Available online at http://www.ssstj.sci.ssru.ac.th

Suan Sunandha Science and Technology Journal

Sound Absorbing Panels from Poly(lactic acid) Non-woven Fabric and Natural Fibers

Mathurot Malimat[1], Nanjaporn Roungpaisan[2], Weraporn Pivsa-Art[3], Sommai Pivsa-Art[1]*

[1]Department of Materials and Metallurgical Engineering, Faculty of Engineering, Rajamangala University of Technology Thanyaburi, Pathum Thani 12110, Thailand

[2]Department of Textile Engineering, Faculty of Engineering, Rajamangala University of Technology Thanyaburi, Pathum Thani 12110, Thailand

[3]Department of Chemical and Materials Engineering, Faculty of Engineering, Rajamangala University of Technology Thanyaburi, Pathum Thani 12110, Thailand

***Corresponding author e-mail: sommai.p@en.rmutt.ac.th**

Received: *3 February 2022* / **Revised**: *30 March 2022* / **Accepted:** *17 June 2022*

Abstract

This research studied the utilization of biodegradable polymer for nonwoven fabric production and applied to fabricate a sound absorbing panel by corporate with natural fiber nonwoven fabric. PLA was used as a biodegradable polymer and hemp nonwoven was used as a natural fiber nonwoven fabric. PLA nonwoven fabric was prepared using a melt jet spinning process. The spinning process was carried out at 250 and 260°C with screw speed of 10 rpm and air blown pressure of 0.3 and 0.5 MPa. The die-to-collector of fabric production was studied at 30 and 60 cm to compare the nonwoven fabric product property. It was found that the process temperature, air pressure and die-to-collector distance have significant effects on the nonwoven fabric thickness, GSM, and fabric density. Air permeability decreased with high fabric thickness as well as fine fibers which supported the property of sound absorbing panels. Therefore, the suitable conditions for sound absorbing panel fabrication were processed at temperature of 260°C, air pressure 0.5 MPa and die-to-collector distance of 60 cm. Sound absorbing coefficient measurement revealed that GSM fabric thickness had an effect on increasing sound absorption. The effect of nonwoven sheet order and arrangement of PLA nonwoven and hemp nonwoven of 3 layers sandwich indicated that the layers order of PLA/PLA/Hemp had high sound absorbing coefficient that was comparable with PLA/PLA/PLA due to fiber size and arrangement.

Keywords: Sound absorbing panel, Poly(lactic acid), Nonwoven, Hemp fiber

1. Introduction

The environmental concern on pollution from plastic waste has a high impact on the utilization of bioplastics to replace the conventional petroleum-based materials. In the automotive industry, the effects of an increase in greenhouse gas emissions and a greater focus on environmental sustainability and vehicle end life management, have all contributed to this trend. Bioplastics are one of the best replacement materials for conventional plastics as well as metals (PricewaterhouseCoopers, 2007).

Noise is a major cause of industrial fatigue, irritation, and one of the major causes in reducing the productivity of industrial processing and one source of occupational accidents. It has been reported that continuous exposure of noise of 90dB or above is dangerous to hearing (Devi, 2014). Various kinds of acoustic materials have been used as either sound barriers or sound absorbers to reduce noise or sound in vehicles to a comfort level or silence. Solid and impermeable materials were used as a sound barrier which reflects the incoming sound in order to prevent sound transmission. On the other hand, porous materials, including foams and fibrous materials with internal pores, were effectively used as sound absorbers, especially in a high frequency range (Prahsarn, Klinsukhon, Suwannamek, Wannid, & Padee, 2020; Sengupta, 2010). Porous sound absorbing materials have been widely used in the construction of aircraft, spacecraft, cars, trucks, and ships (Chavan & Manik, 2008).

Nonwovens are fibrous materials assembled directly from fibers having high porous structures and high surface areas. From these properties

Suan Sunandha Science and Technology Journal

nonwovens are attractive for being used as sound absorbers for many technical applications. When the sound wave enters nonwoven, it moves through tortuous passages and contacts with the fiber surface, resulting in energy dissipation into heat loss (Benkreira, Khan, & Horoshenkov, 2011; Tascan & Vaughn, 2008; Zhu, Nandikolla, & George, 2015). Nonwovens offer advantages over foams as they can be recycled, and their manufacturing methods may have less environmental impact than conventional polyurethane sound absorbers. Compared with foams, nonwovens can absorb more sound over a wider range of frequencies (Yilmaz, Banks-Lee, Powell, & Michielsen, 2011).

