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Experimental Study of Natural Cork and Cork Agglomerates as a Substitute for Expanded Polystyrene Foams under Compressive Load

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Corresponding Author:	Ramon Miralbes, Ph.D. Universidad de Zaragoza Escuela de Ingeniería y Arquitectura Zaragoza, Aragón SPAIN
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Universidad de Zaragoza Escuela de Ingeniería y Arquitectura
Corresponding Author's Secondary Institution:	
First Author:	Ramon Miralbes, Ph.D.
First Author Secondary Information:	
Order of Authors:	Ramon Miralbes, Ph.D.
	David Ranz Angulo, Ph.D.
	Jan Ivens, Ph.D.
	Javier Abad, Ph.D.
Order of Authors Secondary Information:	
Author Comments:	The authors after the review have prepared all the images to be published in black and white. Fig1 has been generated using PPT, fig 2 is a photo, fig 3 to 11 have been generated using excel and they have been introduced in a word or a power point. All the tables are generated using word.
Response to Reviewers:	Dear reviewers and editor, We appreciate your consideration and your comments to improve the quality of the paper that we have tried to follow. We send also the manuscript with the modifications highlighted as a suplementary file- Yours faithfully, The authors Editor The manuscript needs serious and detail focused upgade to meet the standard of WST. So far the manuscripts is alike a research report. Please consider the standards of scientific publishing when revising the manuscript. For example, neither any objectives nor any hypotheses are presented at the end of the introduction. - It has been upgraded the paper to try to fulfill the standard requirements of WST: it has been included some objectives and hyphotesis at the end of the introduction and it has been also included the relationship with the Gibson's model. It has been included the definition of main parameters of the stress-strain curve and the equations to obtain the energy. Additionally, the materials and methods have been upgraded including more information about the testing machines and the acquisition data process. The resilience chapter has also been improved and the conclusions to explain the observations in-depth. The level of scientific discussion needs to be improved, the number of figures might be

reduced (are so many EPS data to be graphed isolated from the cork data?
- It has been removed the results for the EPS75 and EPS and cork figures have been merged. Additionally they have been improved to adapt to the quidelines of the journal: black and white figures with at least 0.5 pt wide (>0.3), different types of lines for the EPS and the cork agglomerates to distinguish them clearly and different markers and a minimum resolution of 1200 dpi.
Quality of the figure 1 and 2 and the line graphs have to be improved as well considerably.
- It has been removed figure 1 that does not add significant information and figure 2 has been substituted with other more representative. Line graphs have been improved and adapted to fulfill the guidelines of the journal.

Reviewer #2:

line 5: "there are but a few articles focused on the mechanical properties of cork", not true just looking to the cited references, please rephrase.
- The reviewer is totally right. It has been rephrased

HIC is used for helmets standards. Do authors tested helmets?
- It has not been studied helmets. HIC is usually used to analyze the Head Injury Criterion but, in essence (see eq. 1), it is used to analyze at the same time the maximum deceleration of the drop tower test and the average deceleration. It is explained in section 3.2.3. HIC study could be used to compare different materials to obtain this that would have better behavior if it is used to build a helmet.

No description of testing apparatus. Please provide techinical details, pictures, acquisition rates, samples positioning, etc.
- Some information of the testing apparatus is provided in section 2 that include the INSTRON model. It has been completed this information. However, the limitations of black and white of the journal prevents from the possibility to generate visible pictures of these apparatus.

Figs 1 and 2: this quality was accidental? Please provide decent figures.
- Fig 1 has been removed and Fig 2 has been replaced for another that provides more information about tested corks.

Fig 3 to 13: Please provide more clear figures, pay attention to colour blind people. Graphs should be black and white, and each series should distinguished by different line types and markers.
- It has been removed the results for the EPS75 and EPS and cork figures have been merged. Additionally, they have been improved to adapt to the guidelines of the journal: black and white figures with at least 0.5 pt wide (>0.3), different types of lines for the EPS and the cork agglomerates to distinguish them clearly and different markers and a minimum resolution of 1200 dpi.

Reviewer #4:

The paper is not acceptable for publication in its present form.

The behaviour of polymeric foams and agglomerated cork under compression load (quasi-static and dynamic loads) is a topic widely studied in the scientific literature. The originality of this work is not so clear. What differs between this work and the previous ones cited in references and present in the literature? The contributions must be emphasised.
- The reviewer is totally right. It has not been sufficiently explained so It has been emphasized at the end of the introduction.

	The authors only describe the results but these observations are not explained in depth. The results are very generic and lack highlights. - It has tried to explain more in depth some of the observations and it has also tried to link this observation with the internal structure of the materials. It has also tried to highlight some of the conclusions and results. They do not explain how some parameters are calculated, as the densification point or the end point of the elastic zone. - It has been explained these points. The study of the resilience of materials needs to be completely reworked to expand. - The study of the resilience has completely reworked and expanded including three quasi-static comparative studies of the resilience capability of the different materials depending on the maximum strain. Figures 1 and 2 need more resolution. - Fig 1 has been removed and Fig 2 has been replaced for another that provides more information about tested corks.

Experimental Study of Natural Cork and Cork Agglomerates as a Substitute for Expanded Polystyrene Foams under Compressive Loads

Authors:

Ramon Miralbes Buil (R. Miralbes). University of Zaragoza. Zaragoza (Spain). miralbes@unizar.es. Corresponding Author.

David Ranz Angulo (D. Ranz). University of Zaragoza. Zaragoza (Spain). dranz@unizar.es

Jan Ivens (J. Ivens). KU Leuven University. Sint-Katelijne Waver (Belgium). jan.ivens@kuleuven.be

Javier Oscar Abad Blasco (J.O. Abad). University of Zaragoza. Zaragoza (Spain). javabad@unizar.es

Abstract

EPS is a material that is widely used in energy absorbing applications, especially in helmets, despite its non-renewable origin. Cork and its derivatives however, are proposed as a substitute for polystyrene foam (EPS) due to their renewable origin and their easy recyclability. In spite of the low-environmental footprint of cork and its derivatives, there is insufficient data on their mechanical behaviour. Consequently, under dynamic and quasi-static loads, four different-density EPS, a natural cork material and five different cork products with different grain sizes and heat treatments have been tested. They have been compared in terms of their stress-strain and specific stress-strain curve, their volumetric capability to absorb energy, their specific energy, average decelerations and peak deceleration.

Finally, EPS foams cannot recover their initial shape upon deformation due to their low resilience capability. This is especially important in applications such as helmets which are bound to be subjected to multiple impacts. However, cork and its products could have this capability for resilience and would therefore be more suitable for certain applications.

Keywords: cork; impact; helmet; agglomerate; polystyrene foam.

1. Introduction

Cork is a natural material that is extracted from the bark of the cork oak tree and therefore has zero- carbon footprint; in addition, once a cork product has reached the end of its lifetime, it can be crushed and recycled to manufacture new products or, if disposed of, it can be easily degraded, generating zero impact on the environment. Additionally, cork has very low permeability to gases and liquids, has good insulating properties, high durability, high energy absorption capability and high viscoelastic return (Pereira 2007). This last aforementioned property means that, under compression, cork shows elastic behaviour and thus recovers its initial shape and properties after being crushed.

Despite its properties, traditionally cork has almost exclusively been used to make wine stoppers. However, at present this may no longer be the case, and there is an increasing tendency to use it as the core of some composite sandwiches that require high strength-to-weight ratio (Sanchez-Saez 2011), as well as to enhance other materials such as polyurethane (Gama 2019), polyethylene (de Vascongelos 2019) or polyfurfuryl (Menager 2019), in order to create materials with a lower carbon-footprint; to reduce the density of other materials such as concrete (Parra 2019); or in energy absorption applications such as helmets.

As previously mentioned, thanks to its energy absorption capabilities, cork is a candidate to become a substitute for non-renewable materials, such as expanded polystyrene foams (EPS) in some applications requiring energy absorption. This is mainly the case of helmets for different types of applications: motorcycling, cycling, snow sports, horse riding, etc. In addition, cork has high viscoelastic return as opposed to EPS and, consequently, could be a better-suited material for helmets undergoing multiple impacts thanks to its return to initial shape and properties after impact.

With regard to the use of cork in helmets, there are studies that analyse the possibility of substituting EPS with cork, such as the study of Coelho (2012) which by means of numerical tools, analyses the behaviour of a head impact against a block of cork and EPS with a density of 50 kg/m^3 where it was concluded that a combination of both materials could be useful for helmet liners. Likewise, Sousa (2012) compared the mechanical properties of EPS with a density of 30 and 50 kg/m^3 with different cork agglomerates (0.2mm, 0.25 mm and 0.3 mm) and concluded that while cork could be used for liners in helmets, EPS had better capability to reduce injuries. Nevertheless, when compared with EPS, the article pointed out that since cork conglomerate can recover its initial shape, it can be more suitable in the event of multiple impacts thanks to cork´s high viscoelastic return properties. This is one of the main conclusions drawn by Willehelm (2017).

Other articles, such as Tay (2014) that compare different natural materials to improve safety in vehicles under oblique impacts include conglomerate cork; the aforementioned study pointed in the same direction and noted the inferior behaviour of the cork under study. Finally, the studies of Fernandes (2019) which explored the use of two different agglomerated (199 and 216 kg/m^3) and one expanded cork (159 kg/m^3) showed cork´s poor adequacy as a substitute for the EPS (90 kg/m^3), with huge modifications in the geometry of the helmet including some holes being required in order to finally obtain a helmet with similar mechanical behaviour to that of EPS, all at the expense of higher weight.

It must be highlighted, though, that some of these studies exclusively focus their analysis on a limited number of types of conglomerate cork despite the diversity of existing products and by-products of cork, each with different mechanical properties resulting from different manufacturing processes. The most common products are natural cork sheets, white cork agglomerate, black cork agglomerate (also called expanded cork) and rubber cork, which will be the focus of this study.

With regard to the mechanical characterization of cork, apart from the data provided by manufacturers- usually providing a short range of mechanical properties (density, Young modulus, etc.), there are some articles focused on the mechanical properties of cork – most of them exclusively related to the specific application of wine stoppers. This is the case of the study of Crousvisier-Urion (2018) which concludes that the use of small particles of cork reduces stiffness; or the case of Sanchez-Gomez (2018) who analyse the mechanical properties of a wine stopper (some natural, others co-extruded with synthetic materials and others with different micro-agglomerates). Other authors analyse the influence of hydration of cork in their mechanical properties (Lagorde-Tachon 2017) and conclude that Young´s modulus has a constant value from 0% to 50% of humidity, with a significant drop from that point onwards.

Anjos (2014) study the influence of density on the compression behaviour of cork and conclude that density is directly associated with the Young´s modulus and stress in the plateau zone. Pinto-Silva (2005) made a review of the properties, capabilities and applications of cork, showing the influence of grain size in Young´s modulus for three different agglomerates; additionally, the reviewer collected some mechanical properties from other authors which show compression modulus for natural cork as well as boiled cork and others undergoing different heat treatments. Another interesting result of this study points out that cork and its agglomerates have better specific properties (specific compression strength and specific modulus) than flexible polymer foams such as EPS. Finally, other authors (Fernandes 2015) compared some conglomerated cork (216 and 199 kg/m3) and expanded ones (159 Kg/m3) with EPS (90 kg/m3) and expanded polypropylene (EPP) (60 and 90 kg/m^3), by means of numerical and experimental tools, reaching the same conclusions, while others (Jardin 2014) obtained the behaviour of some cork conglomerates (216, 199, 178 and 157 kg/m^3) and expanded ones (122, 159 and 182 kg/m^3)

Another application of cork is its use as a core in tome sandwich panels. The results obtained by some authors (Moreira 2019) show that the performance of cork agglomerates depends on density, cohesion procedure of granulates and cork granule size. Therefore, these variables can be adjusted to obtain the desired mechanical properties, as pointed out by some other authors (Santos 2017), too.

With regard to EPS, this material is traditionally used for a huge variety of applications such as helmets or protectors for some goods. This material is generated during a foaming process in which some closed air cells are generated inside the material; these cells can be manipulated to obtain different densities (from 10 to 150 kg/m^3); with the most common densities between 60 to 120 kg/m^3 in the case of helmets.

There are some studies about the mechanical behaviour of EPS under compressive forces. It is clear that there is a direct relation between density and its mechanical properties under quasi-static and dynamic loads (Ouellet 2006, Chen 2015, Krindaevaad 2014). In all cases, the stress-strain curve of EPS has three different zones - a linear elasticity zone; a plateau zone; and a densification zone. In the initial one-the linear elastic zone-, the material could recover its initial shape and shows a linear behaviour; however, it is a small zone which can absorb very little energy. Immediately after that the plateau zone is found. This is a large zone in which the level of stress is more or less constant; this means that in this zone the material can absorb a great deal of energy with the same stiffness. This is the most important zone for helmets as a huge amount of energy needs to be absorbed while they must deform progressively in order to avoid high decelerations in the head. Finally, in the densification zone the stress increases sharply and, as a result, should a helmet reach this zone, the head is subjected to significant deceleration, with ensuing neural injuries.

When analysing the state of the art of the test of helmets conducted by means of different certification standards (ISO 17025 / SNELL, ECE.22.05, DOT), one of the main biomechanical indexes used in order to analyse the brain injury damages is the Head Injury Criterion (HIC) (Versace 2019), which uses the data gathered through an accelerometer in the centre of the head of a dummy. The HIC is determined with this equation:

$$HIC = max\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5} \cdot (t_2 - t_1) \qquad \text{(eq. 1)}$$

This criterion not only analyses the main deceleration peaks, as it includes the study of average decelerations during different periods of time to determine the most critical ones. These aspects are in regard with the movement of the brain inside the skull, which acts like a mass-spring-mass model.

In this article, the main objective is the comparative study of cork products and different densities EPS under compression efforts to analyse the possibility of the former materials to substitute petrol-based latter ones in certain applications in which the capability to absorb energy is essential.

The main hypothesis of this study is that both types of materials, EPS and cork agglomerates have internal cell structures with air inside and, consequently, both will have similar mechanical behaviour; this behaviour has been previously mentioned and it is defined for the polymeric foams by the Gibson's model (Gibson 1997).

The Gibson's model distinguishes three different, well-defined zones in the stress-strain curves of polymeric foam materials (Fig. 1): the initial elastic zone, the plateau zone and a densification zone. The elastic zone characterizes by the capability of the material to recover its initial dimensions and the shape of the curve is a linear elastic one defined by the Young's modulus; in this zone the walls of the internal structure of the foam deforms elastically and can recover its initial shape; during the compression process, the internal pressure of air trapped inside the cells increases and after a certain point the cell walls cannot support the pressure and collapse; then the plateau zone appears; this zone is defined by a constant stress or a curve with a very low increasing slope that is defined with the plateau's modulus. In this zone the material cannot recover its initial shape and progressively collapse; thus similar levels of stress appear what imply constant stiffness and decelerations. Therefore, this zone is significantly more suitable for energy absorption than the elastic zone and, furthermore, the deformation range of this zone is significantly higher, which implies a greater energy absorption and deformation capacity. Finally, when all the cells collapse and all the air trapped inside disappears, the behaviour of the material is similar to the non-foamed original, characterized by an exponential slope in the stress-strain curve defined by the volume modulus of the original material. It should be noted that this implies an exponential increase in the stiffness of the material and, consequently, higher decelerations. That is the main reason why the densification zone should be not reached in impacts.

