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The cell growth-induced orientation of mica in lightweight flexible poly (vinyl chloride) foams and its enhancement on sound insulation

Lifu Xu, Teng Han, Jiang Li, Ying Xiong*, Shaoyun Guo**

The State Key Laboratory of Polymer Materials Engineering, Polymer Research Institute of Sichuan University, Chengdu, 610065, China

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ABSTRACT

The lightweight flexible poly(vinyl chloride) (PVC)/mica composite foams with low density (0.51 g/cm^3) which is 40–60% reduction and high sound insulation performance (an average STL of 28.3 dB) were prepared in this work. And the influences of mica content and foaming time on the cell morphology, mica distribution, and sound transmission loss (STL) were investigated. It was observed that the PVC/mica foams not only showed good sound insulation properties, but also maintained ultra-light in weight when the mica content was below 10 wt%. In addition, as the foaming time became longer, the cell density increased and the cell-wall thickness decreased. As a result, the bi-axial stretching induced by the cell growth would drive the mica platelets to orient along the thin cell walls, which significantly increased the sound insulation properties. Simultaneously, the flexibility and reusability of the foams were tested by cyclic compression. When the mica content was below 10 wt%, the PVC/mica composite foams showed low compressive stress and low permanent strain.

1. Introduction

In recent years, noise pollution has become one of the major concerns of environmental issues and personal unhealthiness, and polymeric soundproofing materials have been extensively used in noise control applications, for instance, constructions and transportation tools [1,2]. Light weight, flexibility, and high sound insulation performance are the main requirements for sound insulation materials so that they can suit for different using conditions [3,4]. But, according to the mass and stiffness laws, the soundproofing properties of polymer materials are adversely affected by their low density and low modulus [5,6], which limits the usage of polymer in sound insulation applications. So, two methods have been carried out to improve the soundproofing performance of polymer: one is the introduction of inorganic particles into polymer matrices [7–12]; For example, Liang and Jiang [7] previously investigated the sound insulation properties of glass bead filled polyvinyl chloride (PVC/GB) composite, calcium carbonate filled PVC (PVC/CaCO3) and hollow glass bead filled polypropylene (PP/HGB) composite, and found that with the contents of filler increasing, the density of samples had a great augment, which significantly contributed to improvement of the sound insulation properties according to mass law, then they derived a new transmission loss equation by studying the mechanisms of the sound insulation in polymer composites filled with inorganic particles [8]. Besides, Lee et al. [11] studied the soundproofing performance of carbon-nanotube (CNT) reinforced acrylonitrile butadiene styrene (ABS) composites, they concluded that the increase in stiffness by adding CNTs would play an important role in the soundproofing-properties of ABS/CNT composites, and Wang et al. [12] also measured sound transmission loss of mica filled PVC composites. They found that the addition of mica in PVC leads to a greater increase in the stiffness. The other is the design of multilayered panel [13,14]. However, the introduction of inorganic particles will make the polymer heavier [15], and the multilayered structures usually have hard layers, which makes them so inflexible as to limit their range of applications in soundproofing fields [16].

Foaming can provide a suitable route to meet the requirement of light weight, through some foaming processes, such as compression molding combined with particulate-leaching technique [17], foam injection molding with supercritical N_2 as the physical blowing agent [18], foam extrusion with supercritical CO_2 as the physical blowing agent [19], and some processes with chemical blowing agent [20], Open-cell foams have been extensively used for sound absorption and reducing the indoor reverberation [21],

* Corresponding author.
** Corresponding author.
E-mail addresses: xiongying@scu.edu.cn (Y. Xiong), nic7702@scu.edu.cn (S. Guo).

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meanwhile its analytical model for predicting the sound absorption coefficient of the foam has also been deeply researched, Yang et al. [22] established a simplistic yet accurate unit cell model of sound absorption for highly porous foams having either fully-open or semi-open cells and achieved good agreement among analytical model predictions, existing experimental data and numerical simulation results. But sound absorption and insulation are different acoustical concepts, sound absorption accompanied with energy dissipation due to forced vibration and viscous friction [23,24], and sound insulation is to prevent the outside sound waves to transmit inside [25]. Closed-cell foams are usually used along with other materials for sound insulation, for instance, sandwich panel and multilayered panel [26,27]. In these researches, foamed layers are confined in adjacent hard layers. The acoustic impedance mismatch between adjacent layers will cause repeated sound reflection, which increases the propagation path of sound waves and attenuates the sound energy in foam layers. However, this structure actually damages the light weight of foams and the constraint of hard layers also makes the panel inflexible.

