Effect of Fiber Content on Sound Absorption, Thermal Conductivity, and Compression Strength of Straw Fiber-filled Rigid Polyurethane Foams

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Rigid polyurethane (PUR) foam is one of the most important insulating materials used today in the construction industry and is the main insulation material used in the global appliances industry. This study developed rice straw fiber-filled PUF (RPUF) and wheat straw fiber-filled PUF (WPUF) and explored the morphology, sound absorption properties, heat transfer, and compressive strength of the PUF composites. The results indicated that, with the higher fiber content, more open cells were observed in SEM images of the composites. The average sound absorption coefficients (ASAC) of both WPUF and RPUF were significantly increased when 5 per hundred polyols (php) by weight and 10 php fiber contents were added. When fiber contents of 15 php and 20 php were utilized, ASAC reduced due to the tortuosity of cells and large holes in the foam. The sound absorption coefficient (SAC) first increased, then decreased, and increased finally as the sound frequency increased from 100 to 2000 Hz for the two composites. The thermal conductivities of both WPUF and RPUF first decreased and then increased as the fiber content increased from 0 to 20 php. When 5 and 10 php straw contents was added, the thermal conductivities were reduced by 25% to 50% compared to that of the pure PU form (0 php), indicating that the improved thermal insulation ability was obtained. The composite compressive strength was reduced by 19% to 28% due to the fiber addition.

Keywords: Straw fiber; Polyurethane foam; Composites; Sound absorption coefficient; Thermal conductivity; Compression strength

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INTRODUCTION

Polyurethane foam (PUF) is typically produced by the interaction between polyols and polyisocyanates through the addition of polymerization. Other additives, such as catalysts, surfactants, and foaming agents, are frequently used (Yuan and Shi 2009). PUF products can be rigid, semi-rigid, or flexible, depending on the raw material used. Rigid polyurethane (PUR) foam is one of the most important insulating materials used today in the construction industry and is the main insulation material used in the global appliances (refrigerators, freezers, *etc*.) industry (Cabulis *et al.* 2012).

The incorporation of fillers improves certain mechanical, thermal, and acoustic properties of PUF composites. Natural fibers are relatively cheap, renewable, and sustainable resources. The densities of natural fibers are similar to those of plastics and are only 40 to 50% that of glass fibers (Bledzki *et al.* 2001). Plastics can therefore be reinforced or filled with fibers without any significant effect on the density of the resulting polymer composites. Furthermore, the hydroxyl groups (-OH) on the surfaces of lignocellulosic fibers interact with isocyanate groups, leading to excellent interfacial bonding between fibers and polyurethane (Mosiewicki *et al.* 2009).

Wood flour has been used as a filler for PUF composites. Yuan and Shi (2009) developed wood-polyurethane hybrid composites containing wood flour up to 20 per hundred polyols (php) by weight. The incorporation of wood flour improved the compressive properties of PUF but diminished its tensile and flexibility properties. The thermal stability of the composites was improved with the addition of wood powders. Racz *et al.* (2009) focused on the production and characterization of lightweight PU composites reinforced with pine wood flour and showed that the strength, modulus, and storage modulus of the composites increased as the filler content increased. Mosiewicki *et al.* (2009) used wood flour as a filler in rigid polyurethane and showed that the chemical reaction between wood flour and isocyanate strongly affected the composite response to thermogravimetric tests. The compression modulus and yield strength of the PU composites decreased as the wood flour content increased. Aranguren *et al.* (2012) developed a tung oil-based polyurethane and wood flour composite and found that the incorporation of wood flour influenced the biodegradation of polyurethane foam composites.

Bast fiber has also been used to reinforce PUF composites. Bledzki *et al.* (2001) prepared reinforced polyurethane-based composites with woven flax and jute fabrics. The composites had an evenly distributed micro-void foam structure. Increasing the fiber content improved the shear modulus and impact strength. The woven flax fiber resulted in composites with better mechanical strength than woven jute fiber composites. Kuranska *et al.* (2013) fabricated rigid polyurethane foams modified with flax and hemp fibers. The mechanical and thermal properties of the final products were improved by incorporating natural fibers. Kenaf fiber-filled polyurethane foams were prepared using the free rising method. The dielectric constants and the loss tangents of the composites were studied as functions of fiber content. The dielectric constant and the loss tangent increased with increasing fiber content, indicating that both the dielectric capability and energy dissipation ability of the composites were improved (Li *et al.* 2014).