The end of the elastic zone is determined using the Young's elastic modulus which is the slope of the curve in the elastic zone. When the curve differs more than a 0.2% from an elastic one, then the plateau zone has been reached. In the same way, the densification point is the intersection point between the line defined by the slope of the plateau zone and a tangent curve in the densification zone that is obtained using the bulk modulus of non-foaming material in the case of the EPS (Fig. 1).

In the case of cork products, their internal structure is an open cell one that has also air inside but that not trapped. As a result, the stress-strain curve is expected to be similar and follow the Gibson's model as well. However, the open cell structure will also suppose that the cell will not collapse and, as a result, the material could recover partially its initial shape if the plateau zone or also if the densification zone is reached. Additionally, some differences could appear in the stress-strain curve especially in the plateau zone so it is expected a higher slope in this zone.

The main parameters of the stress-strain curves are as follows:

- Maximum tensile strength in the elastic zone ($\sigma_{c,e}$)
- Maximum tensile strength at the densification point ($\sigma_{c,d}$)
- Maximum elastic elongation ($\varepsilon_{c,p}$)
- Elongation at the densification point ($\varepsilon_{c,d}$)
- Elastic Young's modulus (E_c)
- Plateau Young's modulus (E_p)

The total energy absorbed per unit of volume by the material can be obtained from this equation:

$$W = \int_o^{\varepsilon_i} \sigma \, d\varepsilon \qquad \text{(eq. 2)}$$

This total energy absorption can be decompound in the following two components:

- Elastic energy absorption $W_e = \int_o^{\varepsilon_{c,p}} \sigma \, d\varepsilon$ (eq. 3)
- Energy absorbed in the plateau zone $W_p = \int_{\varepsilon_{c,p}}^{\varepsilon_{c,d}} \sigma \, d\varepsilon$ (eq. 4)

In relationship with the specific parameters, that are useful to compare materials in terms of properties with the same weight instead of in terms of properties with the same volume, they are obtained by dividing them by the density (ρ) of the material.

It must be highlighted also that, one of the main contributions of this paper, that goes beyond the state of the art, is that it analyses not only one or two types of isolated cork agglomerates, but main different types of existing cork products including natural cork and black agglomerates and it also compares them with main EPS materials. Consequently, it would be possible to obtain a more precise idea of the mechanical properties of different types of cork agglomerates and about their capability to substitute EPS.

Additionally, the paper delves into the capability of these materials to recover its initial shape and absorb a second impact. It must be highlighted here that some studies (Silva 2011) indicate the resilience capability of cork that can absorb multiple impacts and loads, and the least for the EPS (Yanzhou 2015) but there are not in-depth comparative studies about this topic. Hence, the article will be also focused in the comparative study of the resilience of both types of materials.

2. Materials and methods

The materials to be studied are the EPS used for the liners of the helmets and different types of cork. In the case of the EPS, EPS with densities of 60, 75, 80, 100 and 120 kg/m^3 with different grain sizes will be studied.

As for the study of cork, the natural material (NC), a cork agglomerate (AC), three different white cork agglomerates (WC) (usually called too agglomerated cork) and a black cork agglomerate (BC) (usually called too expanded cork) (Table 1) with different grain sizes will be used (Fig. 2).

Natural cork sheets are obtained from the bark of the cork oak by means of axes. With a cutting machine, the external layer is removed and flat regular sheets are obtained. The dimensions of these sheets depend on the cutting process and the tree itself; commercially, the common sheet thickness ranges between 3 and 15 mm, and the length and width between 100 and 600 mm.

Cork agglomerates are obtained after a more complex process. Natural cork and/or recycled cork agglomerates, are chopped into granules using mechanical processes and are subsequently sifted to obtain granules of different sizes. Afterwards, using heat, pressure and/or adhesives the granules join together to obtain regular sheets and bricks. Depending on the sizes of the granules and the joining processes, the obtained material has different mechanical properties. One of the main advantages of the agglomerates is that there are fewer shape and dimension limitations.

White cork agglomerates are manufactured using pressure, heat and adhesives; although biodegradable water based glues are sometimes used, the most common adhesives are resins such as polyester, epoxy, phenolic and vinyl resins. As a result, the final material obtained loses part of its renewable aspect. Depending mainly on the size range of the granules and, to a lesser extent, on the resin used, mechanical properties change.

Black cork agglomerates are manufactured by means of pressure combined with high temperature water steam; the granules expand (hence the name "expanded cork") and suberin -a natural resin-, is exuded, joining the granules.

Natural cork presented in 600x100x10 sheets; four different white agglomerate corks with different adhesives and densities presented in 915x610x10 sheets; and one black agglomerate cork presented in 1000x500x20 sheets have been studied. These materials have different densities and different grain sizes (Fig. 2).

These materials have been studied under a quasi-static compression test using an 8032 INSTRON universal test machine with a 0.2 mm/s velocity until reaching a maximum of 90% strain with an acquisition rate of 0.2 s. The testing machine has been equipped with a 2501 -162 INSTRON compression platens and a INSTRON 2530-50 static load cell (maximum force: 50 kN) and it has been used the INSTRON own digital acquisition system (DAQ).

Cylindrical specimens of φ50 mm and a height of 40 mm have been tested and they have been placed in the centre of the platens using a pattern drawn on lower platen. The forces and displacements used to determine the stress-strain curve and the absorbed energy-strain curve have been obtained using the. By making use of these results alongside density, the specific stress-strain curve and the specific absorbed energy-strain curve have been obtained.

In order to perform the dynamic test, a 28 mm cube has been tested for the EPS to absorb 75 J. As for the corks tested, a 28 mm cube and a 40 mm cube specimen were used to absorb the same energy and therefore, reach a lower volumetric energy level. It has been used a 75 J free weight impact drop tower with a maximum height of 1.5 m and a free weight of 5 kg. This testing apparatus include plain impact platens of φ60 mm and a vertical 482A21 PCB accelerometer that uses a Quantum XMX840B DAQ; the test has been performed with an acquisition rate of 0.06 ms and it has been used also a position pattern drawn on lower platen. Consequently, the impact velocity of the free weight is 5.44 m/s and the initial strain rate for the 40 mm specimen is 136 s^{-1} and for the 20 mm one it is 194 s^{-1}; additionally, it has been applied a channel frequency class (CFD) filter with a frequency of 600 Hz. This method is similar to the one used by Di Landro (2002) with the EPS.

Likewise, the resilience of both materials for the quasi-static test has been studied. In the case of the quasi-static test, all the specimens have been tested to reach three different levels of strain:

90%, 75% and 50%; this will suppose the study of the resilience capability of the materials in three different scenarios: with a high densification, with a low densification and in the plateau zone near the densification point. These test have been performed for two consecutive load cycles to analyse the deformation and the capability to recover the initial shape after the first cycle and additionally the capability to absorb energy in the second cycle. Additionally, it has been performed a second load cycle to depict the new stress-strain curve and compare the behaviour before and after the first load cycle.

Additionally, in the case of the dynamic test, the final strain and the permanent deformation has been measured to analyse the capability to recover the initial shape after an impact. It must be pointed that, in dynamic test, the levels of energy are equal for all the specimens (75J) so the level of strain depends on the material and their stress-strain curve.

For all cases, dynamic and static, the permanent deformation of all materials after the tests has been measured in three different places with a calliper and the average of the measurements has been used to define the permanent deformation. To analyse the maximum deformation for the static test, the INSTRON device's own measuring equipment has been used but, in the case of the dynamic test, a double integration of the deceleration has been used to obtain the maximum displacement / deformation.

Finally, it must be pointed that all the specimens have been machined using a Roland MDX 20 CNC milling machine.

3. Results and discussion

3.1 Results under quasi-static compressive stress

3.1.1 EPS

EPS shows the typical shape of the stress-strain curve that follows the Gibson’s model (Fig. 3) with three differentiated zones: the elastic zone, the collapse plateau and the densification zone. These results are similar to previous ones obtained by other authors (Krundaevaad 2016, Chen 2015). It can be highlighted here that, an increase in density implies higher stress in the collapse plateau zone but a lower densification strain. This might mean that the helmet could absorb less energy before reaching the densification zone. Additionally, higher density implies higher Young´s modulus in the elastic zone and a higher slope in the plateau zone. It is also possible to determine the transition between different zones (Fig. 3) that can be defined with approximate to lines.

Analysing the curve specific stress vs strain (Fig. 4) it can be pointed out that the difference between curves is lower than in the previous case. This curve is important if there is not any limit in the geometry of a helmet and it can be used to compare two specimens with the same weight. It can be pointed out here that higher density implies higher specific stress and higher specific Young´s modulus; however, there are fewer differences than in the previous figure. This means that, with a thicker liner of lower density foam, it is possible to obtain a helmet with the same weight but with fewer differences in stiffness.

Analysing the curve of the absorbed energy vs strain (Fig. 5), it is possible observe that EPS with the highest density can absorb more energy before the densification point and this energy increase with the density. Hence, with the same volume, those materials with higher density will absorb more energy before densification.

Analysing the curve of the specific absorbed energy vs strain (Fig. 6), it is possible see that EPS 120 has the lower value before the densification point. For the other EPS, they have a similar limit but with higher strain. This entails that, with the same weight, the EPS with lower density will have a better behaviour as, on the one hand, it can absorb the same amount of energy before reaching the densification point and, on the another hand, it will have lower stiffness, and thus the deceleration of the head will decrease. At this point it must be highlighted that the thickness of the liner of the helmet cannot increase indefinitely since there are maximum dimensions of the helmet to take into consideration. Table 2 shows the main mechanical properties of the different EPS.

3.1.2 Cork products

Analysing the results of the cork (Fig. 3), these materials have a similar stress-strain shape to that of EPS´s, with an initial zone with a constant slope (similar to the elastic one), a plateau zone with a lower slope than the initial one (but higher than the slope of the EPS in this zone), and an exponential zone similar to the densification zone. For this material, it is difficult to determine the densification point because the transition between the plateau and the densification zone is not abrupt enough, and, furthermore, cork products do not have a bulk modulus that could be used. Similarly, the transition between the elastic and the plateau zone is also difficult to determine.

It can also be pointed out that natural cork, with a density of 260 kg/m^3, has the highest stress value and similar shape behaviour to 120 kg/m^3 EPS; the most similar behaviour to EPS can be observed due to the internal structure of natural cork. Regarding the other cork products, it can be observed that, despite its lower density, cork agglomerate (AC) has the second highest stress values between the corks and, in the case of white agglomerate cork stress values increase with density. Finally, black cork has the lowest stress values. Likewise, it must also be pointed out that higher stress values imply a lower strain limit before the exponential zone. Analysing the results of the white cork agglomerates, it can be observed that lower density implies lower stress levels but also lower strain for the densification point and lower slopes for the elastic and the plateau zone.

When comparing EPS and cork materials (Fig. 3), it can be observed that, in both cases, densification appears in the strain zone when reaching 0.4 to 0.6. However, there are significant differences in the shapes of curves of both materials: the slope in the elastic zone is lower for the cork agglomerates but in the plateau zone is higher.

Comparing EPS and cork values, 275 kg/m3 white corks and 170 agglomerate cork are similar to 75 kg/m3 and 80 kg/m3 EPS. In the case of the 222 kg/m3 white cork, its behaviour is similar to 60 kg/m3 EPS, with black cork having lower stress limits.

Analysing the curve specific stress vs strain (Fig. 4) it can be pointed out, in the case of white cork and black cork, that their curves are similar but with a lower density, the strain before the exponential zone being higher; thus with the same weight, cork products with lower density have better behaviour. In the case of the natural cork, the specific stress values before densification are the highest, followed by agglomerate cork; however, agglomerate cork has a lower strain limit before densification than natural cork and the other materials. When comparing this results with the EPS, all cork specimens have lower specific stress levels due to the lower densities of the EPS.

With regards to energy (Fig 5), natural cork displays the best behaviour, with a similar behaviour to EPS 120. Agglomerate cork comes second in behavioural properties followed by white corks, depending on their density. Finally, black cork is the material that can absorb the least energy. When comparing these results with EPS, these materials have similar energy levels, with white corks and 170 agglomerate cork being similar to the 75 kg/m3 EPS and 80 kg/m3 EPS. In the case of 222 kg/m3 white cork, its behaviour is similar to 60 kg/m3 EPS, with black cork having the lowest stress limits.

In terms of specific energy (Fig. 6), natural cork and agglomerate cork display similar behaviour and, for lower strain levels (before the exponential zone), 1 Kg of natural cork can absorb more energy than agglomerate cork.

In the case of white agglomerate corks, it must be brought to light that all of them have the same behaviour. Thus, 1 kg of these materials can absorb the same amount of energy.

In the case of black agglomerate, it has similar behaviour to white agglomerates until it reaches a strain of approximately 50%. After that point it displays better behaviour. Consequently, the material with the third highest specific energy absorption capability is black agglomerate due to its lower density.

However, compared with the EPS, cork products can absorb less energy per unit of mass due to their higher density.

3.2 Results under dynamic compressive stress

3.2.1 EPS

Analysing the results of the EPS using the drop tower to absorb energy of 75 J (Fig. 7 and Fig. 8), it can be observed that the deceleration curve shows a similar shape to that of the stress-strain curve. At the beginning there is a zone with increasing deceleration in regards with the elastic zone; there is also a zone with constant deceleration related to the plateau zone; and finally there is a high peak in deceleration associated with the densification zone. It must be highlighted that the elastic deceleration slope is directly associated with the density of EPS; the constant deceleration plateau shows the same relationship. Finally, due to the higher capacity of denser EPS to absorb energy before the densification zone, the peak in deceleration is lower for denser EPS. Likewise, the peak in deceleration appears later, especially for EPS 120. As a result, the maximum peak in deceleration is lower for denser EPS. In addition, the average deceleration value (Table 3) is lower too. These results are similar to those by other authors (Krindaevaad 2016).

3.2.2 Cork products

Analysing the results of the cork and its products using the drop tower to absorb energy of 75 J (Fig. 7), it can also be observed that the deceleration curve has a similar shape to the stress-strain curve. At the beginning there is a zone with increasing deceleration associated with the elastic zone; there is a zone with gradually increasing deceleration (but lower than in the previous case) that is related to the plateau zone; and finally there is a high peak in deceleration with regard to the densification zone.

Consequently, when compared, both EPS and corks have similar deceleration curves, with their stress-strain quasi-static curves being closely related. It must be highlighted here that, as with EPS, the elastic deceleration slope is directly related to the stiffness of the material, with the same phenomenon occurring in the plateau zone. Finally, those materials having higher deceleration values in these zones can absorb much more energy and, as a result, the highest peak in deceleration that appears during densification takes place at a later stage, as well as being lower. It can also be observed that natural cork has a significantly lower peak whereas black cork has the highest.

