Sains Malaysiana 44(12)(2015): 1757–1763

Rigid/Flexible Polyurethane Foam Composite Boards with Addition of Functional Fillers: Acoustics Evaluations

(Buih Poliuretana Tegar/Fleksibel Papan Komposit dengan Penambahan Fungsian Pengisi: Penilaian Akustik)

C.H. HUANG, C.W. LOU, Y.C. CHUANG, C.F. LIU, Z.C. YU & J.H. LIN*

ABSTRACT

Following rapid technological and industrial development, factories have been equipped with a great deal of machines. The blend of industrial and residential areas in turn resulted in many environmental problems. In particular, machine operation causes noise pollution that easily causes physiological and psychological discomfort for the human body thus makes noise abatement a crucial and urgent issue. In this study, vermiculite functional fillers were added to polyurethane (PU) foam mixtures in order to form sound absorbent PU foams. The correlations between the contents of functional fillers and the sound absorption of flexible and rigid PU foams were then examined. The optimal PU foams were combined with PET/carbon fiber matrices in order to yield the electromagnetic shielding effectiveness. The sound absorption, noise reduction coefficient (NRC), electromagnetic shielding effectiveness and resilience rate of the composite boards were finally evaluated. The test results indicated that rigid PU foam composites can reach a sound absorption coefficient of 0.8 while the flexible PU foam composites have higher mechanical properties.

Keywords: Functional fillers; noise reduction coefficient; polyurethane (PU) foam; sound absorption coefficient

ABSTRAK

Berikutan perkembangan teknologi dan perindustrian yang pesat, kilang telah dilengkapi dengan mesin yang banyak. Gabungan kawasan perindustrian dan perumahan telah menyebabkan pelbagai masalah alam sekitar. Secara khususnya, operasi mesin menghasilkan bunyi bising dan menyebabkan rasa tidak selesa daripada segi fisiologi dan psikologi untuk tubuh manusia dan ini menjadikan pengurangan bunyi bising suatu isu yang sangat penting dan mendesak. Dalam kajian ini, vermikulit pengisi berfungsi ditambah kepada campuran buih poliuretana (PU) untuk menghasilkan buih penyerap bunyi PU. Korelasi antara kandungan pengisi berfungsi dan penyerapan bunyi buih fleksibel dan tegar PU kemudian dikaji. Buih PU yang optimum digabungkan dengan PET atau matriks gentian karbon untuk menghasilkan keberkesanan perisai elektromagnet. Penyerapan bunyi, pekali pengurangan bunyi (NRC), keberkesanan perisai elektromagnetik serta kadar ketahanan papan komposit akhirnya dinilai. Keputusan ujian menunjukkan bahawa komposit buih PU tegar boleh mencapai pekali bunyi penyerapan 0.8 sementara komposit buih PU fleksibel mempunyai sifat mekanik yang lebih tinggi.

Kata kunci: Pekali mengurangkan hingar; pekali penyerapan bunyi; pengisi berfungsi; poliuretana (PU) buih

INTRODUCTION

The routes of sound propagation mainly involve structure-borne noise, airborne noise and stationary wave. Noises refer to the sounds that cause people to agitate or excessively loud sounds that lead to a precarious health of people. Noises affect people in terms of rest and work and they also interfere with people's hearing. A common method of noise abatement is using the material which can absorb the energy of sound. Hence, the porous materials are often used to absorb the noise in order to decrease the level of reflection from the surface of the absorbed material (Beranek et al. 1988; Huang et al. 2014; Lin et al. 2014b).

There are many different kinds of sound-absorbing material on the market. The majority of sound-absorbing materials are porous sound absorbent materials, which are composed of great deal of pores that are not interconnected. When sound waves enter the pores of the material, the pore walls provide the sound with multi-refractions. Thus, the sound energy will be transformed to heat energy, which strengthens the sound-absorbing effect. The glass wool, rock wool, artificial fibers (Huang & Chuang 2013; Tai et al. 2010) and natural plant fibers are commonly used in the sound-absorbing materials, while phenolic and polyurethane foams are often used as form material (Lin et al. 2014a, 2014b; Yan et al. 2014; Zhang et al. 2012).