Glass fibers have been used for sound absorbing material from their sound absorption characteristics and air flow resistivity among fibrous absorbers (Yilmaz, 2009). However, due to the potential risks posed by glass fibers such as being unsafe to handle, non-recyclable, and posing health risks when inhaled, natural fibers are increasingly gaining attention in diversified engineering end uses in place of glass fibers. The application of natural fibers and biodegradable polymer fibers for sound absorbing panels have been constantly studied (Korte & Staiger, 2008; Oh, Kim, & Kim, 2009). The effect of combination of natural fiber and nonwoven fabric on sound absorption proficiency has not been reported.

In this study, sound absorption of three-layered nonwoven consisting of single and multiple types of fibers were reported. The fiber layers consist of poly(lactic acid) (PLA) nonwoven panel and hemp fibers. The effect of processing conditions of PLA nonwoven fabric property and sequencing of the constituent layers on sound absorption were investigated.

2. Materials and Method

2.1 Materials

Poly(lactic acid) pellets are of Ingeo biopolymer 6100D, with a melt flow index of 24 g/10 min (210°C) and density of 1.24 g/cm^3 (Nature Works LLC). Hemp used in this research was obtained from Hempthai Co. Ltd. (Tak province, Thailand).

2.2 Sample preparation

PLA was dried in the oven at 80°C for 12 h. PLA nonwoven was fabricated by a melt jet spinning machine outfitted with a die with three 0.4 mm spinnerets and a hot air outlet at the center. PLA pellets were fed into the hopper and molten by the extruder process. The screw speed was set at 10 rpm. The nozzle has three holes of spinnerets with a diameter of 0.4 mm that are located above the hot air outlet. The nozzle temperatures were varied for 250 and 260°C. The air pressures were controlled from 0.3 and 0.5 MPa by the air pressure controller. The collector distance between the nozzle and the collector, which is referred to as the collector, was varied at 30 and 60 cm. The molten PLA was blown and stretched by the hot air flow. PLA nonwoven materials were collected on a roller mesh collector at different processing conditions. Three layers of webs from PLA and hemp nonwoven were stacked as given in Table 1 (Figure 1).

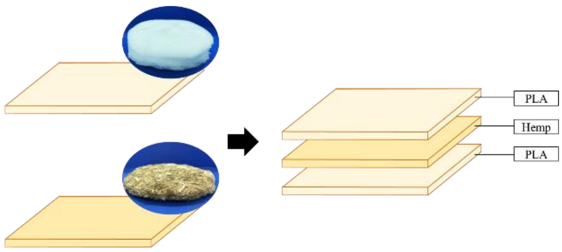

Figure 1. Schematic of multilayer structure of fiber webs.

Table 1. Layering of fiber webs.

Web number	Web code	Layer 1 (A)	Layer 2 (B)	Layer 3 (C)
1	HHH	Hemp	Hemp	Hemp
2	HLL	Hemp	PLA	PLA
3	LHL	PLA	Hemp	PLA
4	LLH	PLA	PLA	Hemp
5	LLL	PLA	PLA	PLA
6	LHH	PLA	Hemp	Hemp
7	HLH	Hemp	PLA	Hemp
8	HHL	Hemp	Hemp	PLA

Note: H = hemp, L = PLA

2.3 Thickness and mass per unit area (grams per square meter, GSM)

Mass per unit area of fabric sample of 1 cm x 10 cm for 10 pieces (g/m^2) were cut randomly and weighed in grams. The thickness of the fabric is ten measurements taken from each sample using a thickness gauge (Telclock Dial thickness gauge SM

112P).

2.4 Morphology and fiber diameter evaluation

Morphology of PLA fiber and hemp fiber was observed by optical microscopy technique (OM) (Olympus Microscope, CX41) beamed at 10 times magnification. Fiber diameters were examined from OM photographs using Image J software.

2.5 Air permeability

The fabric transport property that is most sensitive to fabric structure is air permeability, defined as the volume flow rate per unit area of a fabric when there is a specified pressure differential across two faces of the fabric. Air permeability of the samples were measured based on ASTM D737 Standard Test Method for Air Permeability of Textile Fabrics. The measurements were performed at a constant pressure drop of 100 Pa (20 cm^2 test area).

