Composites Part B 93 (2016) 252–264

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Compressive properties of graphite-embedded expanded polystyrene for vibroacoustic engineering applications

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ARTICLE INFO

Article history:
Received 16 October 2015
Received in revised form
22 January 2016
Accepted 11 March 2016
Available online 18 March 2016

Keywords:
A. Foams
B. Mechanical properties
B. Vibration

ABSTRACT

The transmission of low-frequency floor impact noises in buildings remains a longstanding problem to be solved. To design insulation materials for attenuating the low-frequency floor impact noises, a distinctive property with a dynamic stiffness that is low enough to achieve natural frequencies that are also sufficiently low, without an excessively low structural strength, is required. The mechanical properties of compressively deformed graphite-embedded expanded polystyrene foam were investigated and evaluated for the application to the low frequency insulation. In addition to the role of embedding graphite in decreasing stiffness, compression processing was shown to both reduce the dynamic stiffness and maintain the structural strength of the specimen, which provides an appropriate property for the application. This characteristic is assumed to be associated with the macroscopic deformation mechanics of closed-cell foam in response to compressive stress, which is distinct from that of open-cell foam or fibrous materials. The improved insulation performance of the compressively deformed specimen was verified through laboratory vibroacoustic tests. Moreover, based on the laboratory testing, the effect of changes in the structural wave fields on material optimization is discussed.

1. Introduction

The transmission of low-frequency impact noises from upper-floor to lower-floor dwelling units, which are primarily generated by human walking and can be characterized by the terms “thuds”, “thumps,” and “booming”, is considered to be one of the most annoying noises in multifamily buildings [1–3] and remains a difficult problem to solve. A fundamental approach for attenuating floor impact sound is to decrease the flexural mobility of the floor material, which is inversely proportion to the Young's modulus, density and thickness of the material [4,5]. For finite systems, the mobility is influenced by the peripheral boundary conditions [6]. Because the elastic modulus or density of common floor materials (i.e., wood or concrete) cannot be significantly changed, structural strengthening methods based on controlling the thickness or boundary conditions should be considered for reducing the mobility. Such methods include span shortening, external composites, external plate bonding, external or internal post-tensioning and section enlargement [7,8]. However, these strengthening methods are practically demanding and economically inefficient. As an alternative to structural modifications, the use of floating floors is considered to be an efficient method for impact sound insulation. Cremer et al. [4] and Ver [9] investigated the impact sound insulation mechanism of floating floors. These authors theoretically determined that the isolation of vibrations at frequencies greater than the natural frequency of two parallel plates coupled through an elastic medium determines the improvement in the impact sound insulation.

Because the elastic medium also plays a role as thermal insulant, materials with high thermal insulation capacity such as fibrous materials (e.g., mineral wool) and plastic foams (e.g., polystyrene foam) [10,11] are typically used for the interlayers of floating floors. Although floating floors with the common elastic media are effective in insulating mid-to-high (above 100 Hz) frequency impact sounds because the natural frequency to be near or above 100 Hz [11–14], low-frequency insulation using floating floors has not yet been systematically explored because of difficulties in insulation material development. Recently, the acoustical performances of elastic medium produced using new types of materials, such as rubber fluff [15] or cork granule composites [16], have been reported, but their insulation of frequencies of less than 100 Hz has

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http://dx.doi.org/10.1016/j.compositesb.2016.03.004
1359-8368/

not been evaluated. The frequency component of human footsteps is concentrated in the low-frequency range below 100 Hz [1,17]. For the design of low-frequency insulation materials, a distinctive property with a dynamic stiffness that is low enough to achieve natural frequencies that are also sufficiently low, without an excessively low structural strength, is required for vibroacoustic performance and structural integrity of the floating floor.

Expanded polystyrene (EPS) foam is widely used for thermal insulation in building construction. The integration of graphite flakes into the polystyrene matrix further improves the thermal insulation, where graphite particles reflect and absorb radiant energy, decreasing the materials thermal conductivity [18,19]. The improved insulating performance of graphite-embedded EPS enables the insulation panels to be thinner, which consumes fewer resources, reduces transportation energy usage and translates to lower construction and installation costs. For new residential construction practice, which is becoming more optimal in utilizing space and high cost efficiency of implementation, graphite-embedded EPS constitutes a new generation of EPS.