Different polyurethane (PU) foam sheets are classified according to the differences in raw materials and components. PU foam can thus be made into flexible or rigid sound-absorbing materials. Rigid foams are featured as having a closed-pore structure while soft foams having open-pore structure. The advantages of the rigid foams include a short processing process, efficient production, diversity of raw materials and a broad application range. Compared to rigid foams, flexible foams have higher strengths and a greater resilience. Flexible foams have been used in various industries, such as packaging material, heat-insulating and sound insulation fields. In this research, we mainly aimed to examine how ratio of rigid/flexible PU foam and content of the functional fillers were in relation to the sound absorbing effect (Demharter 1998; Hung et al. 2014). Finally, the resilient rate, sound-absorbing coefficient, value of NRC and the ASC are measured in order to characterize rigid/flexible polyurethane foam composite board.

EXPERIMENTAL DETAILS

High-density flexible polyurethane foam is synthetized by using two-component APEXLONVR® reagents: polyols and isocyanate (Kuang Lung Shing Corporation, Taiwan, ROC). Polyurethane foam solvent includes polyol, a hardener, and isocyanate (MDI), which are purchased from Zhongxing Chemical, Taiwan, ROC.

Vermiculite with three different particle sizes (Topcover Co., Taiwan): S: 0.250 mm, M: 0.71-2 mm, L: 1.4-4 mm. Note that the vermiculite has a hollow structure and its main composition is SiO_2. Vermiculite can have strong hydrogen bonding with PU polar groups on the chain, which provides PU foams with a higher hardness and a greater size stability (Zoran et al. 1998). Carbon fiber (CF) matrices (Yurak International Trading, Taiwan, ROC) has a warp density of 12.5 ends/inch and a weft density of 12.5 picks/inch. PET fiber (Far Eastern New Century Corporation, Taiwan ROC) has a length of 64 mm.

SAMPLE PREPARATION

Flexible PU foams were produced by incorporating polyols and isocyanate agents with a blending ratio of 8: 2 and stirred at a speed of 1200 rpm. The expansion factor of the foams was 4, which is managed by the mold pressure and the density is kept at 250 kg/m^3. Similarly, rigid PU foams were composed of polyol and MDI that were at a hybrid ratio of 5:5. The stirring speed was also set as 1200 rpm and the mass area ratio of the rigid foam material is controlled at 60 kg/m^3. During the aforementioned two processes, 10 or 20 wt. % functional fillers with a particle size of S, M or L were incorporated thus form twelve mixtures. The control groups were pure rigid/flexible PU mixtures. Namely, a total of fourteen mixtures were poured into the metal mold and sealed at once. We used a metal mold to control the volume of the foam materials. Finally, the foam materials undergo a 120 min curing at room temperature. The images of the rigid/flexible PU foam composite board were indicated in Figures 1 and 2, with their different combinations of vermiculite being shown in Table 1. The optimal PU foams were then combined with PET/CF matrices in order to yield the electromagnetic shielding effectiveness.

TESTING STEREOMICROSCOPE

The morphology of rigid/flexible PU foams is observed by a stereomicroscope (SMZ-10A, Nikon Instruments Inc., Japan).

TABLE 1. The denotation and specifications of rigid/flexible PU foams

Particle size (mm)	content (wt. %)	Rigid PU foam named	Flexible PU foam named
0.25	0	R-Pure	F-Pure
	10	R-S10	F-S10
	20	R-S20	F-S20
0.71-2	0	R-Pure	F-Pure
	10	R-M10	F-M10
	20	R-M20	F-M20
1.4-4	0	R-Pure	F-Pure
	10	R-L10	F-L10
	20	R-L20	F-L20