2.6 Sound absorption coefficients

Sound absorption coefficient was measured according to ASTM E 1050-08 standard test method by using an acoustic duct (SCIEN-9301, Korea) two microphones. Samples were cut into two different sizes (30 and 100 mm). The 30 mm tube was used to test the sound absorption coefficient at a (low) frequency between 125 to 1600 Hz. The sound absorption coefficient at a (high) frequency from 500 to 6300 Hz was tested using the 100 mm tube. The calibration was performed before conducting the test. Samples were mounted into the sample holder, which was clamped onto the tube for testing. For each material, three samples were tested in each tube size to cover the whole frequency range between 125 and 6300 Hz. The noise reduction coefficient (NRC) of all the materials were calculated according to Equation (1) (Mohammad, Nik Syukri, & Nuawi, 2019).

$$NRC = \frac{\alpha 250Hz + \alpha 500Hz + \alpha 1000Hz + \alpha 2000Hz}{4} \quad (1)$$

3. Results and Discussion

3.1 GSM and thickness of PLA nonwoven fabric

The effect of GSM and thickness on property PLA nonwoven fabric is shown in Figure 2 (a) and (b). The fiber was produced using air pressure of 0.3 and 0.5 MPa and die-to-collector distance of 30 and 60 cm. The die temperature was controlled for 250 and 260°C. Increasing die temperature resulted in high melting of polymer, and increasing in air pressure, and collector distance evolved significantly in GSM and fabric thickness. Numerous studies that dealt with sound absorption in porous materials have concluded that low frequency sound absorption has a direct relationship with thickness (Coates & Kierzkowski, 2002). It was observed that the samples with higher GSM showed higher thickness. It was reported that thicker materials showed better sound absorption values (Devi, 2014). The fabric GSM showed highest thickness (Figure 2) at temperature 260°C, air pressure 0.5 MPa and die-to-collector distance of 60 cm.

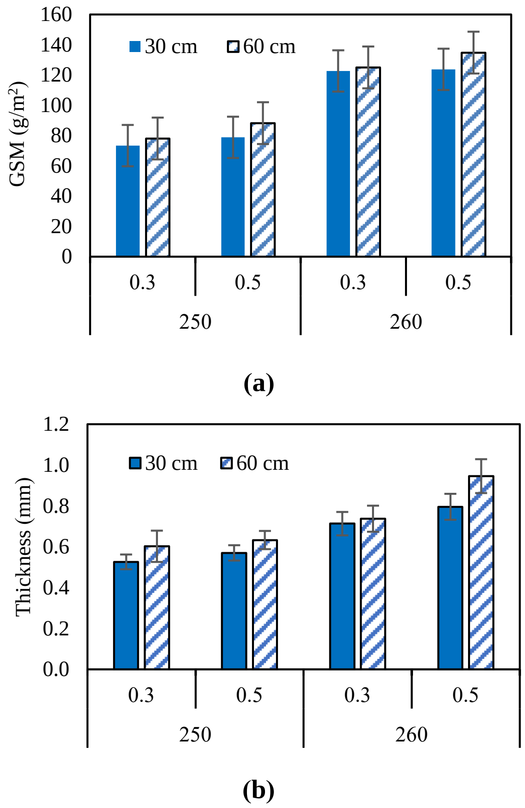

Figure 2. GSM and thickness of PLA nonwoven fabric (Nozzle temperature 250 and 260°C, air pressure 0.3 and 0.5 MPa, collector distance 30 and 60 cm) (a) GSM, (b) thickness.

3.2 Density of PLA nonwoven fabric

The material density is another factor to characterize the nonwoven fabric and is defined as mass per unit volume (g/cm^3). Density influences the acoustic impedance as the impedance determines the reflection of materials. It was reported that noise reduction coefficient increases with decrease in density (Wertel, 2000). In Table 2, increasing die temperature resulted in increasing of the nonwoven fabric density due to the thickness of material (Al-Shammari, Al-Fariss, Al-Sewailm, & Elleithy, 2011). However, with increasing air pressure and collector distance, the density of the nonwoven

Suan Sunandha Science and Technology Journal

fabric decreases. Therefore, the process at 0.5 MPa and die-to-collector distance of 60 cm was the most suitable condition for production of sound absorption panels.

Table 2. Density of PLA nonwoven fiber.