In order to obtain polymeric foams with light weight, flexibility, and good soundproofing performance, we try to seek for inspirations from other foam applications, for instance, electromagnetic interference shielding, electrical conductivity, and thermal conductivity, etc [28,29]. Liang et al. [30] prepared microcellular polyetherimide/grapheme nanocomposite foams. They found that the large extensional flow generated from cell growth led to the enrichment and orientation of graphene in cell walls, which increased the specific electromagnetic interference shielding effectiveness. Ameli et al. [31] fabricated polypropylene/multi-walled carbon nanotube composite foams with different cell densities and cell sizes. They reported that the electrical percolation threshold decreased as the volume expansion increased, and they correlated the results with the effect of foaming action on the alignment and interconnection of carbon fillers. Actually, the phenomenon of alignment of fillers in composite foams was firstly reported by Okamoto et al. in 2001 [32]. The propagation of sound waves at interfaces depends on the acoustic impedance matchability of adjacent mediums: impedance match leads to transmission of sound waves, for example, Xu et al. [33] have investigated the difference of acoustic impedance value between Al-filled composites and Fe-filled composites, and also found that acoustic velocity of Fe-filled gradient composites is less than that of the Al-filled composites under the same mass ratio of epoxy resin and metal fillers. Conversely, impedance mismatch leads to reflection [34]. The transportation rules of sound waves are similar to those of electromagnetic waves [35]. These researchers' works provide us an inspiration, and we wonder if that kind of results in foaming process can be used in sound insulation field. To the best knowledge of the authors, no effort has yet been reported on the acoustic properties of such foamed composites.

In this work, we prepared a series of poly (vinyl chloride) (PVC)/mica composite foams with a wide range of filler loading and densities through the compression molding foaming process. Mica, a platelike silicate with high aspect ratio, was selected as the filler. PVC was selected as the polymer matrix because it's one of the most common thermoplastic materials employed today and its amorphous state is good for foaming process. The sound insulation performance was characterized by a four microphone impedance tube. We systematically investigated the relationship among the expansion ratio, cellular morphology, filler loading and sound insulation property. The alignment of mica in cell walls was observed, and the effect of the alignment of filler on sound insulation performance was explored. In addition, the flexibility and reusability of the composite foams were investigated by conducting a cyclic compression test.

2. Experimental

2.1. Materials

The commercial suspension grade PVC resin with the degree of polymerization of 1000 (SG-5) was purchased from Jinlu Resin Corp. (China). Mica with a length of 20 μm was obtained from Chuzhou Grea Minerals Corp. (China). The chemical blowing agent, azodicarbonamide (ADC) with an average particle size of 7 μm, was kindly supplied by Jiangsu Sopo Corp. (China). Polyacrylate (ACR), used to increase the melt strength of PVC, was supplied by Rohm and Hass China Inc. Other additives including dioctyl phthalate (DOP), calcium carbonate ($CaCO_3$), and organotin stabilizer were commercial products. Besides, specific trade mark of the materials used in this work were also listed in Table 1.

2.2. Sample preparation

The PVC resin, mica, and other ingredients were firstly mixed in a high-speed mixer for 3 min according to the formulations listed in Table 2. Then the PVC dry blends were kneaded by a two roll open mill machine (Labtech Engineering Company, Thailand) at 150 °C for 10 min. Below 150 °C, the blowing agent ADC would not decompose to release gas. After that, the mixed compounds were compression-molded into cylindrical samples with diameter of 60 mm and thickness of 2 mm, which was conducted at 150 °C for 5 min with a pressure of 10 MPa. This step aimed to eliminate the unwanted void within the materials. Finally, in order to initiate the decomposition of the chemical blowing agent, the mold (along with the sample) were moved to another daylight press with the temperature of 180 °C and pressure of 10 MPa and equilibrated at this condition for a period of time. Once the daylight press was opening, the composite foams were obtained.

All the samples were coded as $M_{x\text{-}y}$, where x represented the weight percent of mica and y represented the foaming time. For instance, the sample $M_{5\text{-}10}$ was foamed for 10 min with a mica loading of 5 wt %. Firstly, in order to get optimal ratio for mica, The foamed samples according to all the formulations in Table 2 were prepared with the foaming time of 10 min. The corresponding solid samples were prepared without the foaming process. Then, for the formulation $M_{a\text{-}y}$ (a represented 10 wt % which was obtained from above experiments), we prepared 4 samples with different expansion ratio by setting the foaming time of 4, 7, 10, 13 min, respectively. For comparison, a series of samples with different foaming time according to the formulation $M_{b\text{-}y}$ (b = 0) were also obtained.

2.3. Characterization of sound insulation

Sound insulation properties of the samples were characterized by sound transmission loss (STL), which is defined as follows: [36–39]

Table 1
Main materials in this work.

Materials	Codes	Supplier
PVC resin	SG-2, SG-3, SG-5, SG-8	Sichuan Jinlu
Organotin	T-395A	Beijing Arkema
Ca-Zn stabilizer	–	Self-made
Rare earth stabilizer	JX-308L	Hebei Jingxin Industry
Nano $CaCO_3$	501	Shandong Shengda
Azodicarbonamide (AC)	Dn8	Jiangsu Sopo
Foam additive (ACR)	ZB530	Shandong Huaxing
Plasticizer (DOP)	Chemical pure	Chengdu Kelong
Mica	GA-1	ChuZhou GeRui