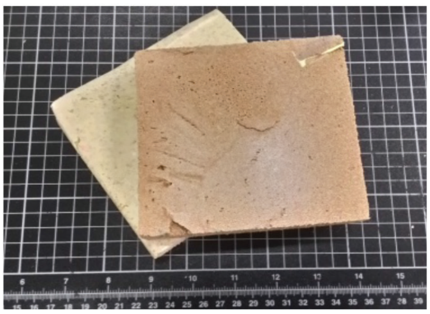

FIGURE 1. Flexible PU foams

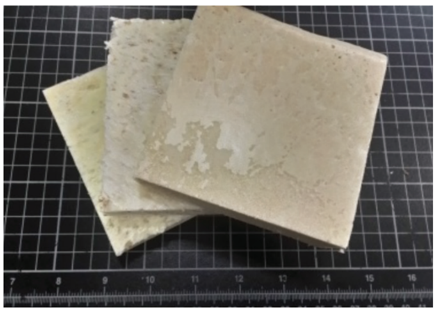

FIGURE 2. Rigid PU foams

RESILIENCE RATE

Resilience rate of PU foams was performed by using a vertical rebound resilience tester (HT-8355V, Hung Ta Instrument, Taiwan, ROC) as specified in ASTM D2632-01 (2008). A total of ten samples for each specification were tested and the samples have a size of 10×10 cm.

SOUND ABSORPTION COEFFICIENT

As specified in ASTM E1050-12, a two-microphone impedance tube (Automotive Research & Testing Center, Taiwan, ROC) measures the sound absorption coefficient of the samples at a frequency between 125 and 4000 Hz. The samples were cut into circular sections with a diameter of 38 mm (Figure 3). The samples include rigid/flexible PU foams and PET/CF/PU foam composites.

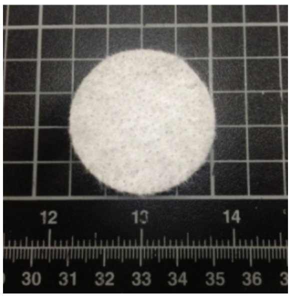

FIGURE 3. Samples of acoustic test

AVERAGE ABSORPTION COEFFICIENT (ASC)

ASTM E1050-12 was followed to measure the sound absorption coefficient of rigid/flexible PU foams at a frequency between 125 and 4000 Hz. The average absorption coefficient was calculated at the frequency range of 250 to 2000 Hz.

NOISE REDUCTION COEFFICIENT (NRC)

Like sound absorption coefficient, NRC was also an overall evaluation of the sound absorption ability of a specified material within a closed space. The sound absorption coefficients of rigid/flexible PU foams at 250, 500, 1000 and 2000 Hz were averaged for the mean.

ELECTROMAGNETIC SHIELDING EFFECTIVENESS (EMI SE)

The EMI SE of the samples was measured in a scan range between 300 kHz and 3.0 GHz, as specified in ASTM-D4935. The samples were PET/CF/PU foam composites. The number of samples was five. After being mounted on the coaxial cable, the samples were tested for EMI SE with a network analyzer (Advantest R3132A, Burgeon Instrument, Taiwan, ROC).

RESULTS AND DISCUSSION

RESILIENCE RATE OF THE RIGID/FLEXIBLE PU FOAMS

The effects of filler content on the surface resilience of rigid/flexible PU foams are shown in Figures 4 and 5. From the results, it was found that the flexible PU foams display a higher surface resilience property than the rigid PU foams. This is mainly due to flexible PU foams that have a higher density and rebound properties, rather than rigid PU foams. Hence, flexible PU foams have a great surface resilience performance when a weight of 40 g dropping hammer hit the surface.

Figure 4 shows that the surface resilience performance decreases as a result of the addition of vermiculite into the rigid PU foams. The density of the vermiculite is very low thus accounts for a large volume in the rigid PU foams. As a result, the PU foaming nucleation and the foaming process were restrained when producing the rigid PU foams. When rigid PU foams were incorporated with vermiculite grains that have a larger size at a greater content, the nucleation and foaming process was hampered in a greater level, which eventually resulted in a low resilient rate of rigid PU foams. The flexible PU foams have higher density and unit mass, in comparison to rigid PU foams. The flexible PU foams become rigid as a result of the incorporation of vermiculite into PU foam material. Therefore, vermiculite with different particle sizes all decrease the resilient rate with their addition amount being 20% of the PU foam material.