Temperature (°C)	Air pressure (MPa)	Collector distance (Cm)	Density (g/cm^3)
250	0.3	30	0.146 ± 0.007
		60	0.130 ± 0.009
	0.5	30	0.139 ± 0.011
		60	0.140 ± 0.008
260	0.3	30	0.176 ± 0.012
		60	0.169 ± 0.017
	0.5	30	0.155 ± 0.009
		60	0.141 ± 0.010

3.3 Morphology and fiber diameter of PLA nonwoven fabric

Figures 3 and 4 present the OM photograph and the distribution of the PLA fibers at 250 and 260°C, pressure of 0.3 and 0.5 MPa and collected at 30 and 60 cm. In Figure 3, the PLA fibers at 250°C are large with near die-to-collector distance while the fiber diameter decreases with long collected distance. The fiber sizes and the distributions were significantly decreased when increasing air pressures and collector distance. In Figure 4 the fibers size and fiber distribution of the nozzle temperatures at 260°C showed similar tendency with 250°C. The PLA fibers size distribution at 260°C with air pressure of 0.5 MPa, 60 cm were smaller than the process at 250°C.

It could be considered that the molten PLA at 250°C was faster solidified than at 260°C which would result in large fiber size. Finer fibers were produced at higher air velocity and collector distance. Consequently, the increasing of the air pressure led to the declination of fiber diameter in PLA melt blown nonwoven fabrics (Chen & Huang, 2003; Chen, Wang, & Huang, 2004). In addition, it was attributed to viscosity of the molten PLA, which high viscosity of the molten PLA was difficult to blow by hot air at low processing temperature. Therefore, at 250°C PLA fibers sizes were large and exhibited broad distribution. Thus, at 260°C the molten PLA was continuously blown by hot air, which resulted in the reduction of the fiber size and the narrow fiber distribution (Ellison, Phatak, Giles, Macosko, & Bates, 2007; Lee & Wadsworth, 1990; Watanabe, Kim, & Kim, 2011). Ellison et al. reported that polymers in their melt blowing process showed a significant reduction in fiber diameter because of an increase in processing temperatures. It was attributed to an increment in the active temperature window that provided the fiber attenuation when processing temperatures increased. Thus, the polymer fibers remained in the melt state for longer periods of time at higher processing temperatures and encountered an additional attenuation before the polymer solidified via sufficient crystallization or became amorphous. In addition, increasing the temperature would result in a substantial decrease in viscosity (Ellison et al., 2007).

The sound absorption coefficient increased with the small fiber size in which smaller fiber had more porosity and more contact surface with the incident sound. Therefore, the suitable conditions for nonwoven PLA fabric fabrications were at the nozzle temperatures at 260°C, air pressure 0.5 MPa, and die-to-collector distance of 60 cm.

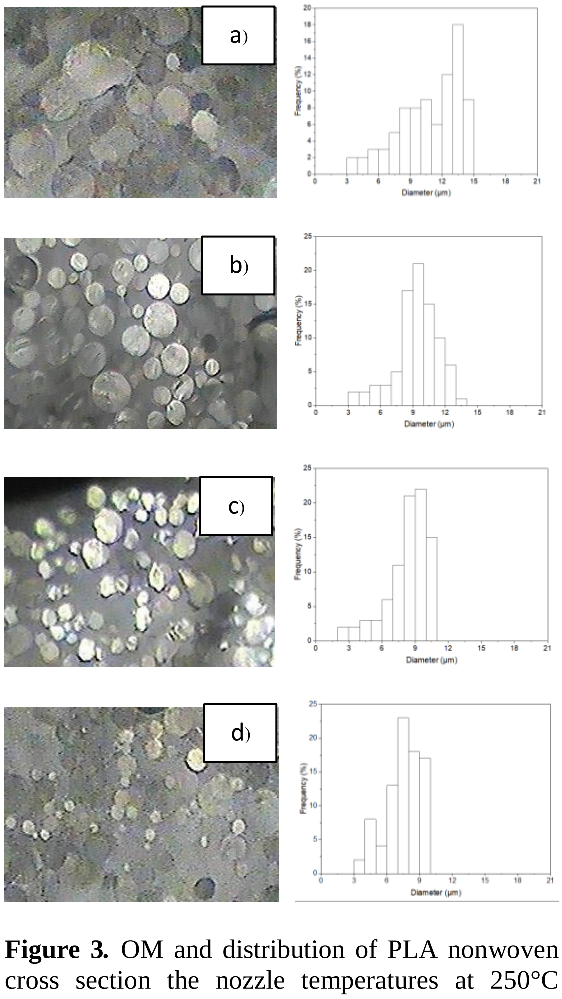

Figure 3. OM and distribution of PLA nonwoven cross section the nozzle temperatures at 250°C (pressure and collector distance): a) 0.3 MPa, 30 cm, b) 0.3 MPa, 60 cm, c) 0.5 MPa, 30 cm and d) 0.5 MPa, 60 cm.

