Materials & Design 82 (2015) 335–341

Contents lists available at ScienceDirect

Materials & Design

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

Comparing the mechanical performance of synthetic and natural cellular materials

F.A.O. Fernandes, R.T. Jardin, A.B. Pereira, R.J. Alves de Sousa *

TEMA Centre for Mechanical Technology and Automation, Department of Mechanical Engineering, University of Aveiro, Campus de Santiago, 3810-193 Aveiro, Portugal

ARTICLE INFO

Article history:
Received 13 May 2015
Revised 27 May 2015
Accepted 3 June 2015
Available online 20 June 2015

Keywords:
Cellular materials
Agglomerated cork
Expanded cork
Polymeric foams
Multiple impact
Dynamic loading
Energy absorption
Sustainable materials

ABSTRACT

This work compares the mechanical performance of agglomerated cork against synthetic materials typically used as impact energy absorbers. Particularly, the study will focus on the expanded polystyrene (EPS) and expanded polypropylene (EPP).

Firstly, quasi-static compression tests are performed in order to assess the energy storage capacity and to characterize the stress–strain behavior cellular materials under study. Secondly, guided drop tests are performed to study the response of these materials when subjected to multiple dynamic loading (two impacts). Thirdly, finite element analysis (FEA) is carried out in order to simulate the compressive behavior of the studied materials under dynamic loading.

Results show that agglomerated cork is an excellent alternative to the synthetic materials. Not only for being a natural and sustainable material but also for withstanding considerable impact energies. In addition, its capacity to keep some of its initial properties after loading (regarding mechanical properties and dimensions) makes this material highly desirable for multiple-impact applications.

1. Introduction

Synthetic and natural cellular materials have been used in many applications. From packaging of goods to military devices, from civil to aerospace engineering, these materials have been used in engineering applications where a good energy absorption capability is a desired feature. These materials are also commonly used in applications such as thermal-acoustic insulation [1].

Cellular materials are the material of election also for personal protective devices where the best example can be found on head protection systems such as road-helmets [2–5]. In fact, under compressive loading, these materials can undergo large strain deformation while maintaining a low stress plateau before reaching densification. This behavior allows them to absorb large amounts of energy under low stresses. Fig. 1 shows a typical compressive stress–strain curve for cellular materials.

Expanded polystyrene (EPS), expanded polypropylene (EPP), cork or even metal foams are examples of these materials. The best material for each application depends on the application itself, depending on the mechanical loading, strain rate, etc. The material's mechanical behavior depends on the density, loading strain rate and it is also affected by the manufacturing process. This dependency attracted many researchers trying to characterize those materials under quasi-static and dynamic loading [1,6–10].

EPS is possibly the most common within these materials, mainly due to a convenient cost-benefit ratio [1], being widely employed in the packaging industry. It is also employed in highly demanding applications such as impact absorption in safety gear. This closed cell foam absorbs energy by crushing mechanisms (collapse of walls). The EPS density is an important property because the yielding stress at which the foam crushes is directly related to it [11]. This parameter influences the EPS energy absorption capability, being responsible for the basic mechanisms of deformation and failure, determining the maximum crushing [1]. The typical stress–strain curve of EPS under compression is similar to the one illustrated in Fig. 1. In this, three regions can be identified: at very low stresses the material presents an almost linear elastic behavior, followed by a wide plateau where the stress remains almost constant, which leads to densification, where stress rises steeply for large strains.

Although this type of foam has an excellent first impact performance, in case of a subsequent impact in the same area, the protection level offered by EPS is minimal since the material deforms permanently without elastic recovery [7,12–14]. Thus, its energy absorption capability is significantly decreased after one impact, particularly in high-energy ones where large strains are reached. In order to overcome this issue, some materials were proposed

* Corresponding author.
E-mail address: rsousa@ua.pt (R.J. Alves de Sousa).

http://dx.doi.org/10.1016/j.matdes.2015.06.004

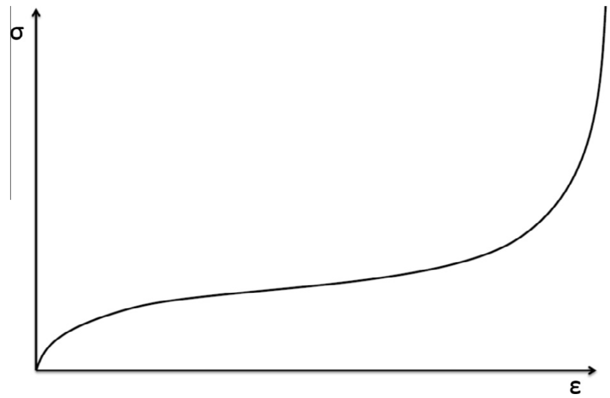

Fig. 1. Typical compressive stress–strain curve for cellular materials.

for multi-impact applications, such as EPP [7] and agglomerated cork [2,3] as motorcycle helmet liners.

