process Conditions using Orthogonal Design

The factors influencing the physical and mechanical properties of the composite boards, *i.e.*, the particle size of bamboo paper sludge, weight ratio for sludge:fly ash floating beads, and the thickness of the boards, were investigated using an orthogonal test (three factors and three levels), as shown in Table 2. The MOR, MOE, 24 hTS, and thermal conductivity were employed as evaluations; the results are listed in Table 4.

It can be concluded that the sequence of significant effect of these factors on the physical and mechanical properties of the composite boards is as follows: particle size of bamboo paper sludge > thickness of boards > weight ratio of sludge and fly ash floating beads, according to the range and variance analyses. The optimal conditions for the physical and mechanical properties of the composite boards were confirmed to be 20 to 40 mesh, 80:20, and 14 mm for the particle size of bamboo paper sludge, weight ratio of sludge:fly ash floating beads, and thickness of boards, respectively.

Table 4. The Result of the Orthogonal Test

Test Number	Factors and Levels			Evaluation Value			
	Particle size of bamboo paper sludge (mesh)	Weight ratio for sludge:fly ash floating beads	Thickness of boards (mm)	MOR (MPa)	MOE (MPa)	24hTS (%)	Thermal conductivity (W/mK)
1	40 to 60	100:0	14	1.905	975	2.18	0.125
2	40 to 60	90:10	16	2.012	860.33	1.82	0.141
3	40 to 60	80:20	20	2.122	1236.67	1.46	0.165
4	60 to 80	100:0	16	1.469	645.72	1.48	0.142
5	60 to 80	90:10	20	1.487	396.45	1.34	0.147
6	60 to 80	80:20	14	1.98	729	1.2	0.155
7	20 to 40	100:0	20	2.2575	871.5	2.14	0.12
8	20 to 40	90:10	14	3.292	1241	1.98	0.134
9	20 to 40	80:20	16	2.846	1246.5	1.79	0.137
K1	10.85	11.7	12.65				
K2	9.45	11.85	11.85				
K3	15.7	12.45	11.5				
R	6.25	0.75	1.15				

Effects on MOE and MOR

The effects of different factors on MOR and MOE are illustrated in Fig. 5. Following an increase in sludge particle size in the panels, there was a resulting decrease in MOE and MOR. The contact area of raw materials increased as the particle size became finer, and tiny particles filled the gaps between the larger particles. The space was very limited after it was filled with adhesives. In the process of hot pressing, the moisture could not completely escape from the inner spaces, and the UF did not glue completely. The internal moisture gradient can produce impulse force to the adhesive, which can give rise to a slight stratification of the panel. Therefore, the MOE and MOR both decreased. Also, an increase in the weight ratio of sludge and fly ash floating beads led to an increase in MOE and MOR. This was due to fly ash floating beads. Fly ash floating beads are mostly composed of silicon-rich oxide, and their mechanical properties are better than those of bamboo paper sludge. With the increase in fly ash floating beads, the MOE also showed an increasing trend. Along with increases in board thickness, the adhesive of the core layer did not completely bind, which led to decreases in the MOR and MOE.

