Windmill Palm Fiber/Polyvinyl Alcohol Coated Nonwoven Mats with Sound Absorption Characteristics

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Windmill palm single fibers (WPSFs) and fiber bundles (WPFBs) were extracted from a windmill sheath mesh. For the palm fiber acoustic application, WPSFs/WPFBs nonwoven materials and windmill palm fiber (WPF)/polyvinyl alcohol (PVA) coated nonwoven mats were developed. The effects of conditions such as the thickness and surface density of the materials and the concentration of PVA were studied. The sound absorption coefficients of all of the samples were measured using an impedance tube instrument. The statistical significance of the differences between these materials was tested using Duncan's grouping method. Based on the results, the windmill palm fiber can be regarded as appropriate for use as a sound absorbing material. The addition of PVA was an effective way to improve the acoustic properties of the WPF/PVA coated nonwoven mats. This coated mat exhibited a greater ability to absorb sound than WPSFs/WPFBs nonwoven materials. The acoustic properties of the materials exhibited good results, with an average sound absorption coefficient of 0.38 when the concentration of PVA was 1 wt.%.

Keywords: Windmill palm fiber; PVA; Sound absorption; Acoustic properties

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INTRODUCTION

Natural fibers have received increasing attention because of their ecological characteristics, biodegradability, low cost, low energy consumption, low density, and abundance (Ashori 2008; Sever *et al.* 2012; Dhand *et al.* 2015; Patnaik *et al.* 2015). Windmill palm fibers (WPFs) are one of the natural fibers that have not been widely used; date palm fibers and oil palm fibers have been studied more. Most of these materials can be used as a reinforcing phase in polymers to prepare composites (Sreekala *et al.* 2002; Alawar *et al.* 2009; Sbiai *et al.* 2010; Alam *et al.* 2012; Shalwan and Yousif 2014 and Jayamani *et al.* 2014). Because there is very limited research on WPFs, their use as an acoustic material has hardly been discussed. Textile fabrics, particularly nonwoven fabrics, are commonly used for sound absorption (Tascan and Vaughn 2008) because of a special structure formed by the fiber or yarn in the fabric. Similarly, WPFs can be considered a potential material used to prepare nonwoven fabrics.

Polyvinyl alcohol (PVA), the most common synthetic water-soluble polymer produced in the world, has valuable properties such as biocompatibility, chemical resistance, and good mechanical properties (Qiu and Netravali 2012; Panaitescu *et al.* 2015). PVA can be degradation by some kinds of biodegrading microorganisms, and the hydroxyl group promotes its degrading through hydrolysis (Chiellini *et al*. 1999; Solaro *et al*. 2000). In the textile industries, PVA has been widely used as a sizing agent because of its good film-forming properties (DeMerlis and Schoneker 2003). These unique properties can potentially have other applications, especially when added to WPF nonwoven materials. PVA can make the structure of materials more suitable for absorbing sound. However, there is a lack of research on the use of WPF/PVA coated nonwoven mats for acoustic applications.

In this paper, windmill palm single fibers (WPSFs) and windmill palm fiber bundles (WPFBs) were extracted from windmill sheath mesh. The WPF nonwoven materials and WPF/PVA coated nonwoven mats were prepared. The main purposes of this study were to manufacture these nonwoven materials, to determine the optimum process parameters, and to explore their potential as biodegradable acoustic materials for industrial applications.

EXPERIMENTAL

Materials

The windmill palm sheath meshes used in this study are shown in Fig. 1. They were obtained from windmill palm trees in Mount Huang Anhui province, China.

Fig. 1. Appearance of windmill palm sheath meshes

PVA used in this study were obtained from the Sinopharm chemical reagent company in Shanghai China. The degree of hydrolysis (HD) is 98%, the molecular weight (Mw) is 78750 g/mol, the Degree of Polymerization (DP) is 1750±50, and the melt flow index (MFI) is 2.16 g/10min.

Methods

Preparation of WPSF and WPFBs

A part of the palm fibers was treated with 4 wt.% hydrogen peroxide (H_2O_2) and 1.5 wt.% sodium hydroxide solution (NaOH) with a 1:50 fiber-to-extracting agent ratio (g/mL) at 90 °C for 4 h. The residue was filtered and then put into a blender (Bm252c, Meidi, China) with the power 250 W and rotational speed of about 20,000 r/min for about 30 s to obtain separated single fibers. The other part of the palm fiber was treated with 2 wt.% H_2O_2 and 1 wt.% NaOH with a 1:50 fiber-to-extracting agent ratio (g/mL) at 75 °C for 3 h to obtain the WPFBs, which were with a small amount of lignin and hemi-cellulose, according to our previous work (Chen 2015). Then, the WPFBs and WPSFs were washed with running water and dried separately. The appearance of these two materials are shown in Fig. 2.

