Green Energy and Technology

Selim Gürgen *Editor*

Cork-Based Materials in Engineering

Design and Applications for Green and Sustainable Systems

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Green Energy and Technology

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Preface

The book *Cork-Based Materials in Engineering Applications* provides a set of case studies and researches from cork-based engineering applications. Engineers, researchers, and scientists benefit from this book to understand the cork-based materials in different engineering applications. The main areas of cork-based materials are thermal insulations, acoustic insulations, vibration damping systems, crashworthiness applications, protective structures, and energy absorbing systems. The content helps understanding the use of cork-based materials in these areas.

Eskişehir, Türkiye — Selim Gürgen

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About the Editor

Selim Gürgen is an Associate Professor in the Department of Aeronautical Engineering at Eskişehir Osmangazi University, and the Director of Eskişehir Vocational School. He received his B.Sc. and M.Sc. degrees in Mechanical Engineering from Gazi University and Middle East Technical University, respectively, and his Ph.D. in Mechanical Engineering from Eskişehir Osmangazi University. He was a visiting researcher at the University of Wollongong for a project on smart materials. He was at the University of Aveiro on natural composites, and worked as a researcher with the School of Transportation at Anadolu University for 4 years. Before his academic life, he worked as a manufacturing engineer in a joint venture of KMWE-Dutch Aero. Dr. Gürgen has contributed to several industrial and research projects in collaboration with major organizations such as Fiat Automobiles, Turkish Aerospace Industries (TAI), and the Turkish Air Force. His projects were funded by the Scientific and Technological Research Council of Turkey (TÜBİTAK) and the European Union (EU). He has many publications in refereed international journals and conferences. He serves as an editorial member for several international journals. His primary area of research is material science.

Chapter 1
Introduction

Selim Gürgen

In the modern engineering, the pursuit of innovative and sustainable materials has taken center stage. In this context, cork has emerged as a remarkable contender in revolutionizing engineering applications. In an era where environmental concerns drive technological advancements, cork-based materials emerge as an exemplar of sustainability. Cork, sourced from the bark of the cork oak tree, boasts inherent eco-friendliness, renewability, and biodegradability. By harnessing the potential of this naturally abundant resource, engineers and researchers are paving the way for a greener future.

Cork is a natural material derived from the bark of the cork oak tree (*Quercus suber L.*), primarily found in Mediterranean regions such as Portugal, Spain, and North Africa. It is renowned for its unique cellular structure, composed of microscopic air-filled pockets surrounded by a matrix of suberin, a waxy substance that renders cork impermeable to liquids and gases. This structure gives cork its exceptional properties, making it lightweight, flexible, buoyant, and highly compressible [1].

In recent years, cork has transitioned from its traditional roles as a bottle stopper and bulletin board material to a versatile and sustainable solution in various engineering applications. The distinct attributes of cork make it a valuable contender for addressing multiple challenges across different engineering fields such as thermal insulation, acoustic insulation, vibration isolation, energy attenuation, shock absorbing, and impact protection. The trapped air pockets in cellular structure of cork provide excellent thermal insulation. It is utilized in construction materials, walls, floors, and roofs to maintain indoor temperatures and enhance energy efficiency [2]. Similar to thermal insulation properties, sound-absorbing properties of cork stem from air content in the structure, resulting in its ability to reduce noise transmission

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[3]. It finds use in spaces where noise control is essential such as theaters, recording studios, and residential buildings. Accordingly, flexibility and compressibility of cork make it effective in absorbing vibrations, reducing the impact of vibrations caused by machinery, equipment, and transportation on nearby structures [4]. On the other hand, the cushioning and shock-absorbing properties of cork make it valuable in absorbing and dissipating energy, preventing damage and reducing risks in various applications, including packaging, transportation, and sports equipment [5]. Resilience and impact resistance in cork contribute to its effectiveness in shock-absorbing applications, such as in footwear, sporting gear, and automotive components. The combination of lightweight nature and its ability to absorb energy makes it useful in designing impact-resistant materials for safety equipment and protective structures [6].

This book takes a holistic approach to address a spectrum of engineering challenges. Whether it is enhancing energy efficiency through superior thermal insulation, creating serene environments via effective acoustic insulation, or improving structural integrity by minimizing vibrations and shocks, cork-based solutions offer a fresh paradigm for eco-friendly and sustainable engineering solutions.

References

1. Pereira H (2007) Cork: biology, production and uses, 1st edn. Elsevier, Amsterdam/London. 336 p
2. Gil L (2015) Cork. In: Gonçalves MC, Margarido F (eds) Materials for construction and civil engineering [Internet]. Springer, Cham, pp 585–627 [cited 2023 Aug 13]. Available from: https://link.springer.com/10.1007/978-3-319-08236-3_13
3. Gil L (2009) Cork composites: a review. Materials 2(3):776–789
4. Sheikhi MR, Gürgen S, Altuntas O, Sofuoğlu MA (2023) Anti-impact and vibration-damping design of cork-based sandwich structures for low-speed aerial vehicles. Arch Civ Mech Eng 23(2):71
5. Sheikhi MR, Gürgen S, Altuntas O (2022) Energy-absorbing and eco-friendly perspectives for cork and WKSF based composites under drop-weight impact machine. Machines 10(11):1050
6. Gürgen S, Fernandes FAO, De Sousa RJA, Kuşhan MC (2021) Development of eco-friendly shock-absorbing cork composites enhanced by a non-Newtonian fluid. Appl Compos Mater 28(1):165–179

Chapter 2
Thermal Insulation with Cork-Based Materials

Ömer Yay, Mahdi Hasanzadeh, Seyid Fehmi Diltemiz, Melih Cemal Kuşhan, and Selim Gürgen

2.1 Introduction

The efficient management of thermal energy within buildings and structures is a fundamental aspect of sustainable architecture and construction. As the global demand for energy continues to rise, finding innovative and eco-friendly solutions to reduce energy consumption and greenhouse gas emissions has become a pressing concern. One promising avenue for addressing these challenges lies in the use of cork-based materials for thermal insulation.

Cork, derived from the bark of the cork oak tree (*Quercus suber L.*), has been utilized for centuries for its versatile properties, but it has gained particular attention in recent years as an environmentally friendly and highly effective insulation material [1]. Its unique cellular structure and inherent thermal properties make it an attractive option for improving the energy efficiency of buildings, thus contributing to the reduction of energy consumption and environmental impact [2, 3].

Cork's unique properties stem from its cellular structure, which sets it apart from other insulation materials. The cork oak's bark is composed of millions of tiny hexagonal cells, each containing a gaseous mixture that provides cork with its exceptional characteristics. The primary component of cork cells is suberin, which makes up the cell walls and provides cork with its impermeability to gases and liquids. In addition, the air inside the cells makes cork lightweight and thereby providing excellent insulation properties. Cellular structure in cork, with its entrapped air,

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results in low thermal conductivity, making it an excellent insulator against heat transfer. Hence, cork has a relatively high specific heat capacity, enabling it to store and release heat slowly, contributing to thermal comfort. Besides its excellent thermal insulating properties, cork provides eco-friendly and sustainable solutions in engineering applications [4, 5]. Cork's appeal as an insulation material extends beyond its thermal properties. Its environmental credentials make it a favorite choice among environmentally conscious engineers and designers. Cork oak trees are renewable resources, and harvesting cork bark does not harm the tree. The sustainability of cork production is a key feature. Cork oak trees can be harvested for their bark every 9–12 years. This renewable cycle ensures a constant supply of cork. Biodegradability is another important behavior with cork. Cork is a natural material that can decompose without causing harm to the environment. Hence, no waste harmful to environment remains after the service life of cork-based materials. On the other hand, cork oak forests play a significant role in carbon sequestration, helping combat climate change by storing carbon dioxide. Moreover, minimal processing of cork lowers the hazardous side effects during the operations. The production of cork insulation typically involves minimal processing so that reducing the environmental footprint compared to other insulation materials [3].

2.2 Thermal Properties of Cork

One of the key reasons cork is a sought-after insulation material is its exceptional thermal insulating properties. At the heart of its thermal performance is its low thermal conductivity. Cork exhibits an impressively low thermal conductivity value, typically in the range of 0.035–0.040 W/m K at room temperature. This low thermal conductivity means that cork is an excellent insulator against heat transfer, making it an ideal choice for reducing heat loss or gain in buildings. Low thermal conductivity of cork can be attributed to its cellular structure, which is filled with air. The trapped air pockets act as insulating barriers, hindering the transfer of heat energy [6]. As a result, cork helps maintain a stable and comfortable indoor temperature by reducing heat flow through walls, floors, and roofs [7].

Beyond its low thermal conductivity, cork also possesses a relatively high heat capacity compared to many other building materials. Heat capacity measures a material's ability to absorb and store heat energy. Heat capacity of cork allows it to absorb heat during the day and release it slowly during the night, contributing to thermal comfort within buildings [8]. Another thermal property is thermal resistance, which quantifies a material's ability to resist heat transfer. Thermal resistance of cork is determined by its thickness and thermal conductivity. The thicker the cork layer, the higher the thermal resistance it provides. Architects and builders often consider thermal resistance when selecting insulation materials to meet specific thermal performance requirements.

Şen et al. [9] investigated the thermal properties of cork and chemical components within cork. Based on this research, cork shows thermal degradation at above

200 °C while ashing at approximately 485 °C. For this reason, thermal insulation with cork-based materials is suggested for low temperature applications. Mounir et al. [10] used cork granules as an additive in clay-based insulation materials. Different types of clays such as red, gray, and yellow clays were mixed with cork granules. The differences in the clays were related to the chemical components in which the mass of silicon dioxide changes from 34.19% to 51.27%. The cork additives were 6.3–8 mm in size after granulation process. Various mixing ratios were investigated by using asymmetrical hot plate and flash methods in this study. According to the results, cork additives reduce the thermal conductivity to a great extent. Cork-included clays have a thermal conductivity of 0.24 W/m K, while it is about 0.41 W/m K in the samples without cork granules. Another important output from this work is that cork-integrated clays are lighter than clays without cork granules. Hence, cork granules are effective to produce lightweight materials for thermal applications. Cherkhi et al. [11] fabricated gypsum-based composite materials including cork granules as shown in Fig. 2.1. These composites were suggested for thermal insulating of buildings in walls or ceilings. It was stated that cork granules enhance the thermal insulation performance in the composites so that thermal conductivity reduces with including cork granules in the gypsum matrix. The experimental results were also verified by various theoretical models such as Hamilton, Maxwell, and Woodside models.

Panesar et al. [12] produced concretes by replacing sand with various size of cork granules. Both thermal conductivity and thermal resistance were measured for the specimens. Based on the measurements, the concrete without cork additives has a thermal conductivity of 1.14 W/m K and a thermal resistance of 0.059 m^2 K/W. On the other hand, thermal conductivity and thermal resistance values of the sample including 0.5–1 mm cork granules at 10 wt% are 1.04 W/m K and 0.066 m^2 K/W, respectively. At the same cork amount, 10 wt%, thermal conductivity reduces to 0.96 W/m K, while thermal resistance reaches 0.071 m^2 K/W by using 3–5 mm cork granules. It is clearly seen that cork inclusion in concrete enhances the thermal insulation performance. Another key point is that there is a direct relationship between material density and thermal conductivity. Trapped air in discrete pockets enhances the insulation performance in the material; however, increasing air gaps in

Fig. 2.1 Macroviews from gypsum-based composite materials including cork granules [11]

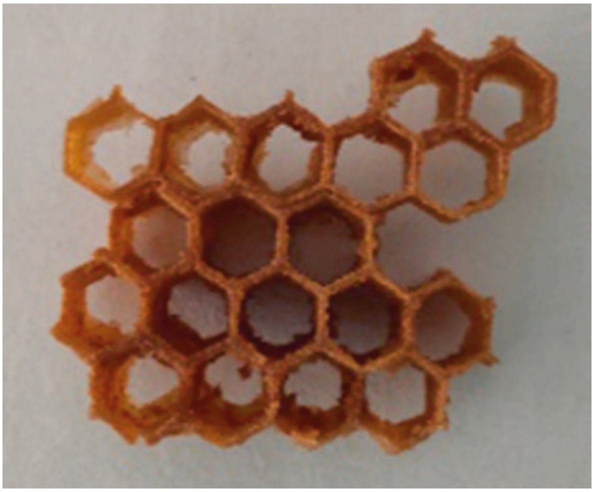

Fig. 2.2 Additively manufactured honeycomb structure made from photo-curable resin and cork powder [13]

the concrete reduces the material density. Romero-Ocana et al. [13] investigated the mechanical and thermal properties of an additively manufactured photo-curable resin-based composites including cork powder. Figure 2.2 shows a honeycomb structure produced with this composite. The authors stated that additive manufacturing with cork powder fillers is plausible based on the mechanical properties of the specimens. Despite a slight reduction in mechanical properties with cork powder inclusions, the composites show still reasonable tensile results. Regarding the cork granule size, finer size granules lead to higher mechanical behavior. Thermal conductivity significantly reduces with the inclusion of cork powder in the composites so that thermal insulation properties are said to be enhanced with cork additives. Thermal conductivity of pristine resin is found as 0.20 W/m K, while it decreases to 0.13 W/m K when adding 5 wt% of cork powder having lower than 45 μm size granules in the resin. The results show the possibility of designing new photocurable composites using waste cork powder as a biomass additive.

De Vasconcelos et al. [14] produced polyethylene-based eco-friendly composites including cork granules. These composites were designed for thermal insulation purposes in eco-friendly and sustainable buildings. Cork granules were incorporated into the polymer matrix by using a twin screw corotating extruder, and then the mixture was injected into the molds. Despite the detrimental effect of cork additives at excessive loading rates, composites with 5 wt% of cork granules show almost same mechanical properties with the pristine polyethylene. On the other hand, thermal conductivity is lowered by the effect of cork additives in the polyethylene matrix so that enhanced thermal insulation behavior is obtained without compromising mechanical properties in the composites. Moreover, cork granules exhibit thermally stable behavior at processing temperatures, and thereby providing robust composites for mass production. With cork integration into polyethylene matrix, eco-friendly and sustainable composites can be efficiently produced for applications in civil construction. Cherky et al. [15] investigated the thermal behavior of composites that include the mixtures of cork granules and plasters. The authors analyzed the thermal conductivity of the specimens. Thermal conductivity reduces by adding more cork granules in the plaster matrix. Moreover, thermal conductivity of the composites decreases as cork granule size increases. Another important output is that mass of the composites reduces by including more cork granules so that cork additives are beneficial to both thermal insulation characteristics and lightweight structures. Malanho et al. [16] investigated the cork-based thermal insulators as an eco-friendly and sustainable alternative to expanded polystyrene-based insulators. In addition to the thermal properties, anti-impact behavior, hygrothermal characteristics, bonding properties, and fire resistance were studied. From the results, cork-based insulators show lower water absorption values in comparison to the polystyrene-based materials. Hence, cork-based materials show good performance for external wall insulation applications. Moreover, cork-based materials have no defect at artificial ageing conditions created in the hygrothermal testing. On the other hand, cork-based insulation boards are more compatible to the bonding systems than the polystyrene-based insulators. They provide good adhesion to the substrate, resulting in a strong bond on the exterior walls. Cork has also good fire resistance and anti-impact properties, making it a good choice for insulations in buildings. Carvalho et al. [17] integrated cork with textiles to produce thermal insulators having a low thickness and high porous structure. For this purpose, wool and polyester fibers in nonwoven form were incorporated with cork granules. The structures were tested for thermal properties to understand the insulation performance. Based on the thermal test results, cork integration into the nonwoven fabrics greatly enhances the thermal insulating performance as well as providing lightweight composites. In addition, air and water permeability can be changed by tailoring the cork contents in the composites. These structures are proposed to home textiles such as blankets. Gomes et al. [18] investigated an aggregate mixed with cork granules for better understanding the thermal insulation effect of cork fillers. The aggregate was composed of clay and some industrial binders, and then cork granules were included in this mixture. Upon completing the mixing, the aggregate was molded to have brick-shaped samples. An 80% reduction in thermal conductivity is obtained when including the cork granules in the aggregate. This is due to the porosity increase in the microstructure provided by the cellular texture of the cork granules. In addition to the thermal advantage, cork integration into the aggregates leads to a lightweight structure by lowering the bulk density up to 87%. This study proves that cork is a good candidate material for thermal insulation applications. Gul et al. [19] studied the thermal and mechanical properties of cork-filled composites for insulation performance in aerospace applications. In this study, ethylene propylene diene monomer (EPDM)-based thermal insulators were integrated with cork granules. Cork reinforcement provides enhanced mechanical properties at low filler ratios. Moreover, cork fillers lead to a good thermal resistance in the composites so that the EPDM-based structures are suggested to thermal insulating applications. Cork is also suggested as an alternative material to asbestos in EPDM-based composites. Harmful effects of asbestos are avoided by this way. However, cork-included EPDM structures show higher ablation rate than those with asbestos, which means that there is a lack of ablation resistance in cork-based composites, and thereby requiring an additional effort to adapt them to the aerospace applications such as nozzles lining in rockets or space shuttles. Sierra-Pérez et al. [20] investigated the environmental impact of an insulation board, which was made from agglomerated cork supplied from forestry cork wastes. The Life Cycle Assessment methodology was used in this study. As a high-performance thermal insulator, the cork itself provides eco-friendly properties, leading to a protective impact to the environment. However, cork production and transportation are challenging operations for reducing the environmental impacts. Because these operations require electricity and fossil fuel, harmful impacts to the environment are necessarily observed indirectly. Some strategies are suggested to overcome these drawbacks in this work. One of them is promoting the acquisition of local raw cork for reduced motion in transportation.

2.3 Cork-Based Insulation Materials

Cork boards and panels are among the most common forms of cork-based insulation materials. They are manufactured by compressing cork granules into rigid sheets or panels. These panels are available in various thicknesses and dimensions to suit different insulation needs. Cork boards and panels offer structural rigidity, making them suitable for wall, roof, and floor applications. They are relatively easy to install, typically using adhesives or mechanical fasteners. Cork boards and panels can be used in both new construction and renovation projects, offering versatility in design and application. In addition to thermal insulation, cork boards and panels provide excellent acoustic insulation properties, reducing sound transmission. Figure 2.3 shows cork panels used in constructions.

Fig. 2.3 Cork panels used in constructions [21]

Cork granules and expanded cork are loose-fill insulation materials made from cork particles. They are particularly useful for insulating cavities and hard-to-reach areas. Cork granules can fill irregular spaces and conform to various shapes, making them ideal for insulating voids and gaps. Both cork granules and expanded cork are lightweight, which simplifies transportation and installation. They are commonly used for insulating wall cavities, attics, and other areas where traditional rigid insulation may be challenging to install. Despite their loose-fill form, cork granules and expanded cork offer excellent thermal and acoustic insulation properties.

Cork-based insulation materials are often combined with other materials to produce composites and hybrids that enhance specific properties. Cork-foam composites are one of these materials combining cork with foam materials to achieve improved insulation performance and moisture resistance as well. Another one is cork–cement composites, blending cork with cement to create durable and fire-resistant insulation materials. Cork is also brought together with various types of textiles. Cork–fabric hybrids are produced by integrating cork with fabric layers to produce flexible insulation materials suitable for unique applications. The choice of cork-based insulation material depends on factors such as the intended application, desired thermal performance, and budget considerations. Architects and builders can select the most suitable type based on project requirements and performance criteria. Figure 2.4 shows some insulation materials based on cork composites.

Cork is mostly used in granule form in insulation materials. After extracting the cork barks from cork oak trees, several processing steps are conducted to obtain the cork granules. The first step is boiling to soften the cork barks and thereby making them easier to work with. In the next step, the boiled cork is dried to remove excessive moisture. Cork is then sorted and graded based on quality and thickness for granulation. Cork granules are compressed and bound together to create rigid cork boards and panels. Adhesives or binders may be used in this process to enhance structural integrity. Cork granules are also used as loose-fill insulation. These granules can be blown or poured into cavities or voids, conforming to the shape of spaces. Cork granules are combined with other materials such as foam, cement, or fabric to create composite insulation materials with enhanced properties. The granules are used as fillers in various types of matrices.

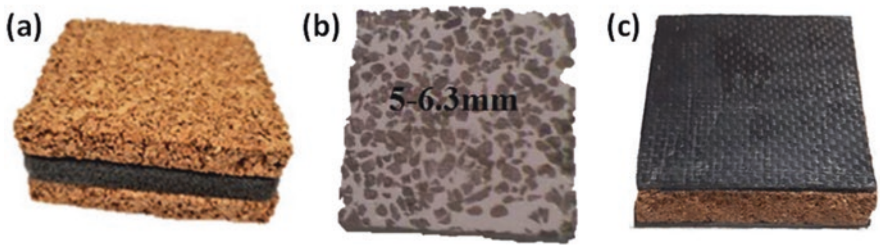

Fig. 2.4 Cork-based insulation composites: (**a**) cork–foam [22], (**b**) cork–cement [23], and (**c**) cork–fabric [24]

Cork-based insulation materials are installed on walls, roofs, and floors in buildings. Installation is conducted with adhesives, or mechanical fasteners in the building applications. In the adhesive bonding method, an additional step, surface preparation is applied to the cork panels. It is essential to ensure that the surface is clean, dry, and free from dust and debris. This preparation step is vital for adhesive bonding and the long-term durability of the insulation. Adhesive compatibility is also critical for a strong and lasting bond. On the other hand, mechanical fasteners or fixings have to be compatible with cork boards, and they ensure that there is no compromise with thermal insulating properties of cork. Sealing is also important in installation. Joints and edges between cork insulation panels or boards have to be properly sealed to prevent air infiltration, which can compromise insulation effectiveness. Sealants and tapes designed for insulation can be used for this purpose. For a long and efficient service life, cork insulation is protected from moisture during and after installation. If the insulation is exposed to moisture, thermal performance may be lowered.

Quality control is a critical aspect of cork-based insulation production to ensure the effectiveness and sustainability of the final product. Different standards and guidelines govern the quality of cork insulation materials such as "ASTM C728: Standard Specification for Perlite Thermal Insulation Board" and "EN 13170: Thermal insulation products for buildings – Factory made products of expanded cork." The production of cork-based insulation materials typically involves minimal processing and has a relatively low environmental impact compared to some other insulation materials. Additionally, the sustainable harvesting of cork oak trees contributes positively to the environment by preserving forests and aiding in carbon sequestration. Cork-based insulation materials can be certified for their sustainability such as Forest Stewardship Council (FSC) certification.

