Polymer Testing 96 (2021) 107061

Contents lists available at ScienceDirect

Polymer Testing

journal homepage: http://www.elsevier.com/locate/polytest

Assessment of agglomerated corks and PVC foams cores crashworthiness under multiple-impact events in different loading conditions

Claudia Sergi [a,b,*], Fabrizio Sarasini [a], Enrique Barbero [b], Sonia Sanchez-Saez [b], Jacopo Tirillò [a]

[a] Department of Chemical Engineering Materials Environment, Sapienza Università di Roma and UdR INSTM, Via Eudossiana 18, 00184, Rome, Italy
[b] Department of Continuum Mechanics and Structural Analysis, Universidad Carlos III de Madrid, Avda de La Universidad 30, Leganés, 2891, Madrid, Spain

A R T I C L E I N F O

Keywords:
Agglomerated cork
PVC Foam
Dynamic compression
Puncture test
Multiple impacts
Dimensional recovery

A B S T R A C T

Thanks to the unique flexural properties, sandwich composites are considered as irreplaceable structures in many industrial fields, but their susceptibility to impact events is still a considerable drawback that undermines their structural integrity determining a reduction of their load-bearing capabilities. Considering that the core material plays the major role to distance the skins, the knowledge of its multiple-impacts response becomes a key design parameter in order to ensure a long-term stability to the structure. In view of this, the present work addresses the multiple-impacts behavior in dynamic compression and puncture impact conditions of bio-based agglomerated cork cores taking into account the effect of density and providing a meaningful comparison with more traditional petroleum-based foams. Despite the inherently higher mechanical properties of the PVC (polyvinyl chloride) foams, agglomerated cork demonstrated to provide a higher dimensional stability to the structure after repeated impacts thanks to its unique microstructure. With a reduction lower than 25% of its initial height after 10 impacts, agglomerated cork NL25 proved to be an exceptional alternative to the common HP130 foam, which undergoes a halving of its initial height after only 3 impacts, to obtain a more eco-friendly and performing sandwich composite.

1. Introduction

Sandwich composites are universally acknowledged as high-performing structures thanks to their peculiar design that ensures unparalleled flexural stiffness and strength-to-weight ratio [1] and makes them unique in many industrial fields such as buildings, transportations, aeronautics, naval, wind turbine blades and sports [2–4]. Despite the stunning flexural properties, sandwich composites are characterized by the main drawback of being extremely prone to impact events that can compromise their structural integrity and cause a significant reduction of their load-bearing capabilities [5,6].

In view of this weakness, numerous research works started to focus on sandwiches impact response with a view to predicting the mechanical response of the overall structure and ensuring its feasibility in the industrial application of interest [7,8]. Most studies focused on sandwich damage resistance and damage tolerance, assessing its ability to prevent damage and to perform adequately after the impact [9–13].

Another key point in the study of sandwich structures dynamic response is the impact behavior of the core material. It plays the major role to distance the skins allowing to take advantage of the I-beam principle that guarantees high flexural performances while keeping low the weight of the structure [1]. The occurrence of an impact event could induce changes in core thickness altering skins spacing and causing a drastic reduction of the flexural properties of the structure. In light of this, many research works addressed the impact behavior of various core materials in different loading conditions [14–16].

A further area of concern is their response to multiple-impact events. The accumulation of damage over time can become severe, thus determining a progressive deterioration of structural efficiency. For example, motorcycle helmets prevent skull fractures and brain injuries during an accident decelerating the head during the impact thanks to the inner liner that absorbs most of the impact energy and reduces the impact force through deformation and crushing [17]. This means that even if the helmet fulfilled perfectly its role after the first impact, it is likely that it would not be able to ensure the same protection to the user because of a significant deformation and alteration of the microstructure.

In addition to impact susceptibility, sandwich composites are characterized by a second drawback related to the use of synthetic

* Corresponding author. Department of Chemical Engineering Materials Environment, Sapienza Università di Roma and UdR INSTM, Via Eudossiana 18, 00184, Rome, Italy.
E-mail address: claudia.sergi@uniroma1.it (C. Sergi).

https://doi.org/10.1016/j.polymertesting.2021.107061
Received 3 September 2020; Received in revised form 1 December 2020; Accepted 6 January 2021
Available online 8 January 2021

reinforcements, such as carbon and glass fibers, and petroleum-based materials, such as the traditional polymeric foams employed as cores, i.e. polyvinyl chloride, polystyrene, polyurethane, and the well-established polymers used as matrix in skins production, i.e. epoxy resin, polypropylene, polyethylene, on industrial scale. The exploitation of synthetic and non-biodegradable materials conflicts with the more restrictive European and international regulations in the field of environmental pollution and waste disposal that encourage the usage of materials from renewable resources, with a potential reduction of the carbon footprint in the production step and at least a partial biodegradability of the component at the end of its life cycle.

With regard to the commonly used foam cores, a valid substitute was identified in agglomerated cork produced from cork wine stopper wastes through an agglomeration process with a suitable polymeric binder [18]. Cork is the bark of the oak and is characterized by appealing properties such as low permeability to liquids and gases, good acoustic and thermal insulation capabilities, fire retardancy, resilience, lightness and stunning dimensional recovery capabilities [18]. Thanks to its worthwhile properties and its origin from natural renewable resources, cork gained increasing interest throughout the years establishing its role in energy absorbing devices [19] and proving to be a satisfying choice to replace traditional synthetic components in sandwich structures.

In this framework, the present work aims to provide experimental evidence of the feasibility of agglomerated cork as an effective core material disclosing key features connected to its multiple-impacts response. Sanchez-Saez et al. [20] already addressed the topic presenting the multiple-impacts results of one type of agglomerated cork in dynamic compression conditions. The current study wants to make a step forward analyzing the multiple-impacts behavior of agglomerated cork examining two different types of impact conditions and considering the effect of density that is always a key parameter to take into account when selecting a core material. In particular, drop weight tower dynamic compression and puncture impact conditions were selected as test environment to probe agglomerated cork reaction under repeated dynamic loads.

The same experimental campaign was also performed on more traditional PVC (polyvinyl chloride) foams characterized by the same densities selected for cork. In this way it is possible to provide a meaningful comparison of the results obtained highlighting advantages and drawbacks connected with the use of agglomerated cork. The use of PVC as benchmark foam enables enrichment of knowledge on synthetic foams multiple-impacts behavior already assessed by Lu et al. [21] who studied the response of a polyethylene foam in dynamic compressive condition and by Fernandes et al. [22] who investigated an expanded polystyrene (EPS) and an expanded polypropylene (EPP) foams. In their research work, Fernandes et al. also provided a comparison with one type of expanded cork and two types of agglomerated corks but considering an impact scenario different from the ones proposed in this work, namely drop weight tower dynamic compressive tests performed with a hemispherical impactor. The use of this type of impactor rather than a flat one does not permit to work in perfect uniaxial compression conditions. Moreover, the mentioned work investigated materials response at only two impacts without pushing the cores to their bearing limit.

2. Materials and methods

2.1. Materials

Agglomerated corks NL10, NL20 and NL25 provided by Amorim Cork Composites® are the three natural core materials selected for this study. These cork planks differ from one another only in density and granule size and are produced bonding together cork granules with a polymeric polyurethane binder expressly devised for cork and designed to make it compatible with all the polymeric resins industrially available. NL10 is characterized by an average density of 140 kg/m^3 and a granule size of 2–4 mm, NL20 by an average density of 200 kg/m^3 and a granule size of 0.5–2 mm and NL25 by an average density of 250 kg/m^3 and a granule size of 0.5–2 mm. The selection of agglomerated corks with different densities allows to evaluate the effect of this parameter that is of paramount importance when choosing a core for sandwich production. The multiple-impacts response of these natural cellular core materials was compared with the one of Divinycell HP130, HP200 and HP250 PVC foams provided by Diab®. These synthetic foams are closed cell foams with an average density of 130 kg/m^3, 200 kg/m^3 and 250 kg/m^3, respectively and were expressly selected to provide a valid comparison of the experimental results granting a reference benchmark. All core planks were supplied as plates with a thickness of 15 mm.

2.2. Dynamic compression tests

Dynamic compression tests were performed at room temperature in a drop weight tower Ceast Fractovis® on cubic samples with 15 mm of side. The tower was equipped with a flat impactor characterized by a diameter of 58 mm and an overall mass of 4.134 kg. Tests were recorded with a high-speed camera, Fastcam SA-Z by Photron®, and the resulting videos were analyzed with the program Photron FASTCAM Viewer 3 in order to control and quantify the effect of progressive impacts on core material deformation through visual inspection.

A prior experimental campaign was carried out in order to identify the impact energies that would have allowed to test each core material in two different conditions, namely when the corresponding maximum deformation is in the plateau region and in the densification stage of the stress-strain curve after the first impact. It is necessary to highlight that impact energies were also selected in order to compare the different materials with a maximum deformation between 55% and 65% for the lower impact energy and between 75% and 85% for the higher impact energy. The selected impact energies for the corresponding core materials are summarized in Table 1.