These results are condensed in Table 3, where average deceleration is also displayed. This table shows that natural cork presents the lowest peak regarding deceleration and average deceleration; whereas black cork presents the highest values; the other materials share similar values. Consequently, natural cork is the material with the best behaviour while the rest have similar ones, with the exception of black cork, whose behaviour is notably the worst.

Comparing results for cork products and EPS, it can be observed that, due mainly to the differences in the shape of the stress-strain curve for each type of material, cork products exhibit lower maximum decelerations but higher initial deceleration at the initial stages of the impact. However, the average deceleration is similar for both types of materials so it is necessary to include an additional criterion to compare these materials.

Another experimental test carried out involved a drop tower test to absorb 75 J but with a 40 mm side box instead of 28 mm, in order to compare materials that must absorb a lower volumetric energy (1/3) as is shown in Fig. 8. This test is representative of a low velocity impact, whereas the previous test represented a high velocity impact.

The results show that materials have an initial zone with a gradual increase in deceleration associated with the elastic zone of the stress-strain curve, as in the previous test. Before that, the curve slope changes depending on the shape of the plateau zone of the stress-strain curve until the material can absorb all the energy. Consequently, the shape changes and the material can either reach the densification zone (agglomerate cork and black cork) or not. In the latter case, the shape of the curve displays a greater disparity to the stress-strain curve. It must be highlighted at this point that materials (with the exception of black cork, which reaches a higher stress in the densification zone), have similar decelerations (Table 3).

The material with the lowest deceleration is middle size grain white cork. When comparing average deceleration, these materials are similar. Consequently, in this case white middle grain cork is the most adequate material; the other types of cork have similar adequacy, with the exception of black cork, whose adequacy is the worst by far.

3.2.3 HIC study

Although the HIC criterion is not specifically designed to compare the decelerations in the drop tower test, in this article, the criterion has been used to compare materials due to the previous mentioned limitations.

It has been assumed here that the material displaying better properties will have lower deceleration peak values and lower average deceleration. In regard to this last point, it must be highlighted that this average deceleration must be analysed in different periods of time along the time domain in order to obtain the worst average deceleration, which will entail the greatest brain damage.

The deceleration of the drop tower test is assumed to be similar to the one found in the accelerometer in the head of a dummy with a helmet, since there are certain similarities between the deceleration curves from drop tower test, and the test carried out by other authors (Gimbel 2008) to test helmets with different EPS.

Table 4 shows the HIC obtained. It can be seen that, for higher impact velocities, EPS with higher density also implies lower HIC levels, as the material does not reach the densification zone and results in too stiff a behaviour. Likewise, natural cork has notably lower HIC values than other materials. On the other hand, black cork displays the most inadequate behaviour, with a significantly high HIC level.

When comparing EPS with cork materials, it must be highlighted that cork products have lower HIC levels than the EPS and, consequently, helmets made of cork will be better suited than those made of EPS. This is mainly due to the fact that cork materials have a different stress-strain shape, with lower initial elastic slope and a constant increase in the slope from a low to a high strain in the plateau zone, which involves increasing deceleration matching the one found in the deceleration curve (Fig. 7).

On the other hand, EPS has a higher slope in the elastic zone, implying higher initial deceleration and a subsequent constant medium stress level in the plateau zone implying a constant higher average deceleration (Fig. 7). As a result, average deceleration values will be lower for cork and cork products.

In the case of low impact velocity (40 mm size specimens) (Fig. 8), natural cork does not have the lowest HIC, given the fact that, in this case, average deceleration reaches higher values, as some other materials do not reach the densification zone. Consequently, agglomerate cork and middle size white cork display the best behaviour.

3.3 Study of the resilience of the materials

Another aspect to study is the capacity of materials to absorb multiple impacts at the same point, which is especially important for a helmet in the event of an accident. Fig. 9, Fig. 10 and Fig. 11 show the stress-strain curve for two consecutive load cycles of some of the materials for three different maximum strains.

It can be observed that the EPS presents different for a maximum strain of a 90%; for lower maximum deformations (50% and 75%) the material presents a high permanent deformation (Table 5); by contrast, in the case of the highest deformation that imply a high densification, the material undergoes a rebound effect and exhibits a lower permanent deformation. This phenomenon has been noticed for all the EPS foams ant it could be due to the fact that, after the densification point, the material acts as a spring and some of the energy absorbed produce a higher recovery of the internal structure. It must be also highlighted that, whilst EPS foams in this particular case has low permanent deformation, their internal structure is totally damaged and, consequently, its capability to absorb energy in successive load cycles is negligible (Table 6). At this point, it must be clarified that, though EPS can absorb around a 25% of the initial energy in the second cycle, the energy corresponds to the densification zone (see Fig. 9 for the EPS).

In relationship with the cork products, Fig. 9, Fig. 10 and Fig. 11 show that, for any the maximum strain, the materials suffer low permanent deformations (between a 10 and a 30%); additionally, these figures show that, the higher maximum strain, the higher permanent deformation undergoes after the first load cycle. Furthermore, higher maximum strains imply also lower stress-strain curve in the second load cycle and, hence, a lower capability to absorb energy (Table 6).

Comparing the results of the absorbed energy for EPS and cork agglomerates for a 75% of maximum deformation (Fig. 10) and for a 50% (Fig. 11) and the absorbed energy (Table 6), it can be observed that, though EPS has a low capability to absorb energy and it also suffer a high permanent deformation, conversely, cork and cork agglomerates have higher capability to absorb energy and they also suffer less permanent deformation. This phenomenon is due to the fact that the internal structure of cork products suffers less damages than those of the EPS.

Additionally, lower maximum deformation implies for cork products lower internal damages and higher capability to recover its initial shape and to absorb more energy in subsequent impacts. In the case of the EPS, the crushing of the closed internal cells during the plateau zone imply permanent damage and, as a result, EPS undergoes high permanent deformation so it can absorb little energy in successive impacts. In the case of the cork agglomerates, due to their internal open cell structure, these structures do not collapse in the same way than those of the EPS and, when the load disappear, they can recover part of internal structure and part of the previously expelled air. Therefore, the resilience this latter material is higher.

It must be also noticed that BCA presents the highest resilience and, behind it, the WCA302. It can also be noticed for the WCA that, the higher the density is, the higher the resilience is but also the permanent deformation.

Analysing also the results of the drop tower test (Table 7), it can be observed that, for the EPS, aforementioned phenomenon appears also for high maximum deformation appears. As a result, EPS bounces and can recover part of its initial shape. In the same way, it can also be observed that cork and cork agglomerates suffer very low permanent deformation and also that lower maximum deformation implies lower permanent one. Finally, it should be noticed that the results of the dynamic and the static test in terms of resilience show significant differences; this could be due to the influence of the strain rate that has not been considered in this study. Some authors (Kake 2019) have noticed for EPS that higher strain rate imply higher stress levels for stress-strain curve, but also that the densification point appears with lower strains.

4. Conclusions

The main conclusion to be drawn is that cork and cork products can be a suitable renewable-origin substitute for EPS, in applications in which it is necessary to absorb energy and reduce the velocity of an element impacting with low deceleration peaks. Additionally, whilst the average deceleration is similar, the maximum deceleration that appears is significantly lower than for the EPS due to the differences in shape of their stress-strain curve, especially in the elastic and plateau zones. In addition, the use of the HIC criterion to compare decelerations reflects that cork products have lower values. Whilst this criterion was formulated to analyse the head injuries, it is also an indicator to compare materials for comparing materials and what it is more important, it uses both maximum deceleration and average decelerations.

It must also be highlighted that the resilience capability of cork and cork products must be taken into consideration in those applications where more than one impact may occur in the same area. In this sense, cork products are much more suitable than EPS foams due to the differences in the internal structure of both materials. While cork products have an open cell structure that can recover part of their initial strength and re-introduce inside part of the air expelled during the impact, the closed-cell structure of the EPS collapse after the impact so they lost most of their strength, cannot recover its shape and also, the expelled air will not be reintroduced.

However, more in-depth analyses of this capability should be carried out to compare their behaviour after 2, 3 or more impacts and also, the influence of the strain rate should be taken into consideration.

Comparing the quasi-static results, it can be pointed out that EPS foams and cork and some sub-products have similar stress-strain curves and can absorb a similar amount of energy before the point of densification. However, it must also be pointed out that cork and cork products have higher density and, as a result, the specific stress-strain curve and the specific energy that they can absorb is notably lower. As a result, cork and cork products will be more suitable in those applications in which weight is not critical and in applications in which volume is the main design factor. On the other hand, EPS will be significantly better in those applications where weight is the main design factor.

Finally, in the case of helmets, it must be pointed out that the results obtained are not conclusive. The use of cork and cork products implies lower peak deceleration, lower HIC and lower average deceleration than if EPS is used for the drop tower test. However, some test with full helmet prototypes are essential to assess the superior behaviour of the cork agglomerates; this is especially important because these materials have higher density and, as a result, the weight of the helmet will increase and could generate higher momentum in the condyle and in the neck; likewise, a heavier helmet implies more rotational accelerations.

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Figure Captions

Fig. 1 Gibson's model for polymeric foams.

Fig. 2 Studied cork and cork agglomerates.

Fig. 3 Stress-strain curve for all the studied materials.

Fig. 4 Specific stress-strain curve for all the studied materials.

Fig. 5 Absorbed energy for all the studied materials.

Fig. 6 Specific absorbed energy for all the studied materials.

Fig. 7 Deceleration (m/s^2) - time curve for all the studied materials for the 75 J dynamic test. Specimen: 28mm box

Fig. 8 Deceleration (m/s^2) - time curve for corks and cork products for the 75 J dynamic test. Specimen: 40mm box

Fig. 9 Stress-strain curve for some of the studied materials under two consecutive load cases with a maximum strain of a 90%

Fig. 10 Stress-strain curve for some of the studied materials under two consecutive load cases with a maximum strain of a 75%

Fig. 11 Stress-strain curve for some of the studied materials under two consecutive load cases with a maximum strain of a 50%

Designation	Type	Density (kg/m^3)	Grain size (mm)	Adhesive
EPS60	Expanded Polystyrene	64.8	2.5	
EPS80	Expanded Polystyrene	80.7	2.15	
EPS100	Expanded Polystyrene	100.9	1.95	
EPS120	Expanded Polystyrene	123.0	1.55	
WA302	White agglomerate	302	2-5	Epoxy
WA279	White agglomerate	279	0.5-2	Epoxy
WA222	White agglomerate	222	1-3	Epoxy
AC170	Cork agglomerate	170	2-7	Biocol
BA104	Black agglomerate	104	4-15	None
NC260	Natural cork	260	None	None

Table 1: *Studied materials, their density and their grain size.*

	EPS60	EPS 80	EPS 100	EPS 120
ρ (kg/m3)	6.48E+01	8.07E+01	1.01E+02	1.23E+02
$\sigma_{c,e}$ (MPa)	5.51E-01	8.20E-01	1.44E+00	1.64E+00
Specific $\sigma_{c,e}$ (MPa)	8.50E-03	1.02E-02	1.43E-02	1.33E-02
E_c (MPa)	7.65E+00	1.24E+00	3.83E+00	3.56E+00
W_e (J/mm^3)	1.98E-02	2.71E-01	2.71E-01	3.77E-01
Specific W_e (J/g)	3.06E+02	3.36E+03	2.69E+03	3.06E+03
$\varepsilon_{c,d}$	6.12E-01	5.84E-01	5.03E-01	4.20E-01
W_p (J/mm^3)	4.50E-01	5.97E-03	7.56E-03	8.08E-03
Specific W_p (J/g)	6.94E+03	7.39E+01	7.49E+01	6.57E+01

Table 2: Main mechanical properties of different EPS

EPS (28 mm)	Max. Dec. peak (m/s^2)	Av. Decel. (m/s^2)	Cork (28 mm)	Max. Dec. peak (m/s^2)	Av. Decel. (m/s^2)	Cork (40mm)	Max. Dec. peak (m/s^2)	Av. Decel. (m/s^2)
EPS 60	2078,9	416,8	WA 222	1513.9	422.2	WA 222	884.6	380.5
EPS 80	2037,6	420,2	WA 275	1366.8	408.2	WA 275	705.5	349.5
EPS 100	1508,8	392,1	WA 302	1455.6	422.8	WA 302	821.4	368.2
EPS 120	1006,6	372,1	NC 260	1049.9	386.7	NC 260	810.6	335.1
			AC 170	1475.6	389.7	AC 170	854.7	341.8
			BA 104	2451.0	414.8	BA 104	1161.0	355.6

Table 3: Maximum Peak deceleration and average deceleration for EPS and cork and cork agglomerates

EPS (28 mm)	HIC	Cork (28 mm)	HIC	Cork (40mm)	HIC
EPS 60	660	WA 222	453	WA 222	245
EPS 80	641	WA 275	368	WA 275	171
EPS 100	633	WA 302	434	WA 302	222
EPS 120	355	NC 260	225	NC 260	245
		AC 170	385	AC 170	168
		BA 104	989	BA 104	279

Table 4: HIC for EPS and cork and cork products.

Static	Static 90%			Static 75%			Static 50%		
	Max strain	Perm. Strain	Recovery (%)	Max strain	Perm. Strain	Recovery (%)	Max strain	Perm. Strain	Recovery (%)
EPS 60	0.9	0.326	63.78	0.75	0.641	14.53	0.5	0.421	15.80
EPS 80	0.9	0.337	62.56	0.75	0.653	12.93	0.5	0.432	13.60
EPS 100	0.9	0.354	60.67	0.75	0.661	11.87	0.5	0.44	12.00
EPS 120	0.9	0.387	57.00	0.75	0.668	10.93	0.5	0.447	10.60
WA 302	0.9	0.382	57.56	0.75	0.152	79.73	0.5	0.065	87.00
WA 275	0.9	0.377	58.11	0.75	0.184	75.47	0.5	0.084	83.20
WA 222	0.9	0.363	59.67	0.75	0.203	72.93	0.5	0.114	77.20
AC 170	0.9	0.342	62.00	0.75	0.211	71.87	0.5	0.0625	87.50
BA 104	0.9	0.357	60.33	0.75	0.123	83.60	0.5	0.0219	95.62
NC 260	0.9	0.255	71.67	0.75	0.208	72.27	0.5	0.12	76.00

Table 5 *Maximum reached strain and permanent strain for EPS. cork and cork products.*

90%	W 1º cyc. (J/mm^3)	W 2º cyc. (J/mm^3)	W red. (%)	75%	W 1º cyc. (J/mm^3)	W 2º cyc. (J/mm^3)	W red. (%)
EPS 60	0.00127	0.00033	25.98	EPS 60	0.00067	0.000027	4.03
EPS 80	0.00149	0.00038	25.50	EPS 80	0.00086	0.000031	3.60
EPS 100	0.00187	0.00046	24.60	EPS 100	0.00103	0.000037	3.59
EPS 120	0.00205	0.00055	26.83	EPS 120	0.00125	0.000044	3.52
WA 302	0.00825	0.00228	27.64	WA 302	0.00244	0.000934	38.28
WA 275	0.00665	0.00145	21.80	WA 275	0.002034	0.0007787	38.28
WA 222	0.00422	0.000695	16.47	WA 222	0.001769	0.000644	36.40
AC 170	0.00176	0.000652	37.05	AC 170	0.00102	0.000335	32.84
BA 104	0.000763	0.000278	36.44	BA 104	0.00035	0.000141	40.29
NC 260	0.00289	0.00065	22.49	NC 260	0.00162	0.00052	32.10

50%	W 1º cyc. (J/mm3)	W 2º cyc. (J/mm3)	W red. (%)
EPS 60	0.000376	0.00003	7.98
EPS 80	0.000462	0.000036	7.79
EPS 100	0.000534	0.000041	7.68
EPS 120	0.000594	0.000047	7.91
WA 302	0.000595	0.000404	67.90
WA 275	0.000606	0.000368	60.73
WA 222	0.000616	0.000328	53.25
AC 170	0.000365	0.000123	33.70
BA 104	0.000119	0.000071	59.66
NC 260	0.000695	0.000312	44.89

***Table 6** Energy absorbed under quasi static test for the first and the second load cycle for different maximum strains*

Table 5 Maximum reached strain and permanent strain for EPS. cork and cork products.