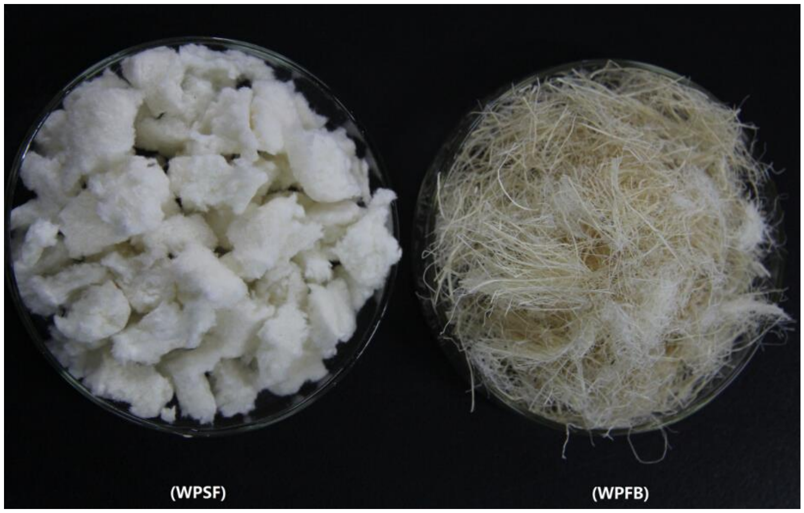

Fig. 2. The aspect of WPSF and WPFB

Preparation of WPF/PVA coated nonwoven mats

In our previous research, 40 wt.% WPFBs were added to WPSF nonwoven materials, which improved the acoustic properties (Chen 2015). In this paper, three types of nonwoven materials were investigated. The first type was composed of WPSFs and WPFBs (60/40, w/w). The amount of fiber that contained WPSFs and WPFBs was changed from 10 g to 40 g in 10-g intervals to obtain samples, which were denoted 1, 2, 3, and 4, respectively.

The second type was composed of WPSFs and WPFBs (60/40, w/w) joined by PVA, with concentrations of 0.1 wt.%, 0.5 wt.%, 1 wt.%, 1.5 wt.%, and 2 wt.%. The amount of the fiber that contained WPSFs and WPFBs for each sample was 20 g. These samples were denoted 5, 6, 7, 8, and 9.

The third type was composed of WPSFs and WPFBs (60/40, w/w) joined by PVA with a concentration of 1 wt.%. The amount of fiber that contained WPSF and WPFB was changed from 10 g to 40 g at intervals of 10 g to achieve the optimal technical process for WPF/PVA coated nonwoven mats. These samples were denoted 10, 11, and 12 (1 wt.% with 20 g WPF was named 7). For convenience of description, the material that contained WPSFs and WPFBs (60/40, w/w) is called WPF throughout the remainder of this paper. Figure 3 shows the appearance of three typical materials.

Table 1. Physical Properties of these Windmill Palm Nonwoven Mats

Sample	1	2	3	4	5	6	7	8	9	10	11	12
Thickness (mm)	4.31	6.49	8.09	9.25	6.73	8.01	7.77	7.85	6.29	7.05	11.2	11.89
Average tensile strength(MP)	0.59	0.60	0.62	0.63	0.60	0.61	0.63	0.64	0.67	0.62	0.63	0.64

The thickness and average tensile strength of these 12 samples were tested by digital fabric thickness gauge (YG141N, Hongda, China) and universal materials tester (Instron 5967, USA). The physical property of these 12 samples are shown in Table 1.

WPF and 500 mL of deionized water or 500 mL of PVA with various concentrations were added to a blender. After blending for 120 s, the compound materials were put into a mesh filter with a diameter of 20 cm. Then, the materials were dried in an oven at 75 °C.