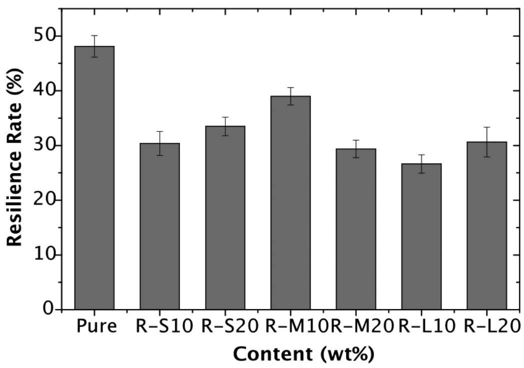

FIGURE 4. The effect of filler loading on the resilience rate of the rigid PU foams

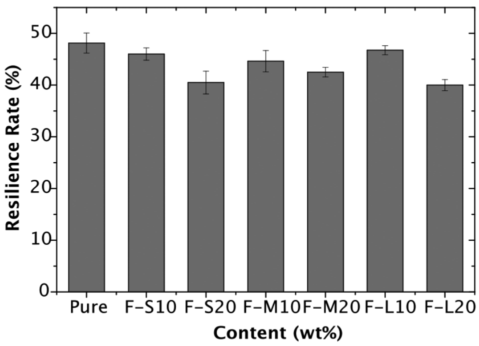

FIGURE 5. The effect of filler loading on the resilience rate of the flexible PU foams

SOUND ABSORPTION COEFFICIENT OF THE RIGID/FLEXIBLE PU FOAMS

Figure 6 shows the result of the absorbing sound property of rigid/flexible PU foams. As in Figure 6, it was found that the rigid and flexible foams display different characteristic peaks for acoustic absorption frequency. The sound absorption coefficient of rigid PU foams reaches 0.8 when acoustic frequency is at 2000 Hz. The characteristic peak has a narrow and sharp shape for the rigid PU foams. In constrast, the sound absorption coefficient of flexible PU foams reaches 0.6 with a corresponding characteristic peak of 2000 Hz. The character of the absorbing peak appears flatter. The different rigid/flexible PU foam pore structure and the density cause the different absorbing peak characters. Rigid PU foams have a closed-cell pore structure, where the pores were not interconnected. In contrast, flexible PU foams have interconnected pores that were small in size and irregular shapes. The sound absorption properties of rigid and flexible PU foams thus differ due to their differences in porous structures.

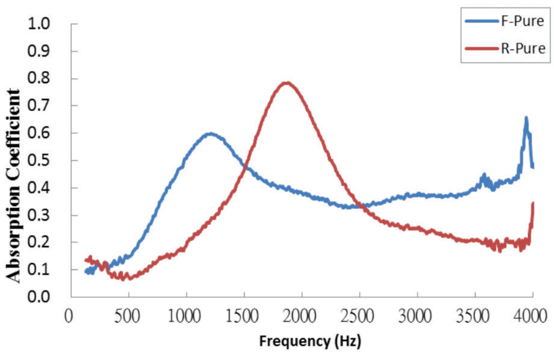

FIGURE 6. The effect of filler loading on the sound absorption coefficient of the rigid/flexible PU foams

The sound-absorbing coefficient of rigid PU foams and flexible PU foams as related to the filler contents are indicated in Figures 7-9 and Figures 10-12, respectively. From the test result of rigid PU foam composite board, it was found that absorption characteristic peaks shift towards the low frequency with an increase in the particle size of vermiculite. The incorporation of vermiculite facilitates the PU nucleation and increases the amount of pores, which in turn changes the particle size and pore structure that the sound-absorbing properties of rigid PU foams depends on.

Figures 10-12 indicate that the incorporation of vermiculite barely improves the sound-absorbing properties of flexible PU foams. This was due to the flexible PU foams, which have a high density and constructed with tiny pores. In addition, the incorporation of vermiculite was also not in relation to the porous structure of flexible PU foams and as such does not cause any significant differences in the characteristic peak of their sound absorption. According to the results of the sound-absorbing coefficient, only R-L20 of rigid PU foams reaches 0.8 with the frequency of sound wave being at 1400 Hz. However, the sound absorption coefficient of flexible PU foams does not fluctuate with different combinations of parameters under different frequencies. Specifically, it reaches a sound absorption coefficient of 0.6 at the frequency of 1000 Hz, regardless of different parameters that the flexible PU foams are made of.