EPP is also a synthetic material like EPS. For a first impact, their mechanical behavior is quite similar [7]. Nevertheless, EPP foam has a multi-impact protection performance [7], as showing a relevant counterpart of elastic deformations. On the other hand, the quasi-static mechanical properties of EPP foams are attractive and available in recent publications, but impact properties are very limited [15].

Cork (in natural or agglomerated versions) is a natural cellular material capable of absorbing considerable amounts of energy [16,7]. Cork is characterized by having both a good energy absorption capacity and a high viscoelastic return (deforms mainly elastically). After one impact, the capacity of this material to keep absorbing energy is almost unchanged. Few researchers recently studying this material also tried to employ it in a great variety of applications, such as road helmets [2,3] and vehicle's passive safety mechanisms [18]. When compared to synthetic cellular materials, cork also appears as a sustainable alternative, once it is fully recyclable and the tree is not harmed as renewing its outer bark every nine years.

Nevertheless, cork is a complex natural cellular material with unknown or not well understood properties [19]. However, many researchers have extensively studied the fundamental aspects of cork's mechanical behavior under quasi-static axial compressive loading [20–27]. More recently, and regarding agglomerated cork (details on how agglomerated cork is produced can be found in [28]), the influence of cork density on cork's mechanical behavior under compression, as well as the subsequent recovery of dimensions were studied by Anjos et al. [29]. However, few researchers studied agglomerated cork's mechanical behavior when subjected to dynamic compressions. Gameiro et al. [19] studied cork's (natural and agglomerated) mechanical behavior under impact loading at strain rates ranging from 200 to 600 s^{-1}. Nevertheless, the recovery dimensions at dynamic rates were not studied. In addition, quasi-static and dynamic tests were performed on agglomerated cork samples by Fernandes et al. [6] and the impacts on cork samples were simulated using finite element analysis (FEA), including the material's compression and relaxation.

The main objective of this study is the comparison of the mechanical response of EPS, EPP, agglomerated cork and expanded cork under multiple dynamic compressive loading (two impacts). There is also interest on the study of expanded cork and on evaluating its suitability as impact energy absorber, since there is no information about it in the literature. In addition, the impacts carried out experimentally were simulated for both agglomerated cork and expanded cork and also for EPS and EPP.

2. Materials and methods

In this study, EPS, EPP, agglomerated cork (AC) and expanded cork (EC) samples were tested. Expanded cork is different from the agglomerated one, mainly because of the manufacture process, which involves expansions under heat, pressure, and water addition. As a result, grain size is dramatically increased, density decreases and no binders are involved. Suberin (a subproduct of cork) acts as binder and the material is a 100% natural, in opposition to typical agglomerated cork that includes polyurethane as binder.

EPS and EPP were tested because they are among the most popular synthetic foams employed in energy absorption applications. Thus, it is possible to carry a comparison between the most used synthetic materials in energy absorption applications and cork solutions.

In order to perform this comparison, compression tests were performed at quasi-static and dynamic strain rates. The latter are guided impact tests, using a drop tower. Regarding the numerical simulations, Abaqus FE code was used to simulate the impacts.

2.1. Materials

In order to compare synthetic and natural cellular materials, EPS with a density value of 90 kg/m^3 and EPP with densities of 60 and 90 kg/m^3 were chosen (Fig. 2a). These are the density values commonly found in protective helmets. Regarding the cork samples (Fig. 2b), two densities were tested for AC, with 199 kg/m^3 and 216 kg/m^3, and one for EC with 159 kg/m^3.

The samples were produced by Petibol (EPP and EPS), Sofalca (EC) and CORKSRIBAS (AC), all of them Portuguese companies.

2.2. Experimental tests

Quasi-static and impact tests were performed in order to characterize and compare the materials for different strain rates. The procedure and setup of both tests is described below.

2.2.1. Quasi-static compression tests

Uniaxial quasi-static compressive tests were carried out using a Shimadzu AG50 KN testing machine with a video extensometer apparatus (Messphysic ME46NG).

The uniaxial compression test proceeded up until a 6.5 MPa stress was achieved. At this value, it is possible to observe densification in agglomerated cork and synthetic foams.

The samples were cubes of an average size of 60 × 60 × 60 mm. These samples were compressed at a velocity of 5 mm/min. The output force–displacement curves allowed to compute the Young moduli and energy absorbed per volume and to plot the stress–strain curve when compressed at quasi-static strain rates.

2.2.2. Impact tests

The impact tests were performed in a drop tower designed by the authors. This test rig consists in a 3 meter-high tube, which guides the hemispherical impactor. The impactor reaches an average impact speed of 4.5 m/s (ranging between 4.3 and 4.7 m/s). This steel impactor has a diameter of 94 mm and weighs 5 kg.

In order to measure the acceleration history during the impact, a uniaxial accelerometer (1201 Measurement Specialties) was placed inside the impactor. In addition, near the impact zone, there are two reflective object sensors (OPB700ALZ). These are separated from each other 15 mm in order to measure the impact speed. The signal from both reflective sensors and the accelerometer are acquired by an acquisition card TD 9816 at an acquisition rate of 2000 Hz. The acceleration history and the speed values were