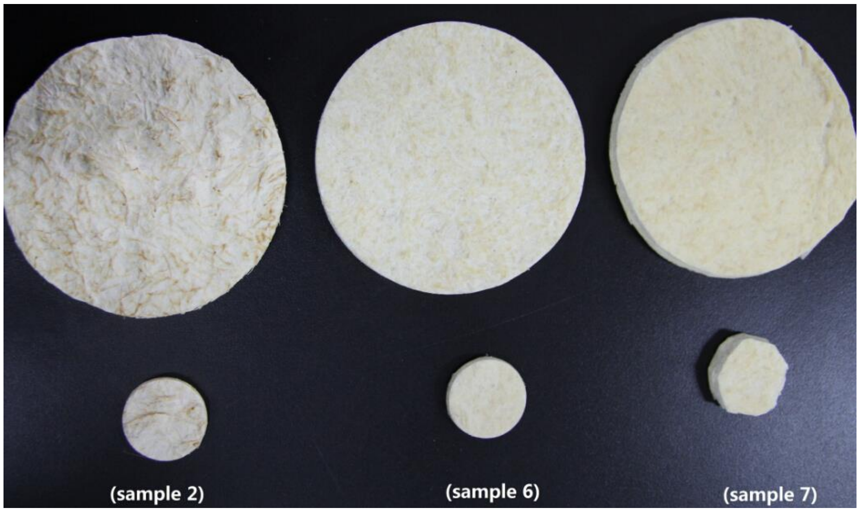

Fig. 3. The WPF nonwoven mats (sample 2) and WPF with the concentration of PVA is 0.5 wt.% (sample 6) and 1.0 wt.% (sample 7) coated nonwoven mats

Characterization of windmill palm materials

The surfaces of WPF nonwoven material and WPF/PVA coated nonwoven mats were observed using a scanning electron microscope (SEM; S-4800, Hitachi, Japan). These surface samples were coated with a thin layer of gold using a plasma sputtering apparatus (E-1045, Hitachi, Japan) to study the morphology. The observations were conducted in high-vacuum mode, and the accelerating voltage was 3 kV.

Surface density test of these materials

Each of the samples had been cut into a regular pattern as a circle with the diameter of 100 mm. Then the mass of the circle samples (*W*) were weighted with an electronic balance (Sartorius, Bas224s, Beijing). The surface density was obtained as the weight over the area of each circle sample.

Sound absorption measurement

The normal incidence absorption coefficient was measured by means of two microphone impedance tubes (SW463, Shengwang, Beijing, China) using the transfer function method. Figure 4 shows a picture of the test instrument. The test specimens for testing in the impedance tube were circular and measured 100 mm and 30 mm in diameter. The larger specimen was employed for measurements over the frequency range of 60 Hz to 1.6 kHz, and the smaller specimen was employed for measurements over the frequency range of 1.6 kHz to 6.3 kHz.

The test samples were dried at 105 °C for about 6 h using the forced air-drying method to decrease the samples' moisture content, until the constant weight was attained. Then the samples were stored in the environment with the temperature about 20±2 °C and the humidity about 65±5% for 24 h to obtain an equilibrium moisture before sound absorption measurement. The environment for sample testing was the same as for the store environment.

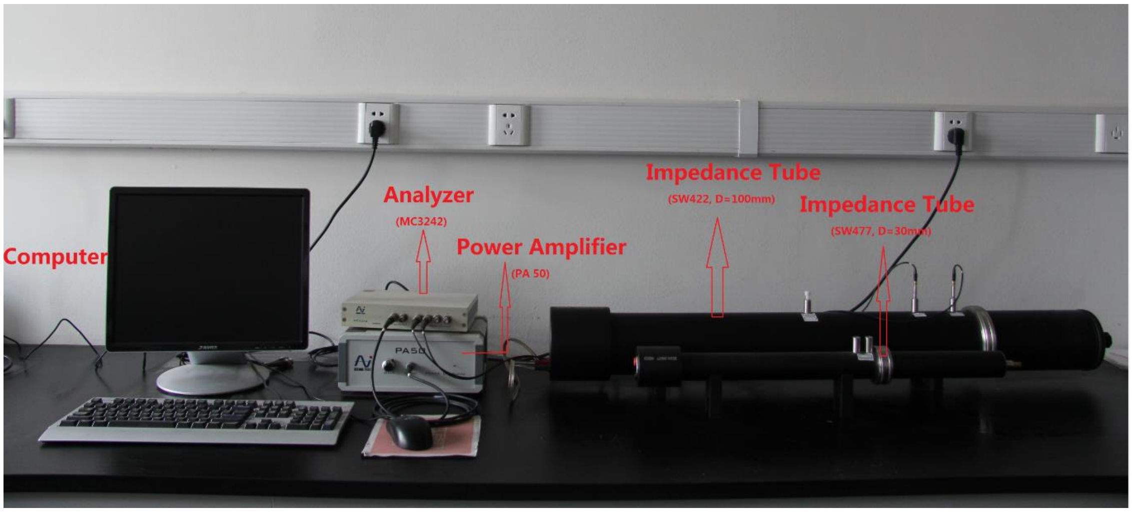

Fig. 4. The impedance tube equipment set-up

Thermo-gravimetric analysis (TGA)