	Dynamic (28 mm)			Dynamic (40 mm)		
	Max strain	Perm. Strain	Recovery (%)	Max strain	Perm. Strain	Recovery (%)
EPS 60	0.81	0.579	28.57			
EPS 80	0.85	0.561	34.03			
EPS 100	0.87	0.554	36.37			
EPS 120	0.86	0.546	36.46			
WA 302	0.90	0.089	90.08	0.72	0.013	98.26
WA 275	0.87	0.054	93.84	0.71	0.019	97.29
WA 222	0.93	0.143	84.64	0.70	0.023	96.79
AC 170	0.93	0.161	82.72	0.72	0.075	89.58
BA 104	0.95	0.111	88.35	0.90	0.043	95.28
NC 260	0.58	0.071	87.68	0.55	0.015	97.27

Table 5 *Maximum reached strain and permanent strain for EPS. cork and cork products.*

Fig. 1 Gibson's model for polymeric foams.

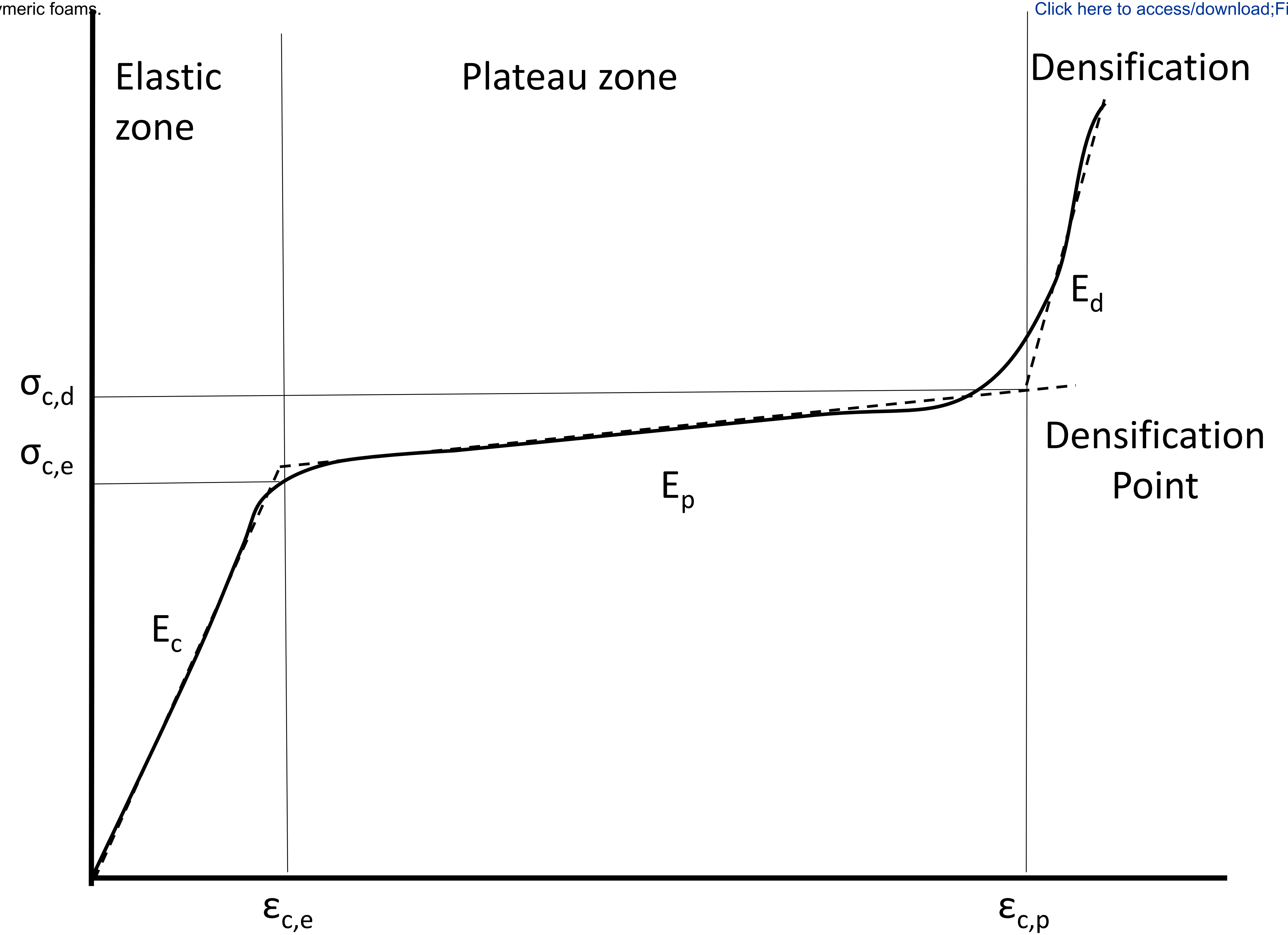

Fig. 2 Studied cork and cork agglomerates.

Click here to access/download;Figure;fig_2.bmp

Fig. 3 Stress-strain curve for all the studied materials.

Click here to access/download;Figure;fig_3.pptx

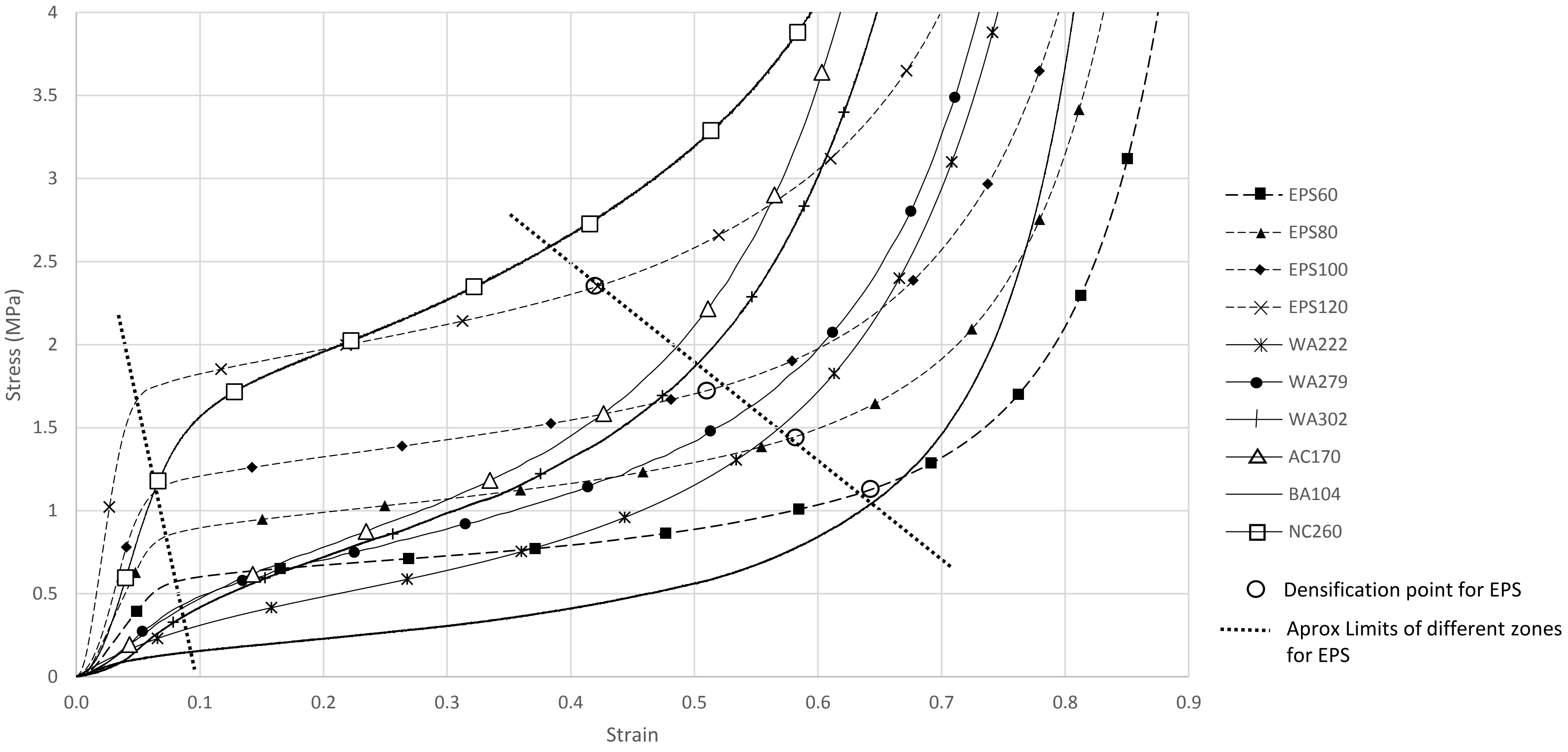

Fig. 4 Specific stress-strain curve for all the studied materials.

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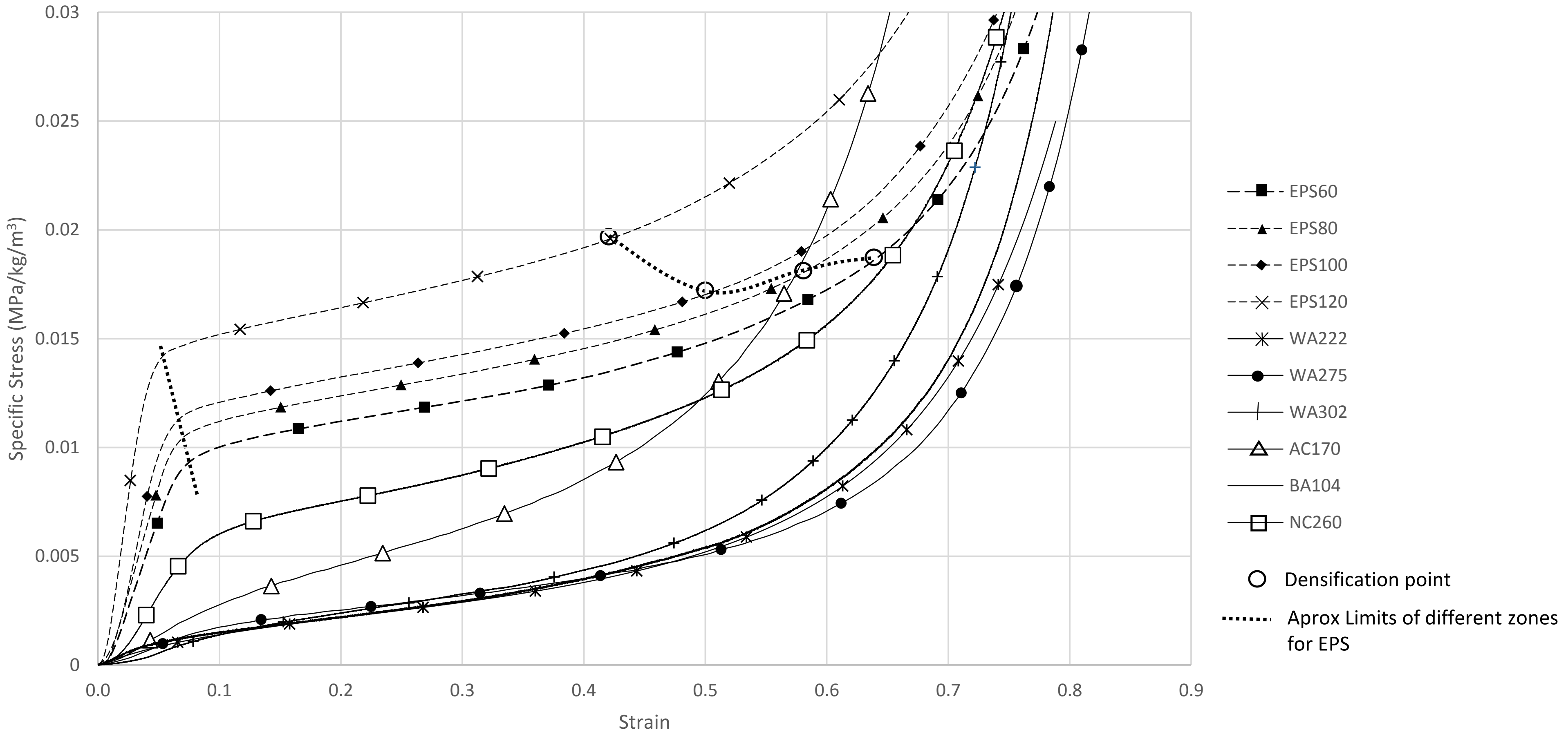


Fig. 5 Absorbed energy for all the studied materials.