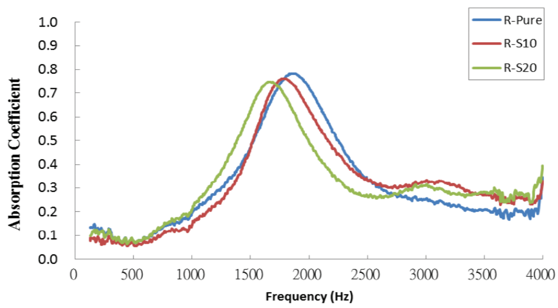

FIGURE 7. The effect of filler loading on the sound absorption coefficient of the rigid PU foams (Particle size: 0.25 mm)

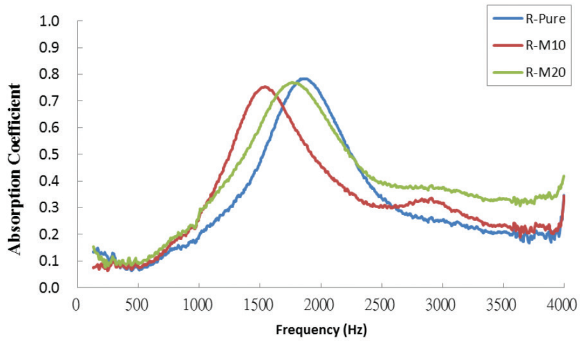

FIGURE 8. The effect of filler loading on the sound absorption coefficient of the rigid PU foams (Particle size: 0.71-2 mm)

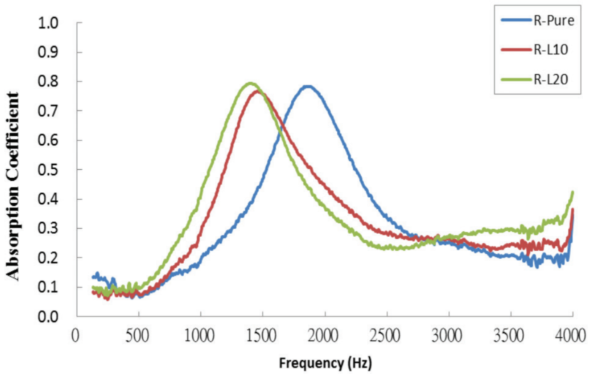

FIGURE 9. The effect of filler loading on the sound absorption coefficient of the rigid PU foams (Particle size: 1.4-4 mm)

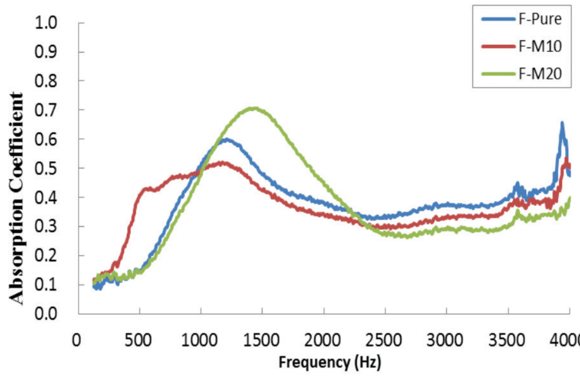

FIGURE 11. The effect of filler loading on the sound absorption coefficient of the flexible PU foams (Particle size: 0.71-2 mm)

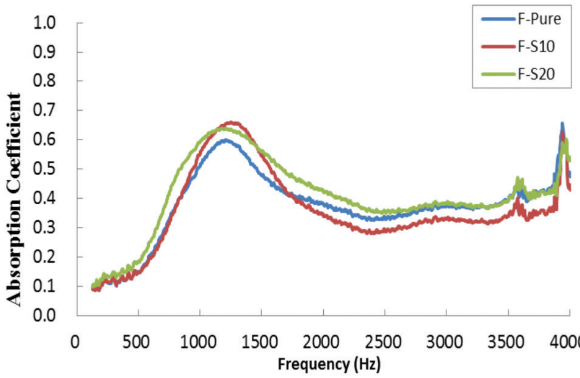

FIGURE 10. The effect of filler loading on the sound absorption coefficient of the flexible PU foams (Particle size: 0.25 mm)