The thermal stability studies, determined by thermo gravity analysis (TGA Diamond 5700, PerkinElmer, USA) were performed to understand the degradation characteristics of these nonwoven mats using thermo-gravimetric analyzer with a constant heating rate of 10 ºC /rain. These samples were placed in ceramic crucibles, while the tests were carried out in nitrogen atmosphere under a nitrogen flow of 50 mL/min , and the temperature ranged from 30 ºC to 800 ºC.

RESULTS AND DISCUSSION

Morphological Investigation of WPF Materials

Representative structures of the WPF nonwoven materials and WPF/PVA coated nonwoven mats are shown in Fig. 5.

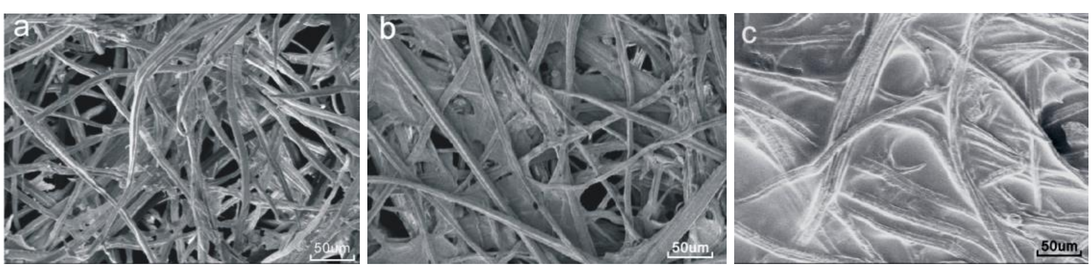

Fig. 5. (a) Morphology of WPF nonwoven material; (b) WPF/1 wt.% PVA coated nonwoven mats; (c) WPF/2 wt.% PVA coated nonwoven mats

The WPF nonwoven materials that were made by the wet-laid process had many interconnected pores. The addition of PVA changed the surface morphology of these materials. With an increase in the concentration of PVA, the number of open surface pores decreased. After adding PVA, a film was formed among the WPF, sealing some of the pores. When the concentration of PVA increased to 2 wt.%, a whole and almost flat film could be observed, as shown in Fig. 1c.

Acoustic Properties of WPF Nonwoven Materials

Figure 6 shows the acoustic response of WPF nonwoven materials with various thicknesses. An increase in the material thickness increased the sound absorption coefficient. The only exception is sample 3 at a frequency of approximately 2500 to 6300 Hz. The main absorptions had values of approximately 0.6 to 0.9 at frequencies of approximately 2000 to 6300 Hz when the thickness of the samples was above 8 mm. The WPF nonwoven materials with various thicknesses have characteristic peak absorptions of 0.2, 0.7, 0.95, and 0.79 at frequencies of approximately 6300 Hz, 6300 Hz, 2500 Hz, and 5000 Hz, respectively. Improvements in absorption coefficients at all frequencies, especially at low frequencies of approximately 80 to 2000 Hz, were observed as the thickness of the nonwoven materials was increased.

Yang *et al.* (2003) and Jayamani *et al.* (2014) observed an interesting decrease and increase of sound absorption coefficient at a specific frequency for the rice straw (1000 Hz), while for the luffa the corresponding value was 3100 Hz. This kind of decrease and increase was due to the specific characteristics of natural fibers reflecting sound at the specific frequency, but absorbing sound in the middle and high frequency ranges (Yang *et al*. 2003). However, the same phenomenon was not apparent in the present work (Fig. 6). As a natural fiber material, windmill palm fiber can be extracted into WPSF and WPFB, which have totally different specific characteristics. As a result, they will reflect sound in the different frequency. The mix of these two kinds of fiber makes the turning point not that obvious.

