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# Static and dynamic mechanical response of different cork agglomerates

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ABSTRACT

Cork is a natural cellular material capable of withstanding considerable amounts of energy and exhibiting a viscoelastic return to its original shape. This feature is particularly interesting to resist to successive impacts. In this study, the behavior of different types of agglomerated cork (AC) and expanded cork (EC) is investigated under static and dynamic loadings. Double impact was carried out on the samples using a hemispheric actuator. The peak acceleration data for all compounds were further analyzed. Static compression tests gave an interesting insight into the stress–strain curve of agglomerates and Poisson's ratio variation during deformation. Results demonstrate a clear influence of agglomerated density and grain size on the resulting mechanical properties and point out a tremendous potential for this sustainable material to be tailored to fit diverse crashworthiness applications.



## 1. Introduction

Cellular materials have been widely employed in engineering applications were good energy absorption capabilities are required. Since the seventies, the class of synthetic cellular materials are being extensively used for all kinds of protective application, from packaging of goods to protective helmets. Some well-known examples are the expanded polypropylene (EPP) or expanded polystyrene (EPS). Other cellular materials are metal foams or honeycombs that are purposely manufactured [1]. Before the advent of synthetic materials, cork, a natural product extracted from the outer layer bark of the cork oak tree (*Quercus suber* L.) was very popular and used in many protective devices [2]. Its a sustainable product removed every 9 years approximately [3]. Cork is composed of dead cells with impermeable walls due to the presence of waxes and a chemical compound named suberin [3].

The most suitable cellular material for each application depends on the usage itself, ranging from simple packaging of fragile goods to helmets. The majority of cellular materials absorb energy by deforming permanently. Indeed, when compressed, cellular materials can maintain low stress levels during a large amount of deformation before reaching densification. This kind of material response, characterized by a long plateau in the stress–strain curve, results in absorbing large amounts of energy.

Nevertheless, after an impact where high strains were reached, the capacity of such materials to absorb further energy is practically none. Some exceptions are cork (and agglomerated cork) [5–7] or EVA (Ethylene vinyl acetate) foam [8] among others, that present the capacity to almost return to its original form after unloading. For EVA, such occurrence can be noticed in many soles shoes and for cork in wine stoppers. Along successive impacts these materials have approximately the same capacity to absorb energy. For cork, the added value is the sustainability and eco-friendliness.

Natural cork, after harvested and stabilized [3,4] demonstrates material anisotropy, with different mechanical responses concerning the loading direction (radial, axial and tangential). Density, porosity, humidity or even fungal colonization influence cork mechanical behavior [9,10]. However, agglomerated cork, produced from compacting randomly oriented cork granules [11], presents a quasi-isotropic response.

Previous works from Gameiro and co-workers [12,13] as well as Paulino and Teixeira-Dias [14] suggest that micro-agglomerate cork is beneficial to improve crashworthiness and energy absorption properties of components subjected to impact or blast loads. Furthermore, micro-agglomerate cork presents similar mechanical behavior when axially compressed, in a dynamic range from 200 to 2500 $s^{-1}$, which may be a very interesting feature to take advantage in applications where strain rate sensitivity is undesirable.

Cork is a material that in recent years has raised a large interest in various investigators due to its particular mechanical properties. Some examples are the utilization of cork to improve the rut (wear) resistance of asphalt when adding a part of 5% [15]. Alcântara et al. [16] developed a specific type of cork composite for absorption of impact energy of filled tubular structures. Sousa-Martins et al. [17] subjected sandwich structures with cork compound cores to blast waves, were the core had a major part in energy absorption. Sanchez-Saez et al. [18] subjected to ballistic impacts structures of agglomerated-cork-cored in an experimental study. Using as

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structure thin plates of aluminum with a cork core, they increased the energy absorption in 30% when compared to a structure without the cork core for impacts of 300 J of energy. Costas et al. [19] studied cork as part of a frontal car hybrid impact absorber.

Another cork product is the expanded or black cork. Initially patented in 1891 [18], in this process grains of cork are expanded with temperature, water and chemical addings so the final structure agglomerates without the need of any resin, being a fully natural material. In fact, agglomeration is obtained with suberin [20,21] which is naturally released during the expansion process. A more modern variant of the expansion process can be found in [23].