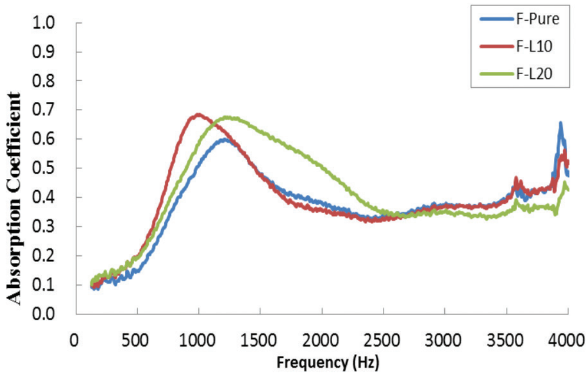

FIGURE 12. The effect of filler loading on the sound absorption coefficient of the flexible PU foams (Particle size: 1.4-4 mm)

NOISE REDUCTION COEFFICIENT (NRC) OF THE RIGID/ FLEXIBLE PU FOAMS

Table 2 shows the effect of filler content on NRR and ASC value for the rigid/flexible polyurethane foams. F-L20 has optimal NRC and ASC values at the frequency ranging from 250 to 2000 Hz. Materials with a high NRC values were less likely to cause sound wave reflection. Flexible PU foams have higher NRC and ASC values than rigid PU foams, which were ascribed to the different characteristic peaks during sound absorption. Flexible PU foams have flat peaks while rigid PU foams have narrow peaks. Therefore, with a specified frequency range beween 250 and 2000Hz, flexible PU foams outperform rigid PU foams in terms of sound absorption performance. In particular, F-L20 obtains an optimal NRC (0.36) and ASC (0.48).

SOUND ABSORPTION COEFFICIENT OF PET/CF/ PU FOAM COMPOSITES

According to the sound absorption results, R-L20 that has the prominent sound absorption coefficient is then combined with PET/CF matrices. Figure 13 shows the

TABLE 2. NRC and ASC of the rigid/flexible PU foams

Hz	R-S10	R-S20	R-M10	R-M20	R-L10	F-S10	F-S20	F-M10	F-M20	F-L10	F-L20
250	0.12	0.14	0.14	0.13	0.13	0.12	0.14	0.14	0.13	0.13	0.13
500	0.15	0.19	0.41	0.15	0.20	0.15	0.19	0.41	0.15	0.20	0.20
1000	0.55	0.59	0.49	0.48	0.68	0.55	0.59	0.49	0.48	0.68	0.59
2000	0.34	0.42	0.34	0.45	0.36	0.34	0.42	0.34	0.45	0.36	0.50
NRC	0.23	0.22	0.22	0.28	0.22	0.29	0.34	0.35	0.30	0.34	0.36
ASC	0.31	0.35	0.38	0.39	0.39	0.41	0.45	0.41	0.45	0.44	0.48

absorption coefficient of the PET/CF/PU foam composites that were made with different orders of R-L20 and PET/CF matrices, which were denoted as matrix/R-L20, R-L20/matrix and matrix/R-L20/matrix. Both R-L20/matrix and matrix/R-L20/matrix have a decreasing characteristic peak of sound absorption coefficient. The PET/CF matrix was composed by needle punching PET fibers and CF woven fabrics, the latter of which cannot consume sound energy via resonance like PU foams, while they also cannot absorb the sounds like porous nonwoven fabrics. As a result, when the composites have the matrix facing the incident sound sources, their sound absorption coefficient was low. However, when the matrix was attached to the bottom of R-L20, the incident sound sources contact the sample by encountering its PU foam first, a part of sound waves was absorbed by the same while the other part being reflected or penetrating the sample. Those sound waves that penetrate the PU foam layers contact the matrix, in which the CF woven fabrics with a high surface density then reflect the sound waves into the PU foam layer. These repetitive cycles thus attain the multi-reflection purpose and debilitate the sound waves. In particular, the matrix/R-L20 group obtains an optimal sound absorption (0.9) at a sound wave frequency of 1000 Hz.

