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Light-weight poly(vinyl chloride)-based soundproofing composites with foam/film alternating multilayered structure

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ABSTRACT

Poly(vinyl chloride)-based (PVC) multilayered composites with alternating foam and film layer structure were designed through a multilayered co-extrusion system. Light-weight composites with good soundproofing properties were obtained. The effects of foaming process, acoustic impedance mismatch, and layer number on the soundproofing properties were investigated. Sound transmission loss (STL) was used to characterize the soundproofing properties. The experimental results revealed that the foam/film multilayered composites showed higher STL and lower density than the film/film multilayered composite without foaming process. In addition, the multilayered composite presented better soundproofing properties when there was a bigger acoustic impedance mismatch between adjacent layers. Moreover, as the layer number increased from 2 to 16, the STL of the PVC composite increased gradually and reached a maximum at 8 layers (an average value of 26.3 dB). However, the STL of 16-layer composite decreased because of the reduction of scattering and reflection of sound waves among the bubbles.

1. Introduction

The booming development of modern industry, civil construction, and transportation has brought about serious noise pollution, which is considered to cause damages to human health and living environment. Thus, the prevention and control of noise have attracted attentions worldwide [1,2]. Polymer materials have been extensively used for sound insulation and absorption for the combination of viscoelasticity, light weight, and formability [3]. However, limited by its light weight and low elastic modulus, the soundproofing properties of pure polymer is still too low to meet the requirement of industrial applications according to the stiffness and mass laws [4,5]. The modifications of polymer for high noise reduction performance have received attentions of many researchers.

Introduction of inorganic fillers into polymer matrix has been widely used to improve the soundproofing properties of polymer [6–8]. Lee et al. investigated the sound insulation properties of carbon-nanotube (CNT) reinforced acrylonitrile butadiene styrene (ABS) composites. They found that the increase in stiffness by adding CNTs would significantly contribute to the soundproofing properties of ABS/CNT composites [6]. Kim et al. fabricated polypropylene (PP)/clay/CNT nanocomposites through solution mixing method. The results revealed that the composites possessed much higher sound transmission loss (STL) than pure PP, especially in high frequency range. The synergistic effect between the homogeneous dispersion and strong adhesion of the CNTs and clay platelets enhanced the sound insulation properties of nanocomposites [7]. Wang et al. used the stiffness and mass laws to simulate the STL of mica filled PVC composites. They found that the STL values predicted by theoretical models were slightly lower than the experimental ones. They attributed the practical improvements of STL to the repeated sound reflection and scattering caused by laminar mica [8]. The mass law predicts that each time the density or thickness of a tested panel is doubled, the transmission loss increases about 6 dB [9]. Though the introduction of inorganic filler into polymer matrix can indeed improve the sound insulation properties, the idea fails to get rid of the constraint of stiffness and mass laws [7,8], which limits the extensive applications in sound insulation fields requiring light weight, for instance, public transportation and construction industries.

Currently, improving the soundproofing properties of polymer by structure design has attracted researchers' attentions. It is well known that the sound propagation at interfaces is dominated by the acoustic impedance matchability of adjacent mediums: acoustic impedance match leads to the incidence of sound waves, and conversely, acoustic impedance mismatch leads to reflection [10]. Sound absorption and insulation are different acoustical concepts, but the sound absorption accompanied with energy dissipation

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also contributes to sound insulation performance [11,12]. It is believed that the energy of incident sound waves partially dissipate as heat energy due to air friction in bubbles caused by forced vibration and viscous friction between adjacent polymer chains [13,14]. The foaming structures are not only effective in sound insulation field, but also reduce the weight, which enables and facilitates the usage in structural engineering [15,16]. Therefore, composites with multi-components and multi-phases are highly desired for soundproofing applications due to the acoustic impedance difference. In addition, multilayered composites with foaming structure may be of great potential in achieving excellent soundproofing properties as well as light weight [17,18]. Bolton et al. designed multi-panel structures composed of metal facing panels, elastic porous polymer materials, and cavity. They carried out the theoretical prediction of STL based on the porous materials theory proposed by Biot, and found that the STL depended critically on the method mounting the foam layer to the facing panels: the structure with cavity existing between metal facing panels and polymer panel showed higher STL than that without cavity [17]. Yoon et al. investigated the sound insulation properties of confined and extensional layer configurations in steel/polyurethane composites. They reported that both extensional and confined structures presented better soundproofing properties than pure steel with the same thickness. But the confined configuration showed higher STL than the extensional one. They attributed the difference to the sound energy attenuation caused by the shear strain and viscoelasticity of the internal elastic layer confined by steel [18].