Maćias-Garcı́a et al. [24] studied the bending strength of black and composite agglomerates of cork and concluded that the presence of carbonized and foreign particles in the agglomerate decreased the bending strength of the composite.

Regarding agglomerated cork (AC) and expanded cork (EC) there is still not a detailed study that characterizes the static mechanical properties and dynamic response at low velocity and high levels of kinetic energy, when properties such as grain size and density are varied. In fact, it will be shown the potential of these materials to have tailored properties to fit different needs. Useful data will be provided that might be useful when selecting cork for any type of crashworthiness application.

## 2. Agglomerated cork

Traditional wine stoppers are made from pure cork. A large quantity of cork remainings is then triturated. An automatic selection process permits to separate cork granules in terms of size and quality. Subsequently, cork granules are agglomerated inside a mold together with polyurethane and a catalyst [11]. After a cure process (which can be heated or not), large plates with several different thicknesses are ready for use (Fig. 1). Nowadays, agglomerated cork (AC) is used in a huge number of applications, from household devices to architecture and civil construction.

Seven distinct types of agglomerated cork were tested in this work. They were chosen in order to provide a wide range of distinct solutions, which in this case can be rendered into different densities and granule sizes. The agglomerated cork samples selected are produced by CorksRibas company. Table 1 provides the agglomerated cork density values.

As previously referred, a different variety of agglomerated cork is the so-called expanded cork (EC) or black cork. EC samples used in this work are produced by Sofalca company. The expansion process can lead to small density values for a cork product


**Fig. 1.** Different plates of agglomerated cork (courtesy CorksRibas).

**Table 1**
Density of specimen.

| Density (kg/m$^3$) | Adopted denomination |
|---|---|
| 216.2 | AC216 |
| 157.0 | AC157 |
| 178.0 | AC178 |
| 199.1 | AC199 |
| 122.9 | EC122 |
| 159.4 | EC159 |
| 182.8 | EC182 |

**Table 2**
Grain size and type of binder.

| Material | Range of grain size (mm) | Binder |
|---|---|---|
| AC216 | 2–4 | Polyurethane |
| AC157 | 2–4 | Polyurethane |
| AC178 | 2–4 | Polyurethane |
| AC199 | 0.5–2 | Polyurethane |
| EC122 | 4–10 | Suberin |
| EC159 | 4–10 | Suberin |
| EC182 | 4–10 | Suberin |

(122 kg/m$^3$), as depicted in Table 1, but larger granule size (Table 2). Nevertheless, for both AC and EC samples a wide range of density values can be found.

A closer look on the material surface (Fig. 2) depicts the granule size and color differences for the several samples. In the case of expanded agglomerated the grain size is much larger than for regular agglomerate, which added to resin absence, makes EC samples generally lighter. Table 2 presents the range of grain sizes utilized for the production. Exact mixture ratios and quantity of binder are commercial well kept secrets.

## 3. Static compressive tests

Quasi-static compressive tests were carried out using a Shimadzu AG50 KN testing machine with a video extensometer apparatus (Messphysic ME46NG), Fig. 3). The elastic modulus was obtained from the curves stress–strain (Fig. 4), calculated as the relationship between stress and strain in the initial part of the curve, here approximately straight, corresponding to stress between 0.015 and 0.1 MPa. The minimum value of 0.015 MPa corresponds to 50 N load which is required to ensure uniform backboard between the support base, the sample and the load punch of the testing machine. 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 tests must be stopped to avoid load cell damage. However, this strain–stress level is more than enough to characterize the static mechanical properties.

The average size of the samples were $60 \times 60 \times 60$ mm. Samples were carefully centered. The compression test proceeded at a velocity of 5 mm/min. After treatment, the force displacement curves allowed calculation of Young's moduli and energy absorbed per volume. Results are rendered in Figs. 4 and 5.