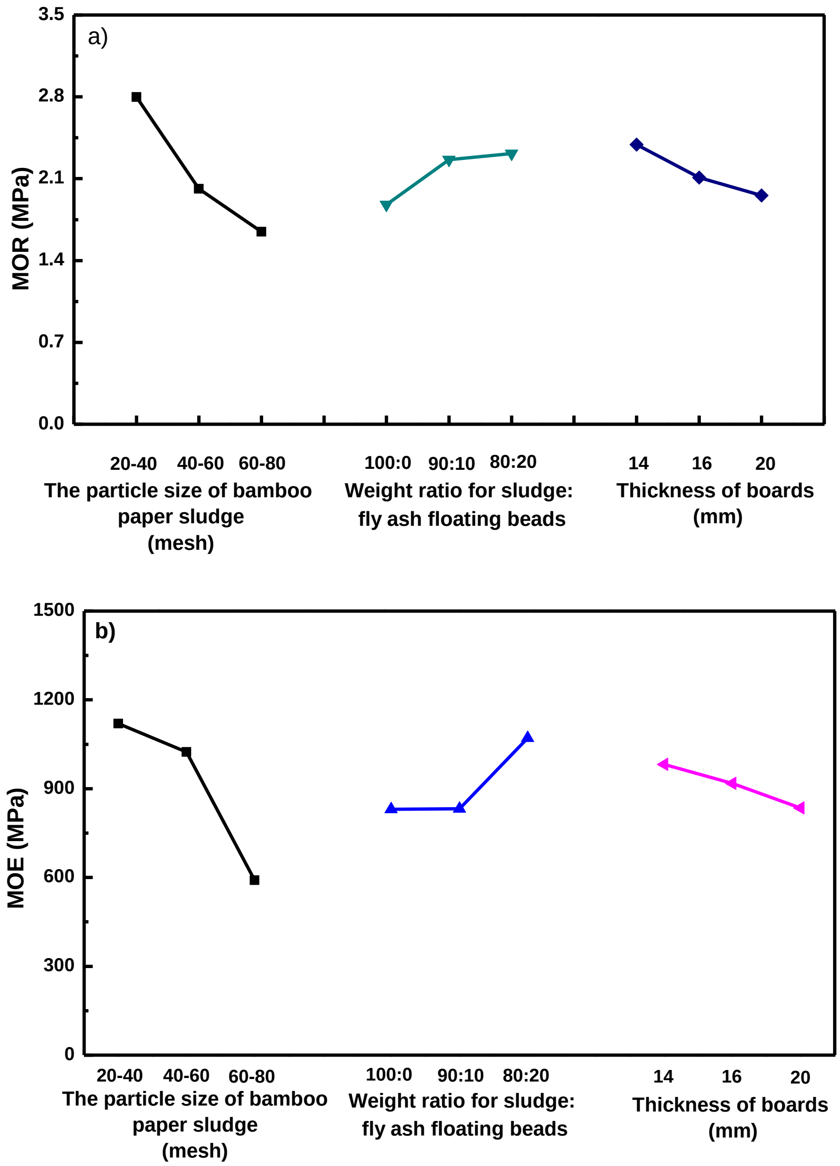

Fig. 5. Effects of different factors on MOR and MOE

Effects on 24hTS

Various factors significantly affected the 24 hTS. There was a noticeable trend of decline when sludge particle size increased (Fig. 6). The contact area of raw materials increased as the bamboo particle size became finer, which caused low porosity. Thus, thickness swelling demonstrated a downward trend.

Increases in the weight ratio of sludge and fly ash floating beads led to decreases in 24 hTS. This is because fly ash floating beads are mostly composed of silicon-rich oxide, which possesses hydrophobicity. With increases in board thickness, moisture needed a longer time to permeate into the core layer. Consequently, the 24 hTS had a downward trend.

