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Assessing impact velocity and temperature effects on crashworthiness properties of cork material

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A B S T R A C T

Impact tests used to certify safety devices are becoming more severe with higher impact energies. Currently, there is a need of liner materials to withstand significant amounts of impact energy without complete deterioration. In addition, these liner materials should have the capacity to keep low accelerations to protect their user. Due to this increasing tendency of having higher impact energies, by using the same liner materials, liners are becoming thicker. Thus, there is also a need for new liner materials that can maintain an adequate thickness in order to permit sophisticated designs. This paper assesses the capacity of three different types of agglomerated cork to withstand large quantities of impact energy. Impact tests with a 9 kg impact mass travelling at velocities up to 13.7 m/s were performed. These are much higher than the ones required by EU and US safety devices certification standards. Finally, the material performance is evaluated under different temperatures to simulate work in diverse environmental conditions. Results attest the robustness of this natural cellular material in the range of studied conditions. Finally, numerical simulations are performed using finite element analysis in order to check the validity of the developed material model for high impact energies.

1. Introduction

Cellular materials have been used in a great variety of applications due to their excellent properties. These materials are mainly recognized by their impact energy absorption characteristics, which makes them excellent for packaging applications, and also by properties such as damping, thermal and acoustic insulation. Polymeric foams such as expanded polystyrene (EPS) and expanded polypropylene (EPP) are common and widespread examples of these materials.

Today's society is facing the challenge to overcome issues related to pollution and material waste, increasing environmental consciousness and leading researchers to look for renewable natural resources to produce goods that keep similar properties when compared to their synthetic equivalents. The problematics of recycling synthetic foams is being taken very seriously, but full, satisfactory solutions for recycling these materials lag. Growing interest has been devoted in recent years to materials derived from renewable resources [1]. Among natural cellular materials, cork is the highlight. The material comes from the harvested bark of *Quercus suber L* tree, usually extracted every 9–12 years [2,3]. Cork is a natural, renewable and recyclable material. Contrary to most synthetic foams, which deform by crushing, developing permanent deformation and losing crashworthiness properties, cork is characterized by returning nearly to its original shape after deformation, being capable to withstand multi-impacts. On top of that, cork is an excellent insulator for vibration, temperature and sound.

Under compression, cork presents a mechanical behaviour typical of a cellular material, characterized by an initial elastic slope under small strain, a stress plateau where most of deformation takes place (due to cell walls buckling) and finally a densification phase, where forces take the final peak value and stress steeply increase.

Cork is a natural cellular material capable of absorbing considerable amounts of energy. This material is characterized by having both a good energy absorption capacity and a high recovery capacity, which means that after an impact, the capacity of this material to keep absorbing energy is almost unchanged, deforming mainly elastically [4]. In addition to cork's great compressibility and dimensional recovery, this material has good thermal and acoustic insulation properties, very low permeability to liquids and gases, chemical stability and durability [5–7]. Due to its potential for impact energy absorption applications, this material has been employed in a great variety of applications, such as road helmets [8,9], vehicle's passive safety mechanisms [10–12] and other types

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of armour subjected to dynamic compressive loading. By having these properties, cork and its agglomerated version are seen as an excellent alternative to polymeric foams [4,8,9,13–16]. According to Castro et al. [15], if one simply compares the specific compressive strength (σ_c/ρ) against the specific modulus (E/ρ), for some specific applications, cork performs better than flexible polymer foams and some rigid polymer foams.

Many researchers have submitted cork to different tests to characterize it, performing tensile tests [17,18], shear tests [19], three-point bending tests [15,19–22], creep tests [23] and mainly quasi-static compressive tests [4,13,24–32]. Regarding cork agglomerates, Castro et al. [15] concluded that cork's granule size, density and the bonding procedure deeply affects the material's performance. Controlling these parameters make cork an excellent tailorable material that can be designed and optimised for specific applications. More recently, Anjos et al. [32] studied the influence of cork's density on its mechanical behaviour, as well as the subsequent recovery of dimensions. Jardin et al. [13] studied the response of cork agglomerates when loaded quasi-statically, demonstrating the influence of agglomerates density and granule size on the resulting mechanical properties, concluding the same as in Castro et al. [15], the tremendous potential for this sustainable material to be tailored to fit diverse crashworthiness applications.