2.4 Benefits and Challenges of Cork in Insulation Applications

Cork-based insulation materials offer a range of advantages and benefits that make them an attractive choice for sustainable construction and renovation. One of the primary advantages of cork-based insulation is its ability to significantly reduce energy consumption in buildings. By effectively preventing heat loss in cold weather and heat gain in warm weather, cork insulation helps maintain a stable indoor temperature. This translates into lower heating and cooling costs for homeowners and businesses alike. Cork insulation materials are also known for their durability and longevity. When properly installed and maintained, cork insulation can last for decades without a significant decrease in performance. This durability not only saves on replacement and maintenance costs but also contributes to long-term energy savings.

Insulation with cork provides consistent temperature control throughout the year, ensuring thermal comfort for occupants. It minimizes temperature fluctuations and drafts, creating a more pleasant indoor environment. Furthermore, cork is a natural material that does not emit harmful volatile organic compounds or other pollutants into the indoor air. This promotes better indoor air quality and a healthier living or working environment. Cork insulation is not only effective at controlling temperature, but it also excels at reducing noise transmission. Its cellular structure and density make it an excellent sound insulator, providing acoustic comfort by minimizing noise from both outside and within the building. On the other hand, cork-based insulation materials are known for their low maintenance requirements and longevity. Unlike some insulation materials that may degrade over time, cork insulation maintains its thermal and acoustic properties for many years, reducing the need for replacement or repairs.

Cork is a renewable resource that is harvested from cork oak trees without harming the trees themselves. This sustainable harvesting practice ensures a continuous supply of cork for insulation and other applications. Moreover, cork oak forests play a crucial role in carbon sequestration. By preserving these forests and using cork-based materials, construction projects can contribute to carbon reduction efforts and mitigate the effects of climate change. Besides, cork insulation materials exhibit good fire resistance properties. They have a relatively high ignition point and slow combustion rate, enhancing building safety. In addition to eco-friendly and sustainable properties, cork-based insulation materials offer design flexibility, allowing architects and builders to incorporate them seamlessly into various architectural styles. Natural appearance and texture of cork can enhance the aesthetic appeal of interior spaces.

Although cork-based insulation materials offer numerous advantages, it is essential to consider the challenges and limitations associated with their use. Cork is a porous material, which means it can absorb moisture if not adequately protected. Moisture infiltration can lead to reduced insulation effectiveness and the risk of mold growth. To protect cork boards from moisture, various techniques are used, including vapor barriers, seals, and corkboard backings. Installing vapor barriers on the warm side of insulation can help prevent moisture from reaching the cork. Similarly, ensuring all joints and edges are properly sealed can minimize the risk of moisture penetration. Some cork insulation products come with a backing that enhances moisture resistance. Another challenge is cost of cork-based materials. Cork-based insulation materials can be more expensive than traditional insulation options, which can affect project budgets. On the other hand, sustainable policies should be planned for mitigating potential drawbacks in cork harvesting. Harvesting cork sustainably and supporting responsible forest management practices can help lower the environmental concerns.

2.5 A Case of Thermal Insulation: Comparison of Insulators

2.5.1 Experimental Details

In the thermal conductivity measurements, a cork panel and an extruded polystyrene (XPS) foam board were investigated to compare the cork agglomerates with a commonly used synthetic insulation material. The cork panel is made from agglomerated cork having 0.5–1 mm granules in a polyurethane resin. The density of cork panel is 170 kg/m^3, whereas the XPS foam board has a density of 35 kg/m^3. The specimens were cut into size of 100 cm × 100 cm while selecting the specimen thickness as 10 mm. Hot plate method was used in the thermal tests, heating the specimens from one side by using an electrically heated plate. The other sides of the specimens were controlled by using a cold plate. The temperatures were 10 and 37 °C for the cold and hot plates, respectively. Heat flow was generated due to the temperature difference in this configuration. Thermal conductivity (λ) was calculated by considering the heat flow ($\dot{Q}$), specimen thickness (d), heating area on the specimen (A), and temperature difference through the specimen (ΔT) as given in Eq. (2.1).

$$\lambda = \frac{\dot{Q} \cdot d}{A \cdot \Delta T} \tag{2.1}$$

2.5.2 Results and Discussion

Table 2.1 shows the thermal conductivity results for the specimens. From these results, the XPS foam board has a lower thermal conductivity than the agglomerated cork panel, which indicates that the XPS foam has better thermal insulation properties in comparison to the cork agglomerates. However, the difference is quite small since the thermal conductivities are 0.034 and 0.037 W/m K for the XPS foam board and the agglomerated cork panel, respectively. It can be stated that the cork panel has good thermal insulation capabilities, quite similar to XPS foam boards, which are extensively used in buildings and constructions. It is also possible to mention that thermal conductivity of cork agglomerates can be reduced to lower levels by changing the materials properties such as cork granule size, resin amount, and panel density. It could also be possible to have better thermal insulation properties than the conventional XPS foam boards upon precisely designing the composition of cork agglomerates.

Table 2.1 Thermal conductivity results for the specimens

Specimen	Thermal conductivity (W/m K)
Cork panel	0.037
XPS foam board	0.034

Cork-based panels have another key feature as thermal insulation materials. This provides eco-friendly and sustainable properties for the users. Comparing to the synthetic materials such as XPS foam boards, cork-based insulation materials are less hazardous to the environment. Cork is processed without any operation harmful to environment. Even the cork oaks are not damaged in the stripping process of cork barks. On the other hand, cork possesses sustainable characteristics with its imperishable nature. Furthermore, cork is a recyclable material so that cork panels can be separated from thermoplastic matrices and thereby obtaining cork granules again and again. These granules can be molded one more time with different types of binders for various purposes such as thermal insulation, vibration isolation, and fashion design. Hence, cork granules can be used in other applications without compromising their performance.

2.6 Conclusions

Thermal insulation properties of cork-based materials are reviewed in this chapter. As an eco-friendly and sustainable material, cork has been adapted to green applications. Cork provides excellent thermal properties for insulation applications as well as lowering the side effects of synthetic engineering materials harmful to environment. Thermal insulation properties of cork are competitive to modern insulation materials that dominate the building and construction sectors. Regarding this issue, a good example is given as a case study in this chapter. A cork panel, which is made from cork granules bonded by polyurethane resin, was compared with a conventional synthetic insulator, XPS foam board, by measuring the thermal conductivities. The thermal conductivity measurements exhibited very promising results for cork-based materials in thermal insulation applications. Cork panel has a thermal conductivity of 0.037 W/m K, which is very close to that of XPS foam board. This indicates that cork panel has a great potential as a thermal insulation material. Moreover, cork panels are more convenient to green applications than the conventional synthetic materials. Cork is produced without any environmentally harmful processes, ensuring that cork oak trees are also undamaged during the bark-stripping process. Additionally, cork is sustainable due to its durable properties. Furthermore, cork is recyclable, allowing for the separation of cork granules from thermoplastic matrices and the repeated production of cork granules. These granules can be molded with different binders for various uses, including thermal insulation, vibration isolation, fashion design, and more, making it possible to employ cork granules in various applications without compromising their performance.

References

1. Sheikhi MR, Gürgen S, Altuntas O (2022) Energy-absorbing and eco-friendly perspectives for cork and WKSF based composites under drop-weight impact machine. Machines 10(11):1050
2. Gil L (2015) Cork. In: Gonçalves MC, Margarido F (eds) Materials for construction and civil engineering [Internet]. Springer, Cham, pp 585–627 [cited 2023 Aug 7]. Available from: https://link.springer.com/10.1007/978-3-319-08236-3_13
3. Pereira H (2007) Cork: biology, production and uses, 1st edn. Elsevier, Amsterdam/London. 336 p
4. Gil L (2009) Cork composites: a review. Materials 2(3):776–789
5. Aroso IM, Araújo AR, Pires RA, Reis RL (2017) Cork: current technological developments and future perspectives for this natural, renewable, and sustainable material. ACS Sustain Chem Eng 5(12):11130–11146
6. Knapic S, Oliveira V, Machado JS, Pereira H (2016) Cork as a building material: a review. Eur J Wood Wood Prod 74(6):775–791
7. Gil L (2015) New cork-based materials and applications. Materials 8(2):625–637
8. Sfarra S, Perilli S, Guerrini M, Bisegna F, Chen T, Ambrosini D (2019) On the use of phase change materials applied on cork-coconut-cork panels: a thermophysical point of view concerning the beneficial effect in terms of insulation properties. J Therm Anal Calorim 138(6):4061–4090
9. Şen A, Van Den Bulcke J, Defoirdt N, Van Acker J, Pereira H (2014) Thermal behaviour of cork and cork components. Thermochim Acta 582:94–100
10. Mounir S, Maaloufa Y, Cherki AB, Khabbazi A (2014) Thermal properties of the composite material clay/granular cork. Constr Build Mater 70:183–190
11. Cherki A, Remy B, Khabbazi A, Jannot Y, Baillis D (2014) Experimental thermal properties characterization of insulating cork–gypsum composite. Constr Build Mater 54:202–209
12. Panesar DK, Shindman B (2012) The mechanical, transport and thermal properties of mortar and concrete containing waste cork. Cem Concr Compos 34(9):982–992
13. Romero-Ocana I, Molina SI (2022) Cork photocurable resin composite for stereolithography (SLA): influence of cork particle size on mechanical and thermal properties. Additive Manuf 51:102586
14. De Vasconcelos GCMS, Carvalho LH, Barbosa R, Alves TS (2019) Evaluation of the morphology, mechanical and thermal properties of cork and green polyethylene ecocomposites. Mater Res Express 6(9):095331
15. Cherki A, Khabbazi A, Remy B, Baillis D (2013) Granular cork content dependence of thermal diffusivity, thermal conductivity and heat capacity of the composite material/granular cork bound with plaster. Energy Procedia 42:83–92
16. Malanho S, Veiga R, Farinha CB (2021) Global performance of sustainable thermal insulating systems with cork for building facades. Buildings 11(3):83
17. Carvalho R, Fernandes M, Fangueiro R (2017) The influence of cork on the thermal insulation properties of home textiles. Proc Eng 200:252–259
18. Gomes MG, Flores-Colen I, Melo H, Soares A (2019) Physical performance of industrial and EPS and cork experimental thermal insulation renders. Constr Build Mater 198:786–795
19. Gul J, Saleemi AR, Mirza S, Feroze N, Mansha M (2010) Thermal and mechanical characteristics of cork filled insulation for aerospace applications. Plast Rubber Compos 39(1):28–32
20. Sierra-Pérez J, Boschmonart-Rives J, Dias AC, Gabarrell X (2016) Environmental implications of the use of agglomerated cork as thermal insulation in buildings. J Clean Prod 126:97–107
21. Barreca F, Tirella V (2017) A self-built shelter in wood and agglomerated cork panels for temporary use in Mediterranean climate areas. Energy Build 142:1–7

22. Sheikhi MR, Gürgen S (2022) Deceleration behavior of multi-layer cork composites intercalated with a non-Newtonian material. Arch Civ Mech Eng 23(1):2
23. Mounir S, Abdelhamid K, Maaloufa Y (2015) Thermal inertia for composite materials white cement-cork, cement mortar-cork, and plaster-cork. Energy Procedia 74:991–999
24. Sheikhi MR, Gürgen S, Altuntas O, Sofuoğlu MA (2023) Anti-impact and vibration-damping design of cork-based sandwich structures for low-speed aerial vehicles. Arch Civ Mech Eng 23(2):71

Chapter 3
Cork Agglomerates in Acoustic Insulation

Ömer Yay, Mahdi Hasanzadeh, Seyid Fehmi Diltemiz, and Selim Gürgen

3.1 Introduction

Sound control and effective acoustic insulation are vital considerations across numerous industries, encompassing construction, automotive, aerospace, and entertainment. As concerns about noise pollution grow and the demand for improved sound management escalates, researchers and engineers continually seek innovative materials to achieve optimal acoustic insulation solutions.

To comprehend the principles of acoustic insulation, it is imperative to first grasp the nature of sound and its propagation through different materials. Sound is a form of mechanical energy that travels in the form of waves, generated by the vibration of a source, such as a loudspeaker or human vocal cords. These sound waves consist of alternating compressions and rarefactions of air particles, propagating outward in all directions from the source. When sound encounters a surface, a portion of the energy is reflected, while the rest is transmitted or absorbed [1]. The ability of a material to reduce the transmission of sound waves is known as sound insulation or soundproofing. Materials with effective sound insulation properties can significantly attenuate noise transmission, thereby creating quieter environments [2].

Acoustic insulation is the process of minimizing sound transmission between spaces or materials. It plays a critical role in controlling noise and achieving acoustic comfort in various settings, ranging from residential and commercial buildings

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to transportation vehicles and industrial facilities. One of the primary objectives of acoustic insulation is to reduce noise transmission from external sources to indoor spaces, providing a peaceful and undisturbed environment for occupants. Another one is minimizing noise transmission between different areas within a building or vehicle, ensuring privacy and acoustic separation. We can also count in enhancing the acoustic performance of products and structures, contributing to a higher quality of sound reproduction and clarity. Effective acoustic insulation is crucial in numerous applications, including home theaters, recording studios, concert halls, classrooms, hospitals, and offices. It also holds immense significance in the automotive and aerospace industries, where it helps mitigate road or engine noise, leading to a more comfortable and enjoyable experience for passengers [2–4].

Cork agglomerates are engineered materials created from the natural bark of the cork oak tree (*Quercus suber L.*). The unique cellular structure of cork, consisting of tiny air-filled chambers enclosed by a flexible cell wall, is a defining characteristic that contributes to its remarkable acoustic insulation properties. The composition of cork agglomerates typically involves granulated cork particles that are carefully processed and bonded together using a binding agent. The granules vary in size and may be mixed with other additives to achieve specific properties and performance characteristics. This flexibility in composition allows cork agglomerates to be tailored for various acoustic insulation applications. When sound waves interact with cork agglomerates, the air trapped within their cellular structure causes sound energy to be absorbed and transformed into heat. Additionally, the flexibility and viscoelasticity of cork cells enable them to convert some of the sound energy into mechanical vibrations, further dissipating the acoustic energy [5]. The combination of these mechanisms results in a material that effectively attenuates sound waves, making cork agglomerates highly effective for acoustic insulation purposes. The intrinsic properties of cork, such as its low density, non-toxicity, and resistance to moisture, also contribute to its suitability for a wide range of applications in sound control and acoustic engineering [6, 7]. Figure 3.1 shows the microstructural views of cork agglomerates.

The manufacturing of cork agglomerates involves several essential steps, each crucial in determining the final material's properties. The first step is harvesting and preparing the cork bark. Cork is sustainably harvested from the cork oak tree's outer bark, ensuring minimal impact on the tree's health. After harvesting, the cork bark is left to dry and age for several months, during which it undergoes natural changes that enhance its properties. The dried cork bark is then crushed or granulated into small pieces of varying sizes. The size of the granules can be tailored to achieve specific acoustic insulation properties. To create cork agglomerates, a binder is added to the cork granules. The binder serves as an adhesive, bonding the granules together to form cohesive blocks or sheets of cork agglomerates. The mixture of cork granules and binder is then placed into molds, where it undergoes compression to form the desired shape and density. The compression process allows for the

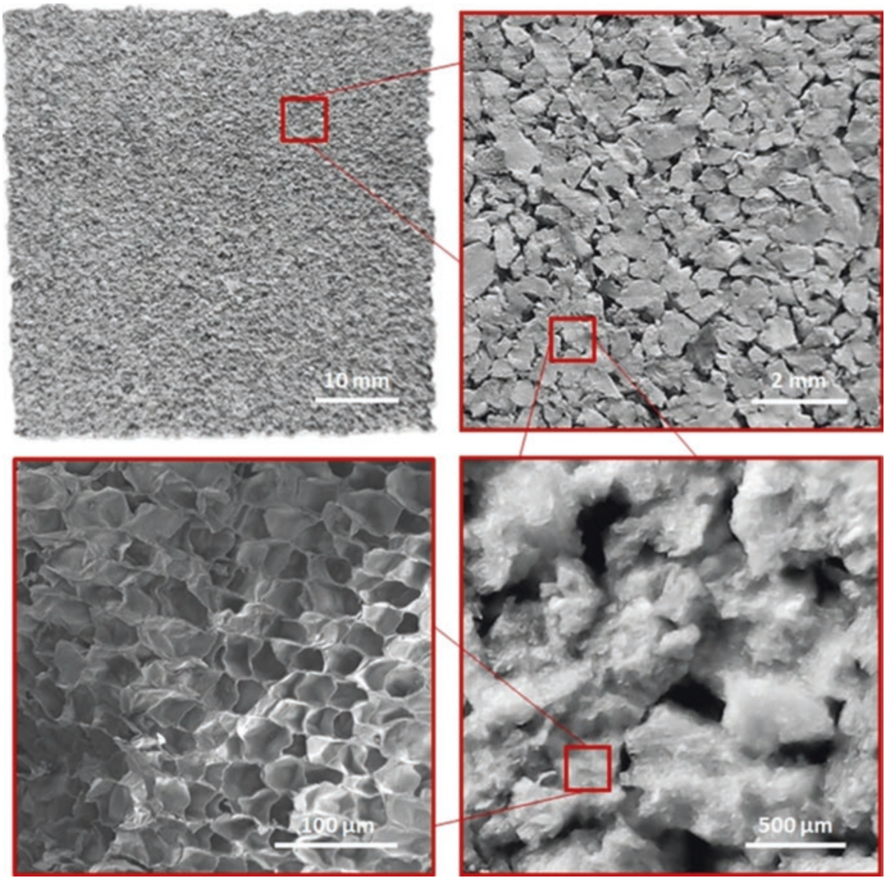


Fig. 3.1 Microstructural views of cork agglomerates [8]

formation of a cohesive and uniform structure. After molding, the cork agglomerates undergo a curing process to allow the binder to set and strengthen the material. This step is essential to ensure the integrity and stability of the final product. Following curing, the cork agglomerates are conditioned in controlled environments to achieve the desired moisture content and acoustic properties. Depending on the application and desired characteristics, the surface of cork agglomerates may undergo additional surface treatment. Surface treatments can include coatings, laminations, or texturing to further enhance acoustic performance or improve aesthetics. The manufacturing process is designed to produce cork agglomerates with consistent properties and reliable acoustic insulation capabilities. The versatility of the material allows for various forms such as cork boards, panels, sheets, or granulated cork, making it adaptable to different installation requirements and applications [9, 10].

3.2 Factors Affecting Acoustic Insulation

The acoustic insulation performance of cork agglomerates is influenced by various factors that engineers and researchers must consider when designing and implementing acoustic solutions. Understanding these factors is essential to optimize the material's effectiveness in different applications. One of the key factors is material density. The density of cork agglomerates plays a significant role in their acoustic performance. Higher density materials generally exhibit better sound insulation capabilities due to increased mass and reduced sound transmission. However, there is an optimal density range for specific applications, as excessively high density may affect the material's flexibility and sound absorption characteristics. Material thickness is another important factor on the acoustic insulation performance. The thickness of cork agglomerates directly impacts their sound absorption and sound insulation properties. Thicker materials can provide higher sound transmission loss and enhanced sound absorption at lower frequencies. For applications requiring effective sound blocking, a thicker layer of cork agglomerates may be necessary to achieve desired results. On the other hand, surface treatments, such as coatings or laminations, can modify the acoustic properties of cork agglomerates. They can enhance sound absorption, reduce sound reflection, and improve durability. Different surface treatments may be applied based on specific application requirements, allowing for a more tailored acoustic solution [6]. Air content in the material is also determinant on the acoustic properties. When using cork agglomerates as part of a partition or sound barrier, the presence of an air gap can significantly impact sound transmission. Air gaps act as additional barriers to sound energy, contributing to higher sound insulation performance. The size and configuration of the air gap relative to the cork agglomerates should be carefully considered to optimize acoustic performance [11, 12]. Temperature and humidity are other factors affecting the mechanical properties of cork agglomerates, potentially influencing their acoustic performance. Extreme temperature fluctuations or high humidity levels might alter the material's dimensions and stiffness, which, in turn, can affect its sound absorption and insulation capabilities [13]. The structural integrity of cork agglomerates is crucial for long-term acoustic performance. Any damages or defects in the material can reduce its effectiveness in sound insulation and absorption. Proper handling, installation, and maintenance are essential to preserve the material's integrity over time. The acoustic properties of cork agglomerates can vary across different frequency ranges. Understanding how the material behaves at various frequencies is essential for matching its performance to specific noise control requirements. The material's ability to absorb sound may be more effective at certain frequencies, while its sound-blocking capabilities may excel at others. Carefully considering these factors and conducting thorough testing and characterization, engineers can optimize cork agglomerates for specific acoustic insulation applications [14]. The interplay of these factors allows for versatile applications, from reducing external noise in buildings to enhancing sound quality in musical or audio environments.

3.3 Position of Cork Agglomerates Among Acoustic Insulating Materials

To evaluate the acoustic insulation capabilities of cork agglomerates effectively, it is essential to compare them with other traditional and innovative materials commonly used for sound control. Each material possesses unique properties that influence its performance in various acoustic conditions. Fiberglass insulation is a widely used material for soundproofing in construction applications. It offers good sound absorption properties due to its fibrous structure, which traps sound energy. However, compared to cork agglomerates, fiberglass can be more challenging to work with due to potential skin irritation during installation and its susceptibility to moisture damage [15, 16]. Cork agglomerates, on the other hand, are naturally resistant to moisture and offer the additional benefits of sustainability and eco-friendliness. Foam insulation materials, such as polyurethane foam, are known for their versatility and ease of installation [17, 18]. While they can offer good sound absorption properties, they may not be as effective as cork agglomerates in blocking sound transmission. Cork's unique cellular structure allows it to excel in both sound absorption and transmission loss, making it a well-rounded option for various acoustic insulation applications. Mass-loaded vinyl (MLV) is a dense, flexible material commonly used for soundproofing [19]. It is highly effective in blocking sound transmission and is often employed in combination with other materials. MLV's strength lies in its ability to add mass to partitions or barriers, but it may not have the same sound absorption capabilities as cork agglomerates. Utilizing cork agglomerates alongside MLV can provide a comprehensive acoustic solution that addresses both absorption and transmission loss. Soundproof drywall incorporates materials such as gypsum and viscoelastic polymers to enhance sound insulation. While soundproof drywall can offer excellent sound-blocking properties, it might lack the sound absorption capabilities of cork agglomerates. Combining soundproof drywall with cork agglomerates can create a balanced approach to achieve optimal sound control in various applications.