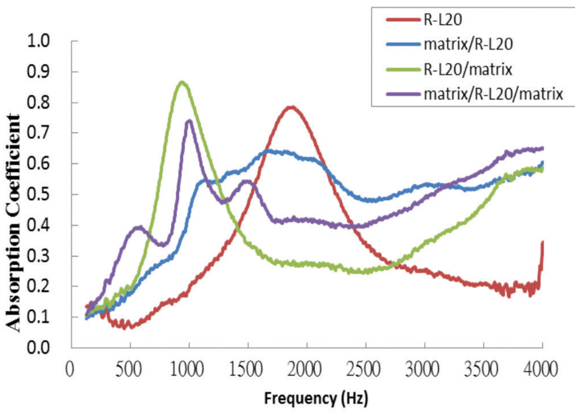

FIGURE 13. The sound absorption coefficients of the composites that are made by laminated R-L20 and matrix in different orders

EMI SE OF PET/CF/PU FOAM COMPOSITES

The EMI SE of the PET/CF/PU foam composites (i.e. matrix/R-L20, R-L20/matrix and matrix/R-L20/matrix) was indicated in Figure 14. The combination of PET/CF matrix significantly contributes to EMI SE of the R-L20. The composites contain R-L20 and PET/CF matrix, the latter of which consists of CF woven fabrics that can yield EMI SE via their absorption loss and reflection loss against electromagnetic waves. In particular, matrix/R-L20/matrix group have an optimal EMI SE that reaches beyond 40 dB in a frequency range between 0.3 MHz and 2.97 GHz. Namely, their EMI SE reaches 99.99%.

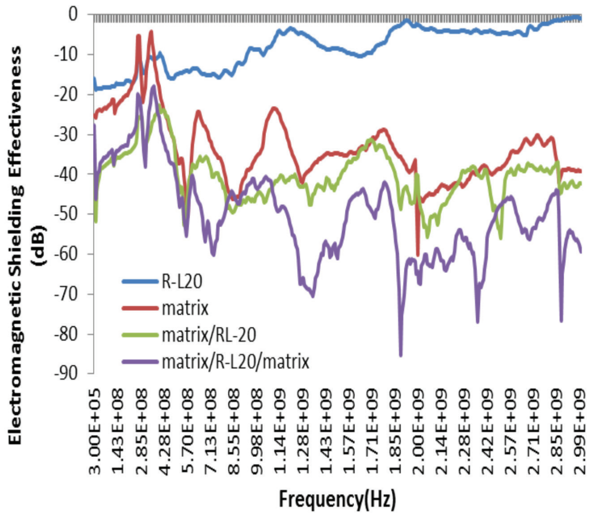

FIGURE 14. The EMI SE of the composites that are made by laminated R-L20 and matrix in different orders

CONCLUSION

In this study, how the incorporation of vermiculite influences the resilience rate and acoustics properties of the rigid/flexible PU foams was examined. The test results indicated that flexible PU foams have a higher resilience rate, exemplified by that F-L10 have an optimal resilience rate of 40%. The sound absorption coefficient results indicated that R-L20 of rigid PU foam has an optimal sound absorption coefficient of 0.8 at a sound frequency of 1400 Hz. Conversely, there were no significant differences in the sound absorption coefficient of flexible PU foams and their sound absorption coefficient was around 0.6, regardless of their parameters. In addition, F-L20 has an optimal NRC of 0.36 and an optimal ASC of 0.48, according to the computation of sound absorption. Finally, among the PET/CF/PU foam composite, the matrix/R-L20 group has an optimal sound absorption coefficient of 0.9 at a frequency of 1000 Hz, while the matrix/R-L20/matrix group has an EMI SE that beyond 40dB in a frequency of 0.3 MHz-2.97G Hz, namely a shielding effect of 99.99%.