For each impact energy and each core type three samples were tested. The selected number of specimens represented a satisfactory compromise between reliability of results and duration of the experimental campaign, though an increase in the number of specimens would enhance the reproducibility of data. Five minutes were allowed between subsequent impacts in order to leave the material enough time to partially recover its initial dimension after the imposed deformation and in order to highlight the great difference between agglomerated cork and PVC foam behavior.

2.3. Puncture impact tests

Puncture impact tests were performed at room temperature in an instrumented drop weight tower Instron Ceast 9340 equipped with a CEAST Data Acquisition Systems DAS 64 K. A hemispherical impactor of 12.7 mm of diameter and 3.055 kg of mass were used to test core materials samples that were placed on a circular base support characterized by an inner diameter of 40 mm. Samples were clamped to the base with a pneumatic system to prevent movements during impacts. Of main importance is the drop weight tower anti-rebound system that prevents a second undesired impact, that could compromise the experimental results, blocking the impactor after the rebound. Tests were carried out

Table 1
Lower and Higher Impact energies selected for each core material to perform multiple-impacts in dynamic compression conditions.

	Lower Impact Energy	Higher Impact Energy
NL10	2 J	5 J
NL20	2 J	5 J
NL25	7 J	10 J
HP130	7 J	10 J
HP200	13 J	18 J
HP250	18 J	25 J

on square samples with 100 mm of side and 15 mm of thickness.

Even for puncture impact tests a preliminary experimental campaign was necessary to identify the most suitable impact energies. All three agglomerated corks displayed the same perforation threshold (P.T.) at 5 J because of the weak interface between cork granules and polymeric binder that leads always to core failure because of intergranular fracture. For this reason, all six types of core materials were tested at 1.25 J and 2.5 J, which are 25% and 50% of agglomerated corks perforation energy, respectively, in order to ensure a direct comparison between agglomerated corks and PVC foams. Furthermore, considering that all the polymeric foams are characterized by a higher perforation threshold, in particular 10 J for HP130, 15 J for HP200 and 17.5 J for HP250, all of them were also tested at 50% and 25% of their perforation threshold. All the impact energies employed are briefly summarized in Table 2.

For each core type and each impact energy three samples were tested. One hour was allowed between subsequent impacts in order to have enough time to perform the post-impact profilometric analysis.

2.4. Profilometry and scanning electron microscopy (SEM) analysis

In order to evaluate the damage extent induced by the impact, all PVC foams were subjected to a profilometric post-impact analysis after every impact. This allowed to sketch the evolution of the residual indentation depth caused by the impactor. A laser profilometer Taylor Hobson Talyscan 150 was employed to carry out the study and the acquired images were processed and analyzed through the software TalyMap 3D.

A morphological analysis of agglomerated corks and PVC foams microstructure was carried out to support the dynamic mechanical results. In particular, changes in core cells morphology due to increasing compressive loads applied to the samples were studied through the field-emission scanning microscope (FE-SEM) MIRA3 by Tescan. Core materials were assembled on a screw stub equipped with a metal sheet that allowed to distribute uniformly the compressive clamping force applied by the screw to the whole sample. Increasing screw displacement and consequently the force applied to the metal sheet and to the sample, it was possible to increase its degree of compression and to evaluate the evolution and transformation of the microstructure. Considering the insulating nature of both cork and PVC, it was necessary to sputter-coat all specimens with a thin layer of gold before observations in order to make them conductive and prevent charging.

3. Results and discussion

3.1. Dynamic compressive impacts

Multiple-impacts dynamic compressive tests allowed to analyze different aspects of the synthetic and natural cellular core materials under study. At first, the execution of these tests highlighted the huge differences in dynamic response that arise between the high-dimensional recovery cork and the rigid PVC foam. At a later time, the effect of density on agglomerated cork was addressed investigating its influence on the main parameters under study.

The observation of the dynamic compressive curves of NL25 and HP130 at 7 J and 10 J shown in Fig. 1 and the analysis of the trends of maximum force, permanent deformation and percentage absorbed energy with increasing number of impacts depicted in Fig. 2 allow to reveal a profound difference in the multiple-impacts response in dynamic compressive conditions of agglomerated cork and PVC foam. If NL25 is able to keep almost unchanged its dynamic compressive curves shape ensuring almost a constant response to the impact, this is not true for HP130 that displays a drastic change in its response curves shape. After two impacts at 7 J (Fig. 1B) and one impact at 10 J (Fig. 1D), the typical wide plateau region, which characterizes synthetic foams and ensures high energy absorbing capabilities together with a low increase in material reaction force, disappears leaving room to a steep increase in the maximum reaction force.

Both NL25 and HP130 are excellent energy absorbing materials characterized by a high percentage absorbed energy that tends to decrease almost with the same tendency in both cases. In particular, NL25 is characterized by a decrease of almost 3.5% at 7 J, moving from 96.7% to 93.2%, and of 3.7% at 10 J, moving from 97.7% to 94%, whereas HP130 is characterized by a decrease of almost 3.8% at 7 J, moving from 99.8% to 96%, and of almost 2% at 10 J, moving from 99.99% to 98% (Fig. 2).

Despite this similarity in the energy absorption efficiency, a clear difference can be observed in the maximum force trend of the two materials. NL 25 is characterized by a logarithmic increase of the maximum force with the number of impacts ($R^2 = 0.9991$ at 7 J and $R^2 = 0.995$ at 10 J) whereas HP130 is characterized by a linear one ($R^2 = 0.9908$ at 7 J and $R^2 = 0.9968$ at 10 J). The situation is even more severe for the denser foams HP200 and HP250 that display an exponential increase of the reaction force with the number of impacts as can be easily observed in the data reported in Fig. A1 of Appendix A. This means that considering the upper limit of the loading cell that is 19 kN, NL25 is able to ensure a safe reaction force even for more than 10 impacts at both 7 J and 10 J whereas HP130 must be stopped at the fifth impact at 7 J and at the third impact at 10 J.

Another highly significant difference between NL25 and HP130 can be observed in the permanent deformation of the samples after every impact as shown in Fig. 3 and in its trends summarized in Fig. 2. Thanks to its dimensional recovery capabilities, agglomerated cork NL25 is able to undergo a permanent deformation of only 24% after bearing 10 impacts at 10 J whereas HP130 undergoes a reduction of almost 55% of its initial height after only 3 impacts at 10 J. Similar results were observed at 7 J, in fact after 10 impacts NL25 undergoes a height reduction of almost 16% whereas HP130 suffers a permanent deformation of 57% bearing half of NL25 number of impacts. These findings lead to a paramount conclusion concerning the employment of this cellular material as core in a sandwich composite, being NL25 able to guarantee a

Table 2
Summary of the impact energies selected to perform multiple-impacts in puncture impact conditions.

	1.25 J	2.5 J	25 % of Perforation Threshold	50 % of Perforation Threshold
NL10	25 % P.T	50 % P.T.	-	-
NL20	25 % P.T	50 % P.T.	-	-
NL25	25 % P.T	50 % P.T.	-	-
HP130	x	25 % P.T.	-	5J
HP200	x	x	3.75 J	7.5 J
HP250	x	x	4.35 J	8.75 J