The advantage of adding graphite with respect to vibroacoustic characteristics can be a reduction in dynamic stiffness. EPS foams typically show a closed-cell structure due to the expansion of the polystyrene beads. Most of the cells in the closed-cell structure are not broken; they resemble inflated balls, piled together in a compact configuration, which makes it strong or rigid. However, cell morphology of graphite-embedded polystyrene foams shows some holes as open-cell wall, due to lack of material during foam expansion [20]. In open-cell structure, the cell walls are broken and air fills all of the spaces in the material, which makes the foam soft or weak, as if it were made of broken balls. The proportion of hole is increased with a high loading of graphite [20]. The partial formation of open cell is assumed to contribute to the reduction in dynamic stiffness. Investigations on the dynamic stiffness of pure and graphite-embedded EPS foams having a same density [21] indicate the reduction in dynamic stiffness with adding graphite.

Recently, Dikavičius and Miškinisin [22] and Dikavičius et al. [23] investigated the dynamic stiffness and compressive strength, respectively, of resilient materials using compressibility tests. The results of these studies imply that compressive deformation of closed-cell foams (elasticized polystyrene) exhibits a reduction of dynamic stiffness while maintaining structural strength. However, these studies determined the deformation characteristics under slight compression; such tests provide insufficient information for the design of low-frequency (below 100 Hz) insulation material. The objective of this paper is to investigate the mechanical properties of compressively deformed graphite-embedded EPS and its insulation performance for the development of low-frequency insulation material.

The remainder of this paper is organized as follows. In section 2, the mechanical properties of the compressively deformed graphite-embedded EPS are analyzed, and the changes in the dynamic stiffness and structural strength are evaluated for the engineering application. Section 3 investigates, through laboratory vibroacoustic tests, the improvement in low-frequency insulation performance of the compressed EPS; moreover, the effect of changes in structural wave fields on material optimization is discussed. Section 4 summarizes the most significant findings of this study.

2. Compressive properties of the graphite-embedded EPS

For the optimization of graphite-embedded EPS for the low-frequency insulant, the changes in the dynamic stiffness and structural strength of the graphite-embedded EPS are examined for a large range of compression such that the specimen achieves a natural frequency of less than 40 Hz (center frequency for the 40-Hz 1/3 octave band). Generally, standards for measurement of sound insulation in buildings [24–26] recommend 50-Hz 1/3 octave band as the lowest frequency range. Therefore, the natural frequency of 40-Hz targeted in this paper is considered to be appropriate for the engineering design of the low-frequency insulation.

2.1. Material processing

EPS foam manufacturing process is divided into two steps: preparing expandable polystyrene beads and fabrication of the beads into a finished cellular plastic article [27]. At the first step, styrene monomer, water, initiator and suspending agents are charged to the polymerization reactor in which the monomer is dispersed in water by the suspending agents throughout the reaction [27,28]. For a process for preparing graphite-embedded expandable polystyrene beads, 5% of pulverulent graphite (Chemical Abstracts Service (CAS) Registry Number 7782-42-5) [29] are homogeneously suspended in the polymerization solution. The particle size of the graphite is less than 45 μm. After polymerization, the polymer water slurry is cooled and centrifuged to separate the water from the polymer beads. The beads are then dried, size-distributed and stored in tanks. The beads, along with water and a blowing agent like pentane or butane, are added to the impregnation reactor. Separating off the aqueous phase gives dark gray beads, in which the graphite is homogeneously distributed in the beads. At the second step, the beads are pre-expanded by steam, hot water or hot air to achieve a proper density. The pre-expanded beads are then aged and placed in a mold. The filled mold is exposed to steam, expanding them once more and fusing them together, and then stabilized by cooling [27,28].

For the compression processing, the molded block is compressed under a static load of a pressing device (0.9–1 MPa) and stabilized after removing the load. The compression level was controlled by the loading time and was evaluated in terms of the resulting bulk density of the EPS: a longer loading time increases the density of the specimen and the level of compression. Fig. 1 shows cross-sections of the EPS specimens for different compression levels.

2.2. Analysis of dynamic stiffness

The apparent dynamic stiffness of the materials used under floating floors per unit area, s_t, is defined in the ISO 9052-1 [30] standard as

$$s_t = 4\pi^2 m_t (f_r)^2 \tag{1}$$

where m_t is the total mass per unit area used during the test and f_r is the resonance frequency of the system. For closed-cell foams, the dynamic stiffness s is equal to the apparent dynamic stiffness s_t because the contribution of the air contained within the material is neglected. To determine f_r for the estimation of s_t, an impact hammer test was conducted using a mass-spring setup; this setup provides the response of the mass in the frequency or time domain. From the obtained response curve, the loss factor of the material can also be measured using the half-power point bandwidth method or the logarithmic decrement method [31].

Fig. 2 shows the dynamic stiffness of the graphite-embedded EPS as a function of the compression level. The dynamic stiffness decreased as the compression level increased. The value was reduced by approximately 70% at high compression levels (20 and 25 kg/m^3) compared to the uncompressed EPS. Table 1 shows the variability in the dynamic stiffness measurements among 10