Cotton and bamboo have been used as reinforcements in polyurethane matrices to improve the sound absorption and thermal conductivity properties of the resulting composites (Büyükakinci *et al.* 2011). Tea-leaf fibers (Celebi and Kucuk 2012) were used as reinforcements in different polyurethane matrices to improve the sound absorption properties of the composites. Although the addition of tea-leaf fibers to rigid polyurethane foam yielded little contribution to the sound absorption properties of the composites, it provided a significant improvement in sound absorption.

Although many kinds of raw materials have been used to fill PUF, there have been no reports regarding PUF filled with rice or wheat straw fibers. As annual crops, abundant rice and wheat straws are produced in China. Burning the wastes is the common method of disposal. It is a problem of growing importance because the waste burning causes serious air pollution in China. In order to moderate the pressure of air pollution, it is a cost-effective method to utilize the straw wastes as a raw structural material. This study concentrated on the development of the rice straw fiber-filled PUF (RPUF) and wheat straw fiber-filled PUF (WPUF). The morphology, sound absorption properties, heat transfer, and compressive strength of PUF composites were explored.

EXPERIMENTAL

Materials

The raw materials used to prepare the foam were obtained from Dongguan Chemistry Corporation (Dongguan, China). The two parts, Part A and Part B, were mixed in equal proportions, and 100 kg/m^3 closed-cell foam was formed by the "free rising" method. Two types of straw fibers, rice and wheat, were used for manufacturing two kinds of straw fiber-filled PUF composites. Wang *et al*. (2006) used jute fiber to reinforce PU composite foam and the composite materials had a better reinforcing effect when the fiber length was 3 mm, therefore the straw fibers with a length of 1 to 3 mm were used in this study. The rice straw and wheat straw were preheated in an oven at 103 °C for 6 h to remove moisture.

Composite Preparation

The PUF samples were prepared using the free rising method. The pure PU foam and two types of composites with different mixtures were produced by mixing PU foam with rice or wheat fiber. After the appropriate weight of Part B was added to a 500-mL disposable plastic box, the fibers were added and mixed with a mechanical stirring at 3000 rpm for 10 to 15 s. Part A was added after the mixture was degassed for 120 s. The stirring was continued for the next 10 to 15 s at the same rotational speed. After Parts A and B were mixed, the forming started within 45 s and continued for a few minutes. The foam expanded to approximately 10 times its liquid volume and was cured. The cured foams were taken out from the plastic box and placed at a room temperature. The fiber contents of the forms were 0, 5, 10, 15, and 20 php. Three replicate samples were used for each measurement, and the average value was reported.

Foam Property Characterization

Morphology

The morphology of the PUF samples was examined with a scanning electron microscope (SEM) (QUANTA200, FEI, Hillsboro, OR, USA). The samples were gold-coated before scanning. The accelerating voltage was 5 kV. The SEM images were obtained at different zones on each sample.

Sound absorption measurements

The sound absorption coefficient (SAC) of composites was measured with use of an impedance tube testing system (AWA6122A, Aihua Instrument, Inc., Hangzhou, China) according to ISO 10534-1 (2011). Figure 1 shows the SAC testing system. Measuring frequency range is 90~2075 Hz.

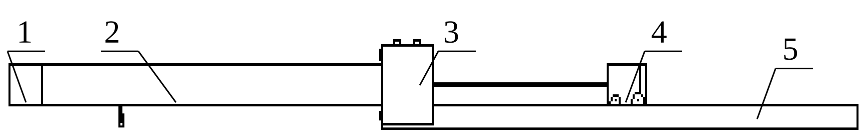

Fig. 1. Experimental setup for measuring the sound absorption coefficient of composites (1 Tested material tube; 2 Standing wave tube, with length of 1000 mm and diameter of 96 mm; 3 Sound box, with speaker power of 10 W and impedance of 6 Ω; 4 Slider; 5 Guide rail, with length of 1000 mm and min scale of 1 mm)

The composite panels were cut with a milling machine to produce acoustic samples with a diameter of 96 mm and thickness of 9 mm. Three replicates were prepared from each panel group. The reported SAC value of each panel group was the average of three independent sample data points, which were collected at 100, 200, 315, 450, 630, 800, 900, 1000, 1400, and 2000 Hz according to 1/3 octave bands frequency analysis and ISO 266 (1975).