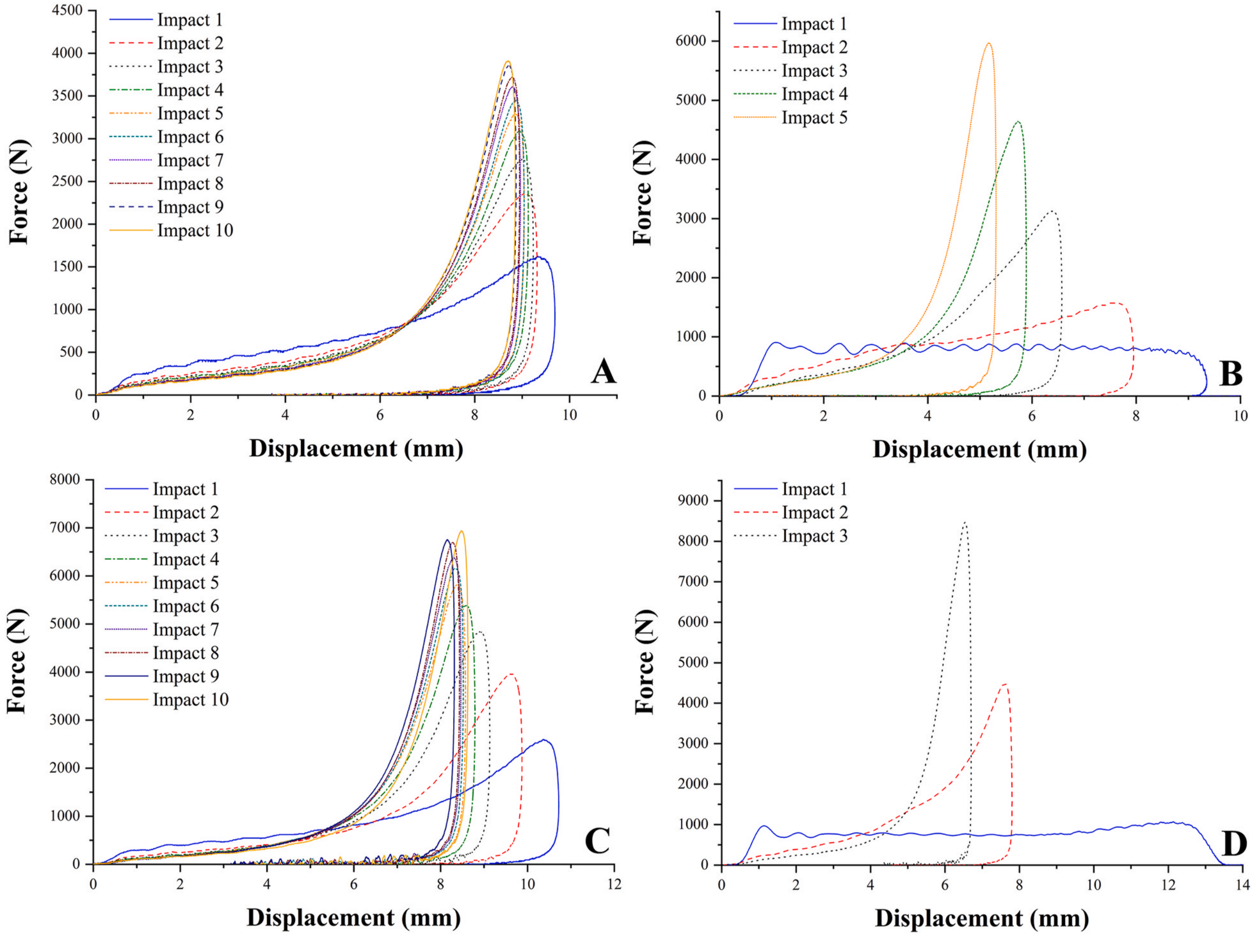

Fig. 1. Dynamic compressive curves after multiple impacts of NL25 and HP130 at 7 J (A and B, respectively) and at 10 J (C and D, respectively).

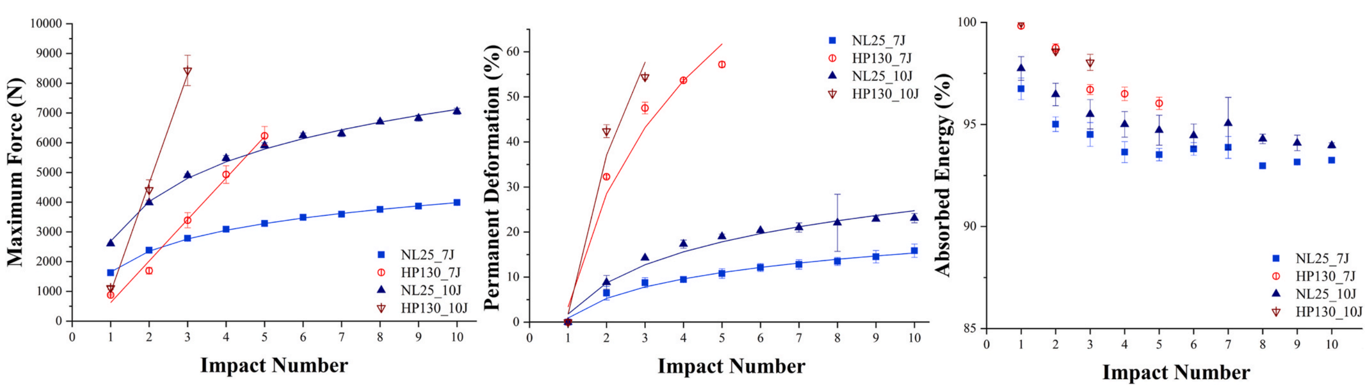

Fig. 2. Maximum force, permanent deformation and percentage absorbed energy trends with increasing number of impacts of NL25 and HP130 performed at 7 J and 10 J.

much higher dimensional stability to the structure. This evidently ensures a more constant spacing of the skins in case of impact preventing a strong reduction of composite flexural modulus and strength that strongly depend on skins distance.

A deeper understanding of the results obtained can be achieved moving to the microstructural analysis of the natural and synthetic core materials. Figs. 4 and 5 show the changes in cells microstructure induced by increasing compressive loads of NL25 and HP130, respectively.

When subjected to a compressive stress, agglomerated cork reacts elastically (Fig. 4A) at first and then enters the plateau region. Once this happened, cork cell walls undulations become more pronounced (Fig. 4B) and this step preempts the progressive approach of opposite cell walls as shown in Fig. 4C and D. Once the complete collapse of the cell occurred (Fig. 4E), the densification region is approached because opposite cell walls start to touch each other (Fig. 4F) determining a strong increase in the stress necessary to continue deforming the material. In light of the micrographs reported, the feature of main interest that differentiates cork from rigid polymeric foams is the capability of cork cell walls to fold completely without undergoing fractures or cracks.

To better appreciate the pronounced difference of behavior, PVC damage progression must be analyzed. After the first elastic region

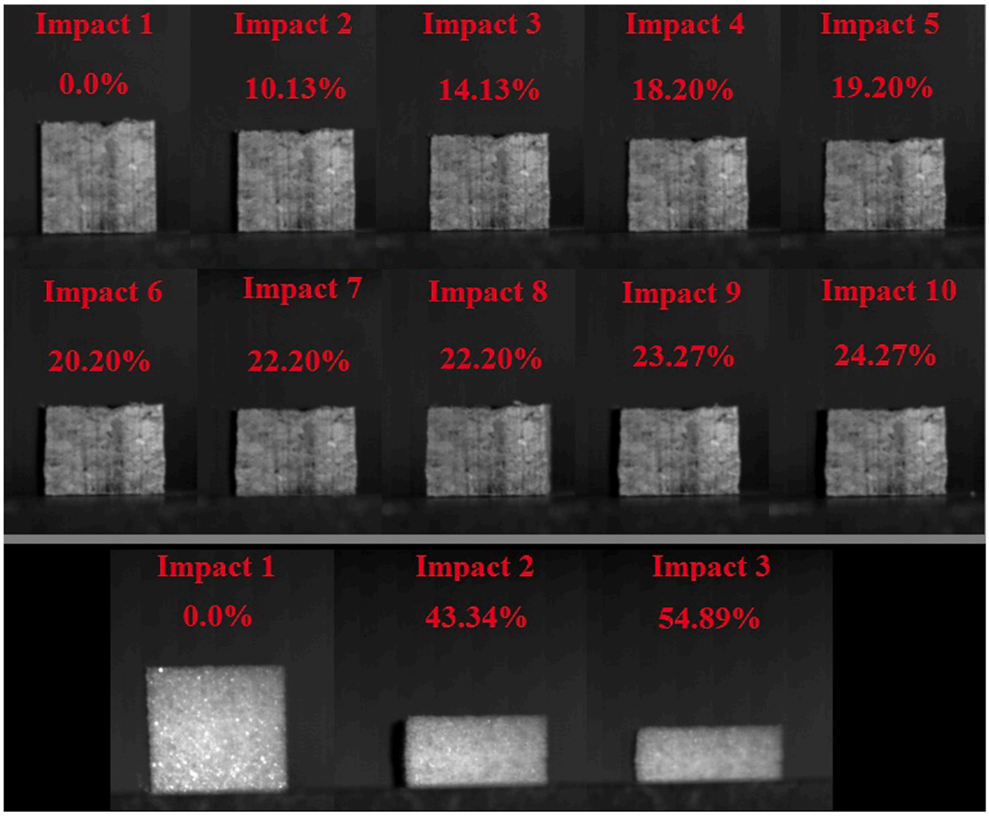

Fig. 3. Permanent deformation of NL25 and HP130 after every impact at 10 J.