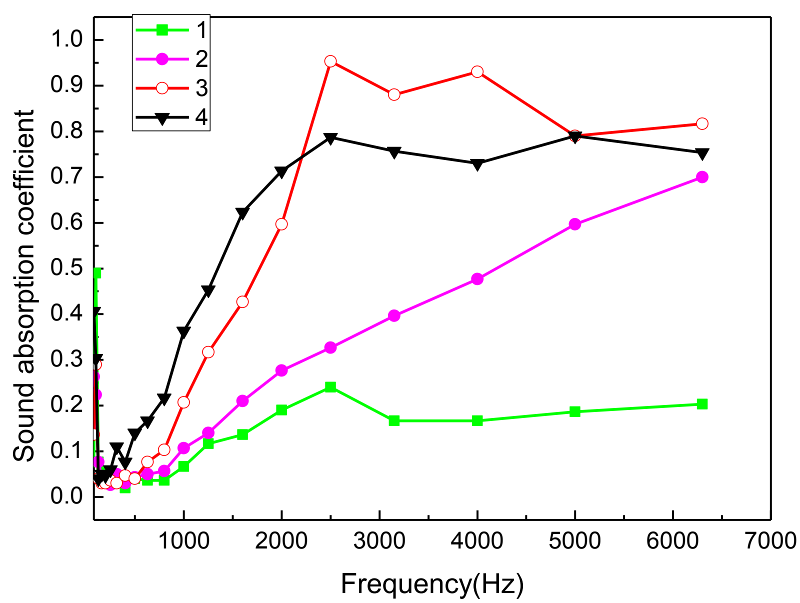

Fig. 6. The sound absorption properties of pure WPF nonwoven materials with various thicknesses

The average sound absorption coefficients $\overline{\alpha}$ of these samples were calculated by measuring the absorption coefficients at frequencies of 250, 500, 1000, 2000, and 4000 Hz (Liu *et al.* 2014). This is given in Eq. 1 as follows:

$$\overline{\alpha} = \frac{\sum \alpha_f}{6} (f = 125, 250, 500, 1000, 2000, 4000) \quad (1)$$

It is clearly apparent in Fig. 7 that the average sound absorption coefficient of WPF nonwoven materials increased as the thickness of the materials increased. It was observed that the nonwoven material with a core thickness of 9.25 mm exhibited an average sound absorption coefficient of approximately 0.34. Similarly, the 4.31 mm, 6.49 mm, and 8.09 mm nonwoven materials exhibited average sound absorption coefficients of 0.09, 0.17, and 0.31, respectively. Figure 3 shows the relationship between thickness and average sound absorption coefficient. This is a direct linear correlation and is represented by Eq. 2 as follows,

$$Y = 0.05278x - 0.14271 \quad (2)$$

where Y refers to the average sound absorption coefficient, x refers to the thickness of WPF nonwoven material [in mm], and the coefficient of determination is $R^2 = 0.93641$.

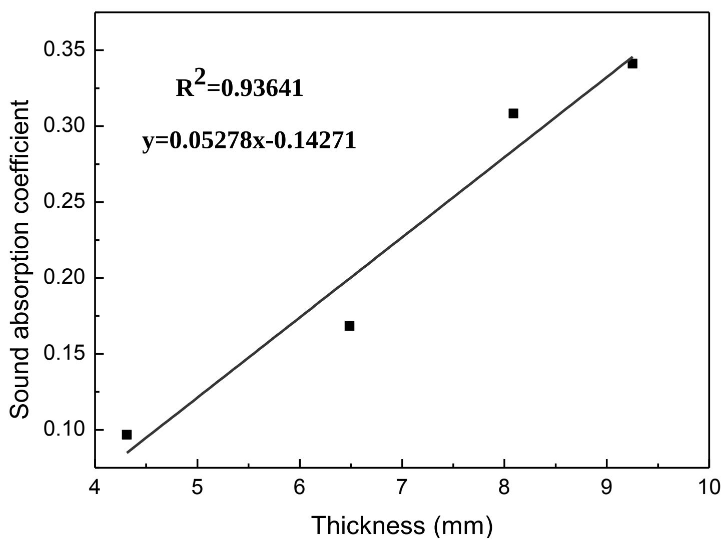

Fig. 7. The relationship between the thickness of a WPF nonwoven material and its sound absorption coefficient

Acoustic Properties of WPF / PVA coated nonwoven mats

Influence of PVA concentration on absorption coefficient

Figure 8 shows the acoustic response of WPF mixed with various concentrations of PVA. All samples showed similar responses, and the sound absorption coefficient increased as the frequency increased. The thickness of these samples shown in Table 1 and average sound absorption coefficient of three parallel materials for each sample and the mean absorption coefficient are shown in Table 2. The differences among average sound absorption coefficient of three parallel specimens of each sample are within an acceptable range. This indicates that the nonwoven mats prepared by wet-laid process have the ability to maintain a stable quality.