Suan Sunandha Science and Technology Journal

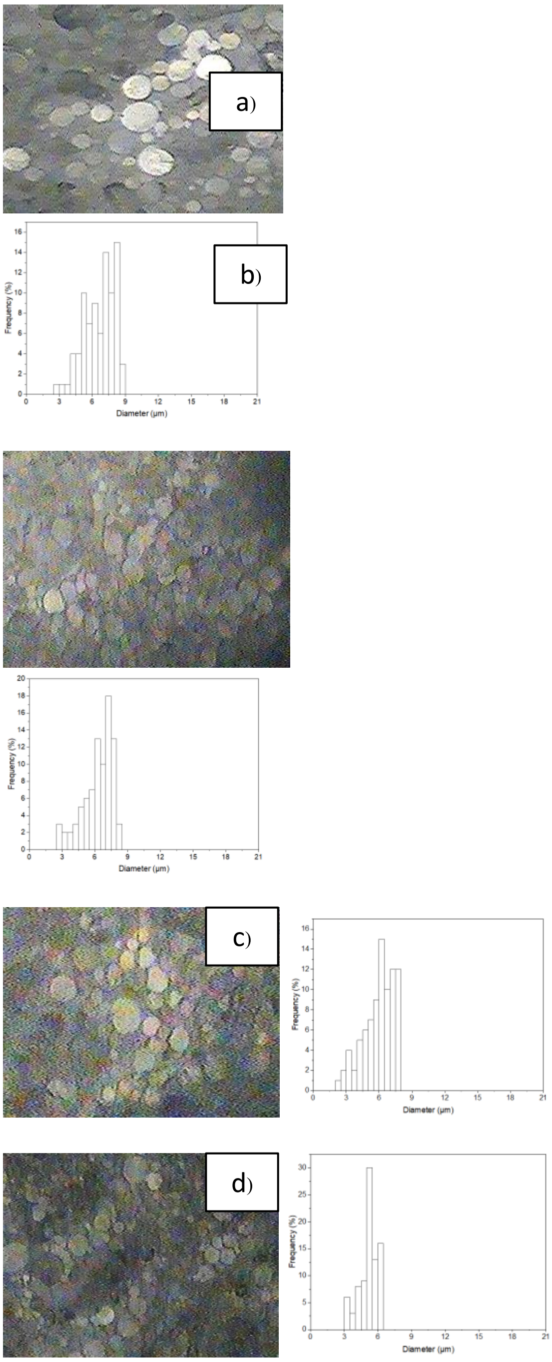

Figure 4. OM and distribution of PLA nonwoven cross section the nozzle temperatures at 260°C (pressure and collector distance): a) 0.3 MPa, 30 cm, b) 0.3 MPa, 60 cm, c) 0.5 MPa, 30 cm and d) 0.5 MPa, 60 cm.

3.4 Air permeability of PLA nonwoven fabric

In order to examine the effect of fiber deformation on the measured air permeability of PLA nonwovens fabric, different pressure gradients at 0.3 and 0.5 MPa were chosen to carry out air permeability testing. The measured air permeability is shown in Figure 5. Since the PLA nonwoven fabric is a loosely bonded fabric, the large spacing between fibers enables the majority of air to flow through these gaps. Obviously, in high nozzle temperatures, air pressures and collector distance present much significant lower air permeability. This is also attributed to their difference in GSM and fabric thickness. For PLA nonwovens fabric with higher GSM and fabric thickness, there is less porosity and air space in textile structure to allow air to go through (Yang et al., 2016). It is observed that air permeability of PLA nonwoven fabric tends to decrease with the increasing GSM and fabric thickness, which is similar to conventional textile fabrics. This is mainly due to the reduction in fiber diameter with increasing air pressure used during melt blowing. Finer fibers lead to reduction in pore size, better packing of the fibers, resulting in reduction in air flow rate through the webs (Broda & Baczek, 2020). Also fibers interlocking in nonwoven are the frictional elements that provide resistance to acoustic wave motion (Ren & Jacobsen, 1993).

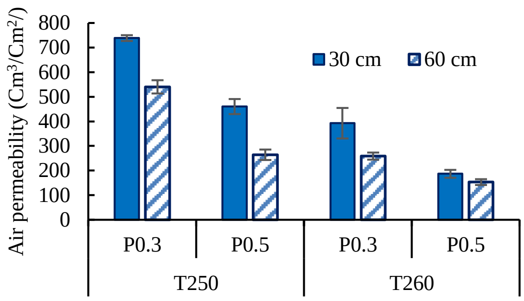

Figure 5. Air permeability of PLA nonwoven fabric (Nozzle temperature 250 and 260°C, Air pressure 0.3 and 0.5 MPa, Collector distance 30 and 60 cm).