In comparison to synthetic or mineral-based materials, cork agglomerates stand out as an eco-friendly and renewable choice for acoustic insulation. Materials such as cork demonstrate low embodied energy, meaning they require minimal energy during production, contributing to a lower carbon footprint. Choosing cork agglomerates aligns with sustainable building practices and environmental consciousness [8, 24]. It is essential to consider specific application requirements when selecting acoustic insulation materials. While cork agglomerates excel in numerous scenarios, the choice of material depends on factors such as the desired acoustic performance, budget constraints, environmental impact, and ease of installation. Cork agglomerates offer a compelling combination of sound absorption and sound insulation capabilities, making them an attractive option for various acoustic challenges. Their eco-friendly nature, low toxicity, and unique cellular structure set them apart

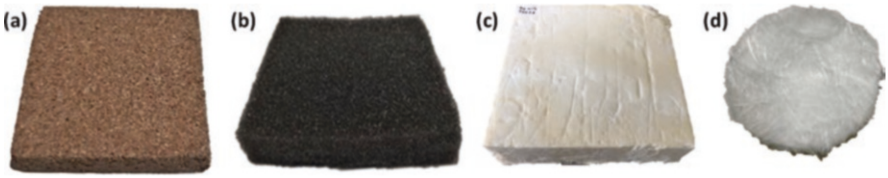


Fig. 3.2 Various insulation materials: (**a**) cork agglomerates [20], (**b**) polyester foam [21], (**c**) polyurethane foam [22], and (**d**) fiberglass [23]

from conventional insulation materials. By carefully assessing project-specific needs and considering material advantages and limitations, designers and engineers can leverage cork agglomerates to create quieter, more comfortable, and environmentally sustainable spaces [25, 26]. Figure 3.2 shows various acoustic insulation materials used in the applications.

3.4 Acoustic Insulation Applications with Cork Agglomerates

The exceptional acoustic insulation properties and eco-friendly nature of cork agglomerates make them highly versatile and well-suited for various applications across different industries. Building and construction sector is one of the biggest application areas for cork agglomerates. In the construction industry, cork agglomerates find extensive use in creating quieter and more comfortable living and working spaces. They are utilized as wall and ceiling panels, flooring underlayment, and acoustic insulation in partition walls. Sound absorption capabilities of cork agglomerates contribute to reducing noise reverberation and improving speech intelligibility, making them valuable additions in classrooms, offices, conference rooms, auditoriums, and entertainment venues [27]. Automotive and transportation are other sectors using cork agglomerates as acoustic insulators. Cork agglomerates play a vital role in these sectors, where noise control is essential for passenger comfort. They are used as insulating materials in vehicle interiors, reducing road and engine noise. By installing cork agglomerates in areas such as door panels, floors, and engine compartments, automotive manufacturers can create quieter and more pleasant driving experiences [28]. In the music and entertainment industry, sound quality and acoustic performance are paramount. Cork agglomerates contribute to creating acoustic environments with enhanced sound clarity and reduced echoes. They are utilized in recording studios, music practice rooms, home theaters, and concert halls to optimize sound absorption and eliminate unwanted reflections, ultimately delivering a superior auditory experience. Industrial facilities often generate significant noise levels from machinery and equipment. Cork agglomerates serve as effective noise barriers and absorbers in these environments, helping to control

Fig. 3.3 Cork-based acoustic panels with different designs [29]

noise pollution and protect workers' hearing health. They are commonly applied to equipment enclosures, machine guards, and plant partitions to mitigate noise transmission. Figure 3.3 shows cork-based acoustic panels with different designs.

Cork agglomerates are utilized in heating, ventilation, and air conditioning (HVAC) systems to reduce the transmission of mechanical noise and vibrations. By incorporating cork agglomerates in HVAC ducts and enclosures, unwanted noise levels can be minimized, ensuring a quieter and more pleasant indoor environment for occupants. In marine and aerospace applications, where space and weight are critical considerations, cork agglomerates offer a lightweight and efficient solution for sound control. They are used in boat and yacht interiors, as well as aircraft cabin components, to achieve effective acoustic insulation without adding unnecessary weight [30]. Cork agglomerates are increasingly finding applications in the renewable energy sector. They are employed as insulating materials in wind turbine components to reduce noise emissions during operation. Additionally, cork agglomerates may be utilized in solar panels to enhance soundproofing and reduce the impact of environmental noise.

3.5 Environmental Impact and Sustainability of Cork Agglomerates

The use of cork agglomerates for acoustic insulation aligns perfectly with the principles of environmental conservation and sustainable practices. As an eco-friendly material, cork agglomerates offer significant advantages that contribute to green building initiatives and sustainable development. Cork agglomerates are derived from the bark of the cork oak tree, which can be harvested without harming the tree. The cork oak tree has a unique ability to regenerate its bark after harvesting, allowing for periodic and sustainable cork extraction. This renewability ensures a continuous supply of raw material without depleting natural resources. Furthermore, cork oak forests serve as valuable carbon sinks, actively sequestering carbon dioxide from the atmosphere. The process of bark regeneration leads to increased carbon absorption, contributing to the mitigation of greenhouse gas emissions. By supporting the use of cork agglomerates, we indirectly support the preservation and expansion of these vital cork oak ecosystems [9, 11, 31].

The production of cork agglomerates requires minimal energy compared to many conventional insulation materials. Low embodied energy refers to the reduced energy consumption during the material's extraction, processing, and manufacturing stages. As a result, cork agglomerates have a lower carbon footprint and are considered a more sustainable option for acoustic insulation. Cork agglomerates can also be recycled and reused for other applications at the end of their life cycle. Recycling cork waste from manufacturing processes or old cork-based products contributes to a circular economy and reduces waste. This recycling capability further enhances the sustainability credentials of cork agglomerates.

Cork agglomerates are biodegradable, meaning they naturally break down over time without causing harm to the environment. When disposed of properly, cork agglomerates do not contribute to pollution or landfill waste, making them an environmentally responsible choice. In addition, cork agglomerates are nontoxic and hypoallergenic, posing no health risks to occupants or installers. Unlike some synthetic insulation materials, cork does not emit harmful chemicals or volatile organic compounds. This ensures a safe and healthy indoor environment, especially in residential and healthcare settings [9]. The environmental benefits of cork agglomerates align with the requirements of various green building certification systems, such as Leadership in Energy and Environmental Design (LEED) by the US Green Building Council. Using cork agglomerates in construction projects can earn credits toward LEED certification, further promoting sustainable building practices. Cork agglomerates exemplify the harmony between acoustic performance and environmental sustainability. As a renewable, carbon-sequestering, low-energy material, cork agglomerates contribute to eco-conscious construction and sustainable development practices. Embracing cork agglomerates for acoustic insulation projects not only enhances sound control and comfort but also supports efforts to protect the planet's natural resources and combat climate change.

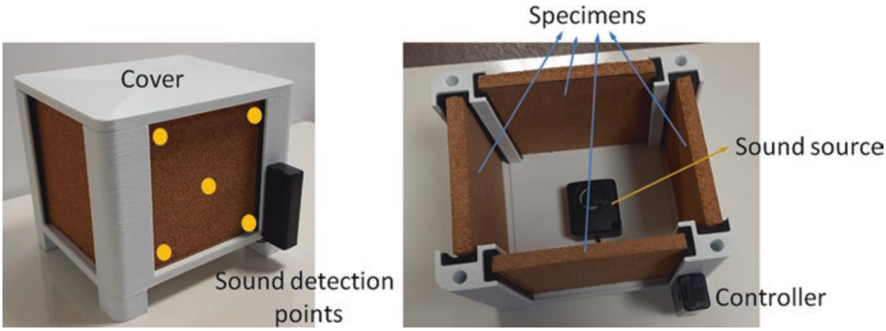


Fig. 3.4 Sound insulation test setup

3.6 A Case of Acoustic Insulation: Comparison of Insulators

3.6.1 Experimental Details

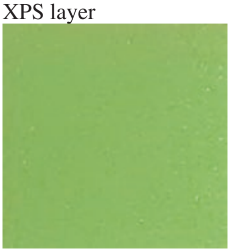
To demonstrate the acoustic insulation performance of cork agglomerates, a set of acoustic insulation materials were investigated by using an in-house test setup as shown in Fig. 3.4. As shown in the figure, a sound source is located at the center of test frame while covering the four sides with the specimens. After closing the cover, the sound is enabled by using the controller unit. The sound source produces a sound with the intensity of 110 dB based on the measurements inside the test system. To investigate the acoustic insulation performances with the specimens, a sound meter was used to measure the insulated sound levels at five sound detection points on each face. The averages of the sound levels were calculated and compared to discuss the acoustic insulation performance of the specimens.

In this study, four materials such as cork agglomerates, AA6061, extruded polystyrene (XPS), and polyurethane (PU) were investigated. The results were compared to each other to understand the position of cork agglomerates among the engineering materials in terms of acoustic insulation performance. The specimens were sized into $120 \times 120\ mm^2$ panels for using them in the test system. The thickness of the specimens was kept at 10 mm. Table 3.1 gives the details of the specimens.

3.6.2 Results and Discussion

Figure 3.5 shows the sound intensity after insulating the sound source with the investigated materials. According to the sound measurements upon cork insulation, the intensity of 110 dB at the sound source reduces to 86.8 dB, which gives the lowest sound intensity among the investigated insulation materials. On the other hand, AA6061 plate shows the lowest performance with the sound intensity of 102.4 dB after insulation. XPS- and PU-based insulators exhibit higher acoustic insulation

Table 3.1 Details of the specimens

Specimen	Properties
Cork agglomerates 	Binder: Polyurethane Granule size: 0.5–1.0 mm Density: 170 kg/m^3
AA6061 plate 	Density: 2670 kg/m^3
XPS layer 	Density: 35 kg/m^3
PU foam 	Density: 40 kg/m^3

performances than AA6061 plate and the sound intensities are measured as 95.1 and 89.9 dB, respectively.

Aluminum alloys do not possess high damping characteristics, which means they do not dissipate sound energy efficiently. Although aluminum alloys may offer some level of sound insulation, they are not the primary choice for acoustic applications. Instead, they are preferred for their mechanical properties and are used in various industries such as aerospace, automotive, construction, and manufacturing. Hence, the lowest performance of AA6061 among the other materials is an expected

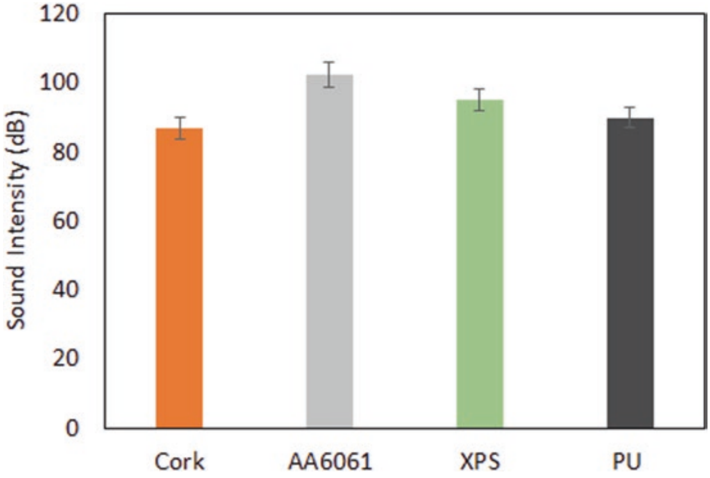


Fig. 3.5 Sound intensity after insulating the sound source

outcome in this work. For acoustic insulation purposes, specialized materials such as cellular structures, acoustic foams, and other dense and porous materials are commonly employed to achieve better soundproofing results. These materials are designed to absorb, block, or dampen sound waves effectively. From this aspect, XPS, PU, and cork agglomerates come to the forefront due to their porous microstructures.

XPS is a type of rigid foam insulation commonly used in construction and building applications. When it comes to acoustic insulation, XPS has some favorable properties that can contribute to reducing sound transmission. XPS has a cellular structure that includes closed cells. These closed cells provide sound absorption properties, helping to reduce the echo and reverberation of sound waves within a space. XPS provides some damping properties that can help reduce the vibration of sound waves passing through it. Therefore, this can contribute to limiting sound transmission. Despite this advantage with XPS, its primary purpose is thermal insulation. On the other hand, PU is a versatile and widely used material known for its excellent insulating properties. Regarding the acoustic insulation, PU-based materials can be effective in certain applications due to its unique characteristics. Due to its porous microstructure, the trapped air in the PU helps dissipate sound energy, making it effective at absorbing and reducing sound reflections and reverberations within a space. It is commonly used in sound-absorbing panels or as an acoustic treatment in studios, theaters, and other spaces where echo and noise control are important. The advantage of cellular structure is also benefitted from cork agglomerates in sound insulation. Air-filled cells within the cork granules allow the material to effectively absorb sound waves and reduce sound reflections and reverberations. In addition, cork-based materials provide sustainable and eco-friendly solutions in engineering applications, which eliminate the side effects of synthetic materials harmful to environment.

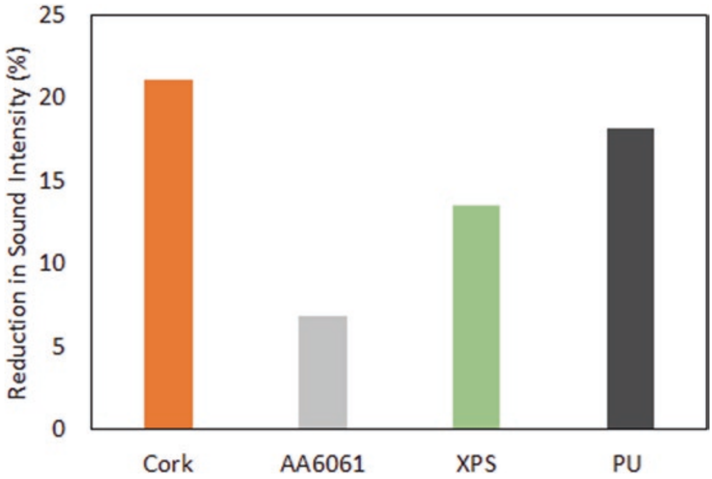


Fig. 3.6 Reduction in sound intensity after insulating the sound source

Figure 3.6 shows the reduction in sound intensity after insulating the sound source. It is clearly seen that AA6061 provides a reduction about 7%, which is quite a low magnitude in sound blocking. On the other hand, the reduction in sound intensity reaches up to 13.5% with XPS insulation. Using PU foam, the reduction in sound intensity jumps higher to the level of 18%. Cork agglomerates enhance the insulation performance and reaching the reduction of 21% in sound intensity. It is also important to note that material density is another key factor in acoustic insulation applications. The density of a material plays a significant role in determining its effectiveness in reducing the transmission of sound waves, and it directly influences the material's sound insulation properties. In this case study, material densities were used as-received and not optimized for better insulation.

3.7 Conclusions

The exploration of acoustic insulation properties by cork agglomerates has unveiled a material that exemplifies the harmonious blend of superior sound control and environmental sustainability. As a renewable resource derived from the bark of the cork oak tree, cork agglomerates offer unique cellular structures that excel in both sound absorption and transmission loss, making them highly effective in creating quieter and more comfortable environments.

Throughout this chapter, we investigated the composition and manufacturing process of cork agglomerates, understanding the factors influencing their acoustic insulation performance. In addition, various applications of cork agglomerates in industries ranging from construction and automotive to music and entertainment were explored to showcase their versatility in addressing diverse sound control challenges. The environmental benefits of cork agglomerates were highlighted, emphasizing their status as a renewable resource, carbon sink, and low-energy material. The eco-friendly nature of cork agglomerates aligns seamlessly with green building practices and sustainable development, contributing to efforts to combat climate change and promote responsible resource management. As we look to the future, the research and development of cork agglomerates are expected to progress, exploring advanced manufacturing techniques, hybrid materials, and smart insulation applications. This ongoing innovation will likely lead to enhanced acoustic performance, further solidifying cork agglomerates' position as a go-to solution for effective sound control.

A case study was carried out to demonstrate the position of cork agglomerates in acoustic insulation applications. In this investigation, cork agglomerates were compared to other engineering materials such as AA6061, XPS, and PU in terms of acoustic insulation performance. The investigation focused on the sound transmission through the materials. According to the results, AA6061 showed the lowest acoustic insulation performance. XPS and PU layers provided enhanced performance in sound insulation due to their porous structures. However, cork agglomerates left behind these materials and provided the highest sound insulation performance in this study. In addition to their promising sound blocking performance, cork agglomerates have demonstrated their merit as a reliable and eco-conscious material in various industries. As engineers, designers, and researchers continue to unlock its full potential, we can anticipate a quieter and more sustainable future, where cork agglomerates play a key role in fostering environments that promote well-being, productivity, and acoustic comfort.

References

1. Zhang Z (2016) Mechanics of human voice production and control. J Acoust Soc Am 140(4):2614–2635
2. Zarastvand MR, Ghassabi M, Talebitooti R (2021) Acoustic insulation characteristics of shell structures: a review. Arch Comput Methods Eng 28(2):505–523
3. António JMP, Tadeu A, Godinho L (2003) Analytical evaluation of the acoustic insulation provided by double infinite walls. J Sound Vib 263(1):113–129
4. Pérez G, Coma J, Barreneche C, De Gracia A, Urrestarazu M, Burés S et al (2016) Acoustic insulation capacity of Vertical Greenery Systems for buildings. Appl Acoust 110:218–226
5. Gil L (2015) New cork-based materials and applications. Materials 8(2):625–637
6. Abenojar J, Barbosa AQ, Ballesteros Y, Del Real JC, Da Silva LFM, Martínez MA (2014) Effect of surface treatments on natural cork: surface energy, adhesion, and acoustic insulation. Wood Sci Technol 48(1):207–224
7. Pedroso M, De Brito J, Silvestre JD (2017) Characterization of eco-efficient acoustic insulation materials (traditional and innovative). Constr Build Mater 140:221–228
8. Gürgen S, Fernandes FAO, De Sousa RJA, Kuşhan MC (2021) Development of eco-friendly shock-absorbing cork composites enhanced by a non-Newtonian fluid. Appl Compos Mater 28(1):165–179
9. Pereira H (2007) Cork: biology, production and uses, 1st edn. Elsevier, Amsterdam/London. 336 p

10. Knapic S, Oliveira V, Machado JS, Pereira H (2016) Cork as a building material: a review. Eur J Wood Wood Prod 74(6):775–791
11. Gil L (2015) Cork. In: Gonçalves MC, Margarido F (eds) Materials for construction and civil engineering [Internet]. Springer, Cham, pp 585–627 [cited 2023 Aug 7]. Available from: https://link.springer.com/10.1007/978-3-319-08236-3_13
12. Lakreb N, Şen U, Toussaint E, Amziane S, Djakab E, Pereira H (2023) Physical properties and thermal conductivity of cork-based sandwich panels for building insulation. Constr Build Mater 368:130420
13. D'Alessandro F, Baldinelli G, Bianchi F, Sambuco S, Rufini A (2018) Experimental assessment of the water content influence on thermo-acoustic performance of building insulation materials. Constr Build Mater 158:264–274
14. Santos PT, Pinto S, Marques PAAP, Pereira AB, Alves De Sousa RJ (2017) Agglomerated cork: a way to tailor its mechanical properties. Compos Struct 178:277–287
15. Cozzarini L, Marsich L, Ferluga A (2023) Innovative thermal and acoustic insulation foams from recycled fiberglass waste. Adv Mater Technol 8(11):2201953
16. Van Loo JM, Robbins CA, Swenson L, Kelman BJ (2004) Growth of mold on fiberglass insulation building materials—a review of the literature. J Occup Environ Hyg 1(6):349–354
17. Diamant RME (1986) Thermal and acoustic insulation. Butterworths, London/Boston. 368 p
18. Verdejo R, Stämpfli R, Alvarez-Lainez M, Mourad S, Rodriguez-Perez MA, Brühwiler PA et al (2009) Enhanced acoustic damping in flexible polyurethane foams filled with carbon nanotubes. Compos Sci Technol 69(10):1564–1569
19. Wareing RR, Davy JL, Pearse JR (2015) Predicting the sound insulation of plywood panels when treated with decoupled mass loaded barriers. Appl Acoust 91:64–72
20. Sheikhi MR, Gürgen S, Altuntas O, Sofuoğlu MA (2023) Anti-impact and vibration-damping design of cork-based sandwich structures for low-speed aerial vehicles. Arch Civ Mech Eng 23(2):71
21. Sheikhi MR, Gürgen S (2022) Deceleration behavior of multi-layer cork composites intercalated with a non-Newtonian material. Arch Civ Mech Eng 23(1):2
22. Khaleel M, Soykan U, Çetin S (2021) Influences of turkey feather fiber loading on significant characteristics of rigid polyurethane foam: thermal degradation, heat insulation, acoustic performance, air permeability and cellular structure. Constr Build Mater 308:125014
23. Begum H, Horoshenkov KV (2021) Acoustical properties of fiberglass blankets impregnated with silica aerogel. Appl Sci 11(10):4593
24. Sheikhi MR, Gürgen S, Altuntas O (2022) Energy-absorbing and eco-friendly perspectives for cork and WKSF based composites under drop-weight impact machine. Machines 10(11):1050
25. Cortês A, Almeida J, Santos MI, Tadeu A, De Brito J, Silva CM (2021) Environmental performance of a cork-based modular living wall from a life-cycle perspective. Build Environ 191:107614
26. Gürgen S, Sofuoğlu MA (2021) Smart polymer integrated cork composites for enhanced vibration damping properties. Compos Struct 258:113200
27. Hernández-Olivares F, Bollati MR, Del Rio M, Parga-Landa B (1999) Development of cork–gypsum composites for building applications. Constr Build Mater 13(4):179–186
28. Gil L (2009) Cork composites: a review. Materials 2(3):776–789
29. Barrigón Morillas JM, Montes González D, Vílchez-Gómez R, Gómez Escobar V, Maderuelo-Sanz R, Rey Gozalo G et al (2021) Virgin natural cork characterization as a sustainable material for use in acoustic solutions. Sustainability 13(9):4976
30. Silva JM, Nunes CZ, Franco N, Gamboa PV (2011) Damage tolerant cork based composites for aerospace applications. Aeronaut J 115(1171):567–575
31. Demertzi M, Silva RP, Neto B, Dias AC, Arroja L (2016) Cork stoppers supply chain: potential scenarios for environmental impact reduction. J Clean Prod 112:1985–1994

Chapter 4
Vibration Damping Applications with Cork Composites

Mohammad Rauf Sheikhi, Mehmet Alper Sofuoğlu, and Jian Li

4.1 Introduction

4.1.1 Cork

Cork is a natural material derived from the bark of the cork oak tree, which is mainly found in the Mediterranean region. Since ancient times, cork has been used for variety of tasks, including the manufacture of shoes, boats, and wine stoppers. Suberin, a hydrophobic biopolymer with lignin, and other components are the major components of natural cork. Cork exhibits a cellular structure with a honeycomb-like morphology (Fig. 4.1) that endows it with several distinctive properties, such as low density, elasticity, compressibility, thermal and acoustic insulation, fire retardancy, biodegradability, and recyclability [1–3]. Table 4.1 shows some of the properties and applications of cork.