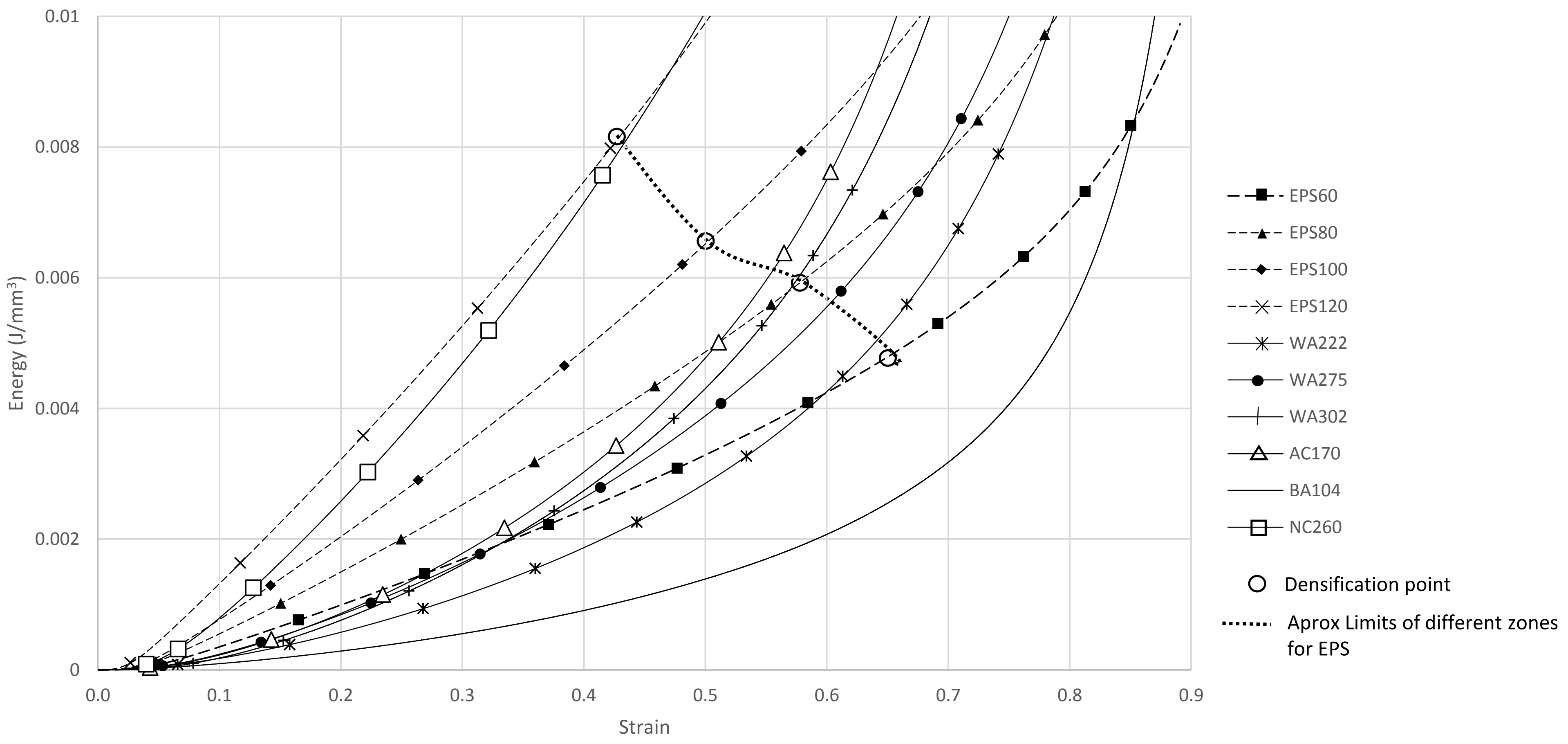


Fig. 6 Specific absorbed energy for all the studied materials.

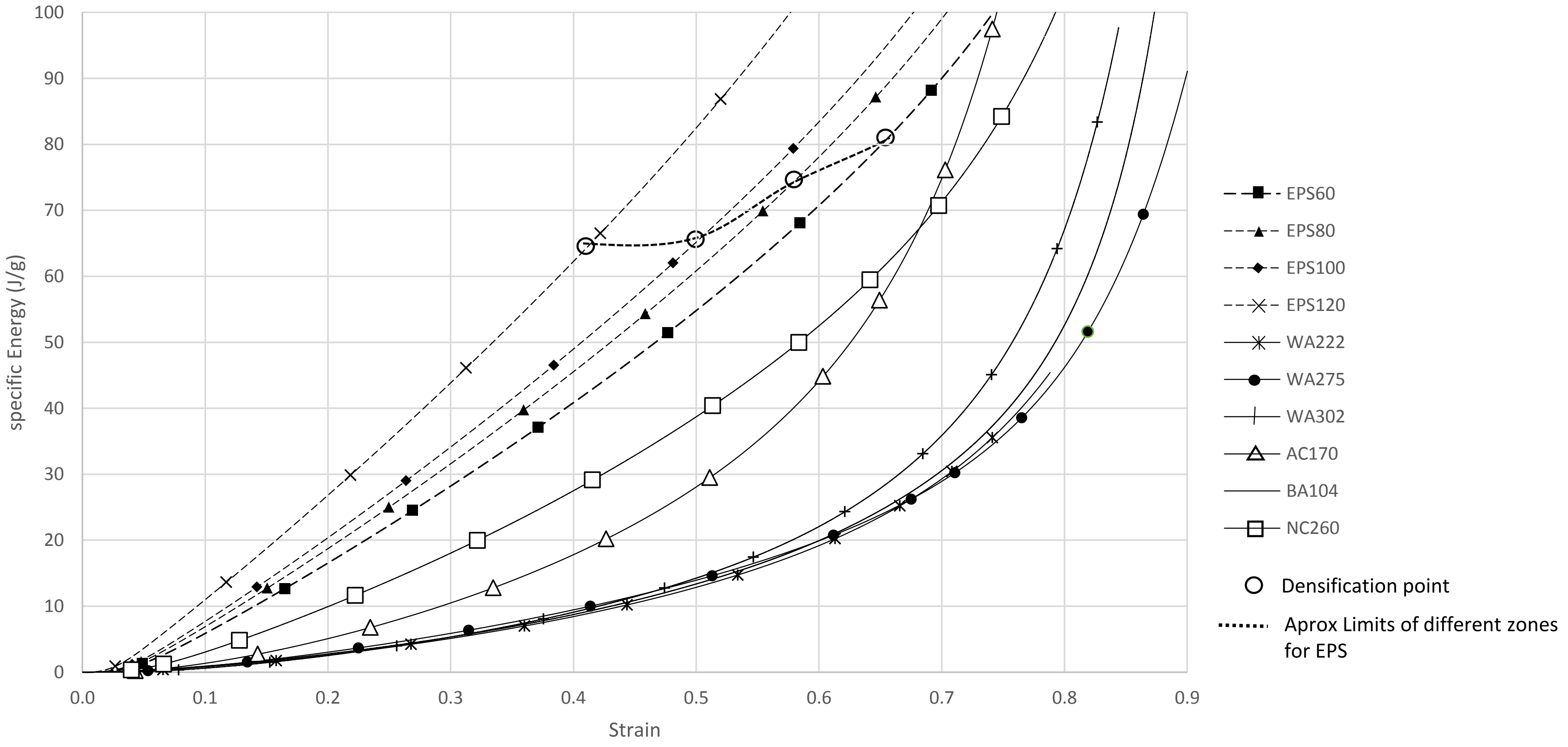


Fig. 7 Deceleration (m/s^2) - time curve for all the studied materials for the 75 J dynamic test. Specimen: 28mm box

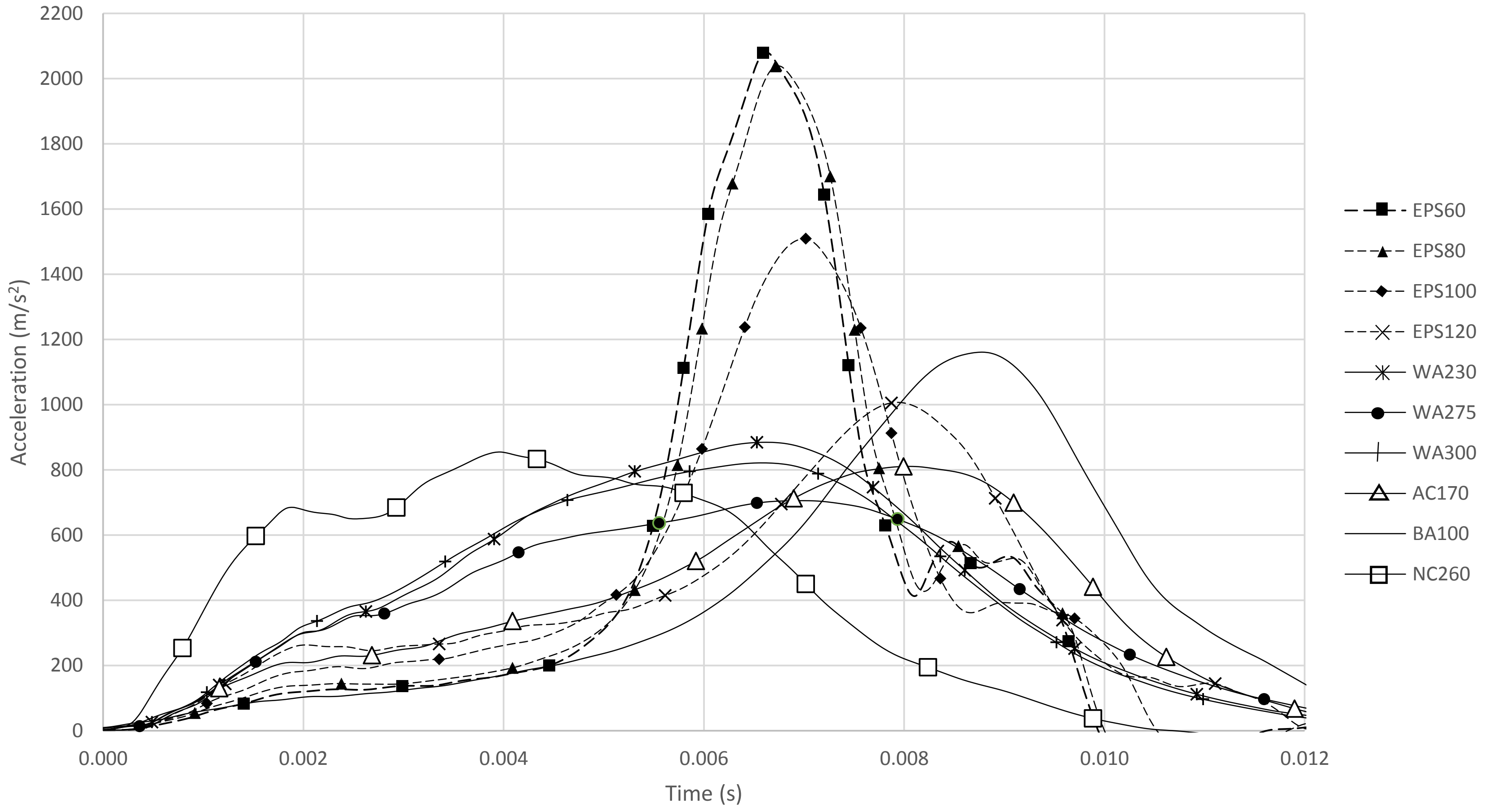


Fig. 8 Deceleration (m/s2) - time curve for corks and cork products for the 75 J dynamic test. Specimen: 40mm box

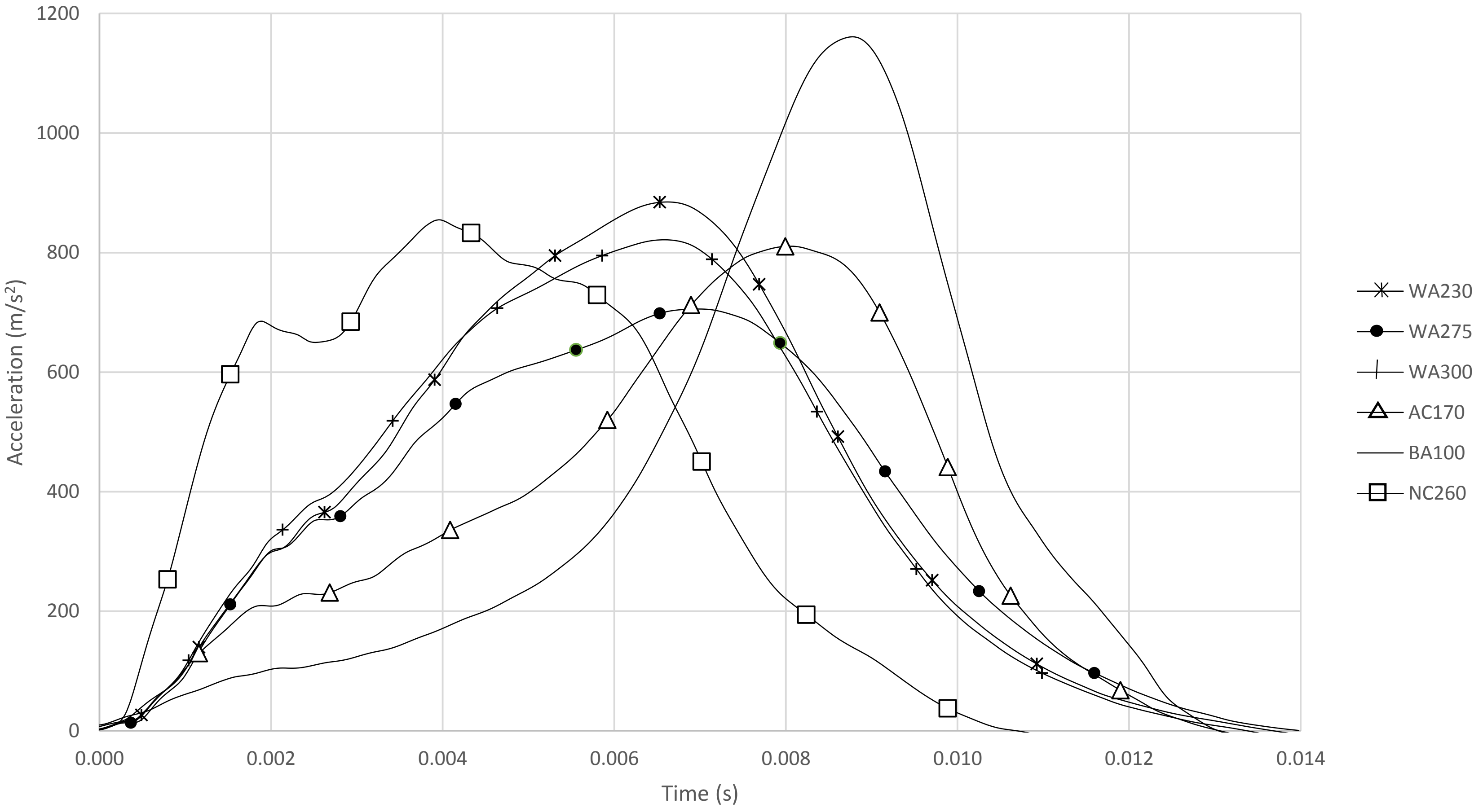


Fig. 9 Stress-strain curve for some of the studied materials under two consecutive load cases with a maximum strain of a 90%