A total of 5 samples per each material were tested and the average result is presented. As expected, for cellular materials its possible to observe a small increase of stress for small uniaxial strains (approx. 5%). Then the materials exhibit a plateau for a wide deformation range (approx. 5–60%) keeping a small stress. This plateau is the key responsible for the energy absorption capacity of cellular materials. Finally the materials reach densification. Here an accentuated increase of stress occurs for small strain variations. The

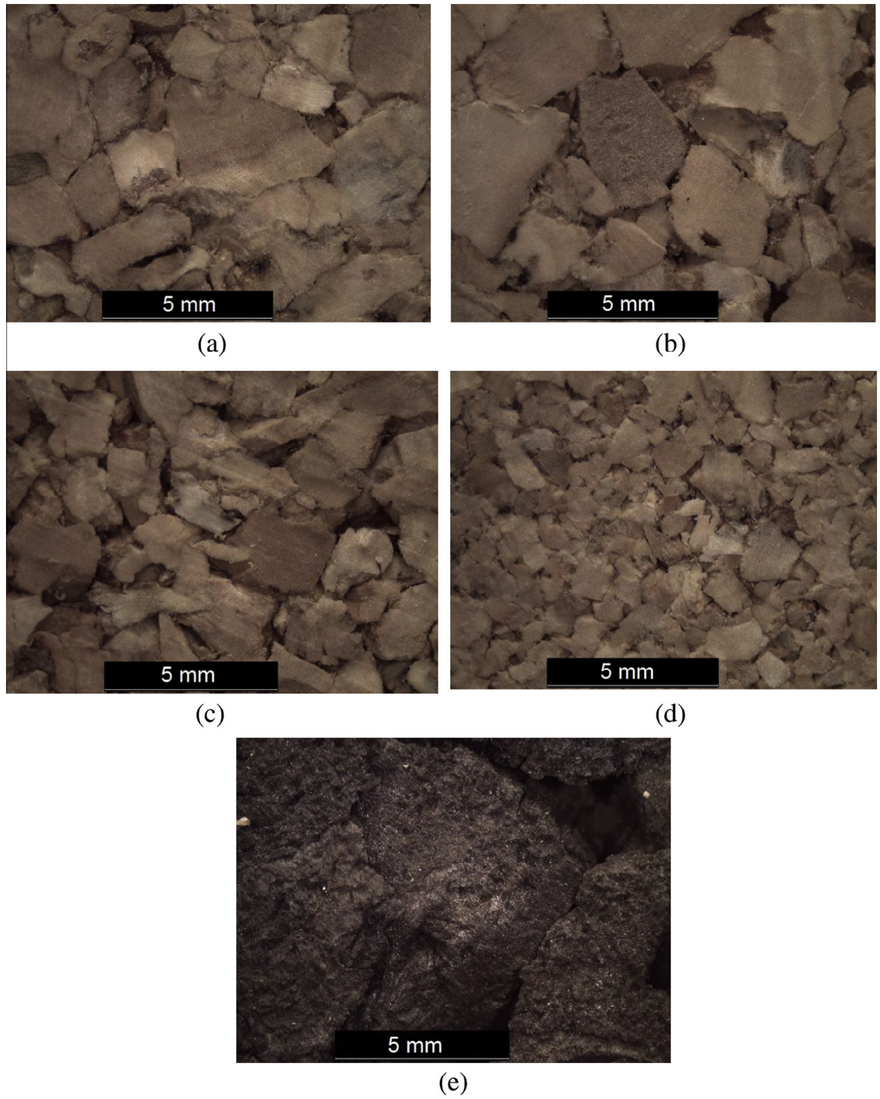


**Fig. 2.** Structure of AC and EC: (a) AC216; (b) AC157; (c) AC178; (d) AC199; and (e) EC159.

same observations were found in Ref. [13] for white cork agglomerates.

Once the goal is withstanding large amounts of energy, the mechanical response preferably should include a long plateau with moderate stress values, followed by densification only reached for high strain values. From this point of view, the AC216 exhibits the highest plateau (Fig. 4), although reaching densification sooner than the other materials. Also AC178 presents densification only for high strains but the plateau zone has low stress values. In the end, the agglomerated material choice will depend on the desired application and on the allowed stress level. Other agglomerates present a commitment between a high plateau and a high strain value before reaching densification.