The cork oak trees are subjected to a periodic harvesting of the bark every 9 years, which does not harm the trees or affect their growth. The harvesting process is performed manually by experienced workers who employ special axes to detach the bark from the trunk. The initial harvesting occurs when the tree reaches

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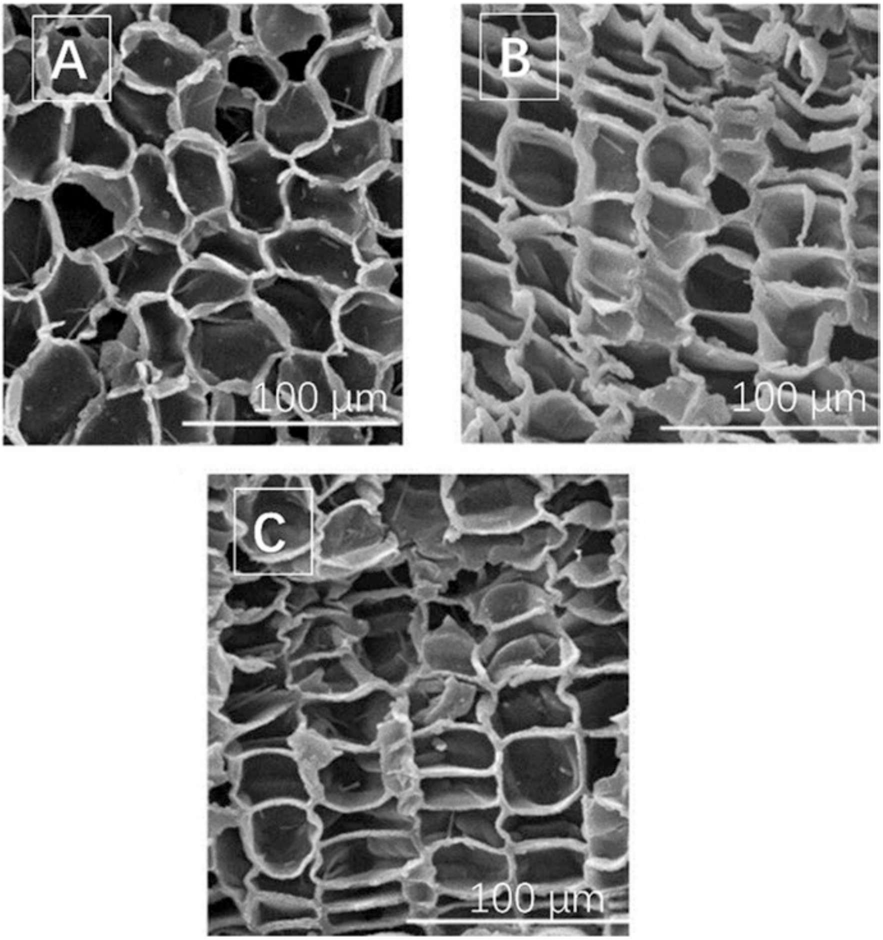

Fig. 4.1 SEM observations of cork from *Quercus cerris* var. *cerris* bark: (**a**) tangential section, (**b**) transverse section, and (**c**) radial section [1]

approximately 25 years of age and yields low-quality cork that is employed for non-stopper applications. The subsequent harvestings produce higher-quality cork that is utilized for manufacturing wine stoppers and other products. The cork oak trees have a lifespan of up to 200 years and can produce cork for about 150 years [6, 7].

The periodic harvesting of cork from the cork oak trees every 9 years stimulates the trees to absorb more carbon dioxide from the atmosphere and store it in their biomass [8]. This diminishes the greenhouse gas emissions that induce global warming and climate change. According to some estimates, the cork oak forests in Portugal alone help offset 10 million tons of carbon every year. Cork is a sustainable material that supports the social and economic development of the regions where it is produced. The cork industry generates employment and income to thousands of

Table 4.1 Properties and potential applications of cork [2–5]

Property	Value	Application
Density	0.15 g/cm^3	Buoyancy, lightness
Thermal conductivity	0.04 W/m-K	Thermal insulation, temperature stability
Sound transmission coefficient	0.1–0.2	Acoustic insulation, noise reduction
Compressive stress at 10% strain	0.4–0.8 MPa	Elasticity, resilience, shock absorption
Fire resistance	Up to 300 °C without igniting or melting	Fire retardant, nontoxic
Biodegradability	Can be decomposed by microorganisms or composted	Environmental protection, waste reduction
Recyclability	Can be reused or transformed into new products or energy	Resource conservation, innovation

people who work in the harvesting, processing, manufacturing, distribution, and marketing of cork products. The cork industry also fosters innovation and research to improve the quality and performance of cork products. The cork industry also respects the cultural heritage and traditions of the local communities who have been using cork for centuries [9–11].

4.1.2 Cork Composites

Cork composites are hybrid materials that incorporate natural cork with other substance such as polymers, resins, rubber to produce novel products with improved properties and functionalities [12]. The adding substances to the natural cork enhance some of the attributes of cork by imparting higher strength, stiffness, hardness, wear resistance, conductivity, or functionality. The nature and proportion of the incorporated constituent, as well as the fabrication parameters, can influence the structure and morphology of the composite, which consequently can affect its mechanical, thermal, acoustic, and electrical properties [13, 14]. Table 4.2 gives some of the differences between cork composites and the origin cork that is extracted from the cork oak tree. The production process of cork composites varies depending on the type and properties of the composite. However, manufacturing steps for cork composites are given in Table 4.3 and Fig. 4.2. Figure 4.3 shows coarse and fine-grained agglomerated cork.

Cork composites exhibit enhanced durability and superior resistance to various environmental factors, including abrasion, moisture, and fire. Cork composites feature an augmented friction coefficient and reduced thermal conductivity compared to their original cork counterpart. They additionally manifest superior fire-retardant characteristics, characterized by the absence of toxic gas emissions during combustion. Furthermore, the versatility and malleability of cork composites render them

Table 4.2 Differences between cork composites and the original cork [12, 14, 15]

Aspect	Original cork	Cork composite
Composition	Suberin, lignin, polysaccharides, and other compounds	Cork particles or granules bonded with other materials such as thermoplastics, thermosets, elastomers, or metals
Structure	Cellular structure with closed cells filled with air and honeycomb-like cell walls	Heterogeneous structure with different phases depending on the type and amount of the added material
Properties	Low density, high resilience, thermal and acoustic insulation, fire resistance, biodegradability, and recyclability	Modified or improved properties by adding other materials that can provide higher strength, stiffness, hardness, wear resistance, conductivity, or functionality

Table 4.3 Regular steps in cork composite manufacturing [12, 16]

Step	Description
1	Cork granules are mixed with the other materials, such as resins or polymers, in a suitable ratio.
2	The mixture is heated and melted to form a homogeneous blend.
3	The blend is molded into the desired shape and size by applying pressure and temperature.
4	The molded composite is cooled and cured to solidify and stabilize its structure.
5	The composite is trimmed and finished to meet the quality standards and specifications.

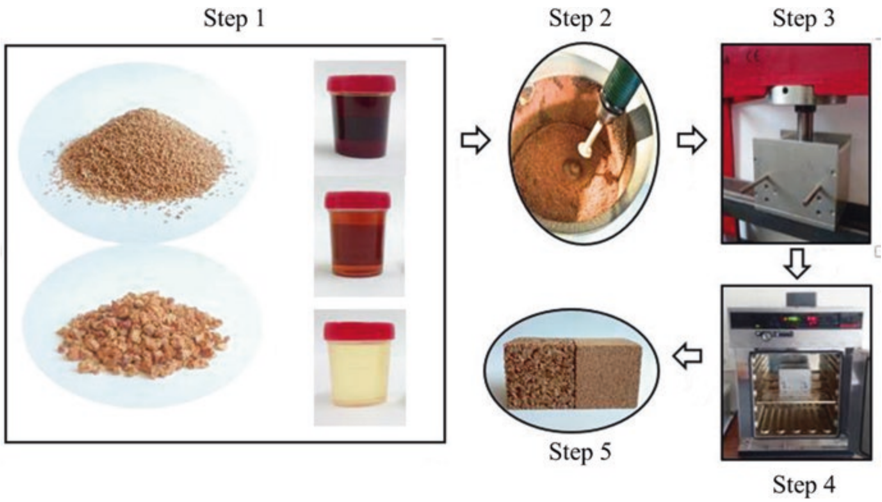

Fig. 4.2 General process of cork composite manufacturing [16]

amenable to diverse shaping processes, such as pultrusion and compression molding. Their compatibility with various additives, such as rubber or thermoplastics, facilitates the creation of innovative products endowed with improved performance attributes. It is noteworthy that cork composites necessitate a diminished quantity of cork, thereby mitigating the demand for cork harvesting and promoting the

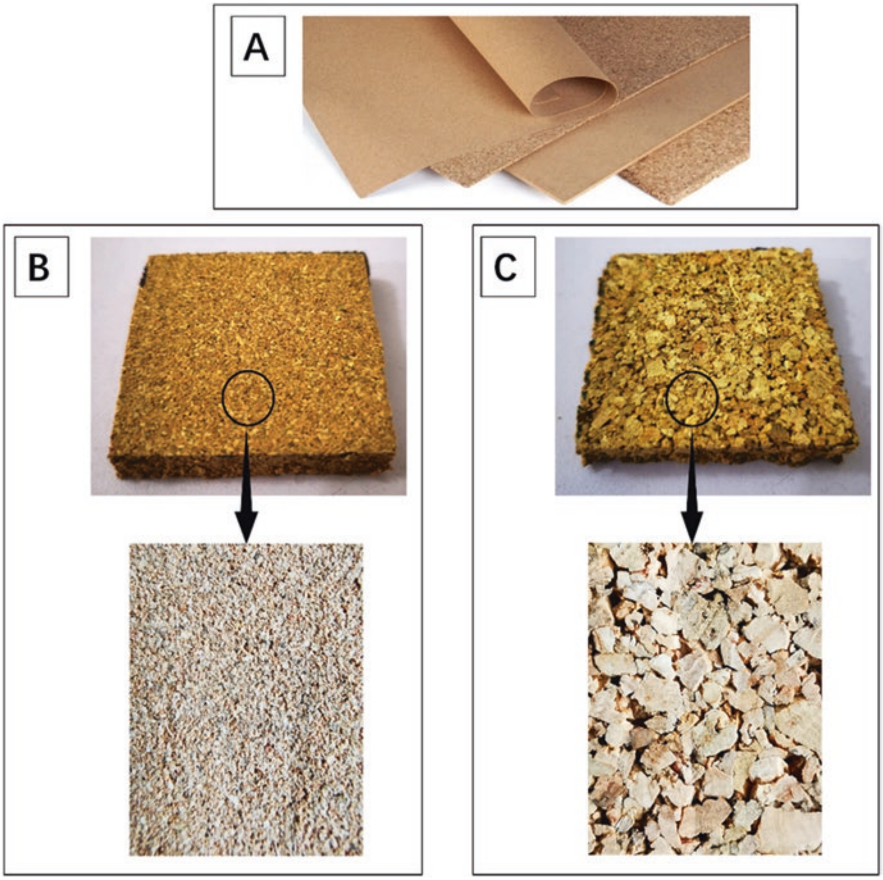

Fig. 4.3 (**a**) Coarse and fine-grained agglomerated cork sheets, (**b**) fine-grained agglomerated cork, and (**c**) coarse-grained agglomerated cork

conservation of cork oak forests. Additionally, their recyclable and biodegradable nature contributes to a reduced environmental footprint in terms of disposal. Some of the mechanical properties of cork composites are given in Table 4.4. Additionally, the potential of cork composites for anti-impact applications has been demonstrated by several studies [19–28]. Cork composites exhibit high energy-absorption and anti-impact performance due to the unique structure of cork, which consists of closed cells filled with air. These cells act as micro-dampers that can undergo elastic deformation and recovery under impact, absorbing and dissipating the kinetic energy of the impactor. Applications of cork composites are given in Table 4.5.

Table 4.4 Mechanical properties of cork composites [12, 17, 18]

Property	Value
Modulus of elasticity	32.7–35.9 MPa (bending)
Bending strength	1.62–1.73 MPa
Internal bond strength	0.26–0.44 MPa
Thermal conductivity	0.04–0.07 W/m K
Specific heat	1.3–1.8 kJ/kg K

Table 4.5 Application of cork composites [29]

Application	Description
Aerospace industry	Cork-based ablative materials can take in a lot of heat, creating a layer that works as a heat shield in space shuttles
Building	By mixing cork granules and different polymers, a range of materials for sound insulation and vibration reduction that is crucial for buildings
Railway	Materials made of cork and other compounds are meant for use as pads and mats for rails, bases, sleepers, and ballast. These materials have different levels of shock absorption, for light and heavy rail uses, in concrete and gravel tracks, and are also used in special track parts such as switches, crossings, and junctions
Expansion joints	Composite cork will help the construction elements to shrink and grow, thus preventing cracks and reducing its need for maintenance. Cork-based solutions, because of the natural qualities and advantages of this material, ensure a sustainable and high technical performance outcome for buildings and large public works over time
Final coating (Corkwall)	Corkwall is an environmentally friendly final layer that can be used for various purposes, from building and renovating external walls to decorating internal walls and ceilings
Mobility acoustic core	Cork and a chosen rubbery compound mix make up Mobility Acoustic Core solutions that have specific features – from heat insulation, noise reduction to fire resistance – while keeping a low surface weight
Panels and multi-layer composites	Multilayer door and wall partition panel and window frame applications
Cork composites for interior components	Cork is a new material for inside vehicle parts that has a nice look and a warm and soft feel

4.2 Vibration Damping of Cork Composites

Vibration damping is the phenomenon of energy dissipation in a structure subjected to dynamic loads. Vibration damping is crucial for many engineering applications, where excessive vibrations can cause damage, fatigue, noise [30]. Cork composites demonstrate remarkable vibration damping properties owing to the viscoelasticity of cork and its interfacial interaction with the polymer and resin matrix. Viscoelasticity is the attribute of a material that exhibits both elastic and viscous behavior. Elastic behavior is the capacity of a material to store and recover energy when deformed. Viscoelastic materials have a frequency- and temperature-dependent response to stress and strain [31, 32]. The viscoelasticity of cork enables it to deform and recover under stress, and also dissipate some of the energy as heat. The energy dissipation of a viscoelastic material is measured by the loss factor, which is the ratio of the energy dissipated to the energy stored per cycle. The higher the loss factor, the better the damping performance [32]. The damping performance of cork composites depends on the size, weight percentage, and location of cork granules in the composite, as well as the type of additive and resin used [33]. Generally, smaller and more dispersed cork granules can increase the internal friction and stress relaxation at the interfaces, leading to higher damping properties [34].

Several studies have explored the vibration damping behavior of cork composites with different configurations and applications. Sheikhi et al. [34] developed and fabricated cork-based structures with impact and vibration resistance for low-speed aerial vehicles. They employed aramid fabric reinforced polymer (AFRP), carbon fiber reinforced polymer (CFRP), and glass fiber reinforced polymer (GFRP) face-sheet composites with a constant core layer of cork as shown in Fig. 4.4b, and evaluated peak deceleration and vibration properties of the composites. They observed that carbon CFRP exhibited better resistance in conjunction with the cork core. Karpenko and Nugaras [37] investigated the frequency-dependent damping properties of a cork-based composite material for potential use in aircraft structures. They utilized a dynamic mechanical analyzer to measure the loss factor and storage modulus of the material at various frequencies and temperatures. They reported that the cork-based composite had higher damping properties than conventional materials such as aluminum alloys and carbon fiber composites.

Gürgen et al. [35], to improve the vibration damping performance of cork products, they used shear thickening fluid (STF) and shear stiffening polymer (SSP) non-Newtonian based smart materials. The STF and SSP are applied as thin films between the cork layers, forming multilayer composites as shown in Fig. 4.4a. Their results concludes that the integration of smart materials into cork products can enhance their adaptive properties and create environmentally friendly products for vibration damping applications. Sheikhi et al. [38] showed that by adding STF to the core of the sandwich structure consisting of GFRP face-sheets and cork core, the damping properties of the structure can be improved. Lopes et al. [39] investigated the effect of cork granules in natural rubber. Vulcanization parameters in the processing were optimized to have enhanced vibration damping behavior. They found that the incorporation of cork increased the hardness and static stiffness of the rubber compounds, while maintaining a similar dynamic behavior to the base rubber. They developed linear regression models to predict or optimize properties related to vibration isolation applications and concluded that cork–rubber composites have a different dynamic behavior from other rubber compounds with various fillers.

Santos Silva et al. [33] investigated the dynamic properties of sandwich structures with cork cores. They used a partial layerwise plate finite element (FE) model to simulate the sandwich plates performed an experimental modal analysis on three test samples with different cork properties (density, granulometry, and thickness).

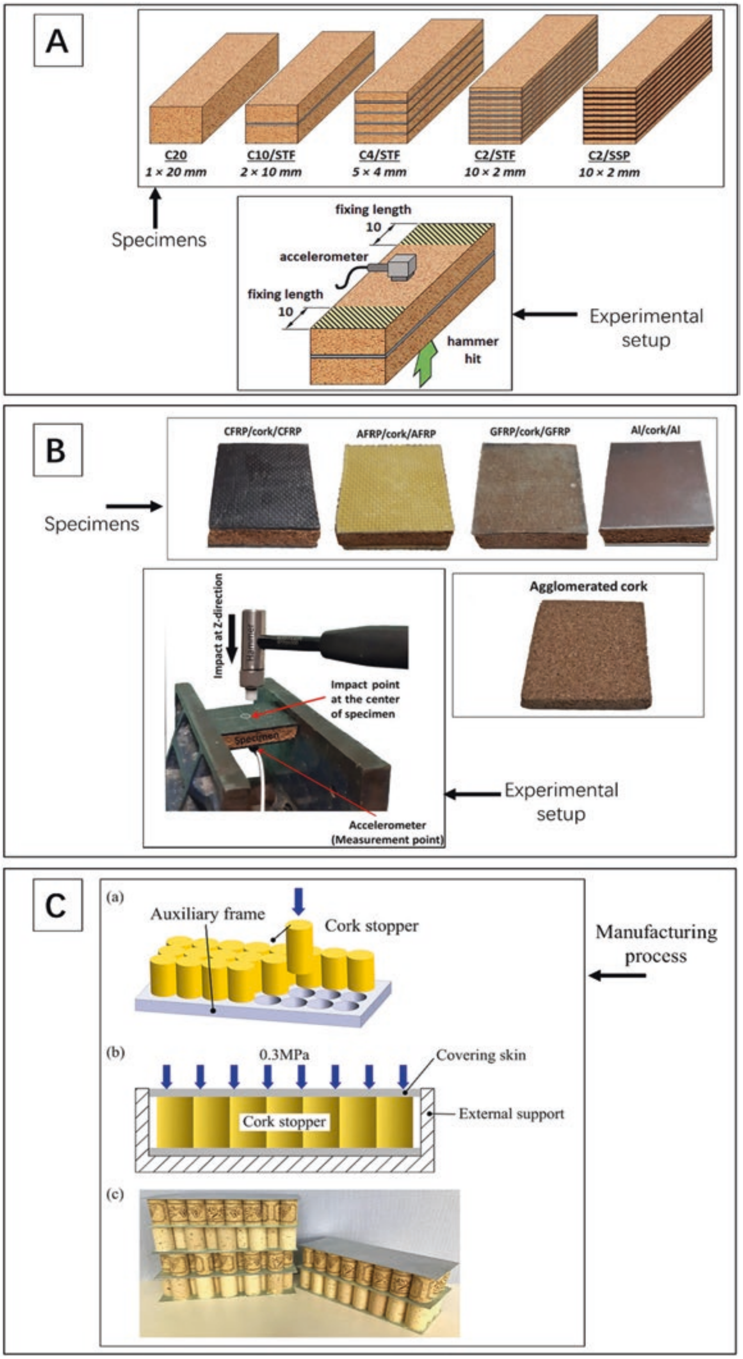

Fig. 4.4 (**a**) Smart polymer integrated cork composites, (**b**) cork-based sandwich structures, and (**c**) sandwich structure with cork stopper cores [34–36]

They found that cork can be used as an effective passive damping in sandwich or multilayer structures, increasing damping capability of the structure.