3.5 Effect of GSM and thickness on sound absorption

The effect of GSM and thickness on the acoustic properties of PLA nonwoven fabric was investigated by fabricating PLA nonwoven fabric at processing conditions the nozzle temperatures at 260°C, air pressures at 0.5 MPa and collector distance at 60 cm with different thicknesses ranging from 6.50 to 14.75 mm, which was fabricated by melt jet spinning method with different area densities of 229 and 502 GSM. Table 3 shows the thickness and area density of the fabricated PLA nonwoven fabric and hemp nonwoven fabric. It was found that the sound absorption coefficient of the fabricated PLA nonwoven fabric and hemp nonwoven fabric as shown in Figure 6, The PLA nonwoven fabric with the higher GSM and thickness resulted in better sound absorption coefficient compared with the lower GSM and thickness. It also showed a higher sound absorption coefficient compared to the hemp nonwoven fabric. GSM of nonwoven fabric refers to the number of fibers in a certain area, and higher area density indicates the presence of higher proportion of fibers in a specific area, which induces more resistance to the sound wave (Broda & Baczek, 2020; Qui & Enhui, 2018) and contributes to the higher sound absorption tendency (Ganesan & Karthik, 2016; Kucuk & Korkmaz, 2012; Putra, Khair, & Nor, 2015).

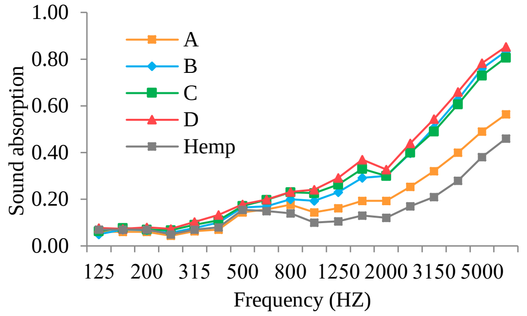

Figure 6. Sound absorption of PLA nonwoven fabric (Nozzle temperature at 260°C, Air pressure at 0.5 MPa, Collector distance at 60 cm) and hemp nonwoven fabric.

Table 3. Effect of GSM and thickness on sound absorption of PLA nonwoven fabric (Nozzle temperature 260°C, Air pressure 0.5 MPa, Collector distance 60 cm) and hemp nonwoven fabric.

Sample	Thickness (mm)	GSM (g/m^2)	NRC
A	6.50 ± 0.25	229 ± 3.35	0.13 ± 0.06
B	10.67 ± 0.58	384 ± 5.25	0.18 ± 0.09
C	13.92 ± 0.58	492 ± 6.03	0.19 ± 0.02
D	14.75 ± 1.75	502 ± 9.00	0.21 ± 0.01
Hemp	10.05 ± 0.19	1094 ± 24.84	0.11 ± 0.04

* NRC = Noise Reduction Coefficient

3.6 Effect of layering sequencing on sound absorption

The effect of layer sequencing on sound absorption was measured with three different placements of the reinforcement fiber layer, i.e., hemp fiber layer, in the composite ''sandwich'' structure. These three different positions of the reinforcement layer were front side (closest to the air flow source), back side (furthest away from it), or in the middle, as shown in Table 1. The fabrics where the reinforcement was nearest to (front side) or farthest away (back side) from the air flow source in fact were the same fabrics, just flipped to the other side for sound absorption coefficient testing. The material parameters of the fabrics with different layer sequencing are given in Figure 7 and Table 4. It is seen that the fabrics that had their reinforcement layer 1 layer (sample HLL, LHL, LLH), tended to have higher NRC values. In Table 4, the sequencing of each of the fabrics in the fabric group HLL, LHL, LLH had distinctively higher NRC values than the fabric group LHH, HLH, HHL. This suggests that the hemp layer had slightly higher resistivity than PLA layers, although the average diameter of hemp was slightly higher than those of PLA. The high variation in fiber diameter and the irregular shape of hemp fibers might have led to a higher tortuous path to frequency through the fabric layer. It was found that the sound absorption PLA/PLA/Hemp layers showed optimum results.

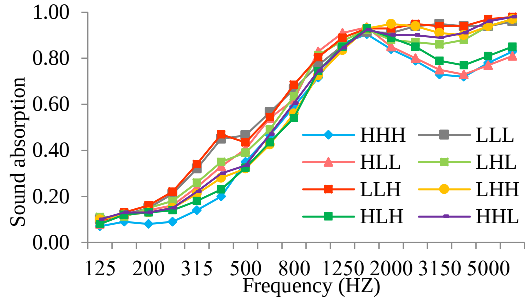

Figure 7. Effect of layering sequencing on sound absorption.