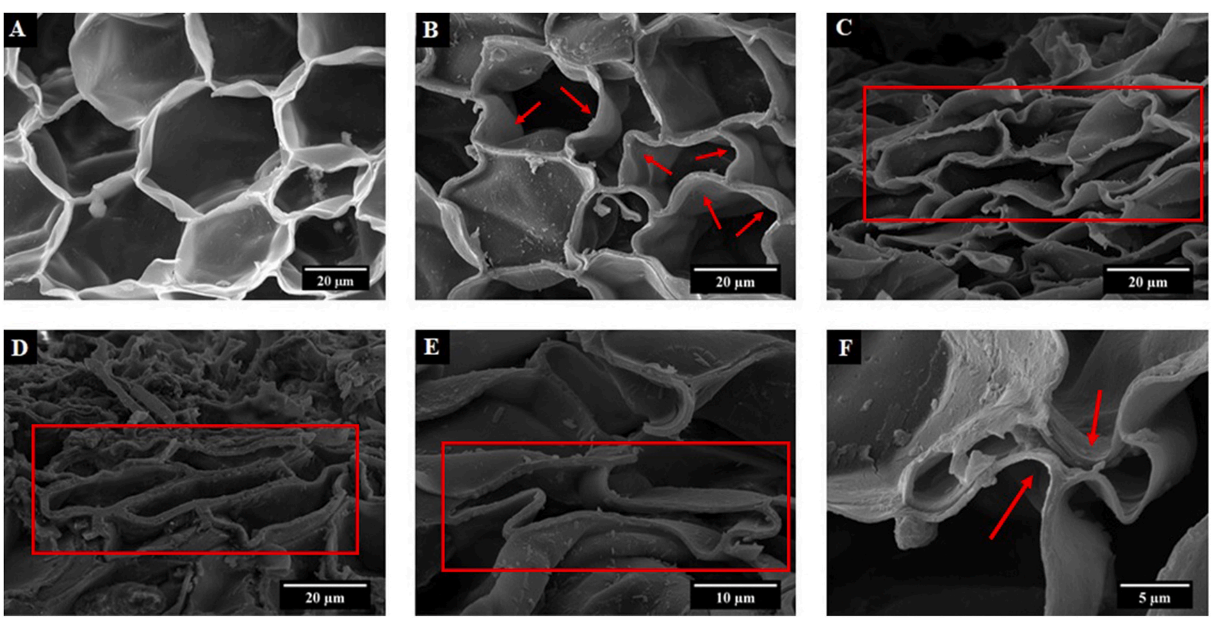

Fig. 4. Changes in NL25 cells microstructure under increasing compressive loads.

(Fig. 5A), even for the PVC foam, the entry into the plateau region leads to a progressive approach of opposite cell walls (Fig. 5B) through bending. Once the bending limit of the wall is reached (Fig. 5C), it fractures (Fig. 5D) causing a complete collapse of the cell (Fig. 5E) and the approach of the densification region.

The ability of cork cell walls to prevent fracture and to unfold when the compressive load is removed is responsible of the impressive dimensional recovery capabilities of this cellular core. This feature has to be ascribed to the suberin macromolecules that are extremely flexible and make up almost half of cork chemical composition [23]. On the other hand, the brittle nature of PVC foam cell walls does not allow to prevent cracks and once the wall fractures, the material loses the possibility to recover its initial shape.

Moving to 2 J and 5 J impacts for NL10 and NL20 cork cores, the effect of density on agglomerated cork multiple-impacts response can be assessed. Maximum force, permanent deformation and percentage

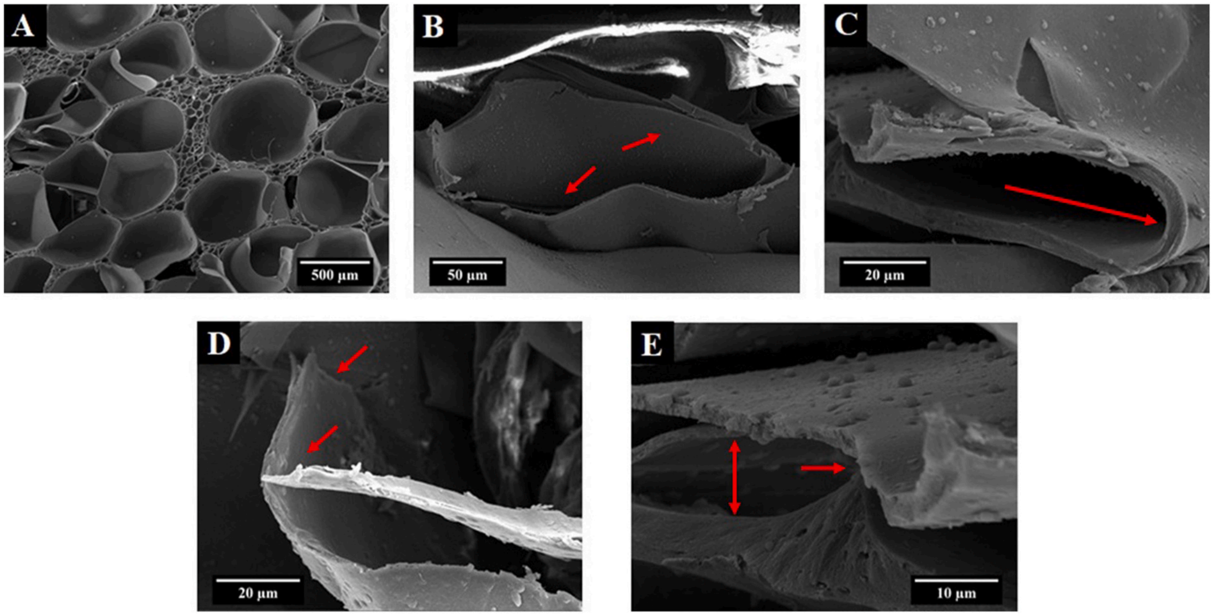

Fig. 5. Changes in HP130 cells microstructure under increasing compressive loads.

absorbed energy trends of both cork types and impact energies are shown in Fig. 6. First of all, it is necessary to highlight that, irrespective of cork density, both core materials can bear more than 10 impacts without reaching the load cell limit.

Concerning the percentage absorbed energy, it is possible to say that both NL10 and NL20 are characterized by good absorbing capabilities as previously observed for NL25. What aroused more interest is that NL10 and NL20 display almost the same absorbed energy and the same decreasing trend for both impact energies despite NL20 has a density two times higher than NL10. In particular, the initial percentage absorbed energy at 2 J is of 92.6% for NL10 and 91.4% for NL20 and the total decrease is of 9.6% for NL10 and 8.5% for NL20. Similar results are observable at 5 J where the percentage absorbed energy is of 96.3% for NL10 and 96.6% for NL20 and the total decrease is of 5.4% for NL10 and 4.8% for NL20.

The effect of density on multiple-impact performances becomes more evident when maximum force and permanent deformation trends are considered. For what concerns the decrease of samples initial height, both materials are characterized by very low values of permanent deformation and in particular lower than 17%, but the denser material seems to ensure a bit higher dimensional stability thanks to the lower air content that delays the densification process being equal the impact energy.

These results are strictly correlated to maximum force ones, in fact NL10 is characterized by a higher maximum force than NL20 especially for the higher impact energy. In particular, for the lower impact energy NL10 shows a maximum force between 14% and 33.7% higher than NL20 whereas for the higher impact energy the difference is much more pronounced and ranges from 73.9% to 79.8%. This can be explained considering that in the densification region slight increases in deformation are connected to steep increases of maximum force. As previously observed for NL25, maximum force trend is logarithmic for NL10 and NL20 at both impact energies ($R^2 = 0.9997$ and $R^2 = 0.9974$ at 2 J and $R^2 = 0.9908$ and $R^2 = 0.9982$ at 5 J, respectively) and this confirms the advantage of agglomerated cork over PVC foam, the former being characterized by a progressive decrease of force increment with the number of impacts.

3.2. *Multiple-puncture impact tests*

The preliminary experimental campaign carried out to identify the perforation threshold of each core material revealed a clear superiority of synthetic foams performances with respect to agglomerated corks ones. The execution of multiple-puncture impacts at 1.25 J and 2.5 J confirmed the evident supremacy of HP200 and HP250 but disclosed a similarity between NL25 and HP130. This is supported by the data

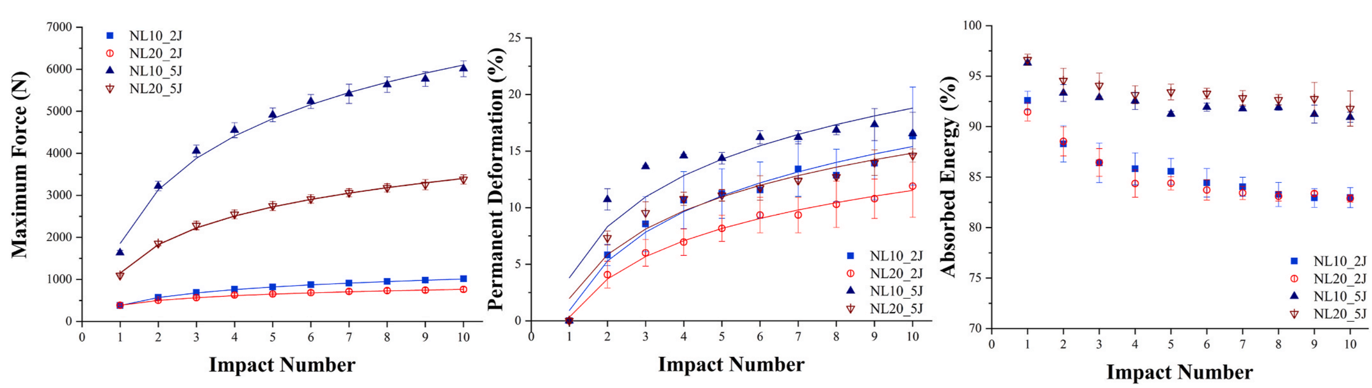

Fig. 6. Maximum force, permanent deformation and percentage absorbed energy trends with increasing number of impacts of NL10 and NL20 performed at 2 J and 5 J.

reported in Table 3, which summarizes the number of impacts that each core material is able to tolerate before undergoing perforation, and in Fig. 7, which shows maximum force and maximum displacement trend with the number of impacts.