Another relevant data can be analyzed from Fig. 4. Three lines point out the approximate point where each cork agglomerate reach a given strain energy per volume. The energy levels chosen are 250, 500 and 750 kJ/m$^3$. A very interesting compromise can be inferred from the data: for the lowest energy density level (250 kJ/m$^3$), the less dense material stores energy at a lower stress level and reaching a larger deformation. This is the ideal situation for any kind of protection system, promoting gentle decelerations. For the intermediate level of energy (500 kJ/m$^3$), the denser material is still not fully compressed, while the others are already on densification stage. And for the highest level of energy (750 kJ/m$^3$), the denser material (AC216) provides the best result once the stress level reached is lower compared to the remaining ones, which presents full densification. Again the application may influence the material choice: for instance, in the numerical analysis of road helmets impact it was found energy levels below 250 kJ/m$^3$ during head-helmet impacts carried out according to the ECE.R22 helmet standard [22].

A different way to derive similar conclusions is evaluating the energy per volume achieved at 6.5 MPa stress level (Fig. 5). The trend is not quite linear but somehow shows a proportional relationship between material density and energy density. Doing so, AC216 and EC122 are respectively the upper and lower bounds in terms of achieved energy under static compression. Although density seems to play a major role, other factors such as grain size and binder may also influence the results, explaining why energy density is not purely proportional to material density.

To give another quantitative insight, Table 3 presents energy density at 60% strain, calculated from the curves shown in Fig. 4. This value was chosen for being an average strain value for the densification onset. It is interesting to compare two agglomerates with very similar densities but different binders: AC178 and EC182 (also EC159 vs. AC 157). The expanded agglomerated seems