Thermal conductivity

Three samples with a diameter of 130 mm and a thickness of 20 mm were cut from the free-raised PU foam mixtures. The thermal conductivity of each sample was measured using a TC-2/A thermal conductivity instrument (Fudan Tianxin Science and Education Instruments Co., Shanghai, China) in accordance with steady state methods for measuring the conductor coefficient of thermal conductivity (Li *et al.* 2009).

Compression test

The compressive properties of the foams were measured using a universal testing machine (AG-A10T, Chanchun Kexin Instruments Co., Changchun, China) in accordance with ISO 844 (2004). Samples were cut to a size of 50 × 50 × 50 mm (width × length × thickness). The orientation was parallel to foam rise direction. The cross-head speed was 2.5 mm/min with a load cell of 5000 N. The load was applied until the foam was compressed approximately 10% of its original thickness. Six replicates per sample were tested, and the results were averaged.

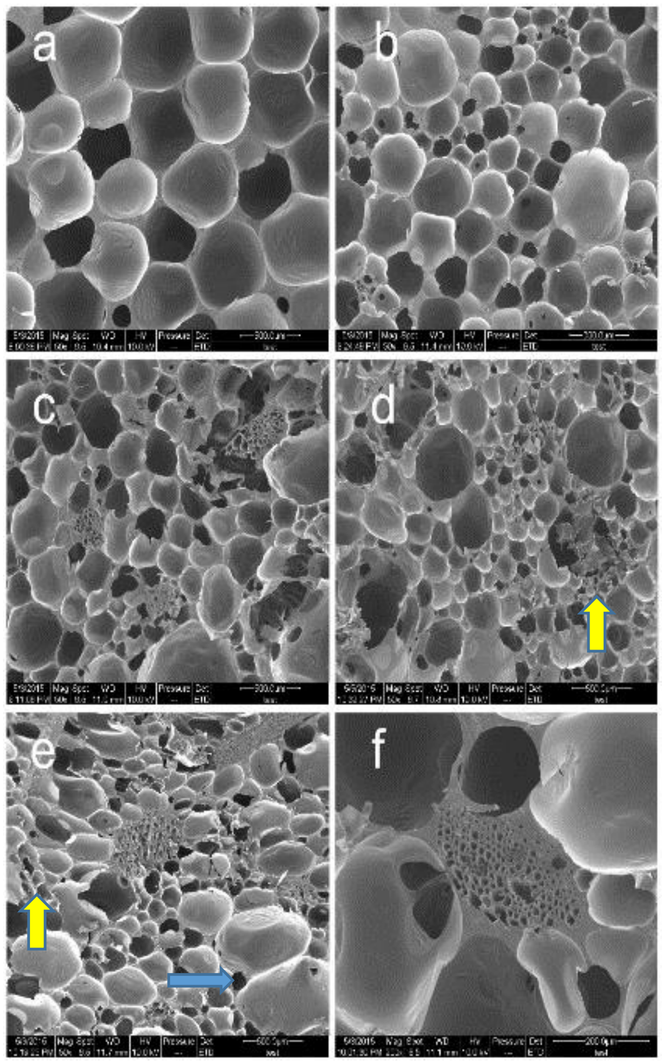

Fig. 2. SEM micrographs of WPUF: (a) blank polyurethane foam, without fiber, (b) 5 php wheat straw fiber, (c) 10 php wheat straw fiber, (d) 15 php wheat straw fiber, (e) 20 php wheat straw fiber, and (f) the cross-section of fiber between cells

RESULTS AND DISCUSSION

Morphology

The cross-sectional surfaces of WPUF samples observed in the free-rising direction are shown in Fig. 2. The blank PUF without fiber had a closed cell structure with a uniform cell sizes (Fig. 2a). However, when the fiber content was increased from 5, 10, 15, and 20 php, the cell size became smaller and non-uniform (Figs. 2b, c, d, and e). The straw fiber was observed between cells, and there was full bonding between the straw fiber and PUF (Fig. 2f). Some closed cell structures were broken because of the fiber addition. With higher fiber content, more open cells were observed, and the cell sizes became much smaller. Some cells were broken probably because the fiber restrained the foam formation and induced cell deformations. Similar structural changes were observed in PUF composites filled with rice straw fiber.