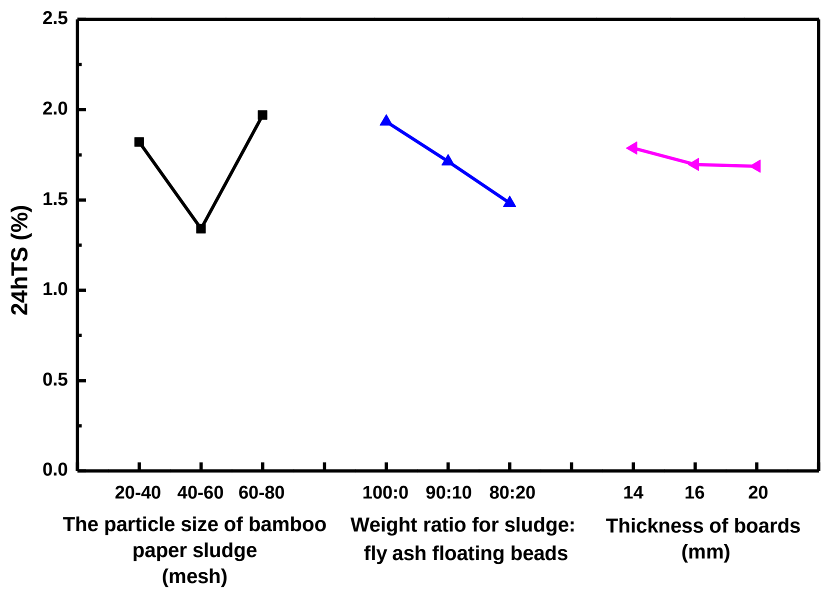

Fig. 6. Effects of different factors on 24 hTS

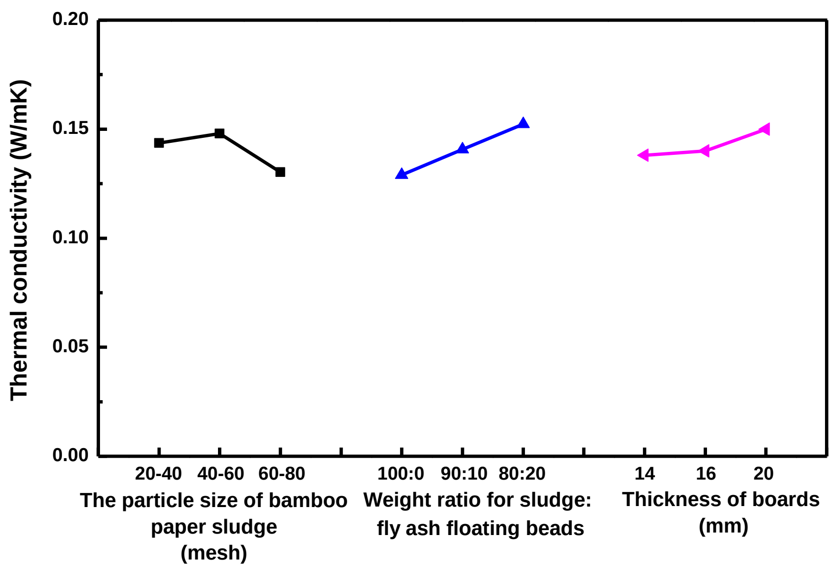

Fig. 7. Effects of different factors on thermal conductivity

Effects on Thermal Conductivity

Thermal conductivity trends are presented in Fig. 7. With increases in the three factors, the coefficient of thermal conductivity also increased. The particle size became smaller as the number of particles increased. When the interior becomes relatively close-grained and has a low porosity, the air thermal conductivity decreases. Theoretically, thermal conductivity should show a decreasing tendency with an increase in the weight ratio of fly ash floating beads. However, the situation was the opposite in this study. This may have been because the fly ash floating beads filled the pores, causing an increase in thermal conductivity. This trend requires follow-up experiments to verify. As is currently known, the thermal conductivity is closely related to the free path of gas molecules. Thus, with increases in board thickness, the collision free path of gas molecules more than doubles, leading to an increase in thermal conductivity.

Table 5 compares the thermal conductivity of boards made from the bamboo paper and fly ash floating beads and other thermal insulation materials. It can be seen that the κ value of the composite board was close to that of lightweight concrete (Saleh 2006), solid pine wood (Zhou *et al.* 2010), coconut coir fiber boards (Khedari *et al.* 2003), and sansevieria fiber-reinforced polyster composites (Ramanaiah *et al*. 2013). Its value is slightly higher than that of coffee husk and hull boards (Bekalo and Reinhardt 2010). However, this value is far less than that of EPS and sheep wool (Asdrubali *et al.* 2015). It should be noted that materials with thermal conductivity less than 0.25 W/mK are generally seen as thermal insulations (Zhou *et al.* 2010). Therefore, it can be concluded that the bamboo paper sludge composite boards may be viewed as a suitable material for thermal insulators.

Table 5. Thermal Conductivity of Various Materials

Materials	Density (kg/m^3)	Thermal conductivity (W/mK)	References
Bamboo paper sludge / fly ash floating beads boards	800 to 845	0.12 to 0.165	
Expanded Polystyrene (EPS)	15 to 35	0.031 to 0.038	Asdrubali *et al*. 2015
Sheep wool	10 to 25	0.038 to 0.054	Asdrubali *et al*. 2015
Wood (pine)	450 to 630	0.151	Zhou *et al*. 2010
Lightweight concrete	551	0.155	Saleh 2006
Coffee husk and hull boards	734 to 747	0.110	Bekalo and Reinhardt 2010
Coconut coir fiber boards	629 to 664	0.132 to 0.144	Khedari *et al*. 2003
Sansevieria fiber-reinforced polyester composites	1410	0.132	Ramanaiah *et al*. 2013

CONCLUSIONS

1. The sequence of significant effects of factors on the physical and mechanical properties of the composite boards was found to be in the order particle size of bamboo sludge > thickness of boards > weight ratio of sludge and fly ash floating beads, according to an orthogonal test design. The verified optimal conditions for the properties of the composite boards were confirmed to be 20 to 40 mesh, 80:20, and 14 mm, representing particle size of bamboo paper sludge, weight ratio of sludge:fly ash floating beads, and thickness of boards, respectively.
2. The thermal conductivity of the boards varied between 0.12 and 0.165 W/mK and met the requirements for thermal insulators (less than 0.25 W/mK).
3. The use of a bamboo paper sludge:fly ash floating beads mixture in composite boards could help to produce inexpensive insulation materials and resolve pollution problems presented by industrial wastes. Further study is necessary to improve the mechanical properties and decrease the density of the composite board.

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