Prabhakaran et al. [40] conducted an experimental study on the impact behavior, sound absorbing characteristics, and vibration suppression properties of sandwich structures made from flax skin reinforcement and agglomerated cork core. They compared their performance with synthetic-based composite sandwiches made of glass as skin reinforcement and cork as core. They used vacuum bagging method to manufacture composite sandwiches with different cork densities and conducted low velocity impact, sound absorption, and vibration damping tests. Their results indicate that cork based sandwich composites had lower perforation energy, higher sound absorption capacity, and higher vibration damping ratio than synthetic based sandwich structures. They suggested that cork based sandwich structures could be an ecologically appealing solution for automobile and construction applications. Liu et al. [36] proposed a environmentally friendly sandwich structure for building applications, utilizing cork stoppers as the core layer. They fabricated sandwich panels with cork stopper cores and aluminum face-sheets as shown in Fig. 4.4c and investigated their vibration performance using modal tests, theoretical analysis, and finite element simulation. They found that the natural frequencies and strain energy of the sandwich panels were affected by the type, size, and arrangement of the cork stoppers.

4.3 A Case Study of Vibration Damping Capability of Cork Composites

4.3.1 Experimental Details

We select three types of cork composites, namely VC-PAD, VC1001, and fine-grained agglomerated cork to compare their vibration properties (supplied by Amorim Cork Composites). VC-PAD-5051 is a polymer matrix composite (PMC) with cork granules as the reinforcement phase, which exhibits effective damping properties for vibration mitigation in the construction sector. It can be applied as a cubic isolator to reduce the transmission of vibrations between floating floors and the underlying structure. VC1001 is another PMC with natural rubber as the matrix phase and cork granules as the reinforcement phase, which offers high isolation performance for vibration control applications that require low resonance frequencies and low loads. It can be used as a pad or a strip isolator to attenuate vibrations in various systems. Fine-grained agglomerated cork is a natural cork material that consists of cork granules bonded by either synthetic or natural agents, which has good elasticity and resilience characteristics for vibration damping. The manufacturers' specifications provide the details of the components as shown in Fig. 4.5.

VC-PAD-5015 | **Fine-grained agglomerated cork** | **VC1001**

VC-PAD-5015

Binder	Polymeric matrix
Density	600 kg/m³
Shore hardness (Shore A)	60 - 70
Elongation at break (%)	> 15
Tensile strength (MPa)	> 0.7

Fine-grained agglomerated cork

Binder	Polyurethane
Density	170-190 kg/m³
Shore hardness (Shore A)	50
Elongation at break (%)	> 15
Tensile strength (MPa)	> 0.6

VC1001

Binder	Natural Rubber
Density	500 kg/m³
Shore hardness (Shore A)	20 - 35
Elongation at break (%)	> 80
Tensile strength (MPa)	> 0.25

Fig. 4.5 Details of the components

We conducted the vibration tests on three different types of cork composites using a hammer-based modal analysis system. Modal analysis is a technique to study the dynamic properties of a system, such as its natural frequencies, stiffness, and damping ratios. To perform modal analysis, we need to apply a force to the structure that covers the frequency range of interest. The force should be measured by a force hammer, which records the magnitude and direction of the impact. The response of the structure should be measured by a sensor, such as an accelerometer, which records the acceleration of the structure. We used a Kistler 9722A2000 hammer model with nylon tip 9904A and 2.13 mV/N sensitivity to excite the cork composites. The nylon tip has a frequency range up to 3000 Hz, which is suitable for our test. We fixed the cork composite specimens to a fixture and hit them with the hammer at a specific point in the X-direction. The impact point was 20 mm from the edge in the width direction and 30 mm from the edge in the height direction, with a 5 mm offset of the specimen. We attached an accelerometer to the opposite face of the impact point to record the acceleration response. Figure 4.6 shows the details of our experimental setup. We determined the optimal placement of the sensor by conducting several preliminary tests. We measured the stiffness coefficients, structural damping ratio, and natural frequency of the specimens using the accelerometer data. These parameters can help us characterize the dynamic behavior of the cork composites.

4.3.2 Results and Discussion

Every oscillating structure has its own natural frequency, which is the frequency at which an object or structure will oscillate after an initial disturbance. When the vibration of the structure increases slowly, resonance occurs when the driving frequency matches the natural frequency of the object or structure. This is a special

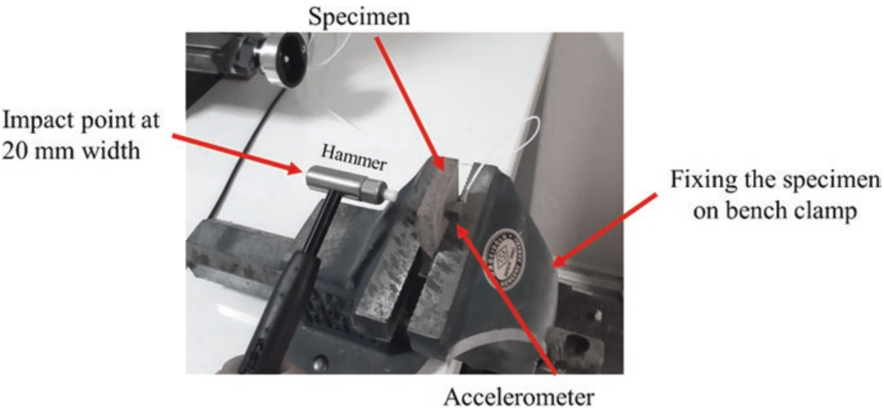

Fig. 4.6 Experimental setup in the vibration tests

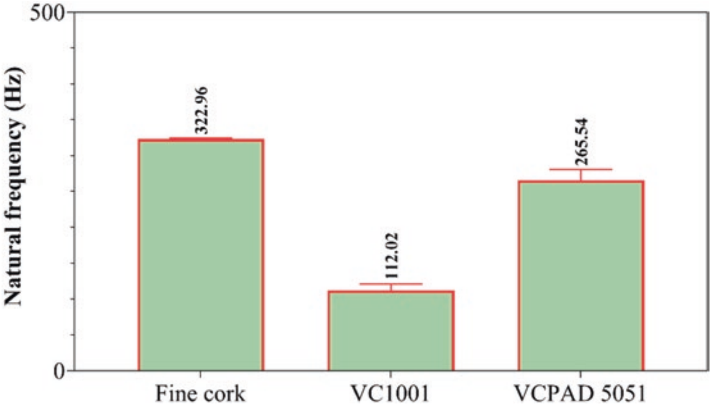

Fig. 4.7 Natural frequency of cork composites

frequency at which the amplitude increases dramatically. By changing the mass and stiffness of the structure, the natural frequency can be changed. Therefore, knowing the natural frequency of the structure is crucial. As shown in Fig. 4.7, fine-grained agglomerated cork has the highest natural frequency (322 Hz), followed by VC1001 (112 Hz) and VCPAD5051 (265 Hz), respectively. The differences in the results can be explained by the differences in their structural uniformity and elastic modulus.

The stiffness coefficients of cork composites are shown in Fig. 4.8. Stiffness is a criterion of an object's resistance to deformation under an applied force and returning to its original shape after removing the force. The obtained stiffness results show that they are consistent with the natural frequencies achieved for the composites. The fine-grained agglomerated cork sample shows the highest value of stiffness coefficient, followed by the VC1001 and VCPAD5015 samples. The stiffness coefficient's relevance in the structure decides when to prevent resonance; the forced

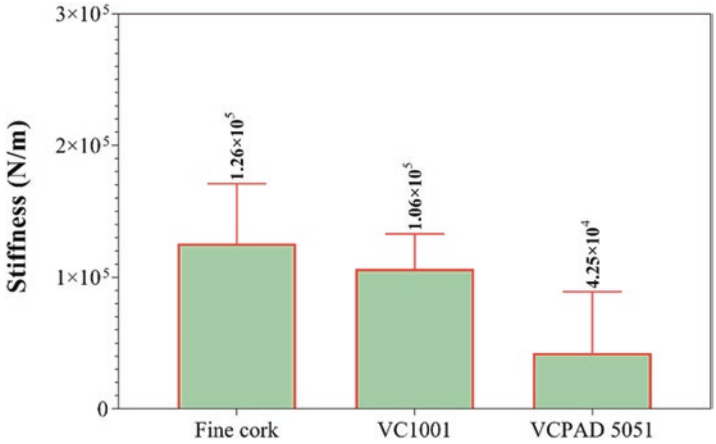

Fig. 4.8 Stiffness coefficient of cork composites

frequency applied to the structure should not be equal to or near the natural frequency. If the forced frequency cannot be adjusted, the natural frequency of the structure must be altered, which can only be accomplished by adjusting the mass or stiffness.

The damping ratios of cork materials are presented in Fig. 4.9. The damping ratio is a nondimensional parameter that quantifies the rate of decay of oscillations in a system subjected to a disturbance. A higher damping ratio implies a faster return to equilibrium with less oscillations. Among the three materials, Fine cork exhibits the highest damping ratio, indicating its superior ability to dissipate energy. Conversely, VC1001 shows the lowest damping ratio, implying a longer duration of oscillations before reaching equilibrium. VCPAD5051 has a similar damping ratio to Fine cork, implying a comparable performance in energy dissipation. The damping ratio of VC1001 is approximately 76.10% lower than that of Fine cork, while the damping ratio of VCPAD5051 is approximately 8.21% lower than that of Fine cork.

4.3.3 Discussion

The stiffness and damping properties of the cork composites vary according to their composition and structure. Fine-grained agglomerated cork exhibits the highest stiffness and damping ratio the three composites, indicating its superior ability to dissipate energy and control vibrations. It could be applied in situations that demand high stiffness and effective vibration attenuation. VC1001 has the lowest stiffness and damping ratio, implying its high flexibility and low energy dissipation. It could be suitable for situations that require some degree of flexibility, but it might not perform well in reducing vibrations rapidly. VCPAD5051 has a moderate stiffness and a damping ratio comparable to fine-grained agglomerated cork, suggesting its

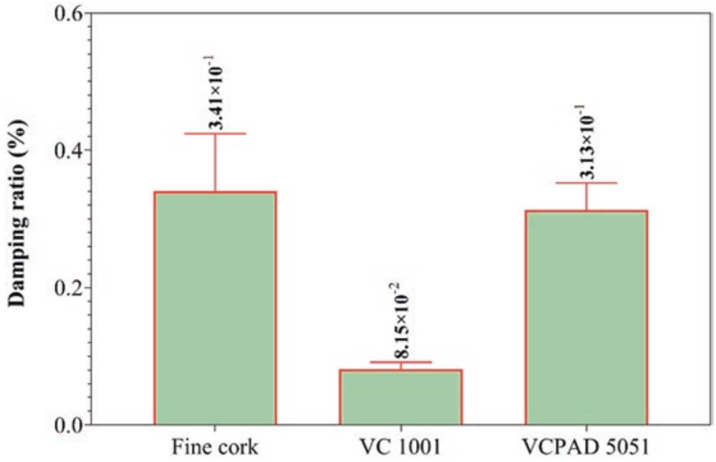

Fig. 4.9 Damping ratio of cork composites

balanced performance in both flexibility and energy dissipation. It could be applied in situations that need moderate stiffness and effective vibration control. The selection of the material depends on the specific requirements of the application such as the desired level of stiffness, vibration attenuation, and energy dissipation. While VC1001 is stiffer than VCPAD5051 (as indicated by the higher stiffness coefficient), its natural frequency is lower. This discrepancy can be explained if VC1001 has a significantly higher mass or weight compared to VCPAD5051. The increased mass would lower the natural frequency, even if the material is stiffer.

Cork has a honeycomb cellular structure, with each cell containing air. This structure confers cork its inherent properties of elasticity and resilience. The air within the cells acts as a natural cushion, which increases its stiffness coefficient. Moreover, cork converts vibration energy into low-grade heat in each cycle, resulting in a low resonance amplification. This enables cork materials to operate effectively across a wide frequency range. This property is crucial for the damping function, which explains why cork has a higher damping ratio than many other materials. VC1001 is a composite of cork and natural rubber. The incorporation of rubber, which has more flexibility and less stiffness than cork, may reduce the overall stiffness of the composite. Cork–rubber composite exhibits improved vibration isolation properties due to the combination of cork's high loss factor and rubber's low damping and high isolation. VCPAD5051 is a composite of cork and a polymeric matrix. The type and proportion of the polymer can affect the stiffness and damping properties of the composite. Furthermore, the manufacturing and processing methods can have a significant impact on the properties of cork-based materials. The cellular structure of cork provides inherent damping due to the friction between the cell walls under vibration. This mechanism accounts for the higher damping ratio in fine-grained agglomerated cork. In contrast, the other VC1001 and VCPAD5051, having additional components such as rubber or polymers, may have different damping mechanisms. The interaction between cork and these components can influence the overall damping behavior. Natural frequency is determined by both stiffness and mass. Fine-grained cork's higher natural frequency indicates that its effective stiffness (considering its density and structure) is higher than the other materials. The higher stiffness coefficient of fine-grained agglomerated cork correlates with its higher natural frequency, as a stiffer material tends to have a higher natural frequency.

4.4 Conclusions

In this chapter, the vibration-damping properties of cork composites were investigated. At first, cork composites and their properties and manufacturing methods were discussed. Then, in the form of a case study, three different types of cork composites (fine-grained agglomerated cork, VC1001, and VCPAD5051) were tested for vibrations, and the damping-ratio, stiffness coefficient, and natural frequency properties of fine-grained agglomerated cork were better than those of VC1001 and VCPAD5015 composites. The difference in the results can be attributed to the different types of structure of the composites due to adding different amounts of rubber and polymer to the natural cork, which changed their vibration properties. Although the results showed the better performance of fine-grained agglomerated cork, considering that VC1001 and VCPAD5015 composites have a stronger structure due to having polymer and rubber additives, they can be expected to get better results in long-term exposure to vibration, and for future studies, it is recommended to test the repeatability and vibration for an extended period of time of the composites used in this study.

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References

1. Şen A et al (2011) The cellular structure of cork from Quercus cerris var. cerris bark in a materials' perspective. Ind Crop Prod 34:929–936
2. Pereira H (2011) Cork: biology, production and uses. Elsevier, Amsterdam
3. Silva S et al (2005) Cork: properties, capabilities and applications. Int Mater Rev 50(6):345–365
4. Silvestre AJ, Neto CP, Gandini A (2008) Cork and suberins: major sources, properties and applications. In: Monomers, polymers and composites from renewable resources. Elsevier, Amsterdam, pp 305–320
5. Gil L (2015) Cork. In: Materials for construction and civil engineering: science, processing, and design. Springer, Cham, pp 585–627
6. Bugalho MN et al (2011) Mediterranean cork oak savannas require human use to sustain biodiversity and ecosystem services. Front Ecol Environ 9(5):278–286

7. Monteiro S et al (2022) Cross contamination of 2, 4, 6-trichloroanisole in cork stoppers. J Agric Food Chem 70(22):6747–6754
8. Domke GM et al (2020) Tree planting has the potential to increase carbon sequestration capacity of forests in the United States. Proc Natl Acad Sci 117(40):24649–24651
9. Costa A et al (2022) Beyond width and density: stable carbon and oxygen isotopes in cork-rings provide insights of physiological responses to water stress in Quercus suber L. PeerJ 10:e14270
10. Demertzi M et al (2016) A carbon footprint simulation model for the cork oak sector. Sci Total Environ 566:499–511
11. Acácio V et al (2017) Landscape dynamics in Mediterranean oak forests under global change: understanding the role of anthropogenic and environmental drivers across forest types. Glob Chang Biol 23(3):1199–1217
12. Gil L (2009) Cork composites: a review. Materials 2(3):776–789
13. Barnat-Hunek D et al (2018) Impact of different binders on the roughness, adhesion strength, and other properties of mortars with expanded cork. Materials 11(3):364
14. Gil L (2015) New cork-based materials and applications. Materials 8(2):625–637
15. Martins CI, Gil V (2020) Processing–structure–properties of cork polymer composites. Front Mater 7:297
16. Santos P et al (2017) Agglomerated cork: a way to tailor its mechanical properties. Compos Struct 178:277–287
17. Gibson L, Easterling K, Ashby MF (1981) The structure and mechanics of cork. Proc R Soc Lond Math Phys Sci 377(1769):99–117
18. Merabti S et al (2021) Thermo-mechanical and physical properties of waste granular cork composite with slag cement. Constr Build Mater 272:121923
19. Sheikhi MR, Gürgen S (2022) Anti-impact design of multi-layer composites enhanced by shear thickening fluid. Compos Struct 279:114797
20. Sheikhi MR, Gürgen S (2022) Deceleration behavior of multi-layer cork composites intercalated with a non-Newtonian material. Arch Civil Mech Eng 23(1):2
21. Sheikhi MR, Gürgen S, Altuntas O (2022) Energy-absorbing and eco-friendly perspectives for cork and WKSF based composites under drop-weight impact machine. Machines 10(11):1050
22. Fernandes FA et al (2019) Helmet design based on the optimization of biocomposite energy-absorbing liners under multi-impact loading. Appl Sci 9(4):735
23. Fernandes F et al (2023) Cork composites for structural applications. In: Green sustainable process for chemical and environmental engineering and science. Elsevier, Amsterdam, pp 29–51
24. Serra GF et al (2022) New hybrid cork-STF (Shear thickening fluid) polymeric composites to enhance head safety in micro-mobility accidents. Compos Struct 301:116138
25. Kaczynski P et al (2019) High-energy impact testing of agglomerated cork at extremely low and high temperatures. Int J Impact Eng 126:109–116
26. Kaczyński P, Ptak M, Fernandes F (2019) Development and testing of advanced cork composite sandwiches for energy-absorbing structures. Materials (Basel) 12
27. Ptak M et al (2017) Assessing impact velocity and temperature effects on crashworthiness properties of cork material. Int J Impact Eng 106:238–248
28. Gürgen S et al (2021) Development of eco-friendly shock-absorbing cork composites enhanced by a non-Newtonian fluid. Appl Compos Mater 28:165–179
29. Composites AC (2023) Amorim cork composites, materials & applications. Available from: https://amorimcorkcomposites.com/en-us/
30. Chung D (2001) Materials for vibration damping. J Mater Sci 36:5733–5737
31. Zhou X et al (2016) Research and applications of viscoelastic vibration damping materials: a review. Compos Struct 136:460–480
32. Jones DI (2001) Handbook of viscoelastic vibration damping. Wiley, New York
33. Santos Silva J, Dias Rodrigues J, Moreira R (2010) Application of cork compounds in sandwich structures for vibration damping. J Sandw Struct Mater 12(4):495–515

34. Sheikhi MR et al (2023) Anti-impact and vibration-damping design of cork-based sandwich structures for low-speed aerial vehicles. Arch Civil Mech Eng 23(2):71
35. Gürgen S, Sofuoğlu MA (2021) Smart polymer integrated cork composites for enhanced vibration damping properties. Compos Struct 258:113200
36. Liu C-X et al (2022) Modal characteristics of a sustainable sandwich structure with cork stopper cores. Constr Build Mater 349:128721
37. Karpenko M, Nugaras J (2022) Vibration damping characteristics of the cork-based composite material in line to frequency analysis. J Theor Appl Mech 60
38. Sheikhi MR, Sofuoğlu MA, Chen Z (2023) Shear thickening fluid integrated sandwich structures for vibration isolation. In: Shear thickening fluid: case studies in engineering. Springer, Cham, pp 27–40
39. Lopes H et al (2021) The influence of cork and manufacturing parameters on the properties of cork–rubber composites for vibration isolation applications. Sustainability 13(20):11240
40. Prabhakaran S et al (2020) Experimental investigation on impact, sound, and vibration response of natural-based composite sandwich made of flax and agglomerated cork. J Compos Mater 54(5):669–680

Chapter 5
Cork Composites for Sustainable E-micromobility Safety

Fábio A. O. Fernandes, João B. S. S. Ferreira, and Ricardo J. Alves de Sousa

5.1 Introduction

Oil-derived materials, such as expanded polypropylene and expanded polystyrene, are widely used to produce safety devices and crashworthy structures. Consumer awareness, go-green tendencies, and the European Union policies push manufacturers to provide eco-friendly alternatives. The Green Deal defines the European Union strategy to reach climate-neutrality, and innovative urban mobility solutions are emerging against rising challenges such as air pollution, noise, and congestion. E-micromobility, with its readily available vehicles and the emergence of sharing services, is becoming increasingly popular among short-distance commuters due to its practicality and rapid growth. However, the legislation and development of protective gear did not keep up with this fast-growing mobility phenomenon, as confirmed by the rapid increase in injuries and fatalities.

Regarding the e-scooters, head injuries are the most common injury, followed by fractures and skin abrasions and lacerations [1], yielding a critical need for novel and innovative personal protective gear. Regular bike helmets are not an option for many e-scooter riders [1], given the patent lack of headgear designed explicitly for e-scooter usage, including the convenience and need for minimalistic and compatible gear with such a concept of transport [2]. Also, the absence of headgear with sustainable characteristics is an issue to tackle in order to develop attractive

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headgear for e-micromobility users [3]. Therefore, there is an urgent need to sustainably develop protective equipment specifically designed for e-micromobility. This goal will be accomplished by developing advanced composite solutions with enhanced energy absorption capacity. Rather than imitating current functions reliant on synthetic materials, the goal is to develop highly innovative eco-composite structures using more intelligent materials and solutions, providing the necessary protective performance and sustainability for life-saving structures.

Cork granules, a by-product or rejected material of wine-stoppers production, are the key ingredient to replace oil-based cellular materials. Cork is a natural, fully sustainable, and recyclable material that presents excellent properties for impact protection, which can be tailored for a specific application [4–12]. Additionally, cork-based composites with enhanced impact energy absorption are possible by combining shear thickening fluids [13]. This chapter reviews the potential of cork composites and structures as sustainable options for e-micromobility safety.

5.2 Cork as an Engineering Material

Cork has been utilized since ancient times, finding applications in items such as fishing tools, floats, and footwear. Its suitability for protective equipment is due to its effective energy absorption during impacts. Cork's recyclability and natural origin make it a superb answer to address environmental sustainability concerns.