Effect of Fiber Content on Sound Absorption Properties

Figure 3 depicts the sound absorption performance of composite at different sound frequencies. Although no significant enhancement of sound absorption coefficient (SAC) was found as the straw content increased in Fig.3, the increases in SAC of RPUF and WPUF were observed when compared to the pure PU forms (0 php) through the all frequency range. SAC increased as the sound frequency increased in the 100 to 630 Hz range for the two composites. From 630 to 2000 Hz, SAC first decreased and then increased, with the lowest SAC at 900 Hz. This result reflected that the sound absorption of the formed pore size and channel were different based on the different sound frequencies. The selective frequency absorption resulted in the sound absorption with varied coefficients, which firstly increased, then decreased, and finally increased, as shown in Fig. 3. The trends of SAC were in consistent with the findings from Maderuelo-Sanz *et al.* (2013) when the acoustical performance of the rubber and polyurethane resin composite were examined.

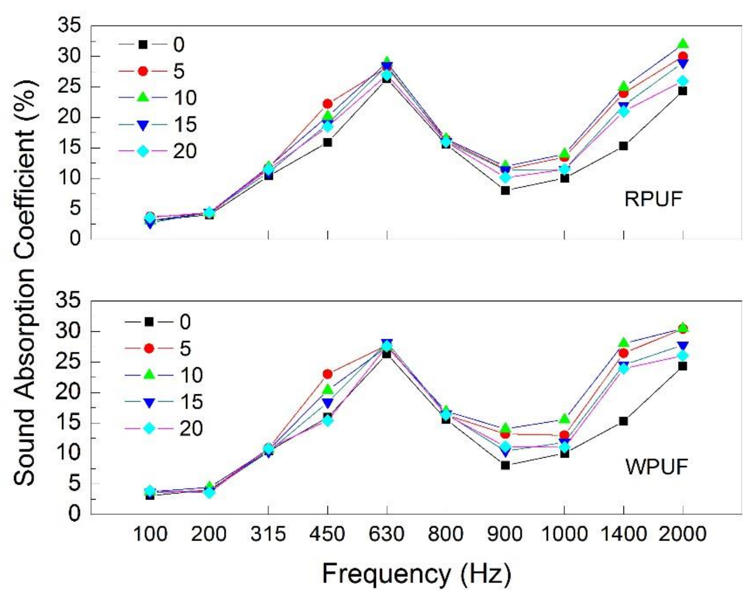

Fig. 3. Effect of fiber content on the sound absorption coefficient of composites as a function of frequency. Fiber content ranged from 0 to 20 php

Figure 4a shows that the average sound absorption coefficient (ASAC) of both WPUF and RPUF had similar changes as the fiber content increased from 0 to 20 php, which initially increased and then decreased from 0 to 2000 Hz. The maximum ASAC values of both composites appeared when the fiber content was 10 php. The ASAC values of WPUF were higher than that of RPUF when the fiber contents were 5 and 10 php, while they were similar when the fiber contents were 0, 15, and 20 php. This effect may be because straw fiber is a porous structure, which improves the absorption properties of materials. According to the SEM images (Fig. 1), the addition of straw fibers damaged the closed cell structure of PUF, resulting in an opened cell structure that probably improved the absorption properties. With increasing fiber content, large holes were observed throughout the foam (point by blue arrow in Fig. 1e), which might decrease absorption performance. The similar as this study, Lin *et al.* (2015) added 5 wt% carbon fibers into the fiber-reinforced PU composite foam and achieved a better acoustic absorption property.

The acoustic absorption behavior of a porous material depends on the porosity, the tortuosity, and the flow resistivity (Maderuelo-Sanz *et al.* 2013). The addition of straw fibers damaged the closed cell structures, resulting in an increase in SAC by opening cell structures of PUF. As the fiber content continued to increase, some tortuous cell walls occurred as shown in Fig. 2d and e (point by yellow arrows), leading to the reduction in average sound absorption when the fiber contents were 15 php and 20 php in Fig.4a.