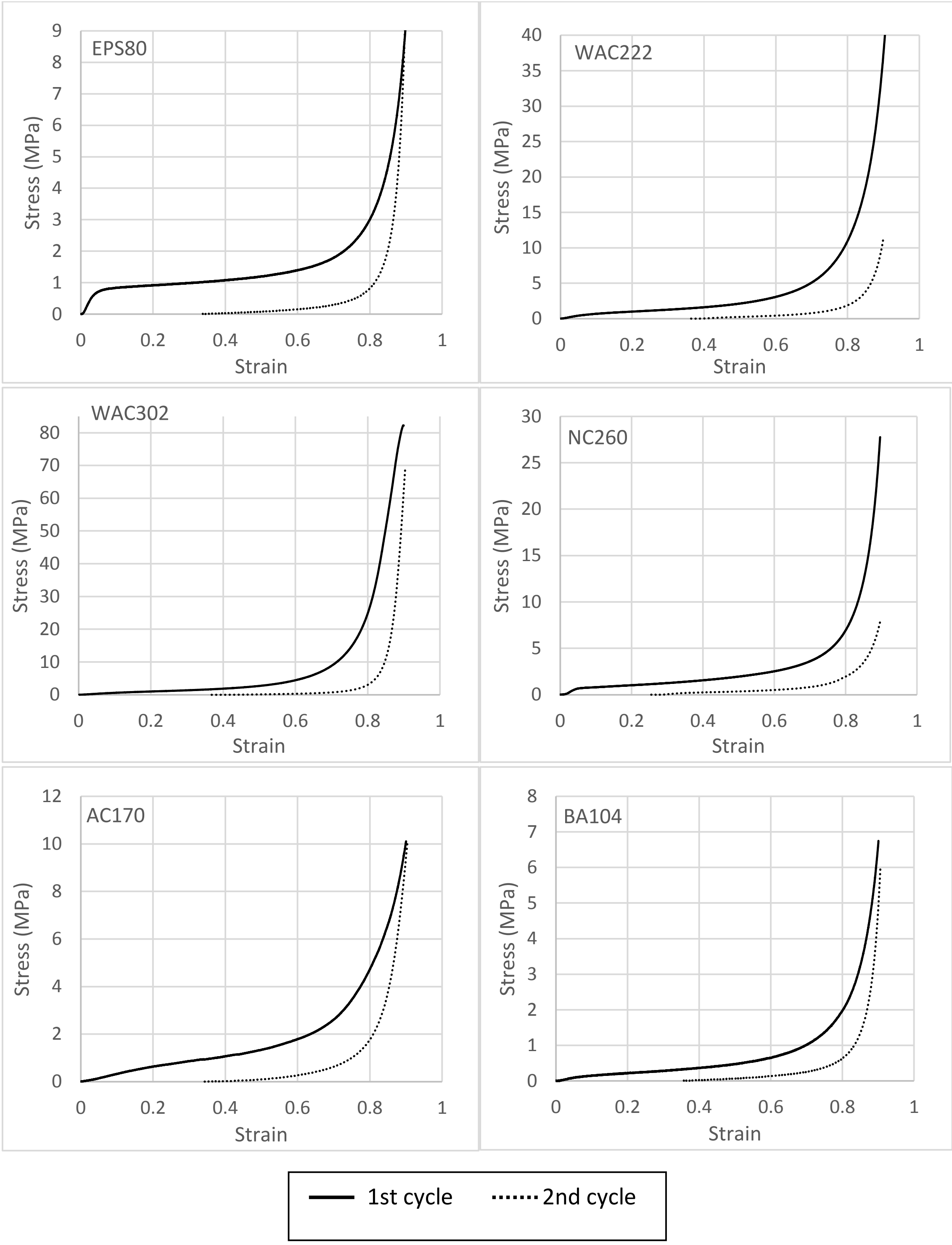


Fig. 10 Stress-strain curve for some of the studied materials under two consecutive load cases with a maximum strain of a

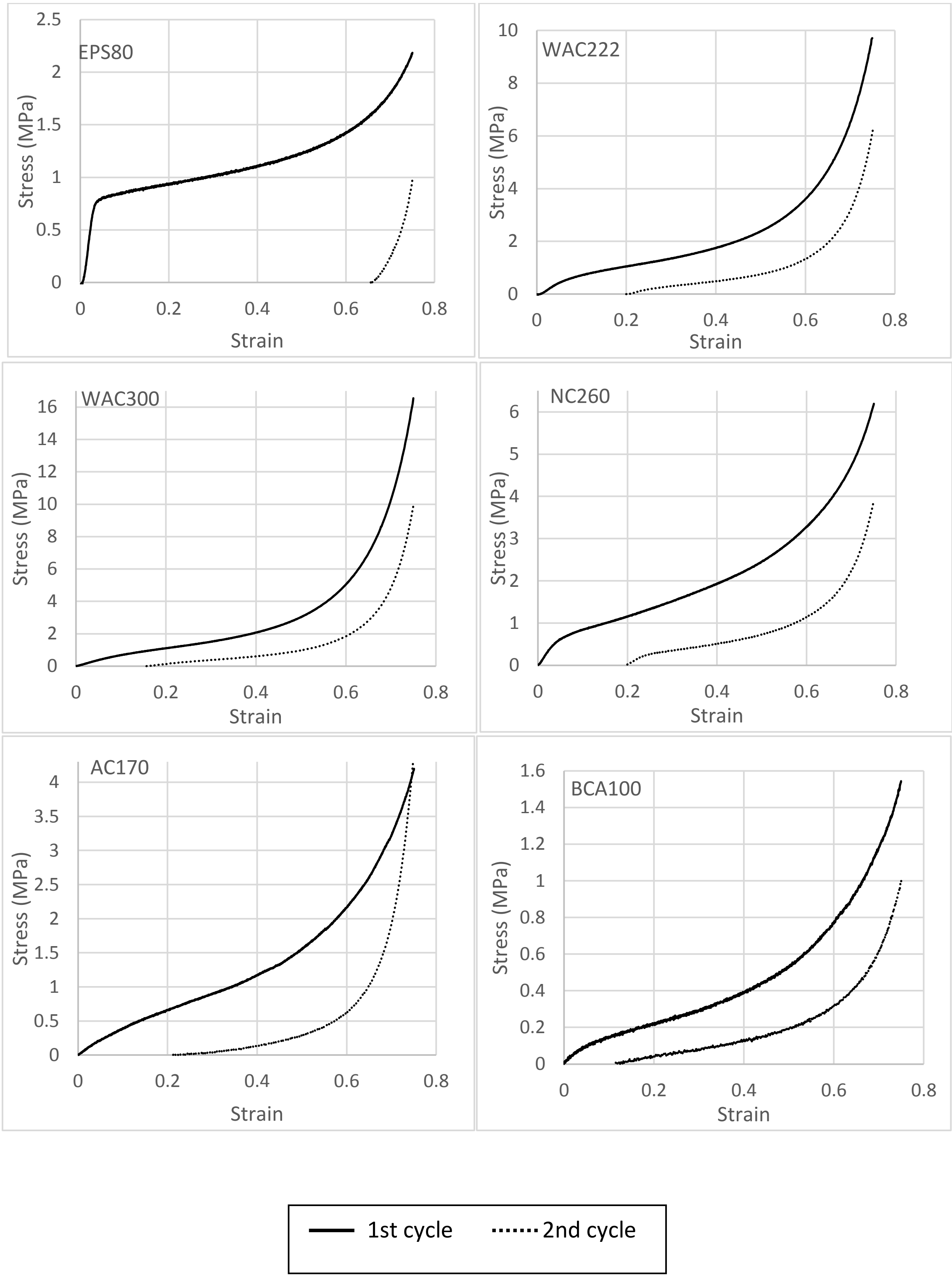
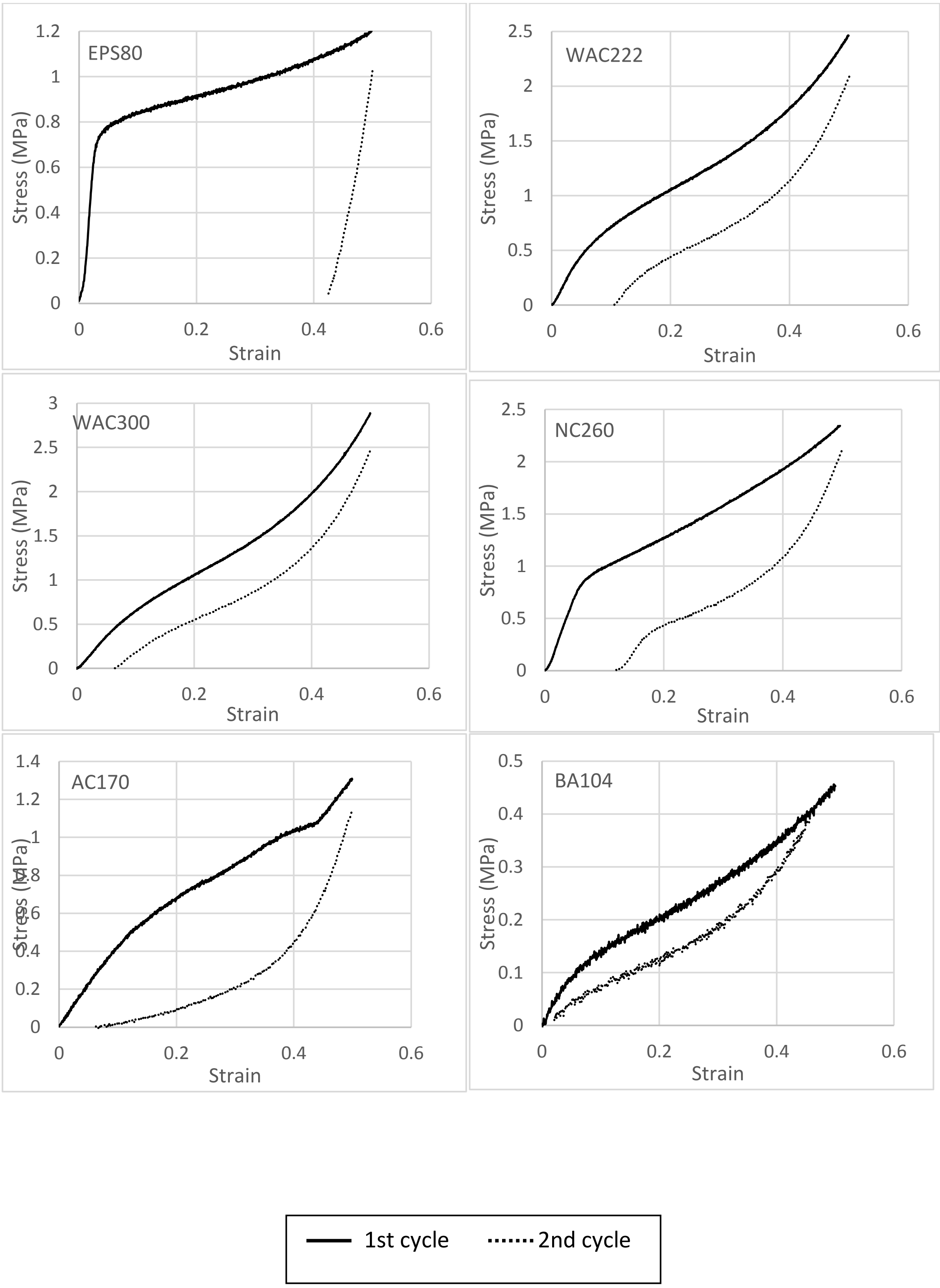


Fig. 11 Stress-strain curve for some of the studied materials under two consecutive load cases with a maximum strain of a



Experimental Study of Natural Cork and Cork Agglomerates as a Substitute for Expanded Polystyrene Foams under Compressive Loads

Authors:

Ramon Miralbes Buil (R. Miralbes). University of Zaragoza. Zaragoza (Spain). miralbes@unizar.es. Corresponding Author.

David Ranz Angulo (D. Ranz). University of Zaragoza. Zaragoza (Spain). dranz@unizar.es

Jan Ivens (J. Ivens). KU Leuven University. Sint-Katelijne Waver (Belgium). jan.ivens@kuleuven.be

Javier Oscar Abad Blasco (J.O. Abad). University of Zaragoza. Zaragoza (Spain). javabad@unizar.es

Abstract

EPS is a material that is widely used in energy absorbing applications, especially in helmets, despite its non-renewable origin. Cork and its derivatives however, are proposed as a substitute for polystyrene foam (EPS) due to their renewable origin and their easy recyclability. In spite of the low-environmental footprint of cork and its derivatives, there is insufficient data on their mechanical behaviour. Consequently, under dynamic and quasi-static loads, four different-density EPS, a natural cork material and five different cork products with different grain sizes and heat treatments have been tested. They have been compared in terms of their stress-strain and specific stress-strain curve, their volumetric capability to absorb energy, their specific energy, average decelerations and peak deceleration.

Finally, EPS foams cannot recover their initial shape upon deformation due to their low resilience capability. This is especially important in applications such as helmets which are bound to be subjected to multiple impacts. However, cork and its products could have this capability for resilience and would therefore be more suitable for certain applications.

Keywords: cork; impact; helmet; agglomerate; polystyrene foam.

1. Introduction

Cork is a natural material that is extracted from the bark of the cork oak tree and therefore has zero- carbon footprint; in addition, once a cork product has reached the end of its lifetime, it can be crushed and recycled to manufacture new products or, if disposed of, it can be easily degraded, generating zero impact on the environment. Additionally, cork has very low permeability to gases and liquids, has good insulating properties, high durability, high energy absorption capability and high viscoelastic return (Pereira 2007). This last aforementioned property means that, under compression, cork shows elastic behaviour and thus recovers its initial shape and properties after being crushed.

Despite its properties, traditionally cork has almost exclusively been used to make wine stoppers. However, at present this may no longer be the case, and there is an increasing tendency to use it as the core of some composite sandwiches that require high strength-to-weight ratio (Sanchez-Saez 2011), as well as to enhance other materials such as polyurethane (Gama 2019), polyethylene (de Vascongelos 2019) or polyfurfuryl (Menager 2019), in order to create materials with a lower carbon-footprint; to reduce the density of other materials such as concrete (Parra 2019); or in energy absorption applications such as helmets.

As previously mentioned, thanks to its energy absorption capabilities, cork is a candidate to become a substitute for non-renewable materials, such as expanded polystyrene foams (EPS) in some applications requiring energy absorption. This is mainly the case of helmets for different types of applications: motorcycling, cycling, snow sports, horse riding, etc. In addition, cork has high viscoelastic return as opposed to EPS and, consequently, could be a better-suited material for helmets undergoing multiple impacts thanks to its return to initial shape and properties after impact.

With regard to the use of cork in helmets, there are studies that analyse the possibility of substituting EPS with cork, such as the study of Coelho (2012) which by means of numerical tools, analyses the behaviour of a head impact against a block of cork and EPS with a density of 50 kg/m^3 where it was concluded that a combination of both materials could be useful for helmet liners. Likewise, Sousa (2012) compared the mechanical properties of EPS with a density of 30 and 50 kg/m^3 with different cork agglomerates (0.2mm, 0.25 mm and 0.3 mm) and concluded that while cork could be used for liners in helmets, EPS had better capability to reduce injuries. Nevertheless, when compared with EPS, the article pointed out that since cork conglomerate can recover its initial shape, it can be more suitable in the event of multiple impacts thanks to cork´s high viscoelastic return properties. This is one of the main conclusions drawn by Willehelm (2017).

Other articles, such as Tay (2014) that compare different natural materials to improve safety in vehicles under oblique impacts include conglomerate cork; the aforementioned study pointed in the same direction and noted the inferior behaviour of the cork under study. Finally, the studies of Fernandes (2019) which explored the use of two different agglomerated (199 and 216 kg/m^3) and one expanded cork (159 kg/m^3) showed cork´s poor adequacy as a substitute for the EPS (90 kg/m^3), with huge modifications in the geometry of the helmet including some holes being required in order to finally obtain a helmet with similar mechanical behaviour to that of EPS, all at the expense of higher weight.

It must be highlighted, though, that some of these studies exclusively focus their analysis on a limited number of types of conglomerate cork despite the diversity of existing products and by-products of cork, each with different mechanical properties resulting from different manufacturing processes. The most common products are natural cork sheets, white cork agglomerate, black cork agglomerate (also called expanded cork) and rubber cork, which will be the focus of this study.