The first traces of the use of cork come from 3000 B.C. in Egypt and Persia, where it was used in fishing tools, shoes, buoys, and so on. The fourth century was the time of the first references to this material in which the Greek botanist and philosopher Theophrastus recognizes the qualities of *Quercus suber* (cork oak) in his botanical texts: "The cork is removed, and they say that it must be removed completely, otherwise the tree will degenerate. But in three years, it covers itself again" [14]. In the fifteenth and sixteenth centuries, this material was also applied to the well-known Portuguese caravels, which led the Portuguese to perform great feats [15]. In the twenty-first century, Portugal is the largest producer and exporter of cork in the world, with the agricultural sector, specifically in manufacturing cork stoppers, one of the largest consumers. Nowadays, this material is also widely used in the aerospace sector, footwear, protective objects, and so on.

Cork is the bark of the cork oak. After the first 25 years of life, and when the trunk diameter is approximately 20–25 cm, this bark can be removed and called virgin cork. Cork oaks have a lifespan of between 150 and 200 years, and every 9 years, their bark is removed, a period that allows the development of the desired thickness. The cork obtained in the second extraction is of better quality than virgin cork. However, it still contains high stresses that cause cracks or other irregularities. Additionally, in the following extractions, the cork possesses a consistent structure characterized by even thickness and smooth surfaces but may still have some shallow cracks. This product, called *amadia*, is the raw material the industry uses to make, for instance, stoppers [16].

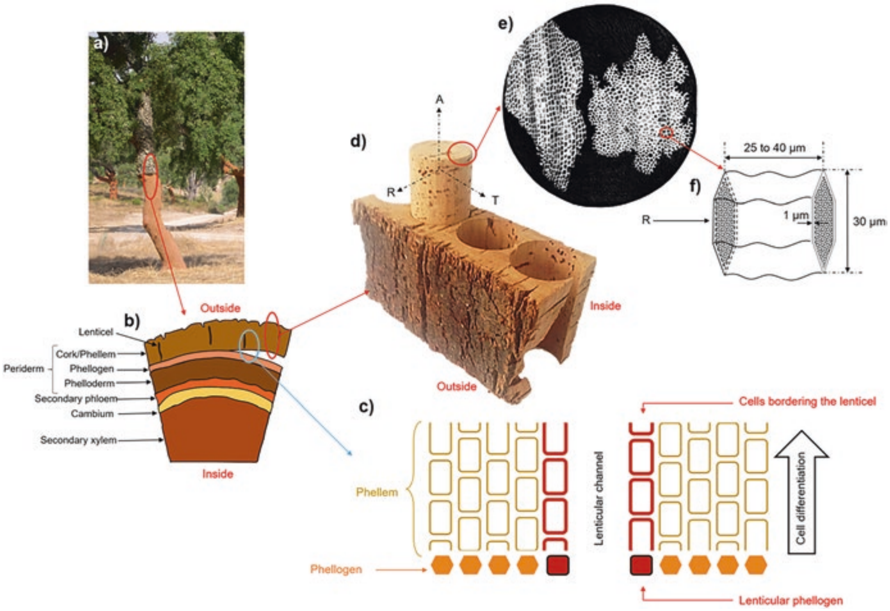

Fig. 5.1 Representation of a cork cell [17]

Cork can be classified as a material in the form of a honeycomb, formed by closed prismatic cells, compacted and ordered from the inside to the outside of the cork oak bark (Fig. 5.1). Its cell walls present undulations along the prism axis, giving them high flexibility, thus determining the mechanical behavior of the cork [7]. This is a cellular material whose cells may have a pentagonal or hexagonal shape. The height of these prisms is around 40–50 μm, with an average of approximately 40 million cells per cubic centimeter. Its chemical composition is suberin (45%), lignin (27%), polysaccharides (12%), ceroids (6%), and tannins (6%) [18].

Unlike expanded polystyrene, cork has a great capacity to return to its original dimensions after being compressed. It is characterized not only by good energy absorption and viscoelastic recovery but also by its low density, impermeability to liquids, good resilience, thermal and acoustic insulation, and chemical and microbial resistance [19]. Another essential characteristic of cork is the presence of lenticular channels that cross its planks in the cork oak trunk, radially connecting the outside of the trunk to the internal living tissues, providing gas permeability (Fig. 5.1). These channels appear in the tangential section of cork as pores with more or less circular shapes, and this porous characteristic is the key factor used to classify it. Cork of high quality will typically display few and small pores, whereas low-quality cork will often exhibit lenticular channels with a larger cross-sectional area [20].

In the work of Barbenchon et al. [21], they studied the complex microstructure of cork and its influence on mechanical behavior. Optical and electron microscopy

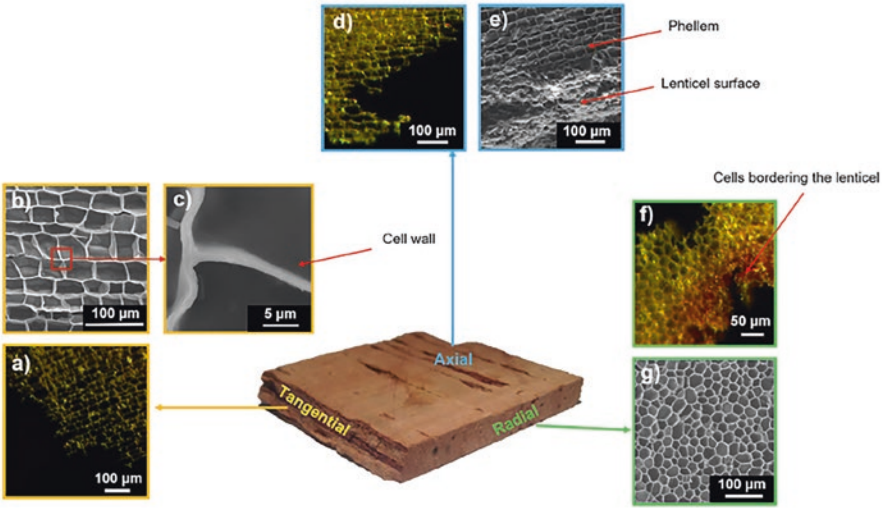

Fig. 5.2 Micrographs of the cork morphology showing its cellular structure [17]

techniques were used in the first place to characterize the microstructure on the surface prior to any deformation from the mechanical tests. An example from another study is depicted in Fig. 5.2 [17]. After quasi-static tests on a cork composite, it was concluded that the angle and shape factor of the grains allow realizing the transversal anisotropy of the cork agglomerate produced by this compression. When the compression is done in the plane direction, the material is more rigid, absorbing more energy, densifying at higher deformations, and having a lower viscoelastic recovery compared to compressions in directions contrary to the plane. Also, a grain- and cell-scale X-ray microtomographic analysis was performed, giving a better 3D perspective of the material. This analysis allowed the authors to confirm the observations made in 2D by capturing structural information such as cell volume distribution, wall defects, and porosity size.

In this industry, the waste is reduced to a minimum amount. Even the cork removed from the first two extractions is used to produce agglomerated cork. Other utensils, such as used stoppers, can be recycled to have new products, and it can be stated that this material is fully reusable and recyclable, thus creating a sustainable market.

There are two types of clusters possible to obtain. The first, called white agglomerate, is an isotropic material with easily controllable properties: the cork is milled, producing granules usually with sizes from 0.5 to 20 mm, and are subsequently washed and dried by hot air flow, giving the granulated required moisture. By controlling pressure and temperature conditions, the agglomerate is formed by agglutinating the granules with the desired size with a binder composed of phenolic, polyurethane (PU), melamine, or even bio-based resins. Mechanical blades or mixers are used to blend the mixture, which is then placed and compressed into a mold to achieve the desired shape. It is subjected to temperatures between 110 and 150 °C, being finally removed from the mold and cooled.

In turn, expanded agglomerate, better known as black agglomerate, is obtained by joining virgin cork granules obtained by pruning cork oak branches with a high concentration of extractives. These are then mechanically processed into granules, filtered to remove impurities, and dried until the desired humidity is obtained. The granules are located in autoclaves at the pressures of approximately 40 kPa and temperatures between 300 and 370 °C. With this conditioning, the granules expand and emit their resin acting as a natural binder, enabling agglomeration without adding additives [16].

5.3 Cork-Based Composites and Structures for Impact Mitigation

In the literature, it is possible to find works that have been developed to improve protective equipment, specifically helmets, studying their materials and geometries to reduce brain injuries. Several addressed experimental impact tests on samples or helmets, but recently there are also examples of numerical studies carried out with this material and for similar purposes. The present section reviews the works that studied cork composites and structures subjected to impact loading.

To create a starting point for the study of the mechanical behavior of cork composites under impact, Gameiro et al. [22] carried out a study comparing the response of this material when subjected to quasi-static and dynamic compressions and the influence of different types of cork, densities, moisture, cell structure, and strain rate. For the analysis of the energy absorption capacity, the same author compressed circular and square aluminum tubes, filled with cork, of different lengths at different static and dynamic deformation rates. It also performed numerical simulations of experimental dynamic compression tests using the finite element software, LS-DYNA. The results showed excellent agreement with the experimental tests, thus suggesting that it may be possible to predict the behavior of structures filled with cork under dynamic loads. It was also observed that cork agglomerates performed better in deceleration and energy absorption for square tubes, concluding this cheaper and lighter material can be used in energy absorption structures.

To study the dynamic compressive behavior and the relaxation in the unloading of the cork agglomerates, Fernandes et al. [7] carried out dynamic tests of impact with a hammer of 5 kg, through a 3 m height drop tower. Analyzing the experimental results, all the samples used had a good performance regarding their elastic recovery, which was higher than 95% after a first impact, making this material interesting for protective equipment or structures subjected to multiple impact loading. Also, in this research, a finite element analysis was performed, employing a new constitutive strategy. The results were compared with those of Gameiro et al. [22], verifying that they were close to those measured experimentally for both loading and unloading.

The thickness of the material used is also an important variable when producing protective components. A study was done on this variable, testing the behavior of dynamic compression by analyzing the influence that its thickness presents in terms of absorbed energy. Using cork composites as a test material, the authors concluded that maximum contact force, maximum displacement, and maximum deformation increase when the ratio between impact energy and thickness increases. Also, increasing the thickness of the sample reduces the contact force for the same impact energy. The relationship between energy absorbed and impact energy/thickness was linear for each sample under study. Finally, the authors also conclude that the energy absorbing by the agglomerated cork under study does not depend on the sample thickness in the range of energies analyzed [23].

In another work, the authors studied the response to multi-impacts of the cork agglomerate NL-10, varying its thickness. In total, 36 tests were realized, from 17.6 and 35 J to samples of 35, 50 and, 70 mm thicknesses. From the three variables studied (absorbed energy, maximum contact force, and maximum deformation), the authors conclude that the maximum force and deformation were lower with increasing thickness of the samples for the two energies analyzed. Also, about 70–80% of the impact energy was absorbed, according to the increase in the energy levels of the impact, thus showing that this cork has an excellent capacity for energy absorption, independently of the number of impacts [24].

Jardin et al. [6] studied the versatility of some cork composites, where several agglomerates are tested, changing some properties between them such as the size of their granules and the binder. The authors performed uniaxial quasi-static compression tests and dynamic impact. Four samples of agglomerated cork (densities of 216, 178, 199, 157 kg/m^3) and three samples of expanded cork (159, 122, 182 kg/m^3) were tested. Due to the lack of binder and carbonized matter, the latter could only withstand one impact, losing its integrity afterward. On the other hand, the agglomerates achieved good results, concluding that: (1) less dense agglomerates have lower Young's modulus and, consequently, a lower stress plateau during their deformation, storing lower energy levels per volume unit. On the other hand, their densification stages are reached for higher strains than those of denser samples; (2) larger granules in the material are reflected in greater mechanical damage, causing their performance in multiple impact situations to be severely compromised. Nevertheless, it must be highlighted that the impact conditions were severe in Jardin et al. [6] since the aim was to produce impacts with energy levels appropriate for applications such as motorcycle helmets. A 10 kg hemispherical steel impactor with 94 mm diameter was employed with an average speed of 4.8 m/s.

The substitution of synthetic materials for natural materials in protection equipment has been increasingly studied. Fernandes et al. [5] carried out a study where two cork agglomerates (densities of 216 and 199 kg/m^3), expanded cork (density of 159 kg/m^3), expanded polystyrene (density of 90 kg/m^3), and expanded polypropylene (densities of 60 and 90 kg/m^3) were tested, being these last two materials usually used as energy absorbers in several types of helmets. The aim of the study was motorcycle helmets, characterized by high impact energies. Expanded polystyrene outperformed cork-based materials for a single impact. However, due to their elastic characteristic, the cork agglomerates showed better results when submitted to multiple impacts, which are likely to happen during a moped accident. Through static tests, it was concluded that synthetic materials could absorb more energy under low stresses. On the other hand, when subjected to dynamic situations (multi-impacts), natural materials obtained better results regarding their performance and resistance. Finite element analyses were also performed, and the results of these simulations were similar to the experimental ones, creating a precise and reliable framework for simulating the mechanical behavior of both natural and synthetic cellular materials. It should be noted that in terms of material choice, each case is unique, depending on the desired application.

In another study, impact tests with the Charpy configuration were conducted on sandwich structures having cork as the core material. The core material of all samples was cork NL 10 characterized by its flexibility, ability to absorb high amounts of energy, and the possibility of manufacturing products with complex geometry. Different types of composite sheets were evaluated based on natural fibers (flax) and glass fiber, while two types of epoxy resin were employed (synthetic and natural-based). The results are positive, concluding that these natural sandwich-type structures perform well in terms of strength and specific resistance when subjected to quasi-static and dynamic impacts. On the other hand, the weight and cost of these materials are still high compared to synthetic options [25].

As previously mentioned, the agglomerated cork, which raw material is obtained from recycled stoppers, can be reused in different applications due to its excellent thermal and acoustic properties. Another important aspect is the random orientation of the granulate makes cork almost isotropic, having a practically null Poisson ratio, making it a good solution in applications where great dimensional stability is demanded. Kaczynski et al. [8] tested four white cork agglomerates where two of them had the same density with different granulate sizes (one with 168 kg/m^3, two with 199 kg/m^3 and different granulate sizes, and one with 216 kg/m^3) and one expanded agglomerate (159 kg/m^3). The dynamic impact tests were carried out at an impact energy of 500 J, aiming to analyze each sample's different behaviors, varying the temperature from −30 to 100 °C. Their conclusions show that the cork agglomerates are significantly affected by the temperature, mainly in high energy impacts. By increasing the temperature of the samples from −30 to 100 °C, the energy absorption capacity decreases to less than a quarter, and as the density of the sample increases, the influence of temperature increases in terms of energy absorbed. These factors should always be considered when developing a new product made from this natural material.

Efforts have been made to optimize helmet performance by creating new helmet geometries and testing various materials for increasingly efficient energy absorption. Fernandes et al. [11] modeled a helmet according to the ECE 22.05 regulation. Four materials were put to the test: two cork agglomerates (199 and 216 kg/m^3), one expanded cork (159 kg/m^3), and one expanded polystyrene (90 kg/m^3). The response obtained with the 216 kg/m^3 agglomerate was the one that obtained wider acceleration–time curves and with lower acceleration peak. This agglomerate obtained the best results in the simulated impact tests and was considered by this study to be more efficient than expanded polystyrene for multiple impacts.

Another helmet was modeled, creating four liners with constant thicknesses (40, 35, 30, and 25 mm). Comparing the liner of 40 mm thick made from 216 kg/m^3 agglomerated cork with expanded polystyrene one shows that the cork helmet provided better protection than the expanded polystyrene one. Similar acceleration curves were obtained for the first impact, with the agglomerated cork having a slightly larger acceleration curve with a small peak acceleration. On the other hand, for the second impact, the acceleration peak of agglomerated cork was lower, making this material more efficient in terms of energy absorption.

More recently, Sergi et al. [26] tested the resistance of several sandwich structures subjected to impact testing. As these structures are constantly used in industry, they report two main drawbacks: exploitation of synthetic materials for their construction and a high susceptibility to impact-based damages. The impact behavior of these bio-based composites was studied with cork agglomerate cores and hybrid flax/basalt skins to address these problems. The materials chosen for the core were three white agglomerates (NL10, NL20, and NL25) and three hybrid composites (HP130, HP200, and HP250). Initially, dynamic experimental tests were performed only on the cores, where it was found, as expected, that the higher the impact energy to be applied to the structure, the greater the damage it undergoes and the greater the reaction force it exerts. Also, it was detected that the higher the material density for the same impact magnitude, the higher the maximum force and the lower the maximum displacement. The cork agglomerates obtained a great capacity for dimensional recovery after the compression in these tests. Based on that, the materials NL25 and HP130 were chosen for the numerical tests, concluding that the intergranular fracture occurring in NL25 is delayed due to its integration with the two hybrid skins. Thus, using this material as a core for sandwich structures allows for an environmentally friendly solution, improving the damage tolerance while only increasing its overall weight by 20%.

Also, Ptak et al. [9] performed dynamic tests on cork composites containing graphene oxide and graphene nanoplates, concluding that densification takes place at higher strains, and there were no significant differences in terms of energy absorbed compared to the cork composite without graphene oxide or graphene nanoplates. Figure 5.3 presents a brief overview of energy absorbed and displacement for the 1st and 2nd impacts for each sample type. The 15 threshold represents a deflection value of 15 mm to which the absorbed energy is calculated for both 1st and 2nd impacts.

This section makes it possible to conclude that cork is a very versatile material with high potential for applications, where the capacity to mitigate impact energy is necessary. Different types of cork composites have been developed with that aim, explicitly designed based on the application's requirements.

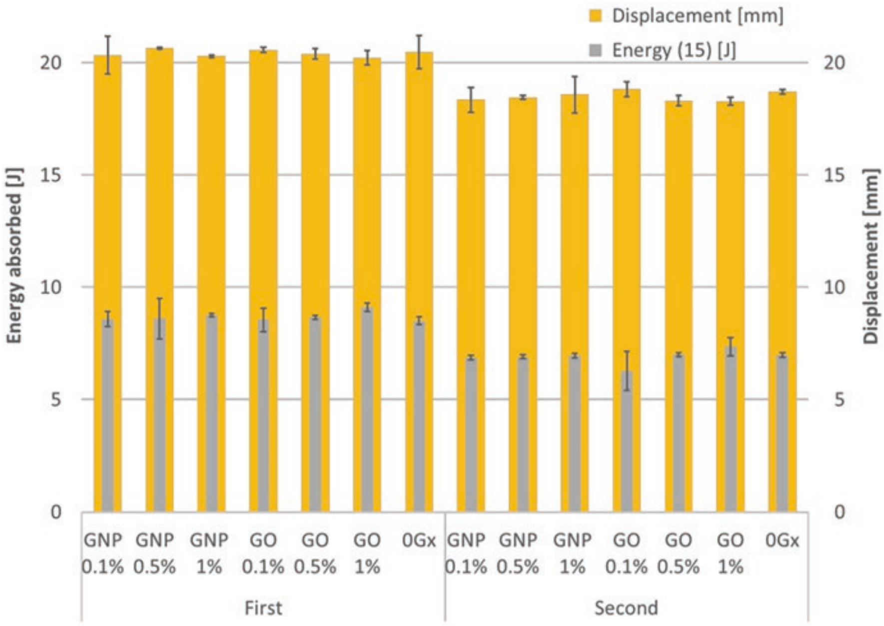

Fig. 5.3 Energy absorbed for a deflection and a displacement of 15 mm for the 1st and 2nd impacts [9]

5.4 Cork-Based Composites and Structures Potential in E-micromobility Safety

E-micromobility safety and the development of high-performance eco-composites are emerging research areas. Although recent studies report alarming numbers of brain-injured e-scooter drivers [1], due to the recency of these events, investigations of accidents involving e-scooters are scarce but have already been investigated [27]. Additionally, no helmets are designed explicitly for e-scooter users, nor a specific safety standard, contrary to other types [2].

Regular bike helmets are not an option for many e-scooter riders [1]. Perceived helmet use barriers among bike users are aesthetics, discomfort (ergonomics and thermal), and inconvenience [28]. Focusing on shared bike riders, engineering new comfortable, low-cost, durable, and hygienic helmets is seen as the way to remove barriers [29]. Helmets designed for e-micromobility need to be compatible with such a concept of transport characterized by its convenience, where designs need to be minimalistic, compact, and portable [2]. Also, considering the absence of mandatory helmet-use legislation and the lack of risk perception by the users, sustainable solutions could be embraced to increase the uptake of protective equipment [2].

Generally, modern bike helmets are made from expanded polystyrene pads covered by a hard-plastic shell designed to reduce linear acceleration. Real-world impact scenarios involve both linear and rotational accelerations. Advanced designs have been proposed to especially mitigate the latter, such as the multidirectional impact protection system and shearing pad inside solution [30]. However, existing solutions are all non-eco-friendly.

As previously seen, some eco-friendly alternatives have shown a great potential to replace synthetic ones in crashworthy structures [4–10, 12, 13, 25], including headgear [11, 31]. Cork provides excellent anti-impact properties, including an excellent multi-impact response [5–7, 9–11], which is an advantage in headgear. Density, granulometry, and binding agents can be adjusted to tailor the mechanical properties to fit diverse applications. Additionally, as previously referred, expanded cork is typically manufactured without adding binder and using cork granules unsuitable for stopper productions, typically for insulation.

Agglomerated cork was revealed as an excellent alternative to expanded polystyrene and expanded polypropylene, typically used in bicycle helmets, by comparing its multi-impact response [5, 11], which is a positive observation considering the inclusion of helmets in shared e-scooter services. Expanded cork presented excellent impact mitigation and densities similar to expanded polystyrene and a much better carbon footprint (negative one). In addition to being lightweight and remarkably compressible due to its microstructure and mechanical properties, cork is also wear-resistant, impermeable to fluids, antistatic and anti-allergic, and known for its high antibacterial activity, all of which are relevant properties for this application.

Non-Newtonian fluids have been gaining popularity for anti-impact purposes and wearable designs [32], being suggested for helmets [33]. There are some examples in the literature where these fluids were employed in the manufacturing of cork composites and cork multilayered structures, showing promising results [13, 34, 35]. Based on this, a new solution was recently explored and validated as protective equipment – the Flattie helmet (Fig. 5.4), designed specifically for e-micromobility, composed of layers of cork composites and shear thickening fluids specifically deposited on strategic points between cork and a thermoplastic shell [36].