Table 4. Sound absorption coefficient and structure parameter information of webs with different sequencing.

Fabric	Thickness (mm)	GSM (g/m^2)	NRC
HHH	29.06 ± 0.50	3292 ± 38.70	0.50 ± 0.02
LLL	42.25 ± 0.71	1483 ± 33.83	0.59 ± 0.03
HLL	35.62 ± 0.82	2121 ± 34.69	0.56 ± 0.02
LHL	34.87 ± 0.62	2112 ± 23.12	0.57 ± 0.04
LLH	35.89 ± 0.64	2083 ± 36.67	0.60 ± 0.03
LHH	32.57 ± 1.57	3107 ± 44.20	0.54 ± 0.07
HLH	32.06 ± 1.50	3114 ± 38.56	0.53 ± 0.07
HHL	32.53 ± 0.94	3120 ± 26.86	0.53 ± 0.05

Suan Sunandha Science and Technology Journal

4. Conclusion

PLA nonwoven fabric was prepared using a melt jet spinning process. The spinning process was carried out at 250 and 260°C with screw speed of 10 rpm and air blown pressure of 0.3 and 0.5 MPa. The die-to-collector of fabric production was studied at 30 and 60 cm to compare the nonwoven fabric product property. The process temperature, air pressure and die-to-collector distance have significant effects on the nonwoven fabric thickness, GSM, and fabric density. Air permeability decreased with high fabric thickness as well as fine fibers which supported the property of sound absorbing panels. Therefore, the suitable conditions for sound absorbing panel fabrication were process temperature of 260°C, air pressure 0.5 MPa and die-to-collector distance of 60 cm. Sound absorbing coefficient measurement revealed that GSM fabric thickness showed effect on increasing sound absorption. The effect of nonwoven sheet order and arrangement of PLA nonwoven and hemp nonwoven of 3 layers sandwich indicated that the layers order of PLA/PLA/PLA showed higher sound absorbing coefficient than the Hemp/Hemp/Hemp due to fiber size and arrangement. However, the sheet layer order of PLA/PLA/Hemp showed a high sound absorbing coefficient comparable with PLA/PLA/PLA. Therefore, produced from biodegradable polymer and natural fiber can be effectively used for sound absorbing panels.

5. References

Al-Shammari, B., Al-Fariss, T., Al-Sewailm, F., & Elleithy, R. (2011). The effect of polymer concentration and temperature on the rheological behavior of metallocene linear low density polyethylene (mLLDPE) solutions. *Journal of King Saud University - Engineering Sciences*, *23*(1), 9-14. doi:10.1016/j.jksues.2010.07.001

Benkreira, H., Khan, A., & Horoshenkov, K. V. (2011). Sustainable acoustic and thermal insulation materials from elastomeric waste residues. *Chemical Engineering Science*, *66*(18), 4157-4171. doi:10.1016/j.ces.2011.05.047

Broda, J., & Baczek, M. (2020). Acoustic properties of multi-layer wool nonwoven structures. *Journal of Natural Fibers*, *17*(11), 1567-1581. doi:10.1080/15440478.2019.1584078

Chavan, A. T., & Manik, D. N. (2008). Optimum design of vibro-acoustic systems using SEA. *International Journal of Acoustics and Vibrations*, *13*(2), 67-72.

Chen, T., & Huang, X. (2003). Modeling polymer air drawing in the melt blowing nonwoven process. *Textile Research Journal*, *73*(7), 651-654. doi:10.1177/004051750307300715

Chen, T., Wang, X., & Huang, X. (2004). Modeling the air-jet flow field of a dual slot die in the melt blowing nonwoven process. *Textile Research Journal*, *74*(11), 1018-1024 doi:10.1177/004051750407401114

Coates, M., & Kierzkowski, M. (2002). Acoustic textiles – Lighter, thinner and more absorbent. *Technical Textile International*, *11*(7), 15-18.

Devi, R. P. (2014). A study on acoustic properties of polyester and hollow polyester non woven fabrics. *International Journal of Advanced Technology in Engineering and Science*, *2*, 446-459.