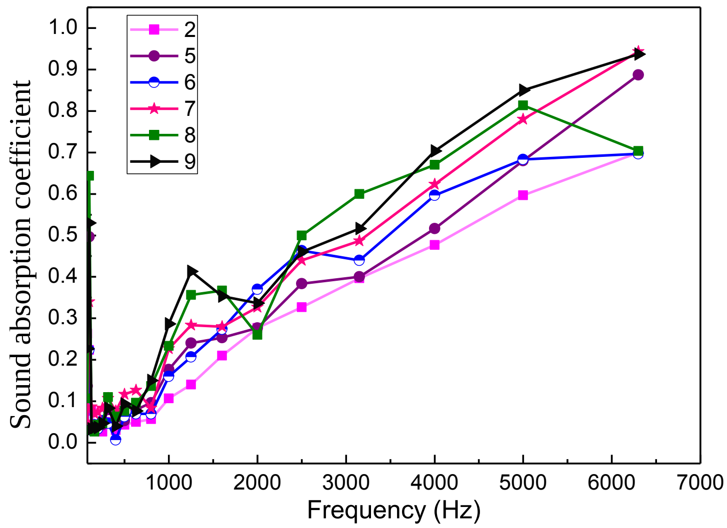

Fig. 8. Sound absorption properties of coated mats mixed with various concentrations of PVA

Table 2. Mean Sound Absorption Properties of Nonwoven Mats

Sample	Concentration of PVA (%)	Absorption coefficient $\bar{\alpha}$			Mean $\bar{\alpha}$
2	0	0.16	0.17	0.18	0.17
5	0.1	0.19	0.18	0.19	0.19
6	0.5	0.20	0.22	0.22	0.21
7	1.0	0.24	0.24	0.25	0.24
8	1.5	0.22	0.23	0.22	0.22
9	2.0	0.25	0.25	0.25	0.25

The $\bar{\alpha}$ values of six WPF/PVA coated nonwoven mats were classified into six different groups, as tested by the Duncan's grouping at the 0.05 significance level (Jiang *et al*. 2009), and the results are shown in Table 3. Based on the results of Duncan's multiple-range comparison test, these six samples were divided into four groups. Compared with the others, sample 2 had significant differences at the 95% confidence level and had the lowest sound absorption properties. This indicated that the addition of PVA was an efficient way to improve the acoustic properties.

As the concentration of PVA increased from 0% to 1%, the acoustic properties increased. Every WPSF was an effective absorption hollow structure unit and was injected into the coated mats by the addition of PVA. The good film-forming properties of PVA in conjunction with mechanical blending allowed the materials to have more effective pores. Sound waves incident upon the sample surface can transmit into the inside through these interconnecting pores. Due to the visco-thermal effect caused by the friction between air and fibers, the incident sound energy can be dissipated and converted into heat (Sun *et al*. 2015). The numerous interconnecting pores in the material due to the mutual overlapping of fibers and conjunction of PVA have a beneficial effect in improving the sound absorption properties. At lower concentration, PVA covers the fibers, the pores between the fibers are maintained and the porosity of each constituent remains open. But at higher concentration, the PVA creates a thin layer around the particles and obstructs the intra-fiber pores (Gle *et al.* 2011; Jayamani *et al.* 2014). As a result, a decrease in the acoustic properties was observed when the PVA concentration was 1.5 wt.%. However, when the concentration increased to 2 wt.%, a whole and almost flat film was present on the surface, as shown in Fig. 1. The film affected the sound waves entering the materials by reflecting them. This increased the probability of the wave rubbing between the air and the pore walls, and the incident sound energy was ultimately consumed as heat (Mohrova and Kalinova 2012). Hence, an increase was observed in the sound absorption properties.

With an increase in the concentration of PVA, the average sound absorption coefficient of different samples increased at the beginning and then began to decrease at 1.5 wt.% PVA. Then, the coefficient experienced a second increase, with the highest coefficient of 0.25 occurring at 2 wt.% PVA.