5.5 Conclusions

The helmet is the most important piece of protection for cyclists, skateboarders, and roller skaters. As a vulnerable road user, they are the most vulnerable vehicle in case of accidents, not having a vehicle's structure or safety belt to protect them. With the widespread use of e-scooters and e-bikes in the context of e-micromobility, which is very attractive for commuters, the lack of a helmet specifically designed for it is a clear need. The first steps were carried out to present an innovative solution for the safety of e-micromobility users [34, 36].

Cork, a natural material with good performance in energy absorption, is a good option for this type of helmet padding to be eco-friendly. New composite structures containing cork, with the potential to be applied in helmets for low-impact energy

Fig. 5.4 Flattie – a new helmet concept designed specifically to improve the safety of e-micromobility users [36]

scenarios, were evaluated in the literature, demonstrating its potential. These were experimentally tested to determine their mechanical behavior when subjected to impact situations. There is no specific regulation, but the case study is based on the guidelines of the EN 1078 standard, where the peak acceleration did not exceed 250 × *g* for both flat and curbstone anvils.

Overall, the literature demonstrates that cork-based composites and structures are one key solution to increase the safety of the users of e-vehicles such as e-scooters and e-bikes in the context of the e-micromobility, while addressing several sustainable development goals, addressing safety and sustainability issues. Future solutions need to be specifically designed for this application, taking into account user needs. It needs to be compatible with such a concept of transport, its convenience, safety and technical requirements, and user needs [2].

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References

1. Trivedi TK, Liu C, Antonio ALM, Wheaton N, Kreger V, Yap A, Schriger D, Elmore JG (2019) Injuries associated with standing electric scooter use. JAMA Netw Open 2:e187381. https://doi.org/10.1001/jamanetworkopen.2018.7381
2. Serra GF, Fernandes FAO, Noronha E, de Sousa RJA (2021) Head protection in electric micromobility: a critical review, recommendations, and future trends. Accid Anal Prev 163:106430. https://doi.org/10.1016/J.AAP.2021.106430
3. Sanders RL, Branion-Calles M, Nelson TA (2020) To scoot or not to scoot: findings from a recent survey about the benefits and barriers of using E-scooters for riders and non-riders. Transp Res Part A Policy Pract 139:217–227. https://doi.org/10.1016/J.TRA.2020.07.009
4. Ptak M, Kaczynski P, Fernandes FAO, de Sousa RJA (2017) Assessing impact velocity and temperature effects on crashworthiness properties of cork material. Int J Impact Eng 106. https://doi.org/10.1016/j.ijimpeng.2017.04.014
5. Fernandes FAO, Jardin RT, Pereira AB, Alves de Sousa RJ (2015) Comparing the mechanical performance of synthetic and natural cellular materials. Mater Des 82:335–341. https://doi.org/10.1016/j.matdes.2015.06.004
6. Jardin RTT, Fernandes FAOAO, Pereira ABB, De Sousa RJA, Alves de Sousa RJ (2015) Static and dynamic mechanical response of different cork agglomerates. J Mater Des 68:121–126. https://doi.org/10.1016/j.matdes.2014.12.016
7. Fernandes FAO, Pascoal RJS, Alves de Sousa RJ (2014) Modelling impact response of agglomerated cork. Mater Des 58:499–507. https://doi.org/10.1016/j.matdes.2014.02.011
8. Kaczynski P, Ptak M, Wilhelm J, Fernandes FAO, de Sousa RJAA (2018) High-energy impact testing of agglomerated cork at extremely low and high temperatures. Int J Impact Eng 126:109–116. https://doi.org/10.1016/j.ijimpeng.2018.12.001
9. Ptak M, Kaczyński P, Wilhelm J, Margarido JMT, Marques PAAP, Pinto SC, de Sousa RJA, Fernandes FAO (2019) Graphene-enriched agglomerated cork material and its behaviour under quasi-static and dynamic loading. Materials 12:151. https://doi.org/10.3390/ma12010151
10. Santos PT, Pinto S, Marques PAAP, Pereira AB, Alves de Sousa RJ (2017) Agglomerated cork: a way to tailor its mechanical properties. Compos Struct 178:277–287. https://doi.org/10.1016/j.compstruct.2017.07.035
11. Fernandes FAO, de Sousa RJA, Ptak M, Migueis G (2019) Helmet design based on the optimization of biocomposite energy-absorbing liners under multi-impact loading. Appl Sci (Switzerland) 9:1–26. https://doi.org/10.3390/app9040735
12. Kaczyński P, Ptak M, Fernandes AO, Chybowski L, Wilhelm J, Alves de Sousa J (2019) Development and testing of advanced cork composite sandwiches for energy-absorbing structures. Materials 12:697. https://doi.org/10.3390/ma12050697
13. Gürgen S, Fernandes FAO, de Sousa RJA, Kuşhan MC (2021) Development of eco-friendly shock-absorbing cork composites enhanced by a non-Newtonian fluid. Appl Compos Mater 28:165–179. https://doi.org/10.1007/S10443-020-09859-7/FIGURES/11
14. Rangel F, Carlos R, Fa M. Coordinación: José Francisco Rangel 6yQLD %RPELFR Carlos Manuel Faísca 3HGUR 0RXULVFR. 0–14
15. Cortiça APd. Cortiça: História. https://www.apcor.pt/cortica/factos-curiosidades/historia/. Accessed 3 Dec 2021
16. Fernandes FAO (2017) Biomechanical analysis of helmeted head impacts: novel materials and geometries
17. Crouvisier-Urion K, Chanut J, Lagorce A, Winckler P, Wang Z, Verboven P, Nicolai B, Lherminier J, Ferret E, Gougeon RD, Bellat JP, Karbowiak T (2019) Four hundred years of cork imaging: new advances in the characterization of the cork structure. Sci Rep 9:1–10. https://doi.org/10.1038/s41598-019-55193-9
18. Cortiça APd (2016) Cortiça: O que é? https://www.apcor.pt/cortica/o-que-e/. Accessed 1 Mar 2022

19. Pereira H (1988) Chemical composition and variability of cork from Quercus suber L. Wood Sci Technol 22:211–218. https://doi.org/10.1007/BF00386015
20. Anjos O, Pereira H, Rosa ME (2008) Effect of quality, porosity and density on the compression properties of cork. Holz Roh Werkst 66:295–301. https://doi.org/10.1007/s00107-008-0248-2
21. Le Barbenchon L, Girardot J, Kopp JB, Viot P (2019) Multi-scale foam: 3D structure/compressive behaviour relationship of agglomerated cork. Materialia (Oxf) 5:100219. https://doi.org/10.1016/j.mtla.2019.100219
22. Gameiro CP, Cirne J, Gary G, Miranda V, Pinho-da-Cruz J, Teixeira-Dias F (2005) Numerical and experimental study of the dynamic behaviour of cork. Des Use Light-Weight Mater II:65–84
23. Sanchez-Saez S, García-Castillo SK, Barbero E, Cirne J (2015) Dynamic crushing behaviour of agglomerated cork. Mater Des 65:743–748. https://doi.org/10.1016/j.matdes.2014.09.054
24. Sanchez-Saez S, Barbero E, Garcia-Castillo SK, Ivañez I, Cirne J (2015) Experimental response of agglomerated cork under multi-impact loads. Mater Lett 160:327–330. https://doi.org/10.1016/j.matlet.2015.08.012
25. Fernandes FAO, Tavares JP, Alves de Sousa RJ, Pereira AB, Esteves JL (2017) Manufacturing and testing composites based on natural materials. Proc Manuf 13:227–234. https://doi.org/10.1016/j.promfg.2017.09.055
26. Sergi C, Boria S, Sarasini F, Russo P, Vitiello L, Barbero E, Sanchez-Saez S, Tirillò J (2021) Experimental and finite element analysis of the impact response of agglomerated cork and its intraply hybrid flax/basalt sandwich structures. Compos Struct 272:114210. https://doi.org/10.1016/j.compstruct.2021.114210
27. Ptak M, Fernandes FAO, Dymek M, Welter C, Brodziński K, Chybowski L (2022) Analysis of electric scooter user kinematics after a crash against SUV. PLoS One 17:e0262682. https://doi.org/10.1371/JOURNAL.PONE.0262682
28. Ledesma RD, Shinar D, Valero-Mora PM, Haworth N, Ferraro OE, Morandi A, Papadakaki M, De Bruyne G, Otte D, Saplioglu M (2019) Psychosocial factors associated with helmet use by adult cyclists. Transp Res Part F Traffic Psychol Behav 65:376–388. https://doi.org/10.1016/J.TRF.2019.08.003
29. Wu X, Xiao W, Deng C, Schwebel DC, Hu G (2019) Unsafe riding behaviors of shared-bicycle riders in urban China: a retrospective survey. Accid Anal Prev 131:1–7. https://doi.org/10.1016/J.AAP.2019.06.002
30. Bottlang M, Rouhier A, Tsai S, Gregoire J, Madey SM (2020) Impact performance comparison of advanced bicycle helmets with dedicated rotation-damping systems. Ann Biomed Eng 48:68–78. https://doi.org/10.1007/S10439-019-02328-8/FIGURES/4
31. Varela MM, Fernandes FAO, Alves de Sousa RJ (2020) Development of an eco-friendly head impact protection device. Appl Sci 10:2492. https://doi.org/10.3390/app10072492
32. Zhang J, Wang Y, Deng H, Zhou J, Liu S, Wu J, Sang M, Gong X (2022) A high anti-impact STF/Ecoflex composite structure with a sensing capacity for wearable design. Compos B Eng 233:109656. https://doi.org/10.1016/J.COMPOSITESB.2022.109656
33. Gürgen S, Kuşhan MC, Li W (2017) Shear thickening fluids in protective applications: a review. Prog Polym Sci 75:48–72. https://doi.org/10.1016/J.PROGPOLYMSCI.2017.07.003
34. Ferreira Serra G, Fernandes FAO, Alves de Sousa JR, Noronha E, Ptak M (2022) New hybrid cork-STF (Shear thickening fluid) polymeric composites to enhance head safety in micro-mobility accidents. Compos Struct 301:116138. https://doi.org/10.1016/J.COMPSTRUCT.2022.116138
35. Antunes e Sousa GJ, Rocha ARS, Serra GF, Fernandes FAO, Alves de Sousa RJ (2023) Shear thickening fluids in cork agglomerates: an exploration of advantages and drawbacks. Sustainability (Switzerland) 15:6764. https://doi.org/10.3390/SU15086764/S1
36. Serra G, Antunes Sousa G, António Oliveira Fernandes F, José Alves de Sousa R, Jorge Henriques Noronha E (2023) Designing for sustainability and safety in urban micro-mobility: a novel helmet concept. https://doi.org/10.21203/rs.3.rs-3088077/v1

Chapter 6
Cork-Based Structures in Energy Absorption Applications

Mohammad Rauf Sheikhi, Zihao Xie, and Jian Li

6.1 Introduction

6.1.1 Energy Absorption in Engineering Structures

The process of transferring kinetic energy into other types of energy like heat, or deformation to lessen impact force and protect the structure or vehicle from damage is energy absorption (EA). EA is critical for engineering structures, particularly those subjected to dynamic loading conditions such as impact and blast pressure (see Fig. 6.1). These incidents can cause catastrophic structural damage or failure, resulting in human deaths, economic losses, or environmental consequences [2, 3]. Therefore, design a structure that can absorb and dissipate impact energy and maintain the integrity of the structure, is essential. There are several ways to achieve EA in engineering structures such as increasing the strength and stiffness of materials, using sacrificial components that deform or fracture plastically, or incorporating devices that dissipate energy through friction, damping [4]. However, these methods often have disadvantages such as increasing the weight and cost of the structure, reducing the performance and useful life of the structure, or requiring complex maintenance and replacement. Therefore, there is a need for alternative solutions that can provide efficient and effective EA with minimal defects. One of these solutions is the use of cellular materials such as foams, honeycombs structures as energy

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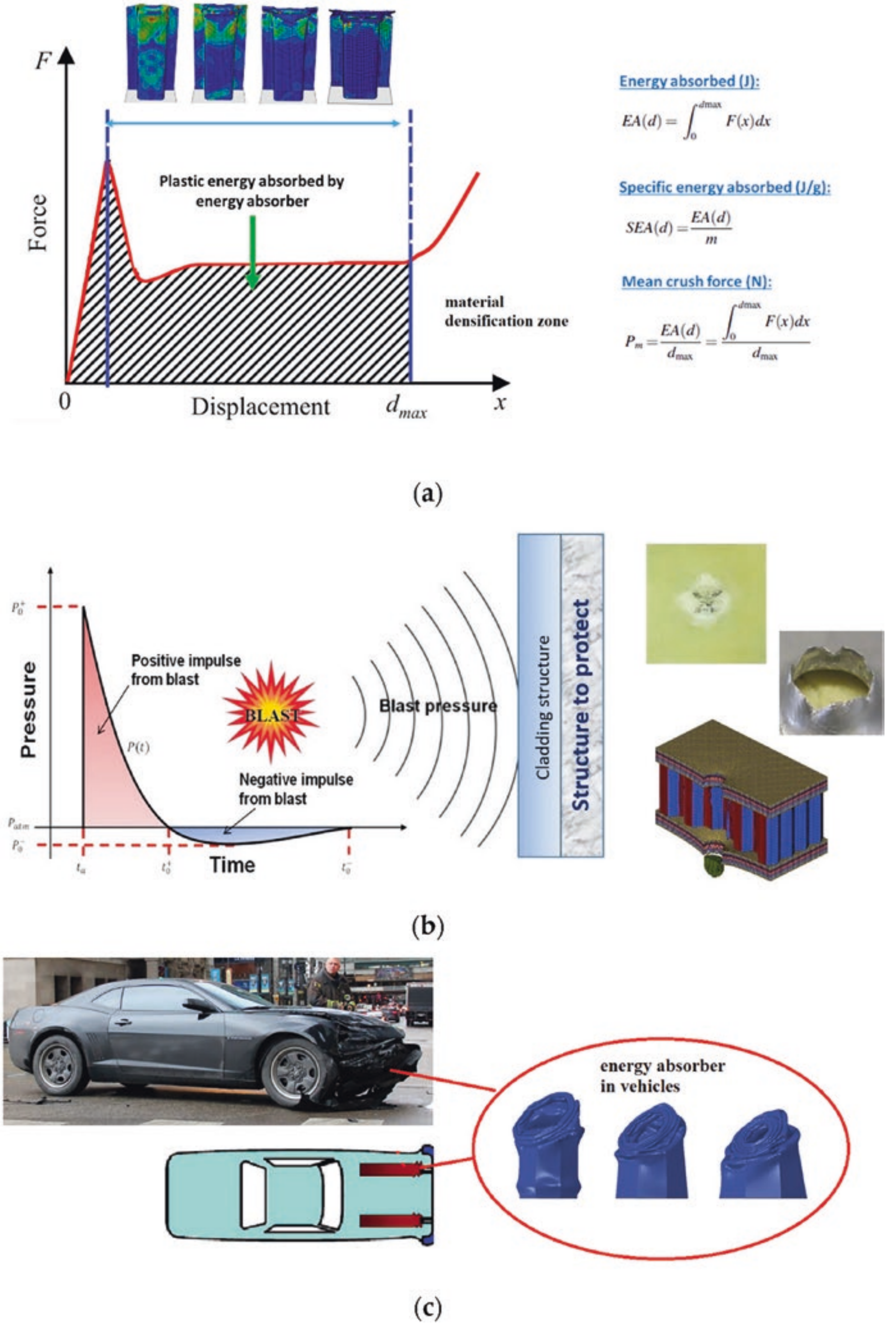


Fig. 6.1 (**a**) EA of thin-walled structures via plastic folding, (**b**) energy absorbers employed as cladding structures for blast resistant applications, (**c**) vehicle safety energy absorbers [1]

absorbers. Cellular materials are porous materials that consist of a network of cells of different shapes and sizes. They have low density and high specific strength and hardness, which makes them suitable for light weight structures. They also have a high specific energy absorption (SEA) capacity, meaning they can absorb a large amount of energy per unit mass. This is because they can undergo large deformation under compressive loading without a significant increase in stress. The deformation mechanism of cellular materials depends on cell geometry and topology, which can be designed to achieve different EA properties [5, 6].

There are two categories of cellular materials which are open-cells and close-cells [7]. First, they can induce large amounts of deformation and energy dissipation without causing high stress levels in the structure. This can reduce the risk of structural failure and increase occupant safety and survival. Second, they can provide tunable and multifunctional properties by changing cell shape, size, density, arrangement, orientation, material composition, or filling medium [8, 9]. This can enable the design of optimal structures that can meet specific requirements for different loading scenarios and applications. Third, they can exhibit self-healing or self-healing capabilities by recovering their shape and properties after deformation. It can increase the service life and reduce the maintenance cost of the structure. Cellular materials have been widely used as energy absorbers in various engineering fields such as aerospace, automotive, civil engineering, medical engineering, sports equipment, packaging industry, and personal protective equipment. Some examples of cellular materials that have been used for EA purposes include metal foams, polymer foams, ceramic foams, composite foams, honeycomb structures, acoustic structures, lattice structures, origami structures, and metamaterials [3, 5].

6.1.2 Cork Definition

Cork is a natural material obtained from the bark of cork oak trees. Cork oak trees are renewable and sustainable, as they can live up to 200 years and regenerate their bark after harvesting [10, 11]. Cork harvesting is a traditional and manual process that does not harm the trees or the environment. The cork is harvested every 9–12 years when the bark reaches a certain thickness and quality. The bark is carefully removed from the trunk and branches of the tree, leaving a thin layer of cork that protects the tree from diseases and insects. The harvested bark is then transported to factories, where it is boiled, cleaned, graded, and made into various cork products [12]. Cork has a unique cellular based structure consisting of closed cells filled with air and surrounded by a thin layer of suberin. Suberin is a hydrophobic substance that makes cork impermeable, buoyant, elastic, and fire resistant. Cork cells are usually pentagonal or hexagonal in shape (as shown in Fig. 6.2c), and their size and density vary depending on the origin and quality of the cork [13, 14]. The cork cell wall consists of a thin middle layer rich in lignin, a thick secondary wall composed of alternating suberin and waxy lamellae, and a thin third wall of polysaccharides (see Fig. 6.2). Early works state that the secondary wall is slippery and

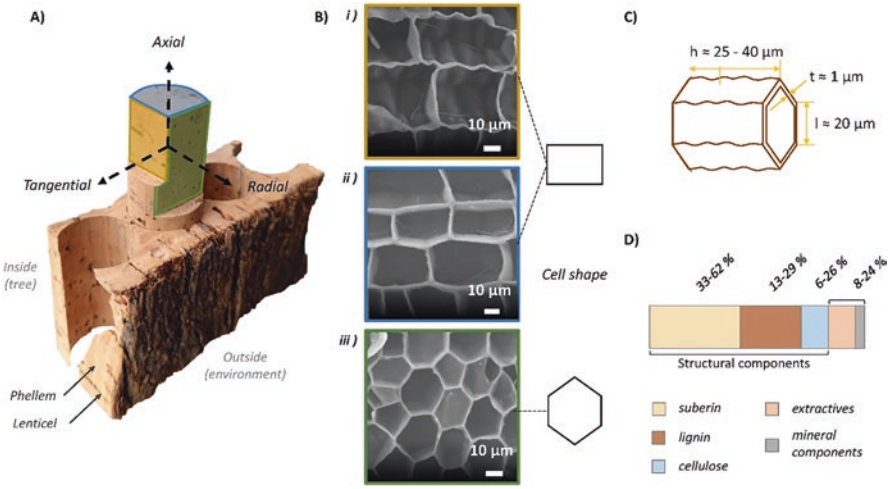


Fig. 6.2 Cork's physical structure and chemical composition: (**a**) a punched bark with a stopper illustrates the macroscopic structure of cork; (**b**) scanning electron microscopy observations from (i) the tangential direction (or radial plane), (ii) the axial direction (or transverse plane), and (iii) the radial direction (or tangential plane); (**c**) the characteristic shape and dimension of a cork cell; (**d**) the percentage of cork's structural components [13, 15–18]

thus may not consist exclusively of suberin and wax. The cork cells are filled with a mixture of gases similar to air, causing them to behave like real "pads," which helps the cork's ability to recover upon compression [19].

Cork has many properties that make it suitable for various applications. Some of the main properties of cork are low density, high compressibility, low thermal conductivity, low sound transmission, high coefficient of friction, high resistance to wear and tear, fire, water, chemicals, and biodegradation. These properties make cork a light, buoyant, elastic, flexible, insulating, durable, fire-resistant, water-resistant [20]. Cork can be classified into two types: origin cork and composite cork. Original cork is natural cork obtained directly from the bark of the cork oak tree. This cork can be used to make wine stoppers, coasters, bulletin boards, floor tiles, and other products that require the natural look and properties of cork. Composite cork obtained by mixing granulated cork with synthetic resins or rubber. Composite cork can be used to make gaskets, seals, pads, sheets, rolls, and other products that require enhanced mechanical and chemical properties of cork [21, 22].

6.1.3 Cork Applications

Cork materials used as insulation component, which effectively regulates temperature and sound, improves indoor comfort, and reduces energy consumption. Also, it can be used on the roof, wall, and floor of different buildings. It is also popular for flooring, where it offers durability and comfort [23]. Origin cork can be combined with other materials to create lightweight composites that increase their structural integrity and acoustic properties. These composites are used in facade, roof, and interior design elements and create stable and beautiful spaces. It can also decorate walls, ceilings, and room dividers with panels and tiles that add sound and heat insulation to different environments [22].

Cork-based structures have transcended traditional applications and are now at the forefront of innovation in the automotive, transportation, and aerospace industries, offering many possibilities [24]. Cork composites, are being explored for automotive interiors, providing aesthetic appeal and durability (for example used in Mazda MX-30). These composites, when used for dashboards, door panels, and seat frames, reduce overall vehicle weight, increase fuel efficiency, and reduce carbon emissions and at the same time they have good looking in interior of the cabin [21]. P50 and P45 sheets of cork materials have been used in the thermal protection system (TPS) of spacecrafts for a long time. The combination of different polymers and cork granulates creates a diverse range of materials for vibration control and acoustic insulation. Cork is a natural material candidate for the sustainable energy sector for example electric mobility and power industry because of its low thermal conductivity, sealing capacity, durability to severe temperatures, and excellent damping capacity. Additionally, cork is utilized in underlayment accessories and a flooring system that includes a top layer, inlay, core layer, and pre-attached underlayment. Furthermore, because of its special qualities, cork is utilized to make sports surfaces, shock pads, shoes, toys, and interior decor for houses and offices. Cork is still being studied and tested for use in other applications [25–29].