HP200 and HP250 are characterized by a much higher stiffness and strength that are responsible for the greater maximum reaction force of the materials and for their lower tendency to deform and bend reaching a lower maximum displacement. Their higher mechanical properties are also confirmed by the fact that they can tolerate more than 10 impacts without undergoing perforation at both 1.25 J and 2.5 J, which is not true for the other core materials.

Moving to NL25 and HP130, it is possible to underline that even if the intrinsic nature of the PVC foam makes it stiffer than cork determining a higher reaction force and a lower deformation, both materials endure the same number of impacts at 2.5 J and NL25 is even able to tolerate a higher number of impacts at 1.25 J. All previous considerations can be confirmed also by the data related to 1.25 J impacts reported in Fig. A2 of appendix A.

Focusing on the behavior of the three agglomerated corks, it is possible to investigate the effect of density through the results plotted in Figs. 8 and 9. Even if the preliminary experimental campaign demonstrated that the perforation of all these natural core materials must be ascribed to the intergranular fracture caused by the failure of the interface between cork granules and the polymeric binder, a certain effect of density can be revealed.

At 1.25 J (25% of perforation energy) the denser corks NL20 and NL25 display almost a constant behavior confirmed by the limited oscillation in maximum force, maximum displacement and absorbed energy that continue throughout all the ten impacts. This is not true for NL10 that undergoes failure at the fifth impact displaying a parabolic tendency in maximum force decrease and maximum displacement increase ($R^2 = 0.9997$ and $R^2 = 0.8995$, respectively). This failure could be explained considering that the lower density implies a higher air content of the planks, due to a lower compaction of cork granules, which reduces the amount of material available to counteract the impact increasing the shear and bending loads to which the polymeric binder is exposed to.

Moving to 2.5 J (50% of perforation energy) the behavior observed for NL10 at 1.25 J can be detected even for NL20 and NL25 that show a parabolic decrease of the maximum force ($R^2 = 1$ and $R^2 = 0.9995$, respectively) and a parabolic increase of the maximum displacement ($R^2 = 1$ and $R^2 = 0.9631$, respectively). The lower the density, the steeper the curvature of the parabola that even degenerates in a straight line in the case of NL10.

As previously demonstrated, a direct comparison of PVC foams and agglomerated corks behavior at 1.25 J and 2.5 J was not possible because of the much higher stiffness and strength of the first ones, but more interesting results can be obtained comparing the response of each core material at 25% and 50% of its own perforation energy. The data necessary for this analysis are summarized in Table 4, which sums up the number of impacts that each core material is able to tolerate before undergoing perforation at 25% and 50% of its perforation threshold, and in Fig. 10, which depicts maximum displacement and absorbed energy trends with the number of impacts at 50% of perforation energy. Comparing agglomerated cork with the PVC foam with the corresponding density, it is possible to notice that similar number of impacts

Table 3
Summary of the number of impacts that every core material is able to bear before undergoing perforation at 1.25 J and 2.5 J

	Impacts before perforation at 1.25 J	Impacts before perforation at 2.5 J
NL10	5	2
NL20	>10	3
NL25	>10	4
HP130	10	4
HP200	>10	>10
HP250	>10	>10

can be tolerated by both materials and actually agglomerated corks can tolerate one or two impacts more than the corresponding foam. Moreover, the maximum displacement and percentage absorbed energy values appear close and perfectly comparable as also observable by the data plotted in Fig. A3 of Appendix A that can confirm and support the ones of Fig. 10.

The results reported until now demonstrate that HP130 is the only foam that can be directly compared with the agglomerated corks in this impact condition and it is characterized by multiple-impact performances close to NL25 ones. For this reason, these are the two core materials selected to describe the marked difference in material damage progression in this loading condition as shown in Fig. 11 for NL25 and Fig. 12 for HP130.

Concerning NL25, it is possible to notice that no permanent indentation can be detected in the cellular material thanks to the remarkable dimensional recovery capabilities that allow almost a complete restoration of granules initial size. The only type of damage, which can be observed before reaching the complete perforation, is a progressive detachment of cork granules in correspondence of the impacted area due to the gradual failure of the polymeric binder.

The situation is completely different for HP130, and more generally for all PVC foams, which displays a pronounced indentation already after the first impact that deepens progressively with increasing impacts. If agglomerated cork is able to store energy through the increase of cell walls corrugation that is recovered progressively after the impact, the only way to dissipate energy for the rigid foam is cell walls fracture that causes cells collapse and consequently material permanent deformation. This can easily explain why already after the first impact sharp traces of the impactor are visible on the impacted area.

Considering this feature of rigid foams, it is interesting to analyze the progression of the permanent indentation as a function of the number of impacts as shown in Fig. 13. At 1.25 J it is possible to notice that HP130 displays a parabolic increase of the permanent indentation ($R^2 = 0.994$) whereas HP200 and HP250 a logarithmic one ($R^2 = 0.9958$ and $R^2 = 0.9982$, respectively). This means that in all cases there is a progressive deceleration of the permanent damage induced by the impactor, but HP130 undergoes a stronger deformation in the first steps that leads earlier to perforation. Similar findings were obtained by the data connected to the impacts at 2.5 J where HP200 and HP250 still display a logarithmic trend ($R^2 = 0.9974$ and $R^2 = 0.9977$, respectively) even if with a greater slope, whereas HP130 moves from a parabolic trend to a linear one meaning that no deceleration took place in the permanent deformation progression. These results are not surprising considering that denser foams are characterized by thicker cell walls that can dissipate a higher amount of energy before undergoing fracture and causing cell collapse.

4. Conclusions

The aim of the present work was to investigate the multiple-impacts behavior of agglomerated cork in different impact conditions in order to validate its feasibility as an effective and almost bio-based core material to replace the more traditional synthetic foams largely employed at industrial scale. The exploitation of materials from natural renewable resources would allow to face the environmental challenges connected with waste disposal and water and air pollution. The issues related to waste disposal can be faced taking advantage of cork biodegradability even if it is partially reduced when used in the agglomerated form due to the presence of the polymeric binder. Moreover, the production of agglomerated cork planks allows to exploit the wastes derived from wine stoppers production that otherwise would be lost thus permitting an optimization of the harvested material. In this view, this research work studied the multiple-impact response in drop weight tower dynamic compression and puncture impact conditions of three agglomerated corks assessing the effect of density and providing a constructive comparison with three traditional PVC foams with the same density of the

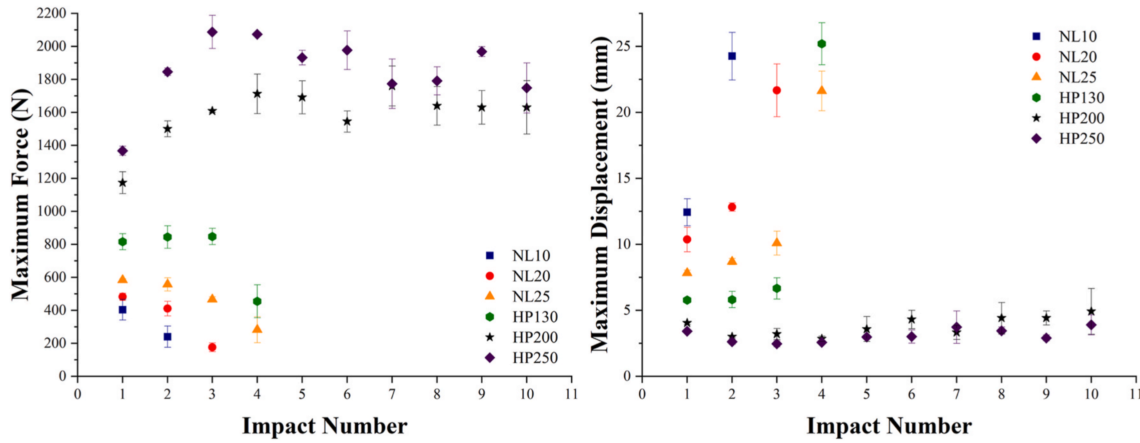

Fig. 7. Maximum force and maximum displacement of all six core materials when subjected to multiple impacts at 2.5 J.