The analysis results for the mean sound absorption coefficients of the WPF/PVA coated nonwoven mats are shown in Table 3. The WPF mixed with 1 wt.% and 2 wt.% PVA showed no significant differences. Additionally, the 1 wt.% PVA reduced the consumption of resources and it became easy to prepare the coated mats. Thus, the 1 wt.% PVA was selected to determine the optimal process for making the WPF/PVA coated nonwoven mats.

Table 3. Analysis of the Mean Sound Absorption Coefficient for WPF/PVA Coated Nonwoven Mats

Samples	N	α = 0.05			
		5	6	7	8
Duncan 2	3	0.17000			
5	3		0.18667		
6	3			0.21333	
8	3			0.21944	
7	3				0.24333
9	3				0.25000
sig.		1.000	1.000	0.341	0.301

Influence of the surface densities of the coated mats on the absorption coefficient

As shown in Fig. 9, the WPF/PVA coated nonwoven mats with a surface density of 80 g/m^2 did not absorb sound effectively. The sound absorption coefficient was below 0.2 at the frequency range of 80 to 1600 Hz. However, when the surface density was increased, a remarkable shift was observed in the sound absorption properties, especially at higher concentrations above 630 Hz. Initially, the average sound absorption coefficient increased as the surface density increased. When the surface density reached 240 g/m^2, the sound absorption coefficient reached a peak of approximately 0.96 at a frequency of 3150 Hz. However, further increases in the surface density led to a significant decrease in the average sound absorption properties.

Because PVA possesses good film-forming properties, the addition of PVA had a positive effect on the acoustic properties. During the process of preparing the coated nonwoven mats, additional pores were formed relative to the materials with no PVA. The dense packing of fibers led to a reduction of porosity and to an increase in the reflection of sound waves by the materials. Continuously increasing the surface density leads to the decrease of sound absorption coefficients since every fibrous acoustic damping material has an optimal range of surface density for obtaining best noise reduction behavior (Xiang *et al.* 2013). This could be the reason why we observed a significant decrease in the sound absorption properties at 240 g/m^2.

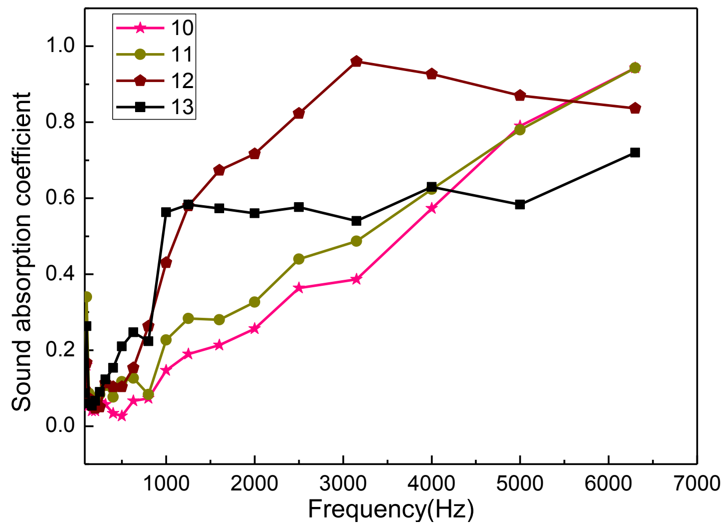

Fig. 9. Sound absorption properties of coated mats with various thicknesses

Comparison of Sound Absorption Properties

The results indicated that samples 4 and 12 had the highest acoustic properties of the WPF and WPF/PVA nonwoven materials, respectively. The acoustic properties of these two materials were compared, and the results are shown in Table 4. The addition of 1 wt.% PVA saved 10% of the palm fibers and improved the average sound absorption coefficient by 12%. Adding the PVA was an effective and economic way to improve the sound absorption performance.