With regard to the mechanical characterization of cork, apart from the data provided by manufacturers- usually providing a short range of mechanical properties (density, Young modulus, etc.), there are some articles focused on the mechanical properties of cork – most of them exclusively related to the specific application of wine stoppers. This is the case of the study of Crousvisier-Urion (2018) which concludes that the use of small particles of cork reduces stiffness; or the case of Sanchez-Gomez (2018) who analyse the mechanical properties of a wine stopper (some natural, others co-extruded with synthetic materials and others with different micro-agglomerates). Other authors analyse the influence of hydration of cork in their mechanical properties (Lagorde-Tachon 2017) and conclude that Young´s modulus has a constant value from 0% to 50% of humidity, with a significant drop from that point onwards.

Anjos (2014) study the influence of density on the compression behaviour of cork and conclude that density is directly associated with the Young´s modulus and stress in the plateau zone. Pinto-Silva (2005) made a review of the properties, capabilities and applications of cork, showing the influence of grain size in Young´s modulus for three different agglomerates; additionally, the reviewer collected some mechanical properties from other authors which show compression modulus for natural cork as well as boiled cork and others undergoing different heat treatments. Another interesting result of this study points out that cork and its agglomerates have better specific properties (specific compression strength and specific modulus) than flexible polymer foams such as EPS. Finally, other authors (Fernandes 2015) compared some conglomerated cork (216 and 199 kg/m3) and expanded ones (159 Kg/m3) with EPS (90 kg/m3) and expanded polypropylene (EPP) (60 and 90 kg/m^3), by means of numerical and experimental tools, reaching the same conclusions, while others (Jardin 2014) obtained the behaviour of some cork conglomerates (216, 199, 178 and 157 kg/m^3) and expanded ones (122, 159 and 182 kg/m^3)

Another application of cork is its use as a core in tome sandwich panels. The results obtained by some authors (Moreira 2019) show that the performance of cork agglomerates depends on density, cohesion procedure of granulates and cork granule size. Therefore, these variables can be adjusted to obtain the desired mechanical properties, as pointed out by some other authors (Santos 2017), too.

With regard to EPS, this material is traditionally used for a huge variety of applications such as helmets or protectors for some goods. This material is generated during a foaming process in which some closed air cells are generated inside the material; these cells can be manipulated to obtain different densities (from 10 to 150 kg/m^3); with the most common densities between 60 to 120 kg/m^3 in the case of helmets.

There are some studies about the mechanical behaviour of EPS under compressive forces. It is clear that there is a direct relation between density and its mechanical properties under quasi-static and dynamic loads (Ouellet 2006, Chen 2015, Krindaevaad 2014). In all cases, the stress-strain curve of EPS has three different zones - a linear elasticity zone; a plateau zone; and a densification zone. In the initial one-the linear elastic zone-, the material could recover its initial shape and shows a linear behaviour; however, it is a small zone which can absorb very little energy. Immediately after that the plateau zone is found. This is a large zone in which the level of stress is more or less constant; this means that in this zone the material can absorb a great deal of energy with the same stiffness. This is the most important zone for helmets as a huge amount of energy needs to be absorbed while they must deform progressively in order to avoid high decelerations in the head. Finally, in the densification zone the stress increases sharply and, as a result, should a helmet reach this zone, the head is subjected to significant deceleration, with ensuing neural injuries.

When analysing the state of the art of the test of helmets conducted by means of different certification standards (ISO 17025 / SNELL, ECE.22.05, DOT), one of the main biomechanical indexes used in order to analyse the brain injury damages is the Head Injury Criterion (HIC) (Versace 2019), which uses the data gathered through an accelerometer in the centre of the head of a dummy. The HIC is determined with this equation:

$$HIC = max\left[\frac{1}{t_2-t_1}\int_{t_1}^{t_2} a(t)dt\right]^{2.5} \cdot (t_2 - t_1) \qquad \text{(eq. 1)}$$

This criterion not only analyses the main deceleration peaks, as it includes the study of average decelerations during different periods of time to determine the most critical ones. These aspects are in regard with the movement of the brain inside the skull, which acts like a mass-spring-mass model.

In this article, the main objective is the comparative study of cork products and different densities EPS under compression efforts to analyse the possibility of the former materials to substitute petrol-based latter ones in certain applications in which the capability to absorb energy is essential.

The main hypothesis of this study is that both types of materials, EPS and cork agglomerates have internal cell structures with air inside and, consequently, both will have similar mechanical behaviour; this behaviour has been previously mentioned and it is defined for the polymeric foams by the Gibson's model (Gibson 1997).

The Gibson's model distinguishes three different, well-defined zones in the stress-strain curves of polymeric foam materials (Fig. 1): the initial elastic zone, the plateau zone and a densification zone. The elastic zone characterizes by the capability of the material to recover its initial dimensions and the shape of the curve is a linear elastic one defined by the Young's modulus; in this zone the walls of the internal structure of the foam deforms elastically and can recover its initial shape; during the compression process, the internal pressure of air trapped inside the cells increases and after a certain point the cell walls cannot support the pressure and collapse; then the plateau zone appears; this zone is defined by a constant stress or a curve with a very low increasing slope that is defined with the plateau's modulus. In this zone the material cannot recover its initial shape and progressively collapse; thus similar levels of stress appear what imply constant stiffness and decelerations. Therefore, this zone is significantly more suitable for energy absorption than the elastic zone and, furthermore, the deformation range of this zone is significantly higher, which implies a greater energy absorption and deformation capacity. Finally, when all the cells collapse and all the air trapped inside disappears, the behaviour of the material is similar to the non-foamed original, characterized by an exponential slope in the stress-strain curve defined by the volume modulus of the original material. It should be noted that this implies an exponential increase in the stiffness of the material and, consequently, higher decelerations. That is the main reason why the densification zone should be not reached in impacts.

The end of the elastic zone is determined using the Young's elastic modulus which is the slope of the curve in the elastic zone. When the curve differs more than a 0.2% from an elastic one, then the plateau zone has been reached. In the same way, the densification point is the intersection point between the line defined by the slope of the plateau zone and a tangent curve in the densification zone that is obtained using the bulk modulus of non-foaming material in the case of the EPS (Fig. 1).

In the case of cork products, their internal structure is an open cell one that has also air inside but that not trapped. As a result, the stress-strain curve is expected to be similar and follow the Gibson's model as well. However, the open cell structure will also suppose that the cell will not collapse and, as a result, the material could recover partially its initial shape if the plateau zone or also if the densification zone is reached. Additionally, some differences could appear in the stress-strain curve especially in the plateau zone so it is expected a higher slope in this zone.

The main parameters of the stress-strain curves are as follows:

- Maximum tensile strength in the elastic zone ($\sigma_{c,e}$)
- Maximum tensile strength at the densification point ($\sigma_{c,d}$)
- Maximum elastic elongation ($\varepsilon_{c,p}$)
- Elongation at the densification point ($\varepsilon_{c,d}$)
- Elastic Young's modulus (E_c)
- Plateau Young's modulus (E_p)

The total energy absorbed per unit of volume by the material can be obtained from this equation:

$$W = \int_{o}^{\varepsilon_i} \sigma \, d\varepsilon \qquad \text{(eq. 2)}$$

This total energy absorption can be decompound in the following two components:

- Elastic energy absorption $W_e = \int_{o}^{\varepsilon_{c,p}} \sigma \, d\varepsilon$ (eq. 3)
- Energy absorbed in the plateau zone $W_p = \int_{\varepsilon_{c,p}}^{\varepsilon_{c,d}} \sigma \, d\varepsilon$ (eq. 4)

In relationship with the specific parameters, that are useful to compare materials in terms of properties with the same weight instead of in terms of properties with the same volume, they are obtained by dividing them by the density (ρ) of the material.

It must be highlighted also that, one of the main contributions of this paper, that goes beyond the state of the art, is that it analyses not only one or two types of isolated cork agglomerates, but main different types of existing cork products including natural cork and black agglomerates and it also compares them with main EPS materials. Consequently, it would be possible to obtain a more precise idea of the mechanical properties of different types of cork agglomerates and about their capability to substitute EPS.

Additionally, the paper delves into the capability of these materials to recover its initial shape and absorb a second impact. It must be highlighted here that some studies (Silva 2011) indicate the resilience capability of cork that can absorb multiple impacts and loads, and the least for the EPS (Yanzhou 2015) but there are not in-depth comparative studies about this topic. Hence, the article will be also focused in the comparative study of the resilience of both types of materials.

2. Materials and methods

The materials to be studied are the EPS used for the liners of the helmets and different types of cork. In the case of the EPS, EPS with densities of 60, 75, 80, 100 and 120 kg/m^3 with different grain sizes will be studied.

As for the study of cork, the natural material (NC), a cork agglomerate (AC), three different white cork agglomerates (WC) (usually called too agglomerated cork) and a black cork agglomerate (BC) (usually called too expanded cork) (Table 1) with different grain sizes will be used (Fig. 2).

Natural cork sheets are obtained from the bark of the cork oak by means of axes. With a cutting machine, the external layer is removed and flat regular sheets are obtained. The dimensions of these sheets depend on the cutting process and the tree itself; commercially, the common sheet thickness ranges between 3 and 15 mm, and the length and width between 100 and 600 mm.

Cork agglomerates are obtained after a more complex process. Natural cork and/or recycled cork agglomerates, are chopped into granules using mechanical processes and are subsequently sifted to obtain granules of different sizes. Afterwards, using heat, pressure and/or adhesives the granules join together to obtain regular sheets and bricks. Depending on the sizes of the granules and the joining processes, the obtained material has different mechanical properties. One of the main advantages of the agglomerates is that there are fewer shape and dimension limitations.

White cork agglomerates are manufactured using pressure, heat and adhesives; although biodegradable water based glues are sometimes used, the most common adhesives are resins such as polyester, epoxy, phenolic and vinyl resins. As a result, the final material obtained loses part of its renewable aspect. Depending mainly on the size range of the granules and, to a lesser extent, on the resin used, mechanical properties change.

Black cork agglomerates are manufactured by means of pressure combined with high temperature water steam; the granules expand (hence the name “expanded cork”) and suberin -a natural resin-, is exuded, joining the granules.

Natural cork presented in 600x100x10 sheets; four different white agglomerate corks with different adhesives and densities presented in 915x610x10 sheets; and one black agglomerate cork presented in 1000x500x20 sheets have been studied. These materials have different densities and different grain sizes (Fig. 2).

These materials have been studied under a quasi-static compression test using an 8032 INSTRON universal test machine with a 0.2 mm/s velocity until reaching a maximum of 90% strain with an acquisition rate of 0.2 s. The testing machine has been equipped with a 2501 -162 INSTRON compression platens and a INSTRON 2530-50 static load cell (maximum force: 50 kN) and it has been used the INSTRON own digital acquisition system (DAQ).

Cylindrical specimens of φ50 mm and a height of 40 mm have been tested and they have been placed in the centre of the platens using a pattern drawn on lower platen. The forces and displacements used to determine the stress-strain curve and the absorbed energy-strain curve have been obtained using the. By making use of these results alongside density, the specific stress-strain curve and the specific absorbed energy-strain curve have been obtained.

In order to perform the dynamic test, a 28 mm cube has been tested for the EPS to absorb 75 J. As for the corks tested, a 28 mm cube and a 40 mm cube specimen were used to absorb the same energy and therefore, reach a lower volumetric energy level. It has been used a 75 J free weight impact drop tower with a maximum height of 1.5 m and a free weight of 5 kg. This testing apparatus include plain impact platens of φ60 mm and a vertical 482A21 PCB accelerometer that uses a Quantum XMX840B DAQ; the test has been performed with an acquisition rate of 0.06 ms and it has been used also a position pattern drawn on lower platen. Consequently, the impact velocity of the free weight is 5.44 m/s and the initial strain rate for the 40 mm specimen is 136 s^{-1} and for the 20 mm one it is 194 s^{-1}; additionally, it has been applied a channel frequency class (CFD) filter with a frequency of 600 Hz. This method is similar to the one used by Di Landro (2002) with the EPS.

Likewise, the resilience of both materials for the quasi-static test has been studied. In the case of the quasi-static test, all the specimens have been tested to reach three different levels of strain:

90%, 75% and 50%; this will suppose the study of the resilience capability of the materials in three different scenarios: with a high densification, with a low densification and in the plateau zone near the densification point. These test have been performed for two consecutive load cycles to analyse the deformation and the capability to recover the initial shape after the first cycle and additionally the capability to absorb energy in the second cycle. Additionally, it has been performed a second load cycle to depict the new stress-strain curve and compare the behaviour before and after the first load cycle.

Additionally, in the case of the dynamic test, the final strain and the permanent deformation has been measured to analyse the capability to recover the initial shape after an impact. It must be pointed that, in dynamic test, the levels of energy are equal for all the specimens (75J) so the level of strain depends on the material and their stress-strain curve.

For all cases, dynamic and static, the permanent deformation of all materials after the tests has been measured in three different places with a calliper and the average of the measurements has been used to define the permanent deformation. To analyse the maximum deformation for the static test, the INSTRON device's own measuring equipment has been used but, in the case of the dynamic test, a double integration of the deceleration has been used to obtain the maximum displacement / deformation.

Finally, it must be pointed that all the specimens have been machined using a Roland MDX 20 CNC milling machine.

3. Results and discussion

3.1 Results under quasi-static compressive stress

3.1.1 EPS

EPS shows the typical shape of the stress-strain curve that follows the Gibson’s model (Fig. 3) with three differentiated zones: the elastic zone, the collapse plateau and the densification zone. These results are similar to previous ones obtained by other authors (Krundaevaad 2016, Chen 2015). It can be highlighted here that, an increase in density implies higher stress in the collapse plateau zone but a lower densification strain. This might mean that the helmet could absorb less energy before reaching the densification zone. Additionally, higher density implies higher Young´s modulus in the elastic zone and a higher slope in the plateau zone. It is also possible to determine the transition between different zones (Fig. 3) that can be defined with approximate to lines.

Analysing the curve specific stress vs strain (Fig. 4) it can be pointed out that the difference between curves is lower than in the previous case. This curve is important if there is not any limit in the geometry of a helmet and it can be used to compare two specimens with the same weight. It can be pointed out here that higher density implies higher specific stress and higher specific Young´s modulus; however, there are fewer differences than in the previous figure. This means that, with a thicker liner of lower density foam, it is possible to obtain a helmet with the same weight but with fewer differences in stiffness.

Analysing the curve of the absorbed energy vs strain (Fig. 5), it is possible observe that EPS with the highest density can absorb more energy before the densification point and this energy increase with the density. Hence, with the same volume, those materials with higher density will absorb more energy before densification.

Analysing the curve of the specific absorbed energy vs strain (Fig. 6), it is possible see that EPS 120 has the lower value before the densification point. For the other EPS, they have a similar limit but with higher strain. This entails that, with the same weight, the EPS with lower density will have a better behaviour as, on the one hand, it can absorb the same amount of energy before reaching the densification point and, on the another hand, it will have lower stiffness, and thus the deceleration of the head will decrease. At this point it must be highlighted that the thickness of the liner of the helmet cannot increase indefinitely since there are maximum dimensions of the helmet to take into consideration. Table 2 shows the main mechanical properties of the different EPS.