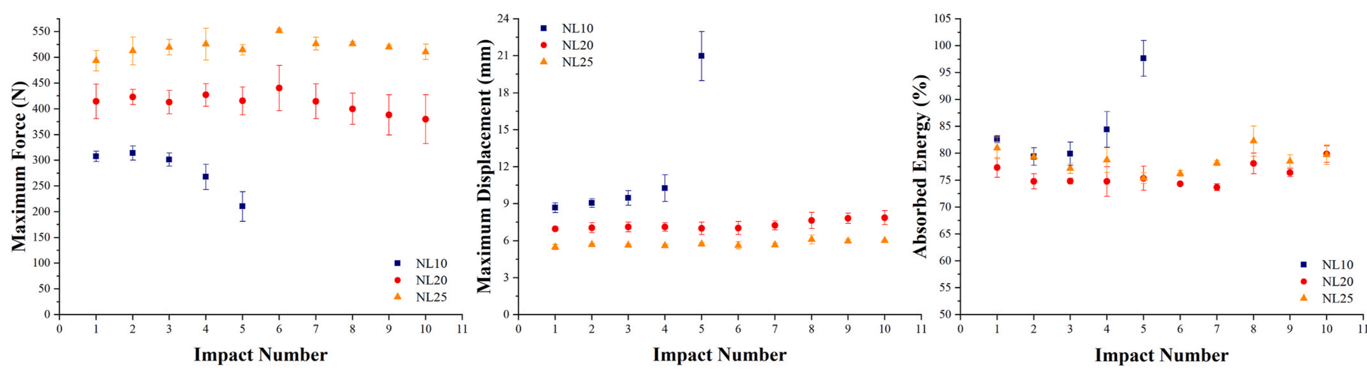

Fig. 8. Maximum force, maximum displacement and percentage absorbed energy trends of all three agglomerated corks at 1.25 J.

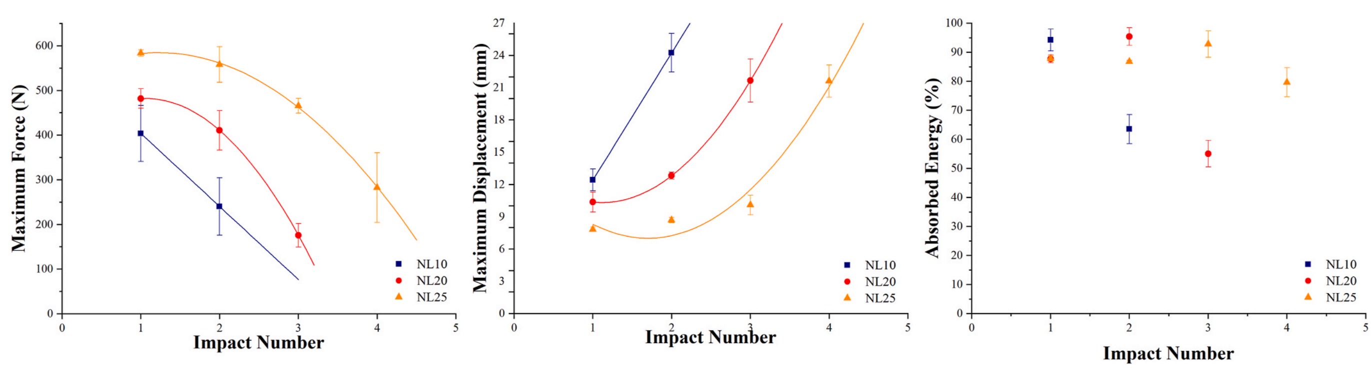

Fig. 9. Maximum force, maximum displacement and percentage absorbed energy trends of all three agglomerated corks at 2.5 J.

cork under study. The results obtained allow to draw many interesting conclusions.

Dynamic compression tests displayed a remarkable difference in PVC foams and agglomerated corks behavior. If cork is characterized by a logarithmic increase of maximum force that ensures a reasonable and controllable scenario even after a considerable number of impacts, this is not true for the PVC foams. They are characterized by a linear or exponential increase of the maximum force that can cause serious damages or injuries already after a small number of impacts.

Another point in favor of agglomerated cork is its stunning dimensional recovery capacity that ensures almost a complete restoration of the initial height of the sample guaranteeing a much higher dimensional stability to the sandwich structure produced with it even after a huge number of impacts. This stability is fundamental to preserve the flexural properties of the structure ensuring a higher degree of safety throughout time.

The contrast observed in the dynamic compressive behavior of these core materials must be ascribed to the strong differences in microstructure and chemical composition. If agglomerated corks cell walls are able to fold completely without undergoing fracture or crack and ensuring a partial restoration of the initial conditions, the rigid walls of the foams fracture once reached their bending limit causing cell collapse and preventing any recovery.

Another important finding of the dynamic compression tests is the effect of density on cork response. Considering comparable the energy absorbing efficiency, the use of a less dense cork is preferable when the designer needs to produce a structure with the main aim to reduce the overall weight, but if the reduction of the maximum force with

Table 4
Summary of the number of impacts that every core material is able to bear before undergoing perforation at 25% and 50% of their perforation threshold.

	Impacts before perforation at 25 % P.T.	Impacts before perforation at 50 % P.T.
NL10	5	2
NL20	>10	3
NL25	>10	4
HP130	4	2
HP200	10	3
HP250	9	3

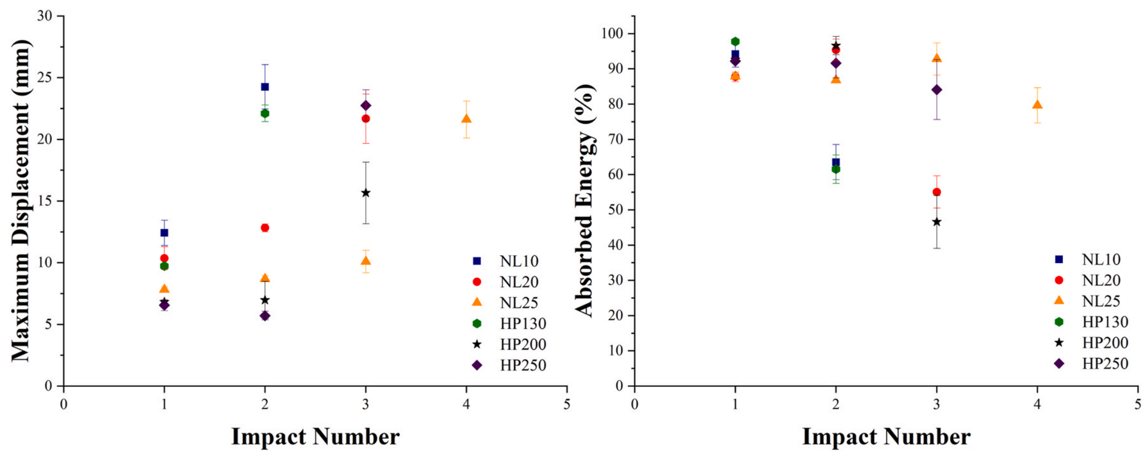

Fig. 10. Direct comparison of maximum displacement and percentage absorbed energy of the six core materials at 50% of their perforation energy.

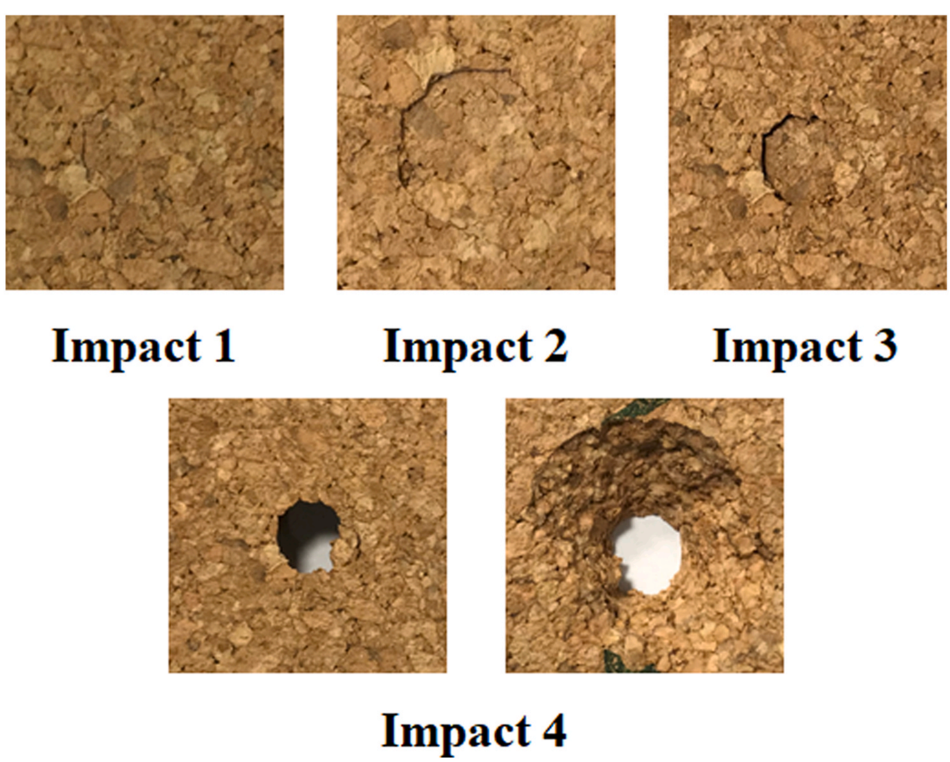

Fig. 11. Damage progression of NL25 sample impacted at 2.5 J.