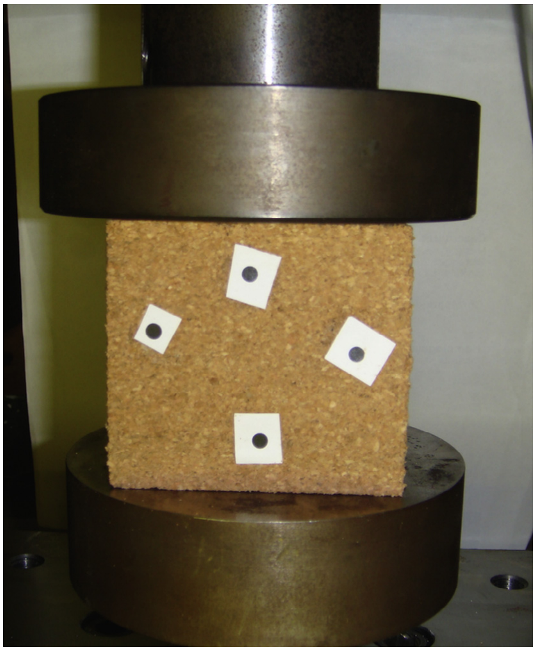

**Fig. 3.** Uniaxial compression tests.

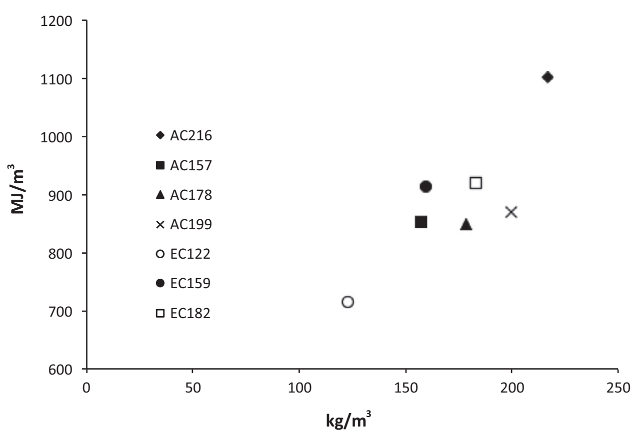


**Fig. 4.** Static compression response of AC and EC.

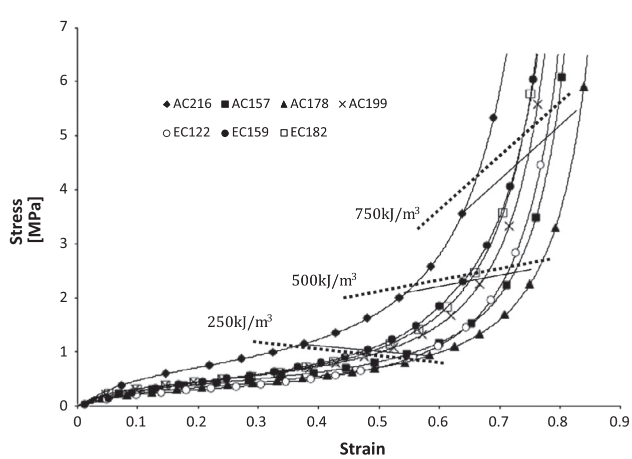


**Fig. 5.** Energy density vs. material density.

**Table 3**
Energy density at 60% compressive strain.

| Reference of specimen | $MJ/m^3$ at 6.5MPa | $MJ/m^3$ up to 60% deformation |
|---|---|---|
| AC216 | 1101.3 | 633.5 |
| AC157 | 854.5 | 322.8 |
| AC178 | 849.2 | 344.8 |
| AC199 | 871.2 | 341.3 |
| EC122 | 715.2 | 210.1 |
| EC159 | 914.9 | 406.3 |
| EC182 | 921.2 | 385.1 |

to have a slight advantage over the non-expanded one, which suggests that is the presence of polyurethane as binder does not affect crashworthiness properties. On the other hand, recalling Fig. 4, it is possible to verify that expanded agglomerate tend to reach densification stages earlier when compared to its non-expanded agglomerated counterparts.

The static compressive tests permitted also to obtain classical data like the Young modulus and Poisson's ratio. Concerning the Young modulus, values ranged from about 2.5 MPa for the less dense material to 6 MPa for the denser AC216. The remaining agglomerates showed values between 2.7 MPa (EC159) and 4.3 MPa (AC199). However, a significant deviation between different samples from a given material was observed, but indicated in Fig. 6.

Regarding Poisson's ratio, uniaxial compressive data showed an interesting evolution (Fig. 7). Similar tests were carried by Fortes and Nogueira [25], but regarding natural cork. The coefficient was calculated in the very classical way ($\nu = -\varepsilon_x/\varepsilon_y$), where $\varepsilon_x$ and $\varepsilon_y$ are the transverse and longitudinal strain, Fig. 3, respectively. The video extensometer software continuously record $x$ and $y$ coordinates of the four black dots on white background bonded to specimen. Doing so, the transverse and longitudinal strains are expressed by:

$$\varepsilon_x = \left|(x_{t,2} - x_{t,3})/(x_{i,2} - x_{i,3})\right| \quad (1)$$

$$\varepsilon_y = \left|(y_{t,1} - y_{t,4})/(y_{i,1} - y_{i,4})\right| \quad (2)$$

where the indices ($t$) points to the instant of measurement (an acquisition rate of 5 Hz was used) and ($i$) to the read value without any applied load.

Given the experimental difficulties found to analyse the agglomerates, and for the sake of clearness, only 3 material curves are shown. At the beginning of compression, Poisson's ratio is approximately 0.15 for all agglomerates. As deformation takes places, and – at microscopic scale – cells walls start to collapse and buckle – the value drops to very low values (circa 0.05). As densification starts to take place, the coefficient value rises again. In this sense, it is possible to state that there is no fixed value for Poisson's ratio concerning cork agglomerates, as it varies with the level of deformation imposed.