However, few researchers studied cork's mechanical behaviour when subjected to dynamic compressive tests. Gameiro et al. [24] studied cork's mechanical behaviour under impact loading at strain rates ranging from 200 to 600 s^{-1}. Nevertheless, the recovery dimensions at dynamic rates were not studied. Fernandes et al. [4], using a drop tower, subjected agglomerated cork samples to impacts and validated a numerical material model using the results from these experiments and from Gameiro et al. [24].

Sanchez-Saez et al. [16] studied the dynamic crushing behaviour of agglomerated cork and observed an increase in the maximum contact force, displacement and strain when the impact-energy/thickness ratio increased. Nevertheless, the impact energies in this study were relatively lower. Jardin et al. [13], using the same test equipment as in Fernandes et al. [4], performed impacts with higher energies than Fernandes et al. [4] or Sanchez-Saez et al. [16]. In addition, different densities of agglomerated cork and a different type of agglomerate, the so-called expanded cork, were tested. Recently, Fernandes et al. [14] compared the mechanical performance of synthetic and natural cellular materials, by using the same experimental apparatus and performing impacts with the same impact energies as in Fernandes et al. [4].

The aim of this work is to analyse the dynamic crushing behaviour of the agglomerated cork when subjected to impacts of higher energies. The most demanding standards, such as ECE. R22, specify impact energies ranging between 100–200 J, which is not compatible at all with the reality of sport or motorcycle accidents. Thus, in this work, agglomerated cork was subjected to impacts of energies up to 850 J to reproduce more realistically impacts as in downhill ski or motorbike crashes. This will make possible to study the capability of this material to withstand even greater impacts and if it is possible to employ cork as an energy absorber in extremely demanding applications.

2. Materials and methods

After harvesting, cork oak barks are stabilized and cut in several stripes that are used to extract cork stoppers. However, approximately only 30% of the strip is used to produce the stoppers. The left-overs can be triturated and then agglomerated. Oppositely to natural cork that demonstrates material anisotropy, agglomerated cork, produced from compacting randomly oriented cork granules, presents a quasi-isotropic response. Grain size and binder quantity are two parameters that can deeply influence mechanical behaviour in cork agglomerates. Agglomerated cork has been finding numerous applications in civil construction and architecture, benefiting from the outstanding insulation capabilities.

Another cork product is the expanded or black cork. In the basic process, as initially patented in 1891, grains of cork are expanded with temperature and water, so the final structure agglomerates without the need of any resin, being a fully natural material. Modern versions of the process include chemical additions. Agglomeration is obtained from suberin, a substance that is naturally released during the expansion process.

In this study three distinct variants of cork agglomerate were studied (courtesy of CorksRibas and Sofalca, Portugal): Two white agglomerates, with different grain sizes and densities (Fig. 1, Table 1), and one black agglomerate, the lighter from three but with higher grain size.

The materials under study were already evaluated for quasi-static compression and low-energy impact tests, (Jardin et al., 2015). In this reference, impact energies were circa 115 J, whereas in this work ranges from 120 J to 850 J.

Impact tests were carried out using the Instron Dynatup 9250hv, as shown in Fig. 2. Maximum capacity for this machine is equal to 222.41 kN. Maximum, physical drop height equals to 1.25 m. In order to obtain impact velocity from 5 to 20 m/s, corresponding to simulated drop height 20.5 m, additional springs (spring constant: 75 kN/m) were used in addition to gravitational fall. The sample rate of the load cell was set to 204.8 kHz. Also, a high-speed Phantom V12 camera recorded the tests, which allowed the authors to post-processes the impact kinematics. The camera cines were recorded at the sample rate of 10 000 fps with the exposure of 99.5 μs and acquired resolution of 512 × 800 pixels. The footages were further analysed by TEMA Motion software (Image Systems), which enabled the generation of displacement and velocity graphs of characteristic, high-contrast markers

Fig. 1. Cork agglomerates studied: From top to bottom (EC159: expanded, large grain black cork; AC216: medium grain, white agglomerate; AC199: small grain, white agglomerate).

Table 1
Three varieties of agglomerated cork under study.

Material	Range of grain size (mm)	Density (kg/m^3)
EC159	4–10	159.4
AC216	2–4	216.2
AC199	0.5–2	199.1