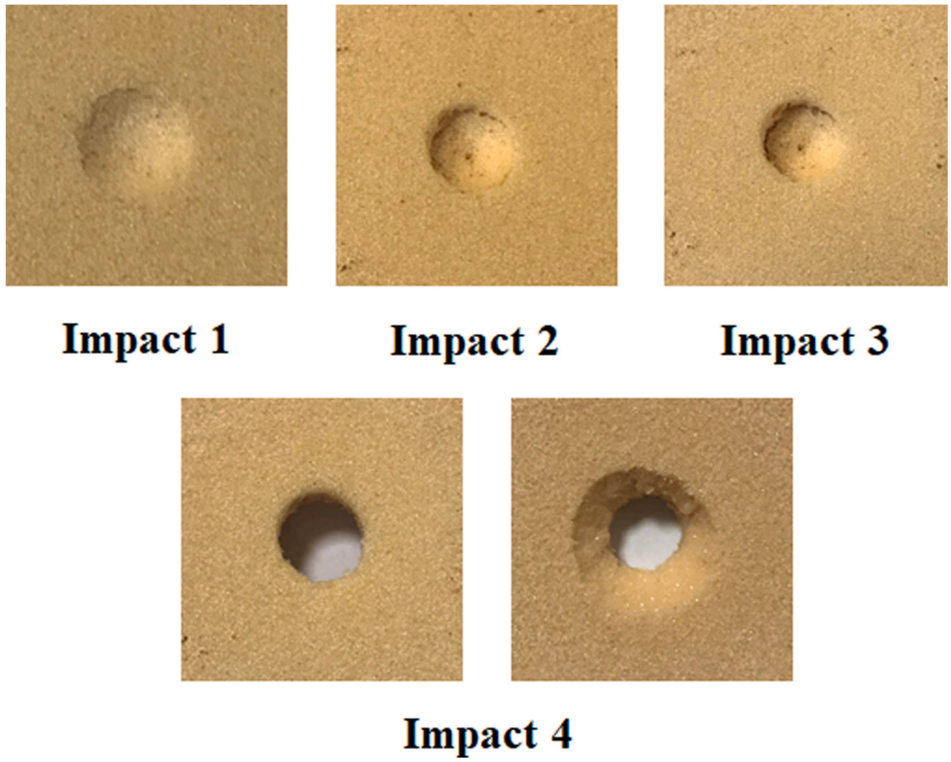

Fig. 12. Damage progression of HP130 sample impacted at 2.5 J.

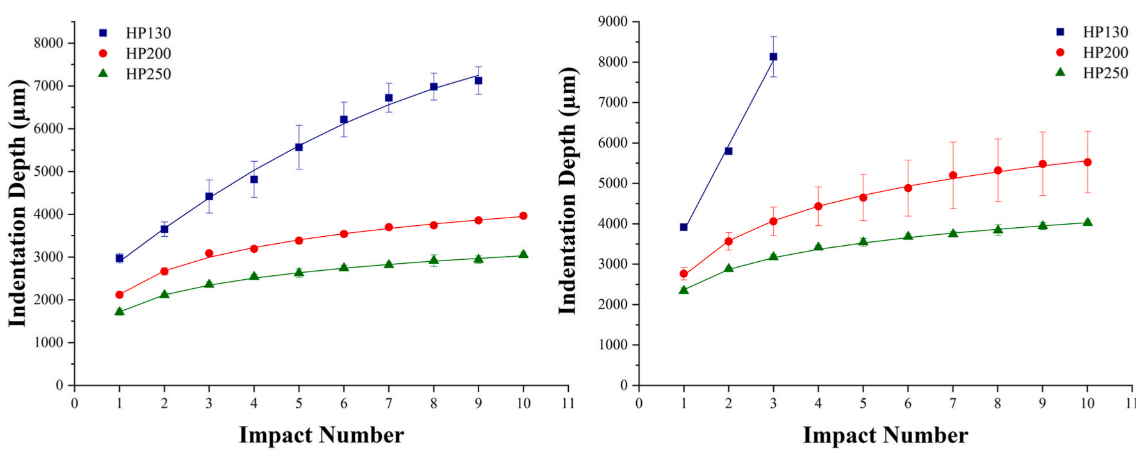

Fig. 13. Permanent indentation depth evolution of the PVC foams subjected to multiple impacts at 1.25 J and 2.5 J.

increasing number of impacts is the main goal, i.e. helmet production, a denser cork would be more appropriate.

Multiple-puncture impact tests confirmed a well-defined discrepancy in damage progression mode between agglomerated corks and PVC foams always ascribed to the marked differences in microstructure. Even if the denser foams demonstrated to be much more performing than the corresponding agglomerated corks, comparable results were obtained for NL25 and HP130. In particular, being equal the impact energy, NL25 is able to resist the same or a higher number of impacts than HP130.

Concerning the effect of density on agglomerated cork multiple-puncture impacts, it is possible to conclude that the higher air content in the less dense cork causes an excessive overload in shear and bending of the polymeric binder leading to an earlier intergranular failure and to an untimely perforation of the component.

In view of all these observations, even if the use of NL25 in place of HP130 could cause a little increase of the structure weight, it turned out to be more than a valid alternative as core material in all those structures that can tolerate a little increase of weight without major consequences, ensuring an uncountable amount of advantages, first and foremost a more ecofriendly composite.

Data availability statement

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

CRediT authorship contribution statement

Claudia Sergi: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - original draft. **Fabrizio Sarasini:** Methodology, Validation, Writing - review & editing. **Enrique Barbero:** Investigation, Conceptualization, Methodology, Supervision, Writing -

review & editing. **Sonia Sanchez-Saez:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Jacopo Tirillò:** Conceptualization, Formal analysis, Supervision, Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

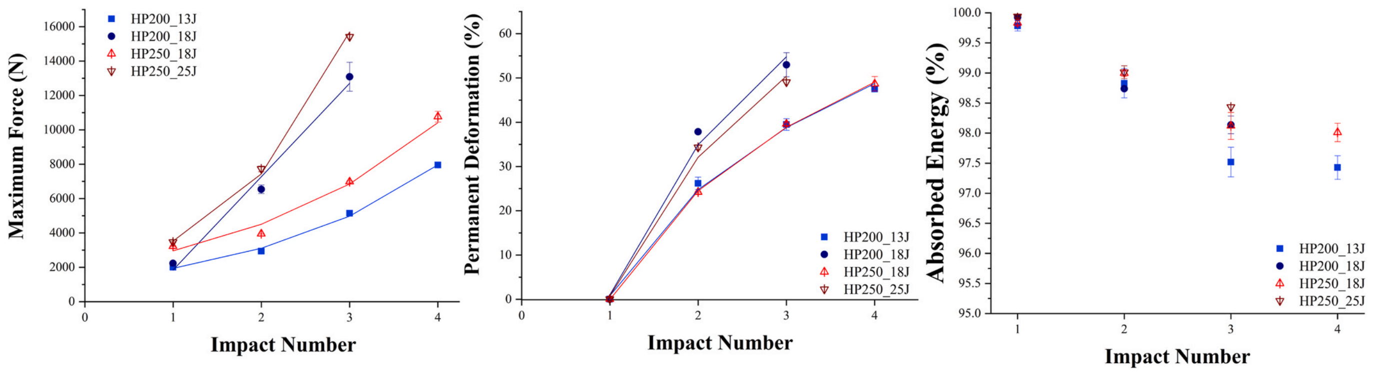

Fig. A1. Maximum force, permanent deformation and percentage absorbed energy trends with increasing number of impacts of HP200 tested at 13 J and 18 J and of HP250 tested at 18 J and 25 J