## 4. Dynamic tests

Following quasi-static tests, its necessary to evaluate the agglomerates performance concerning impact tests. To do so, impact analysis was conducted at the University of Aveiro laboratories using a 3-m tall drop tower (Fig. 8). Samples were crushed with an impactor reaching an average speed of 4.8 m/s. The 10 kg steel impactor geometry is hemispherical with Ø = 94 mm. The backing structure is a steel solid cylinder made of the same material of the impactor. Inside the impactor, a uniaxial accelerometer (Measurement Specialties 1201) measures the acceleration during the impact. Acquisition frequency was 2000 Hz and impact

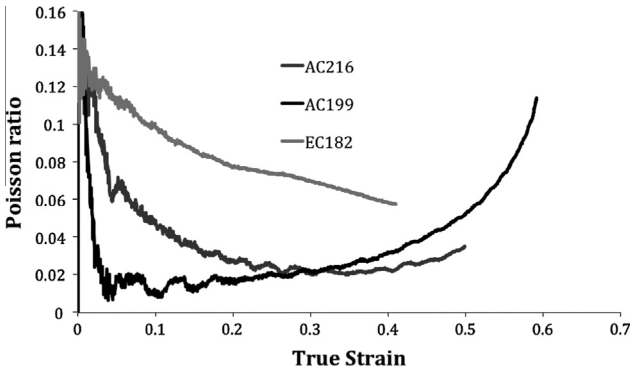


**Fig. 6.** Young's modulus from static uniaxial compressive tests.

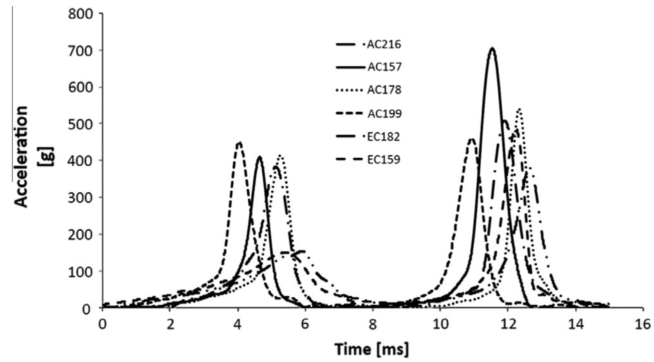


**Fig. 9.** Double impact response of AC and EC.

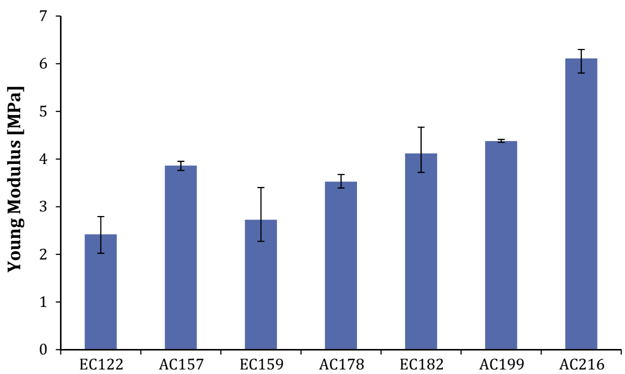


**Fig. 7.** Strain vs. Poisson's ratio.

**Table 4**
Mean acceleration in impacts.

| Material | No of impact | Mean acceleration (g) | Increase of acceleration between impacts (%) |
|---|---|---|---|
| AC216 | 1° | 364 | |
| | 2° | 493 | 35 |
| AC157 | 1° | 408 | |
| | 2° | 703.5 | 73 |
| AC178 | 1° | 445 | |
| | 2° | 452.5 | 2 |
| AC199 | 1° | 403.5 | |
| | 2° | 539 | 34 |
| EC159 | 1° | 148.5 | |
| | 2° | 404.6 | 172 |
| EC182 | 1° | 148.2 | |
| | 2° | 377.5 | 155 |