3.1.2 Cork products

Analysing the results of the cork (Fig. 3), these materials have a similar stress-strain shape to that of EPS´s, with an initial zone with a constant slope (similar to the elastic one), a plateau zone with a lower slope than the initial one (but higher than the slope of the EPS in this zone), and an exponential zone similar to the densification zone. For this material, it is difficult to determine the densification point because the transition between the plateau and the densification zone is not abrupt enough, and, furthermore, cork products do not have a bulk modulus that could be used. Similarly, the transition between the elastic and the plateau zone is also difficult to determine.

It can also be pointed out that natural cork, with a density of 260 kg/m^3, has the highest stress value and similar shape behaviour to 120 kg/m^3 EPS; the most similar behaviour to EPS can be observed due to the internal structure of natural cork. Regarding the other cork products, it can be observed that, despite its lower density, cork agglomerate (AC) has the second highest stress values between the corks and, in the case of white agglomerate cork stress values increase with density. Finally, black cork has the lowest stress values. Likewise, it must also be pointed out that higher stress values imply a lower strain limit before the exponential zone. Analysing the results of the white cork agglomerates, it can be observed that lower density implies lower stress levels but also lower strain for the densification point and lower slopes for the elastic and the plateau zone.

When comparing EPS and cork materials (Fig. 3), it can be observed that, in both cases, densification appears in the strain zone when reaching 0.4 to 0.6. However, there are significant differences in the shapes of curves of both materials: the slope in the elastic zone is lower for the cork agglomerates but in the plateau zone is higher.

Comparing EPS and cork values, 275 kg/m3 white corks and 170 agglomerate cork are similar to 75 kg/m3 and 80 kg/m3 EPS. In the case of the 222 kg/m3 white cork, its behaviour is similar to 60 kg/m3 EPS, with black cork having lower stress limits.

Analysing the curve specific stress vs strain (Fig. 4) it can be pointed out, in the case of white cork and black cork, that their curves are similar but with a lower density, the strain before the exponential zone being higher; thus with the same weight, cork products with lower density have better behaviour. In the case of the natural cork, the specific stress values before densification are the highest, followed by agglomerate cork; however, agglomerate cork has a lower strain limit before densification than natural cork and the other materials. When comparing this results with the EPS, all cork specimens have lower specific stress levels due to the lower densities of the EPS.

With regards to energy (Fig 5), natural cork displays the best behaviour, with a similar behaviour to EPS 120. Agglomerate cork comes second in behavioural properties followed by white corks, depending on their density. Finally, black cork is the material that can absorb the least energy. When comparing these results with EPS, these materials have similar energy levels, with white corks and 170 agglomerate cork being similar to the 75 kg/m3 EPS and 80 kg/m3 EPS. In the case of 222 kg/m3 white cork, its behaviour is similar to 60 kg/m3 EPS, with black cork having the lowest stress limits.

In terms of specific energy (Fig. 6), natural cork and agglomerate cork display similar behaviour and, for lower strain levels (before the exponential zone), 1 Kg of natural cork can absorb more energy than agglomerate cork.

In the case of white agglomerate corks, it must be brought to light that all of them have the same behaviour. Thus, 1 kg of these materials can absorb the same amount of energy.

In the case of black agglomerate, it has similar behaviour to white agglomerates until it reaches a strain of approximately 50%. After that point it displays better behaviour. Consequently, the material with the third highest specific energy absorption capability is black agglomerate due to its lower density.

However, compared with the EPS, cork products can absorb less energy per unit of mass due to their higher density.

3.2 Results under dynamic compressive stress

3.2.1 EPS

Analysing the results of the EPS using the drop tower to absorb energy of 75 J (Fig. 7 and Fig. 8), it can be observed that the deceleration curve shows a similar shape to that of the stress-strain curve. At the beginning there is a zone with increasing deceleration in regards with the elastic zone; there is also a zone with constant deceleration related to the plateau zone; and finally there is a high peak in deceleration associated with the densification zone. It must be highlighted that the elastic deceleration slope is directly associated with the density of EPS; the constant deceleration plateau shows the same relationship. Finally, due to the higher capacity of denser EPS to absorb energy before the densification zone, the peak in deceleration is lower for denser EPS. Likewise, the peak in deceleration appears later, especially for EPS 120. As a result, the maximum peak in deceleration is lower for denser EPS. In addition, the average deceleration value (Table 3) is lower too. These results are similar to those by other authors (Krindaevaad 2016).

3.2.2 Cork products

Analysing the results of the cork and its products using the drop tower to absorb energy of 75 J (Fig. 7), it can also be observed that the deceleration curve has a similar shape to the stress-strain curve. At the beginning there is a zone with increasing deceleration associated with the elastic zone; there is a zone with gradually increasing deceleration (but lower than in the previous case) that is related to the plateau zone; and finally there is a high peak in deceleration with regard to the densification zone.

Consequently, when compared, both EPS and corks have similar deceleration curves, with their stress-strain quasi-static curves being closely related. It must be highlighted here that, as with EPS, the elastic deceleration slope is directly related to the stiffness of the material, with the same phenomenon occurring in the plateau zone. Finally, those materials having higher deceleration values in these zones can absorb much more energy and, as a result, the highest peak in deceleration that appears during densification takes place at a later stage, as well as being lower. It can also be observed that natural cork has a significantly lower peak whereas black cork has the highest.

These results are condensed in Table 3, where average deceleration is also displayed. This table shows that natural cork presents the lowest peak regarding deceleration and average deceleration; whereas black cork presents the highest values; the other materials share similar values. Consequently, natural cork is the material with the best behaviour while the rest have similar ones, with the exception of black cork, whose behaviour is notably the worst.

Comparing results for cork products and EPS, it can be observed that, due mainly to the differences in the shape of the stress-strain curve for each type of material, cork products exhibit lower maximum decelerations but higher initial deceleration at the initial stages of the impact. However, the average deceleration is similar for both types of materials so it is necessary to include an additional criterion to compare these materials.

Another experimental test carried out involved a drop tower test to absorb 75 J but with a 40 mm side box instead of 28 mm, in order to compare materials that must absorb a lower volumetric energy (1/3) as is shown in Fig. 8. This test is representative of a low velocity impact, whereas the previous test represented a high velocity impact.

The results show that materials have an initial zone with a gradual increase in deceleration associated with the elastic zone of the stress-strain curve, as in the previous test. Before that, the curve slope changes depending on the shape of the plateau zone of the stress-strain curve until the material can absorb all the energy. Consequently, the shape changes and the material can either reach the densification zone (agglomerate cork and black cork) or not. In the latter case, the shape of the curve displays a greater disparity to the stress-strain curve. It must be highlighted at this point that materials (with the exception of black cork, which reaches a higher stress in the densification zone), have similar decelerations (Table 3).

The material with the lowest deceleration is middle size grain white cork. When comparing average deceleration, these materials are similar. Consequently, in this case white middle grain cork is the most adequate material; the other types of cork have similar adequacy, with the exception of black cork, whose adequacy is the worst by far.

3.2.3 HIC study

Although the HIC criterion is not specifically designed to compare the decelerations in the drop tower test, in this article, the criterion has been used to compare materials due to the previous mentioned limitations.

It has been assumed here that the material displaying better properties will have lower deceleration peak values and lower average deceleration. In regard to this last point, it must be highlighted that this average deceleration must be analysed in different periods of time along the time domain in order to obtain the worst average deceleration, which will entail the greatest brain damage.

The deceleration of the drop tower test is assumed to be similar to the one found in the accelerometer in the head of a dummy with a helmet, since there are certain similarities between the deceleration curves from drop tower test, and the test carried out by other authors (Gimbel 2008) to test helmets with different EPS.

Table 4 shows the HIC obtained. It can be seen that, for higher impact velocities, EPS with higher density also implies lower HIC levels, as the material does not reach the densification zone and results in too stiff a behaviour. Likewise, natural cork has notably lower HIC values than other materials. On the other hand, black cork displays the most inadequate behaviour, with a significantly high HIC level.

When comparing EPS with cork materials, it must be highlighted that cork products have lower HIC levels than the EPS and, consequently, helmets made of cork will be better suited than those made of EPS. This is mainly due to the fact that cork materials have a different stress-strain shape, with lower initial elastic slope and a constant increase in the slope from a low to a high strain in the plateau zone, which involves increasing deceleration matching the one found in the deceleration curve (Fig. 7).

On the other hand, EPS has a higher slope in the elastic zone, implying higher initial deceleration and a subsequent constant medium stress level in the plateau zone implying a constant higher average deceleration (Fig. 7). As a result, average deceleration values will be lower for cork and cork products.

In the case of low impact velocity (40 mm size specimens) (Fig. 8), natural cork does not have the lowest HIC, given the fact that, in this case, average deceleration reaches higher values, as some other materials do not reach the densification zone. Consequently, agglomerate cork and middle size white cork display the best behaviour.

3.3 Study of the resilience of the materials

Another aspect to study is the capacity of materials to absorb multiple impacts at the same point, which is especially important for a helmet in the event of an accident. Fig. 9, Fig. 10 and Fig. 11 show the stress-strain curve for two consecutive load cycles of some of the materials for three different maximum strains.

It can be observed that the EPS presents different for a maximum strain of a 90%; for lower maximum deformations (50% and 75%) the material presents a high permanent deformation (Table 5); by contrast, in the case of the highest deformation that imply a high densification, the material undergoes a rebound effect and exhibits a lower permanent deformation. This phenomenon has been noticed for all the EPS foams ant it could be due to the fact that, after the densification point, the material acts as a spring and some of the energy absorbed produce a higher recovery of the internal structure. It must be also highlighted that, whilst EPS foams in this particular case has low permanent deformation, their internal structure is totally damaged and, consequently, its capability to absorb energy in successive load cycles is negligible (Table 6). At this point, it must be clarified that, though EPS can absorb around a 25% of the initial energy in the second cycle, the energy corresponds to the densification zone (see Fig. 9 for the EPS).

In relationship with the cork products, Fig. 9, Fig. 10 and Fig. 11 show that, for any the maximum strain, the materials suffer low permanent deformations (between a 10 and a 30%); additionally, these figures show that, the higher maximum strain, the higher permanent deformation undergoes after the first load cycle. Furthermore, higher maximum strains imply also lower stress-strain curve in the second load cycle and, hence, a lower capability to absorb energy (Table 6).

Comparing the results of the absorbed energy for EPS and cork agglomerates for a 75% of maximum deformation (Fig. 10) and for a 50% (Fig. 11) and the absorbed energy (Table 6), it can be observed that, though EPS has a low capability to absorb energy and it also suffer a high permanent deformation, conversely, cork and cork agglomerates have higher capability to absorb energy and they also suffer less permanent deformation. This phenomenon is due to the fact that the internal structure of cork products suffers less damages than those of the EPS.

Additionally, lower maximum deformation implies for cork products lower internal damages and higher capability to recover its initial shape and to absorb more energy in subsequent impacts. In the case of the EPS, the crushing of the closed internal cells during the plateau zone imply permanent damage and, as a result, EPS undergoes high permanent deformation so it can absorb little energy in successive impacts. In the case of the cork agglomerates, due to their internal open cell structure, these structures do not collapse in the same way than those of the EPS and, when the load disappear, they can recover part of internal structure and part of the previously expelled air. Therefore, the resilience this latter material is higher.

It must be also noticed that BCA presents the highest resilience and, behind it, the WCA302. It can also be noticed for the WCA that, the higher the density is, the higher the resilience is but also the permanent deformation.

Analysing also the results of the drop tower test (Table 7), it can be observed that, for the EPS, aforementioned phenomenon appears also for high maximum deformation appears. As a result, EPS bounces and can recover part of its initial shape. In the same way, it can also be observed that cork and cork agglomerates suffer very low permanent deformation and also that lower maximum deformation implies lower permanent one. Finally, it should be noticed that the results of the dynamic and the static test in terms of resilience show significant differences; this could be due to the influence of the strain rate that has not been considered in this study. Some authors (Kake 2019) have noticed for EPS that higher strain rate imply higher stress levels for stress-strain curve, but also that the densification point appears with lower strains.

4. Conclusions

The main conclusion to be drawn is that cork and cork products can be a suitable renewable-origin substitute for EPS, in applications in which it is necessary to absorb energy and reduce the velocity of an element impacting with low deceleration peaks. Additionally, whilst the average deceleration is similar, the maximum deceleration that appears is significantly lower than for the EPS due to the differences in shape of their stress-strain curve, especially in the elastic and plateau zones. In addition, the use of the HIC criterion to compare decelerations reflects that cork products have lower values. Whilst this criterion was formulated to analyse the head injuries, it is also an indicator to compare materials for comparing materials and what it is more important, it uses both maximum deceleration and average decelerations.

It must also be highlighted that the resilience capability of cork and cork products must be taken into consideration in those applications where more than one impact may occur in the same area. In this sense, cork products are much more suitable than EPS foams due to the differences in the internal structure of both materials. While cork products have an open cell structure that can recover part of their initial strength and re-introduce inside part of the air expelled during the impact, the closed-cell structure of the EPS collapse after the impact so they lost most of their strength, cannot recover its shape and also, the expelled air will not be reintroduced.

However, more in-depth analyses of this capability should be carried out to compare their behaviour after 2, 3 or more impacts and also, the influence of the strain rate should be taken into consideration.

Comparing the quasi-static results, it can be pointed out that EPS foams and cork and some sub-products have similar stress-strain curves and can absorb a similar amount of energy before the point of densification. However, it must also be pointed out that cork and cork products have higher density and, as a result, the specific stress-strain curve and the specific energy that they can absorb is notably lower. As a result, cork and cork products will be more suitable in those applications in which weight is not critical and in applications in which volume is the main design factor. On the other hand, EPS will be significantly better in those applications where weight is the main design factor.

Finally, in the case of helmets, it must be pointed out that the results obtained are not conclusive. The use of cork and cork products implies lower peak deceleration, lower HIC and lower average deceleration than if EPS is used for the drop tower test. However, some test with full helmet prototypes are essential to assess the superior behaviour of the cork agglomerates; this is especially important because these materials have higher density and, as a result, the weight of the helmet will increase and could generate higher momentum in the condyle and in the neck; likewise, a heavier helmet implies more rotational accelerations.

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Figure Captions

Fig. 1 Gibson's model for polymeric foams.

Fig. 2 Studied cork and cork agglomerates.

Fig. 3 Stress-strain curve for all the studied materials.

Fig. 4 Specific stress-strain curve for all the studied materials.

Fig. 5 Absorbed energy for all the studied materials.

Fig. 6 Specific absorbed energy for all the studied materials.

Fig. 7 Deceleration (m/s^2) - time curve for all the studied materials for the 75 J dynamic test. Specimen: 28mm box

Fig. 8 Deceleration (m/s^2) - time curve for corks and cork products for the 75 J dynamic test. Specimen: 40mm box

Fig. 9 Stress-strain curve for some of the studied materials under two consecutive load cases with a maximum strain of a 90%

Fig. 10 Stress-strain curve for some of the studied materials under two consecutive load cases with a maximum strain of a 75%

Fig. 11 Stress-strain curve for some of the studied materials under two consecutive load cases with a maximum strain of a 50%