ACKNOWLEDGEMENTS

This work would especially like to thank the National Science Council of the Taiwan, for financially supporting this research under Contract MOST 103-2622-E-035-019-CC3.

REFERENCES

Beranek, L.L. 1988. *Noise and Vibration Control*. New York: McGraw Hill. p. 672.

Demharter, A. 1998. Polyurethane rigid foam, a proven thermal insulating material for applications between +130°C and -196°C. *Cryogenics* 38: 113-117.

Huang, C.H., Lin, J.H. & Chuang, Y.C. 2014. Manufacturing process and property evaluation of sound-absorbing and thermal-insulating polyester fiber/polypropylene/

thermoplastic polyurethane composite board. *J. Ind. Text*. 43: 627-640.

Huang, C.H. & Chuang, Y.C. 2013. The design and optimization of nonwoven composite boards on sound absorption performance. *Applied Mechanics and Materials* 365-366: 1217-1220.

Hung, T.C., Huang, J.S., Wang, Y.W. & Lin, K.Y. 2014. Inorganic polymeric foam as a sound absorbing and insulating material. *Constr. Build Mater*. 50: 328-334.

Lin, J.H., Li, T.T. & Lou, C.W. 2014a. Puncture-resisting, sound-absorbing and thermal-insulating properties of polypropylene-selvages reinforced composite nonwovens. *J. Ind. Text*. doi: 10.1177/1528083714562088.

Lin, J.H., Li, T.T., Hsu, Y.H. & Lou, C.W. 2014b. Preparation and property evaluation of sound-absorbing/thermal-insulating PU composite boards with cushion protection. *Fiber Polym*. 15(7): 1478-1483.

Li, T.T., Chuang, Y.C., Huang, C.H., Lou, C.W. & Lin, J.H. 2015. Applying vermiculite and perlite fillers to sound-absorbing/ thermal-insulating resilient PU foam composites. *Fiber Polym*. 16(3): 691-698.

Tai, K.C., Chen, P., Lin, C.W., Lou, C.W., Tan, H.M. & Lin, J.H. 2010. Evaluation on the sound absorption and mechanical property of the multi-layer needle-punching nonwoven. *Advanced Materials Research* 123-125: 475-478.

Yan, R.S., Wang, R., Lou, C.W. & Lin, J.H. 2014. Manufacturing technique and acoustic evaluation of sandwich laminates reinforced high-resilience inter/intra-ply hybrid composites. *Fiber Polym*. 15(10): 2201-2210.

Zhang, C.H., Li, J.Q., Hu, Z., Zhu, F.L. & Huang, Y.D. 2012. Correlation between the acoustic and porous cell morphology of polyurethane foam: Effect of interconnected porosity. *Mater. Design* 41: 319-325.

Zoran, S.P., Ivan, J. & Vladimir, D. 1998. Structure and physical properties of segmented polyurethane elastomers containing chemical crosslinks in the hard segment. *Journal of Polymer Science Part B: Polymer Physics* 36(2): 221-235.

C.H. Huang
Department of Aerospace and Systems Engineering
Feng Chia University, Taichung City 40402
Taiwan

C.W. Lou
Institute of Biomedical Engineering and Materials Science
Central Taiwan University of Science and Technology
Taichung 40601
Taiwan

Y.C. Chuang & J.H. Lin*
Laboratory of Fiber Application and Manufacturing
Department of Fiber and Composite Materials
Feng Chia University, Taichung 40402
Taiwan

C.F. Liu
Office of Physical Education and Sports Affairs
Feng Chia University, Taichung 40402
Taiwan

Z.C. Yu
Functional Textile Materials Laboratory
School of Chemical Engineering and Material Science
Eastern Liaoning University, 118003 Dandong
China

Z.C. Yu
School of Textiles, Tianjin Polytechnic University
300387 Tianjin
China

J.H. Lin*
School of Chinese Medicine, China Medical University
Taichung 40402
Taiwan

J.H. Lin*
Department of Fashion Design, Asia University
Taichung 41354
Taiwan

*Corresponding author; email: jhlin@fcu.edu.tw

Received: 14 June 2015
Accepted: 17 August 2015