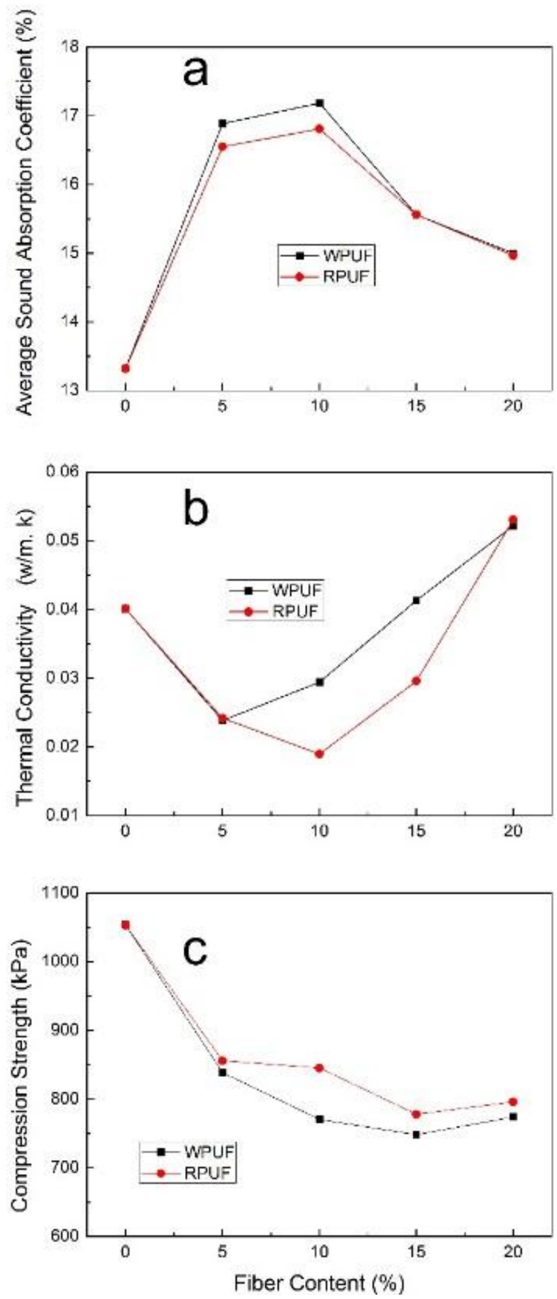

Fig. 4. Effect of fiber content on the average sound absorption coefficients, thermal conductivity and compressive properties

Effect of Fiber Content on Thermal Conductivity

The thermal conductivity (TC) of WPUF and RPUF had a similar trend as the fiber content increased from 0 to 20 php, which first decreased and then increased (Fig. 4b). When 5 and 10 php straw contents was added, the thermal conductivities were reduced by 25% to 50% compared to that of the pure PU form. Since the addition of straw fibers, the cell size became smaller and gave the foam better thermal insulation (*i.e.* reduced TC). As the fiber content continued to increase, TC was increased because some closed cell structures were broke and the air can flow between cells. The TC of WPUF and RPUF were similar in samples having 5 and 20 php fiber contents. However, the TC of RPUF was lower than in WPUF when the fiber contents were 10 and 15 php. RPUF with 10 php rice fiber had the best thermal insulation ability. It was reported that the lowest thermal conductivity of the PU foam composite form reached 0.153 W/mK after the addition of 5 wt% carbon fibers (Lin *et al.* 2013). That finding is comparable with the results in this study.

Effect of Fiber Content on Compressive Property

As shown in Fig. 4c, the fiber addition reduced the compressive strength of both composites. At a given fiber content, the compressive strength of RPUF was higher than that of WPUF. The cell structure were partially destroyed by the fiber addition, which decreased the compressive strength. Nar *et al.* (2015) also found that the compressive modulus and strength of the rigid polyurethane foams were reduced by adding kenaf-core fibers.

CONCLUSIONS

1. With higher fiber content, more open cells were observed in SEM images of the composites.
2. The sound absorption coefficients (SAC) of RPUF and WPUF were increased when compared to the pure PU forms (0 php) in the 100 to 2000 Hz range.
3. The average sound absorption coefficients (ASAC) of both WPUF and RPUF were significantly increased when 5 php and 10 php fiber contents were added. When fiber contents of 15 php and 20 php were utilized, ASAC reduced due to the tortuosity of cells. The maximum ASAC values appeared when the fiber content was 10 php.
4. The thermal conductivities of both WPUF and RPUF first decreased and then increased as the fiber content increased from 0 to 20 php. When 5 and 10 php straw contents was added, the thermal conductivities were reduced by 25% to 50% compared to that of the pure PU form (0 php), indicating the improved thermal insulation ability was obtained.
5. The compressive strength of the composites was reduced due to the fiber addition.

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