Table 4. Comparison of Sound Absorption Properties of WPF Nonwoven Materials With and Without PVA

Frequency (Hz) Samples	α_{125}	α_{250}	α_{500}	α_{1000}	α_{2000}	α_{4000}	$\bar{\alpha}$
4	0.04	0.06	0.14	0.36	0.71	0.73	0.34
12	0.07	0.05	0.10	0.43	0.72	0.92	0.38

Thermal Properties

TG/DTA is an effective tool for determining the thermal stability of the material (Saini *et al*. 2015). Figure 10 shows the TGA and DTA curves of nonwoven mats. In the initial stage between 30 and 130 °C, specimens lost a totally different amount of weight due to the evaporation of a small amount of moisture present in the fibers. A mass loss of about 10%, 5%, and 2.5% was observed for sample 2 WPF nonwoven material, sample 7 WPF nonwoven material coated with 1% PVA, and sample 9 WPF nonwoven material coated with 2% PVA. The equilibrium moisture regains of WPF and PVA were about 12% and 5%, respectively (Chen 2015). The increases of the concentration of PVA decreased the mass loss at the first stage. In the second degradation stage, a dramatic decrease of mass loss of about 70% can be seen. The major degradation began at about 250 °C and was fully completed at about 380 °C. Nonwoven mats coated with PVA exhibited a higher thermal stability than uncoated mats. As cellulosic materials decompose quickly in the range of 220 to 350 °C (Hossain *et al*. 2014), this decomposition stage is mainly attributable to the degradation of cellulosic substances. The maximum mass loss is accompanied by an exothermic peak at a temperature of about 330 °C, as shown in the DTA curve (Fig. 10 (b)). The exothermic peaks of these specimens were quite similar; however, they were slightly higher for sample 9. The high thermal stability of coated nonwoven mats is due to the interaction between the binder and the fiber, which produces additional intermolecular bonding (Jayamani *et al.* 2014). The third stage is the decomposition of lignin and PVA (Ishak *et al.* 2012; Saini *et al.* 2015). Lignin is the most difficult to decompose compared to hemicelluloses and cellulose from 160 °C to as high as 900 °C (Ishak *et al.* 2012; Chen *et al.* 2014). The thermal changes indirectly affected the sound absorption properties of the nonwoven mats by changing the expansion of airflow size and porosity inside the natural mats (Jayamani *et al.* 2014).

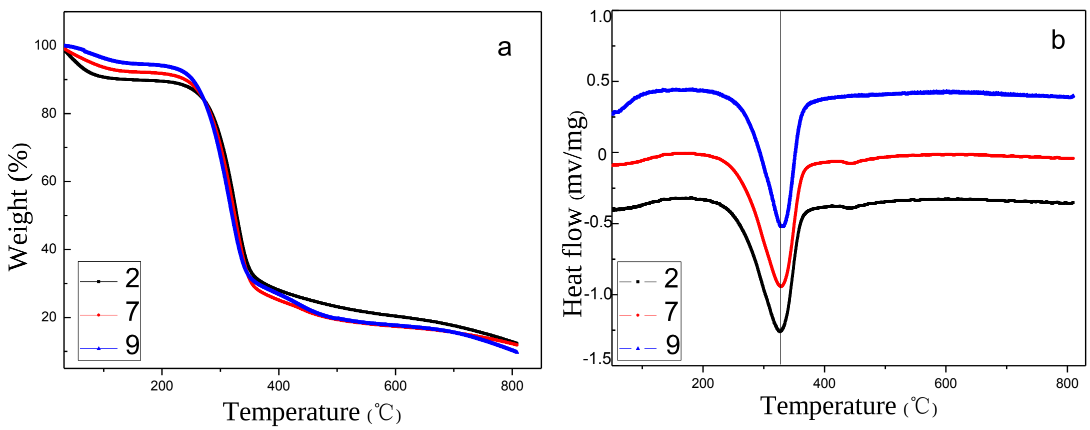

Fig. 10. (a) The TGA of nonwoven mats and (b) the DTA of nonwoven mats

CONCLUSIONS

WPF nonwoven materials and WPF/PVA coated nonwoven mats were produced, and their acoustic properties for sound absorption were investigated using the statistical method of Duncan's grouping analysis. The results are as follows:

1. Windmill palm fiber was found to be appropriate for use as a sound absorbing material. Also, the addition of PVA improved the sound absorption ability, significantly.
2. The coated nonwoven mats with 1 wt.% PVA had significantly higher sound absorption coefficients than the WPF coated nonwoven mats. Meanwhile, the surface density of 240 g/m^2 was the most significant parameter for the coated mats with 1 wt.% PVA.

3. The sound absorption coefficient of WPF/PVA coated nonwoven mats reached a peak of approximately 0.96 at a frequency of 3150 Hz, and the average sound absorption coefficient was 0.38. Considering the biodegradability and the low cost of the palm fiber raw material, the WPF/PVA coated nonwoven mats has the potential to be used as a high-performance and cost-effective acoustic material.

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