Ellison, C. J., Phatak, A., Giles, D. W., Macosko, C. W., & Bates, F. S. (2007). Melt blown nanofibers: Fiber diameter distributions and onset of fiber breakup. *Polymer*, *48*(11), 3306-3316. doi:10.1016/j.polymer.2007.04.005

Ganesan, P., & Karthik, T. (2016). Development of acoustic nonwoven materials from kapok and milkweed fibres. *The Journal of The Textile Institute*, *107*(4), 477-482. doi:10.1080/00405000.2015.1045251

Korte, S., & Staiger, M. P. (2008). Effect of processing route on the composition and properties of hemp fibre. *Fibers and Polymers*, *9*, 593-603. doi:10.1007/ s12221-008-0095-0

Kucuk, M., & Korkmaz, Y. (2012). The effect of physical parameters on sound absorption properties of natural fiber mixed nonwoven composites. *Textile Research Journal*, *82*(20), 2043-2053. doi:10.1177/0040517 512441987

Lee, Y., & Wadsworth, L. C. (1990). Structure and filtration properties of melt blown polypropylene webs. *Polymer Engineering and Science*, *30*(22), 1413-1419. doi:10.1002/pen.760302202

Mohammad, M., Nik Syukri, N. I. R., & Nuawi, M. Z. (2019). Sound properties investigation of date palm fiber. *Journal of Physics: Conference Series*, *1150*(1). doi:10.1088/1742-6596/1150/1/012003

Oh, K. W., Kim, D. K., & Kim, S. H. (2009). Ultra-porous flexible PET/Aerogel blanket for sound absorption and thermal insulation. *Fibers and Polymers*, *10*(5), 731-737, doi:10.1007/s12221-010-0731-3

Suan Sunandha Science and Technology Journal

Prahsarn, C., Klinsukhon, W., Suwannamek, N., Wannid, P., & Padee, S. (2020). Sound absorption performance of needle-punched nonwovens and their composites with perforated rubber. *SN Applied Sciences*, *2*(4). doi:10.1007/s42452-020-2401-4

PricewaterhouseCoopers. (2007). *The automotive industry and climate change*. Retrieved from http://www.pwc.com/th/en/automotive/assets/co2

Putra, A., Khair, F. A., & Nor, M. J. M. (2015). Utilizing hollow-structured bamboo as natural sound absorber. *Archives of Acoustics*, *40*(4), 601-608. doi:10.1515/aoa-2015-0060

Qui, H., & Enhui, Y. (2018). Effect of thickness, density and cavity depth on the sound absorption properties of wool boards. *Autex Research Journal*, *18*(2), 203-208. doi:10.1515/aut-2017-0020

Ren, M., & Jacobsen, F. (1993). A method of measuring the dynamic flow resistance and reactance of porous materials. *Applied Acoustics*, *39*(4), 265-276. doi:10.1016/0003-682X(93)90010-4

Sengupta, S. (2010). Sound reduction by needle-punched nonwoven fabrics. *Indian Journal of Fibre and Textile Research*, *35*(3), 237-242.

Tascan, M., & Vaughn, E. A. (2008). Effects of total surface area and fabric density on the acoustical behavior of needlepunched nonwoven fabrics. *Textile Research Journal*, *78*(4), 289-296. doi:10.1177/0040517507084283

Watanabe, K., Kim, B. S., & Kim, I. S. (2011). Development of polypropylene nanofiber production system. *Polymer Reviews*, *51*(3), 288-308. doi:10.1080/15583724.2011.594195

Wertel, S. J. (2000). Experimental analysis of noise reduction properties of sound absorbing foam. (Master's thesis). University of Wisconsin-Stout, Menomonie.

Yang, T., Xiong, X., Mishra, R., Novák, J., Chaloupek, J., Sanetrnik, F., & Militký, J. (2016). Investigation on acoustic behavior and air permeability of struto nonwovens. *Fibers and Polymers*, *17*(12), 2078-2084. doi:10.1007/s12221-016-6967-9

Yilmaz, N. D. (2009). *Acoustic properties of biodegradable nonwovens* (Doctoral dissertation). North Carolina State University, North Carolina.

Yilmaz, N. D., Banks-Lee, P., Powell, N. B., & Michielsen, S. (2011). Effects of porosity, fiber size, and layering sequence on sound absorption performance of needle-punched nonwovens. *Journal of Applied Polymer Science*, *121*(5), 3056-3069. doi:10.1002/ app.33312

Zhu, W., Nandikolla, V., & George, B. (2015). Effect of bulk density on the acoustic performance of thermally bonded nonwovens. *Journal of Engineered Fibers and Fabrics*, *10*(3), 39-45. doi:10.1177/155892501501000316