The conventional methods for preparing multilayered soundproofing composites are compression molding and paste process, which are difficult to obtain ordered multilayered foaming structure with high layer number [19,20]. In recent years, a facile route to fabricate the multilayered structures by using multilayered co-extrusion system was used to construct foam/film alternating multilayered composite. Ranade et al. manufactured foam/film alternating multilayered composite with microlayer co-extrusion for the first time, and found that the composite had unique mechanical properties [21]. In our previous research, multilayered foam/film composite showed good sound absorption properties [22]. In this work, the multilayered composites with alternating foam layers and films layer were prepared through multilayered co-extrusion system designed by our group. Benefit from its low cost and wide applications in construction and transportation field, PVC was selected as the polymer matrix in this work, meanwhile, the elastic modulus and acoustic impedance of PVC sheet can be modified by adding dioctyl phthalate (DOP) [8,23]. The layer structures were observed by a polarized optical microscope (POM) and the sound transmission loss was characterized by a four microphone impedance tube. The effects of the multilayered structure, acoustic impedance mismatch, and layer number on the soundproofing properties were investigated.

2. Experimental

2.1. Materials

In this work, the PVC resin was a commercial suspension grade with the degree of polymerization of 1000 (SG-5, Tianjin Dagu Chemical Factory, China). Barium sulfate ($BaSO_4$) with the average particle size of 5 μm and density of 4.5 g/cm^3 was obtained from Qingdao Linke Chemical Factory, China. Azodicarbonamide (AC) with an average particle size of 7 μm was used as chemical blowing agent (Zibo Kailian Chemical Factory, China). Nano-$CaCO_3$ obtained from Shanghai Haichao Industrial Co. was used as nucleating agent. Polyacrylate (ACR) used to increase the melt strength of PVC was supplied by Rohm and Hass China Pte. Other additives including DOP, calcium-zinc stabilizer, and stearic acid were commercial products.

2.2. Specimen preparation

The PVC resin and additives were initially kneaded by a two roll mill (Labtech Engineering Company, Thailand) at 145 °C for 10 min. The formulations and processing temperatures of multilayered composites and monolayer samples were listed in Table 1. LA, LB and LC stand for the three different multilayered samples. Then the foam/film alternating PVC multilayered composites were manufactured through the multilayered co-extrusion system designed by our group [24–28]. Fig. 1 showed the schematic of the alternating multilayered co-extrusion system and the foam/film alternating multilayered composite. During the process, the foam and film components were extruded through extruder A and B, respectively, and then the melts steams were combined into a two-layer sheet in the co-extrusion block (C). When the two layers flowed through the layer multiplying element (LME) (D), the melt was first divided vertically, and then spread horizontally and finally recombined Consequently, an assembly of n LMEs would produce a multilayered composite with 2^{n+1} layers, where n was the number of LME. The temperatures of extruders were both 145 °C (below foaming temperature), in order to stabilize the chemical blowing agent in foam components in extruder A. The temperature of LMEs was 145 °C or 170 °C (above foaming temperature). The film/film specimens without foaming structure were prepared under 145 °C for comparison. While under 170 °C, the chemical blowing agent would decompose and the generated gas dissolved within the polymer melt due to the high melt pressure. Once outside the die (E), the dissolved gas started to nucleate into bubbles as the pressure dropped. Then, the foam/film alternating multilayered PVC composites were obtained. In this work, the 2-, 4-, 8-, and 16-layer foam/film alternating multilayered composites were obtained with applying 0, 1, 2, and 3 LMEs, respectively.

Table 1
Formulation and processing temperature of multilayered and monolayer specimens.

Content (phr)[a] and processing temperature (°C)	Multilayer						Monolayer		
	LA		LB		LC				
	Film	Foam	Film	Foam	Film	Foam	S1	S2	S3
PVC	100	100	100	100	100	100	100	100	100
DOP	30	60	30	60	50	60	30	30	30
AC	0	1	0	1	0	1	0	0	1
$BaSO_4$	50	0	50	0	50	0	0	50	0
ACR (phr)	0	4	0	4	0	4	0	0	4
Stabilizer	5	5	5	5	5	5	5	5	5
Stearic acid	1	1	1	1	1	1	1	1	1
Processing temperature of LMEs	145		170		170		170	170	170

[a] phr: parts per hundred parts of resin.