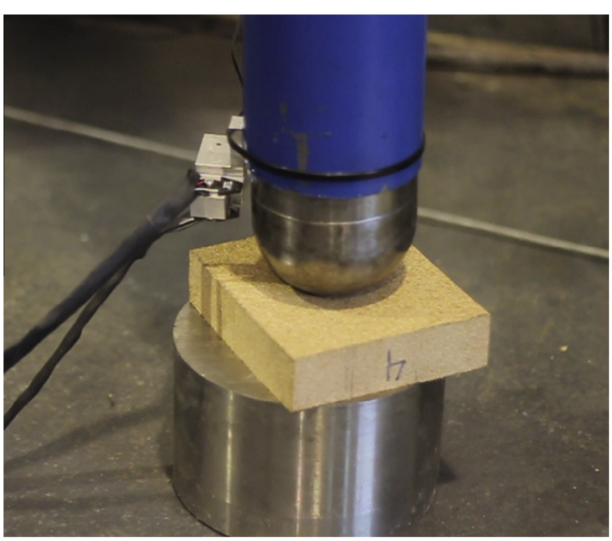

**Fig. 8.** Lower end of the drop test machine [5].

velocity was measured resorting to two objective reflector sensor (OPB700ALZ) at a distance of 15 mm from each one were and placed adjacently the place where the impact occurred. The data from de accelerometer and the two objective reflector sensors were collected with a Data Translation DT9816. Data was processed using MATLAB to determine the velocity and the acceleration curve. These data were not filtered, since from observing Fig. 9, the noise level is irrelevant.

Each specimen was subjected to two impacts (with approximately 30 s interval). It was a goal to infer the capacity of cork material to keep its impact resistance during multiple impacts, which consists in its major advantage (besides recyclability) compared to expanded polystyrene (EPS) material used in the majority of energy absorbing applications. However, one of the expanded cork agglomerate (the less dense one, EC122), failed to withstand the second impact as being completely crushed after the first impact. Doing so, to prevent damage in the accelerometer, no second impact was carried out for EC122 and the curve for the first impact was considered not representative, being removed from Fig. 9.

In safety applications, besides keeping properties after multiple impacts, it is desirable that the peak acceleration be as low as possible and that the rate of deceleration be not too severe. This would imply impact curves with low peaks and large bases. From analyzing Fig. 9, it becomes evident that the first impact performance of AC samples leads to higher values of peak acceleration in shorter timer intervals. On an opposite trend, EC samples deliver bigger impact time spans and lower peak accelerations. From this point of view the expanded corks (EC159 and EC182) have the best response for both the first and the second impacts, while EC182 exhibits a better response for the second impact. Nevertheless, it must be stressed that these conclusions hold for the specific impact energy level sustained in the performed tests.

In fact, after the two impacts, expanded cork samples were completely degraded while non-expanded ones were intact. The performance difference between impacts is considerable for EC material while negligible for non-expanded samples, as shown in Table 4. This is due to its manufacturing process, where – as explained – the lack of binder and the presence of carbonized matter contribute negatively to an accentuated degradation in properties. This characteristic makes the type of AC material much more promising in application dealing with higher impact energy levels when compared to the ones here studied. Under this viewpoint, AC199 displays the lowest degradation in properties and a better overall performance.

## 5. Conclusions

In this paper, uniaxial quasi-static compressive and impact tests were performed for a range of distinct agglomerated corks. This range included different grain sizes and binders.

The reported results showed that agglomerated cork materials can exhibit very diverse material properties depending on the agglomerated grain size, the quantity of binder and even on the processing method. In literature, agglomerated cork is usually referred generally as a single type of material. Here, a range of agglomerated variations was studied and it was shown that its properties can indeed have significant variations and even be tailored to fit a particular application.

In a general sense, it was shown that: (i) less dense agglomerates have lower Young's modulus and a lower stress plateau during deformation stages. So, they store lower levels of energy per unit volume; (ii) however, they reach densification stages later than more dense samples; (iii) specimens with larger grain size are much more prone to damage mechanisms; doing so, their performance during multiple solicitations (e.g., double impact) is severely compromised.

Conclusively, it was possible to shown that the agglomerated cork is a very versatile material. By changing parameters such as grain size or binder, it can easily tuned and tailored to fit some set of desired properties (like density, Young's modulus and densification strain) depending on the final application. It is important to draw attention to this aspect and further develop it for safety applications.

Cork is a natural material, harvested from a tree every 9 years. The tree is not harmed. Thus, it is fully sustainable and recyclable. Its mechanical properties can rival with other synthetic cellular materials that are usually employed in safety and packaging applications.

## Acknowledgements

Portuguese companies CorksRibas (agglomerated cork) and Sofalca (expanded agglomerated cork) are deeply acknowledged to supply samples for testing. Ricardo Pascoal (TEMA) for helping with acceleration measurements. FCT PhD Grant Number SFRH/BD/91292/2012 (Fabio Fernandes).

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