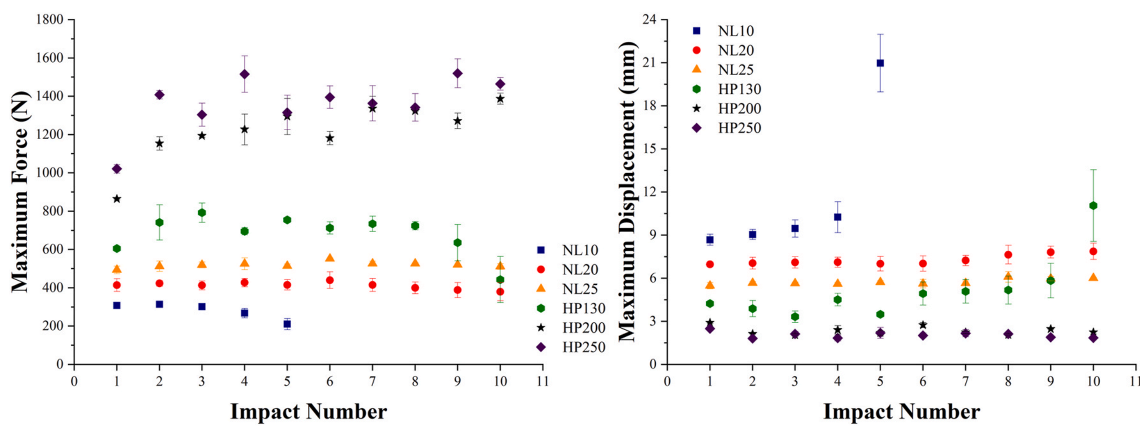

Fig. A2. Maximum force and maximum displacement of all six core materials when subjected to multiple impacts at 1.25 J

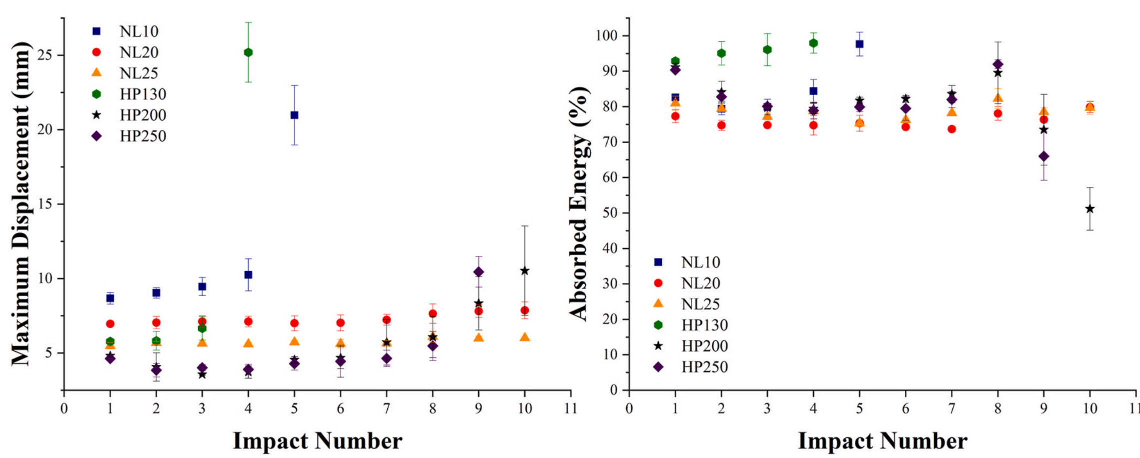

Fig. A3. Direct comparison of maximum displacement and percentage absorbed energy of the six core materials at 25% of their perforation energy

References

[1] J. Vinson R, The Behavior of Sandwich Structures of Isotropic and Composite Materials, Technomic publishing CO.,INC., 1999.

[2] D. Zenkert, The Handbook of Sandwich Construction, Engineering Materials Advisory Services Ltd, 1997.

[3] J.F. Jensen, J.P. Schultz, C. Berggreen, K. Branner, Application of load carrying sandwich elements in large wind turbine, in: Sandw. Struct. 7 Adv. With Sandw, Struct. Mater., 2005, https://doi.org/10.1007/1-4020-3848-8.

[4] C. Borsellino, L. Calabrese, R. Passari, A. Valenza, Study of snowboard sandwich structures, in: Sandw. Struct. 7 Adv. With Sandw, Struct. Mater., 2005, https://doi.org/10.1007/1-4020-3848-8.

[5] G.B. Chai, S. Zhu, A review of low-velocity impact on sandwich structures, Proc. Inst. Mech. Eng. Part L J. Mater. Des. Appl. 225 (2011) 207–230, https://doi.org/10.1177/1464420711409985.

[6] S. Abrate, Localized impact on sandwich structures with laminated facings, Appl. Mech. Rev. 50 (1997).

[7] R. Olsson, Engineering method for prediction of impact response and damage in sandwich panels, J. Sandw. Struct. Mater. 4 (2002), https://doi.org/10.1106/109963602023192.

[8] C.C. Foo, G.B. Chai, L.K. Seah, A model to predict low-velocity impact response and damage in sandwich composites, Compos. Sci. Technol. 68 (2008) 1348–1356, https://doi.org/10.1016/j.compscitech.2007.12.007.

[9] M.A. Hazizan, W.J. Cantwell, The low velocity impact response of foam-based sandwich structures, Compos. B Eng. 33 (2002) 193–204, https://doi.org/10.1016/j.compscitech.2012.07.006.

[10] P.M. Schubel, J.J. Luo, I.M. Daniel, Low velocity impact behavior of composite sandwich panels, Compos. Part A Appl. Sci. Manuf. 36 (2005) 1389–1396, https://doi.org/10.1016/j.compositesa.2004.11.014.

[11] P.M. Schubel, J.J. Luo, I.M. Daniel, Impact and post impact behavior of composite sandwich panels, Compos. Part A Appl. Sci. Manuf. 38 (2007) 1051–1057, https://doi.org/10.1016/j.compositesa.2006.06.022.

[12] A. Arteiro, A.L.M.A. Reis, P.J.R.O. Nóvoa, L.F.M. Silva, M. Zupan, A.T. Marques, Low velocity impact and flexural performance of sandwich structures with cork and polymer foam cores, Cienc. e Tecnol. Dos Mater. 25 (2013) 79–84, https://doi.org/10.1016/j.ctmat.2014.03.003.

[13] L.A. Bernard, Low Velocity Impact Testing of Sandwich Panels with Polymeric Cores, 2011.

[14] M. Avalle, G. Belingardi, R. Montanini, Characterization of polymeric structural foams under compressive impact loading by means of energy-absorption diagram, Int. J. Impact Eng. 25 (2001) 455–472, https://doi.org/10.1016/S0734-743X(00)00060-9.

[15] M. Ptak, P. Kaczynski, F.A.O. Fernandes, R.J. Alves de Sousa, Assessing impact velocity and temperature effects on crashworthiness properties of cork material, Int. J. Impact Eng. 106 (2017) 238–248, https://doi.org/10.1016/j.ijimpeng.2017.04.014.

[16] P. Kaczynski, M. Ptak, J. Wilhelm, F.A.O. Fernandes, R.J.A. De Sousa, High-energy impact testing of agglomerated cork at extremely low and high temperatures, Int. J. Impact Eng. 126 (2019) 109–116, https://doi.org/10.1016/j.ijimpeng.2018.12.001.

[17] F.A.O. Fernandes, R.J.A. De Sousa, Motorcycle helmets — a state of the art review, Accid. Anal. Prev. 56 (2013) 1–21, https://doi.org/10.1016/j.aap.2013.03.011.

[18] S. Knapic, V. Oliveira, J.S. Machado, H. Pereira, Cork as a building material: a review, Eur. J. Wood Wood Prod. 74 (2016) 775–791, https://doi.org/10.1007/s00107-016-1076-4.

[19] P. Kaczynski, M. Ptak, F.A.O. Fernandes, L. Chybowski, J. Wilhelm, R.J. Alves de Sousa, Development and testing of advanced cork composite sandwiches for energy-absorbing structures, Materials 12 (2019), https://doi.org/10.3390/ma12050697.

[20] S. Sanchez-Saez, E. Barbero, S.K. Garcia-Castillo, I. Ivañez, J. Cirne, Experimental response of agglomerated cork under multi-impact loads, Mater. Lett. 160 (2015) 327–330, https://doi.org/10.1016/j.matlet.2015.08.012.

[21] F. De Lu, G. Hua, L. Wang, H. Jiang, D. Gao, A phenomenological constitutive modelling of polyethylene foam under multiple impact conditions, Packag. Technol. Sci. 32 (2019) 367–379, https://doi.org/10.1002/pts.2445.

[22] F.A.O. Fernandes, R.T. Jardin, A.B. Pereira, R.J. Alves de Sousa, Comparing the mechanical performance of synthetic and natural cellular materials, Mater. Des. 82 (2015) 335–341, https://doi.org/10.1016/j.matdes.2015.06.004.

[23] H. Pereira, The rationale behind cork properties: a review of structure and chemistry, BioResources 10 (2015) 1–23, https://doi.org/10.15376/biores.10.3.Pereira.