6.2 Literature Review on Energy Absorption in Cork Structures

In this section, we will review several studies conducted on the use of cork materials in engineering structures. Paulino et al. [30] present a novel application of cork derivatives in energy absorption and crashworthiness systems for passive automotive safety. They compare the performance of agglomerated cork (AC) with other cellular materials such as polyurethane foam, aluminum foam, and impact polypropylene in terms of EA, penetration, and peak acceleration. They developed a numerical model of a side crash test using LS-DYNA and simulated the effects of placing a AC pad inside the side door of a vehicle. They found that AC has a significant improvement over other materials in terms of reducing impact loads, increasing EA by the structure, reducing penetration levels, and reducing peak acceleration values. Tai et al. [31] conducted a study on the effect of different cellular materials on increasing the crashworthiness of a vehicle during a side impact. They used a finite element (FE) model of a sedan with different types of cellular materials sandwiched between the door panels. They simulated side impacts and measured penetration,

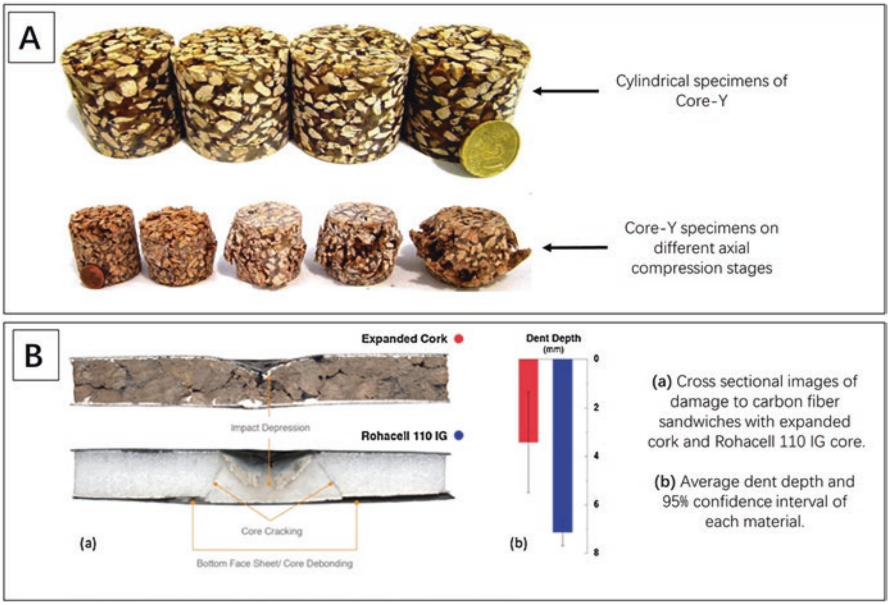


Fig. 6.3 (**a**) Combination of granular cork and an epoxy resin; (**b**) cork core–carbon fiber sandwich composite [32, 33]

internal acceleration, and EA of cellular materials. They found that the inclusion of cellular material significantly reduced passenger compartment penetration and vehicle deceleration by at least 30%.

Alcantara et al. [32] presented an innovative composite, Core-Y, made of cork granular and epoxy resin (as shown in Fig. 6.3a) and investigated its potential applications in structural elements exposed to impact. They describe the Core-Y manufacturing process and perform quasi-static axial compression tests on cylindrical specimens to determine its mechanical properties. They also developed a numerical model based on experimental results to simulate the EA of metallic tubular structures with Core-Y. They concluded that Core-Y has a huge capacity for crushing and is a good candidate for various applications in the automotive industry. In another study, Walsh et al. [33] conducted a study to compare the performance of expanded cork with a synthetic foam (Rohacell), as core materials in sandwich structures with carbon fiber-based face sheets (see Fig. 6.3b). They conducted various tests to measure the bending stiffness, sound and vibration damping, and impact resistance of the composites. They found that expanded cork has lower flexural stiffness than Rohacell but significantly higher sound and vibration damping and impact resistance. They concluded that expanded cork can be a good alternative to synthetic foams for sandwich composites because of better EA and environmental benefits.

Furthermore, Miralbes et al. [34] carried out a study to compare the mechanical properties of cork and AC with expanded polystyrene (EPS) foam under compressive loads. Using energy and yield diagrams, they selected the most suitable material based on the required EA or the maximum stress that should not be exceeded. They also considered certain properties per unit mass, which are more relevant for applications where weight is critical. They found that natural cork had the highest nonspecific and specific properties among cotton products but reached density earlier. EPS had better nonspecific and specific properties than AC due to its low density and larger plateau area. The efficiency graphs showed that EPS has the highest efficiency, followed by natural cork, and the efficiency is related to the compression point.

Serra et al. [35] conducted a study on the impact resistance of hybrid composites made of cork and other materials containing shear thickening fluid (STF) for head protection devices used in micro mobility (see Fig. 6.4a). They tested different combinations of cork sheets, polymers, fabric, and STF under different impact energies. They compared the peak acceleration, strain energy density, strain and impact duration of the composites. They found that two types of composites performed well: (1) one with STF sandwiched between cork and thermoplastic polyurethane (TPU), which reduced peak acceleration and increased deformation levels; (2) fabric with cork and fabric impregnated with STF, which had the highest amount of strain and duration of impact and the lowest density. They concluded that these composites are good candidates for using in helmets. In a subsequent study, Le Barbenchon et al. [36] studied the microstructure and mechanical behavior of AC, made from natural cork granules and bio resin (see Fig. 6.4b). They used optical and scanning electron microscopy (SEM) and X-ray computed tomography to investigate the surface and

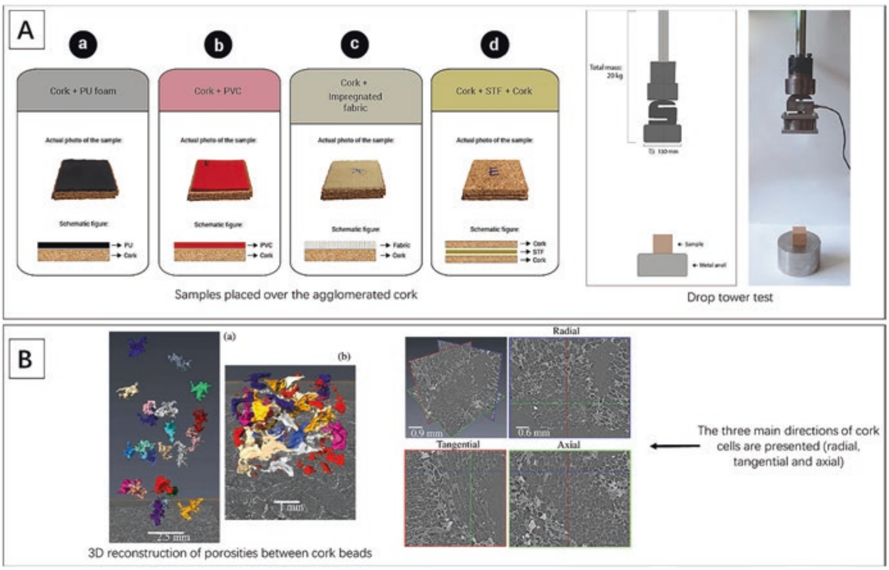


Fig. 6.4 (**a**) The authors made different sandwich samples from Polyanswer and cork; (**b**) 3D reconstruction of porosities between cork beads [35, 36]

spatial arrangement of cork grains and cells. They found that the material has a transversely anisotropic geometry and structure, which affects its mechanical properties under pressure. They performed quasi-static compression tests and used digital image correlation (DIC) to measure the strain and EA of the material. They observed that the material has different stiffness, density, and viscoelastic recovery in different directions. They also identified high strain inhomogeneities and localization bands on the surface of the material. They suggested that their findings could be used to develop better models for AC and understand their behavior at higher strain rates.

Paulino et al. [37] performed a numerical study on the impact behavior of four cellular materials: polyurethane foam, IMPAXX™ 300, aluminum foam, and AC. They used analytical and FE models to compare the energy-absorbing capability, performance index, and peak acceleration of each material under different initial impact kinetic energies. They found that aluminum foam had the highest EA capacity, followed by cork, while IMPAXX™ had the highest specific energy absorption (SEA), followed by AC. They also found that AC and aluminum foam had the lowest peak acceleration values, indicating better crashworthiness. They concluded that AC is the most beneficial material for low kinetic energy values, while aluminum foam is better for larger kinetic energies.

In a separate study, Coelho et al. [38] investigated the potential of cork as a material to absorb impact energy, especially in comparison to expanded polystyrene (EPS), which is commonly used in safety systems such as helmets (see Fig. 6.5b). They simulated compression tests and double impacts on different configurations of hybrid layers consisting of AC and EPS. They found that EPS performed better on the first impact, but lacked spring return and lost EA capacity on the second impact. On the other hand, the AC had a good level of EA with almost full spring return. They also observed that parallel systems, where the AC and EPS layers alternated, had higher accelerations and shorter impact durations than sequential systems, where the AC and EPS layers were separated. They concluded that there is no clear optimal arrangement for hybrid layers, but suggested some possible candidates that balance thickness reduction, deceleration, and weight reduction. Moving on to the next study, Kaczynski et al. [39] conducted a study on the impact behavior of AC under different temperature conditions. They tested five types of AC with different densities and grain sizes and subjected them to impact tests at temperatures from −30 to 100 °C (see Fig. 6.5a). They measured the amount of absorbed EA by cork samples during impact and developed a material model to describe the relationship between temperature, density, and EA. They found that temperature had a significant effect on the performance of AC, especially for high-energy impacts.

Sánchez-Saez et al. [40] performed an experimental study on the dynamic crushing behavior of AC (see Fig. 6.6a), which can be used as a substitute for polymer foams for impact absorbing elements in vehicles. They investigated how the sample thickness affects the energy-absorbing capability, contact force, and strain of cork under dynamic compressive loads. They performed weight loss tests with samples of four different thicknesses and measured the variables mentioned above. They found that the maximum contact force and strain increased with the impact to

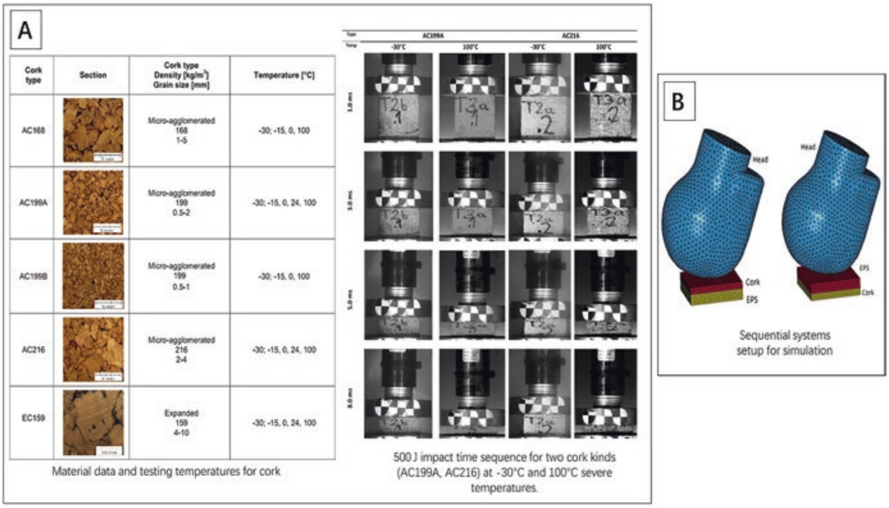


Fig. 6.5 (**a**) The authors made five sandwich samples from Polyanswer and cork; (**b**) 3D reconstruction of porosities between cork beads [38, 39]

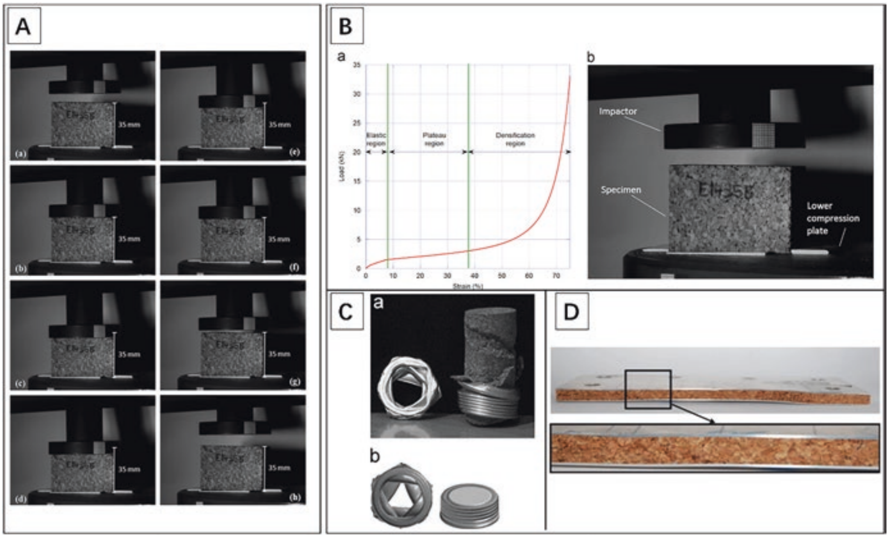


Fig. 6.6 (**a**) Dynamic crushing test impactor and AC specimen displacement; (**b**) (a) NL-10 AC compression load—strain curve and (b) 35 mm thick specimen low-velocity impact test; (**c**) experimental and numerical shape histories of empty and cork-filled tubes in drop-weight device; (**d**) sandwich structure based on cork [40–43]

energy/thickness ratio, while the energy absorbed by the cork was independent of the sample thickness. They concluded that AC has great potential for EA applications, but it also has a large scatter in results due to its natural origin and diversity of properties. In another study, Sánchez-Saez et al. [41] conducted an experimental investigation on the multi-impact behavior of AC (see Fig. 6.6b). They tested specimens with various thicknesses and two impact energy levels using a low velocity impact tower and measured the maximum contact force, maximum strain, and EA in each test. They found that AC cork agglomerates have great EA capability, as the energy absorbed is independent of the number of impacts. They also observed that the maximum contact force and maximum strain were affected by the sample thickness and impact energy level, and they related these variables to the load–strain curve of AC under pressure. They concluded that AC can be a good alternative for some engineering applications subject to multiple impacts.

Shifting focus to another study, Gamiro et al. [42] conducted a study on the use of fine AC as filler inside aluminum tubes to increase their EA during impact loading (see Fig. 6.6c). They performed dynamic experimental tests and numerical simulations with LS-DYNATM software to compare the load-deformation properties, energy-absorbing characteristics, and collapse mode transition of empty and cork-filled tubes with different diameters, thicknesses, and lengths. They found that the percentage increase in absorbed EA by cork-filled tubes depends on the slenderness ratio of the tubes, which is defined by the diameter-to-thickness ratio and the length-to-diameter ratio. They observed that the percentage increase in absorbed energy increases with increasing diameter-to-thickness ratio and decreasing length-to-diameter ratio.

Continuing the exploration, Souza-Martinez et al. [43] conducted an experimental study on the burst response of sandwich structures with AC composite cores and aluminum alloy sheets (see Fig. 6.6d). They tested different core thicknesses and densities under a constant blast load and measured the transmitted impulse and deflection of the faceplates. They also analyzed the internal deformation and damage of the core material and the bond between the core and face plates. They found that core thickness and density have a significant effect on the structural response of sandwich specimens. They also observed that the core material exhibits an almost constant stress region for increasing strains until solidification, allowing it to absorb significant amounts of energy by crushing. Le Barbenchon et al. [44] investigated the effects of temperature and strain rate on the compressive behavior of AC. They performed quasi-static and dynamic tests at different temperatures and strain rates and measured stress–strain curves and foam material parameters. They found that temperature and strain rate both have significant effects on the mechanical behavior of the foam, but with opposing effects. They attributed this to the viscoelastic nature of cork, one of the foam's constituents. They also observed different failure mechanisms under different loading conditions. They developed a specific experimental setup for performing high strain rate experiments at temperature and demonstrated its feasibility by testing the foam at −20 °C in the dynamic regime.

Sheikhi and Gürgen [45] conducted a study on the deceleration behavior of multilayer composites made of AC and STF for protective applications. They aim to exploit the advantages of AC as an eco-friendly material with high EA and STF as a smart material that changes its viscosity under loading. They designed different configurations of AC, foam, and STF layers and tested their performance under impact loading. They found that encapsulation of STF-impregnated foam layers in the composites reduced the peak velocity and increased the time period of velocity deceleration with increased shear thickening formation. They proposed that their eco-friendly smart composites could be used to coat internal components in sensitive systems such as electronic systems, robotic devices, and unmanned aerial vehicles (UAVs). An experimental study of multilayer composites made of AC and warp-knitted spacer fabrics (WKSF) for anti-impact applications was carried out by Sheikhi et al. [46]. They designed and created eight different configurations of composites (see Fig. 6.7b – bottom) with a laser cutting machine and tested their EA capacity using a low-velocity impact machine. They also calculated the life cycle assessment (LCA) of the composites to evaluate their environmentally friendly properties. They found that the structures composed of AC and WKSF layers provide great performance for protective applications, but the position of the components in the multilayer structures affects the EA (see Fig. 6.7b – top). They also found that AC has lower carbon emissions than WKSF and dominates the LCA criteria. In a contrasting study, Sheikhi and Gürgen [47] investigated the EA of STF-enhanced multilayer composites under low energy impact test. They used AC, WKSF, and foam as the main components of the composite and filled STF in the foam layers (see Fig. 6.7a). They compared the performance of composites with and without STF in terms of maximum reaction forces (RF), EA, and SEA. They found that the inclusion of STF improved the anti-impact properties of the composites by increasing the viscosity and dissipating the impact energy over a larger area. They also found that the most effective design was Config-12, which had one layer of coarse-grained AC, one layer of foam, and one layer of WKSF.

Sánchez-Saez et al. [48] investigated the effect of AC on the high-velocity impact behavior of thin aluminum plates. They performed impact-perforation tests on three types of samples: neat AC, pure aluminum plates, and aluminum plates with a AC core (see Fig. 6.8a). They measured the ballistic limit, residual velocity, and EA of each sample. They found that AC has a lower ballistic limit and absorbs less energy than aluminum plates. However, when the cork was utilized as a core material between two aluminum plates, it increased the ballistic limit and absorbed more energy than pure aluminum plates. They concluded that the AC core did not change the failure mechanism of the aluminum plates but improved their ballistic performance.

Moving to another investigation, Fernandes et al. [49] compared the mechanical performance of AC and synthetic materials (EPS and EPP) as shock energy absorbers. They performed quasi-static compression tests, guided drop tests (see Fig. 6.8b), and finite element analysis to evaluate the energy storage capacity, stress–strain behavior, and multiple dynamic loading response of the materials. They found that AC is an excellent alternative to synthetic materials because it is a natural, stable, and resilient material that can withstand significant impact

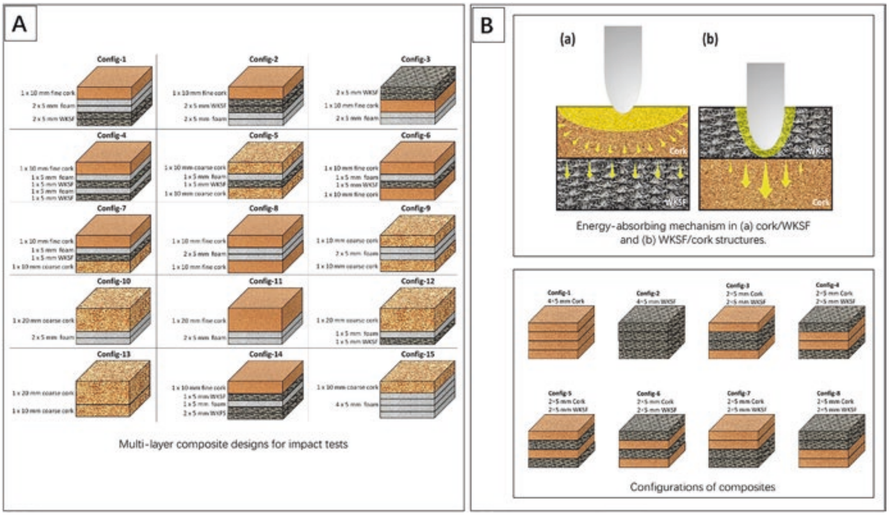


Fig. 6.7 (**a**) Anti-impact design of AC-based multilayer composites enhanced by shear thickening fluid; (**b**) energy-absorbing properties of AC and WKSF-based composites [46, 47]

energies and retain some of its original properties after loading. They also developed a reliable framework for simulating the mechanical response of natural and synthetic cellular materials. They concluded that replacing synthetic foams with natural foams is an acceptable and better solution for protective liners. Shifting our focus to a separate research, Fernandes et al. [50] investigated the application of AC as a cushioning material in helmets (see Fig. 6.8c), as a sustainable alternative to EPS. They developed a finite element model of a motorcycle helmet and compared the performance of AC and EPS liners under impact scenarios. They also created a generic helmet model with different thicknesses and sections of AC liners and assessed their head injury risk using another finite element head model. They found that AC liners have excellent impactability properties and can be recovered after compression, making them suitable for multi-impact applications. They also suggested that thinner helmets with AC liners are possible and that AC could be used in other types of helmets.

The effect of low-velocity impact damage on the ballistic performance of composite sandwich panels with AC core and integrated sheets was investigated by Ivañez et al. [51]. They compared the impact behavior of both types of samples at two impact energies of 25 and 40 J and measured the peak load, force–displacement curves, impact bending stiffness, absorbed energy, impact indentation ratio, and ballistic limit in surface density. They found that low-velocity impact damage did not significantly affect the sandwich panels but reduced the ballistic resistance of the panels. They concluded that the AC core improved the impact resistance of previously damaged composite structures.

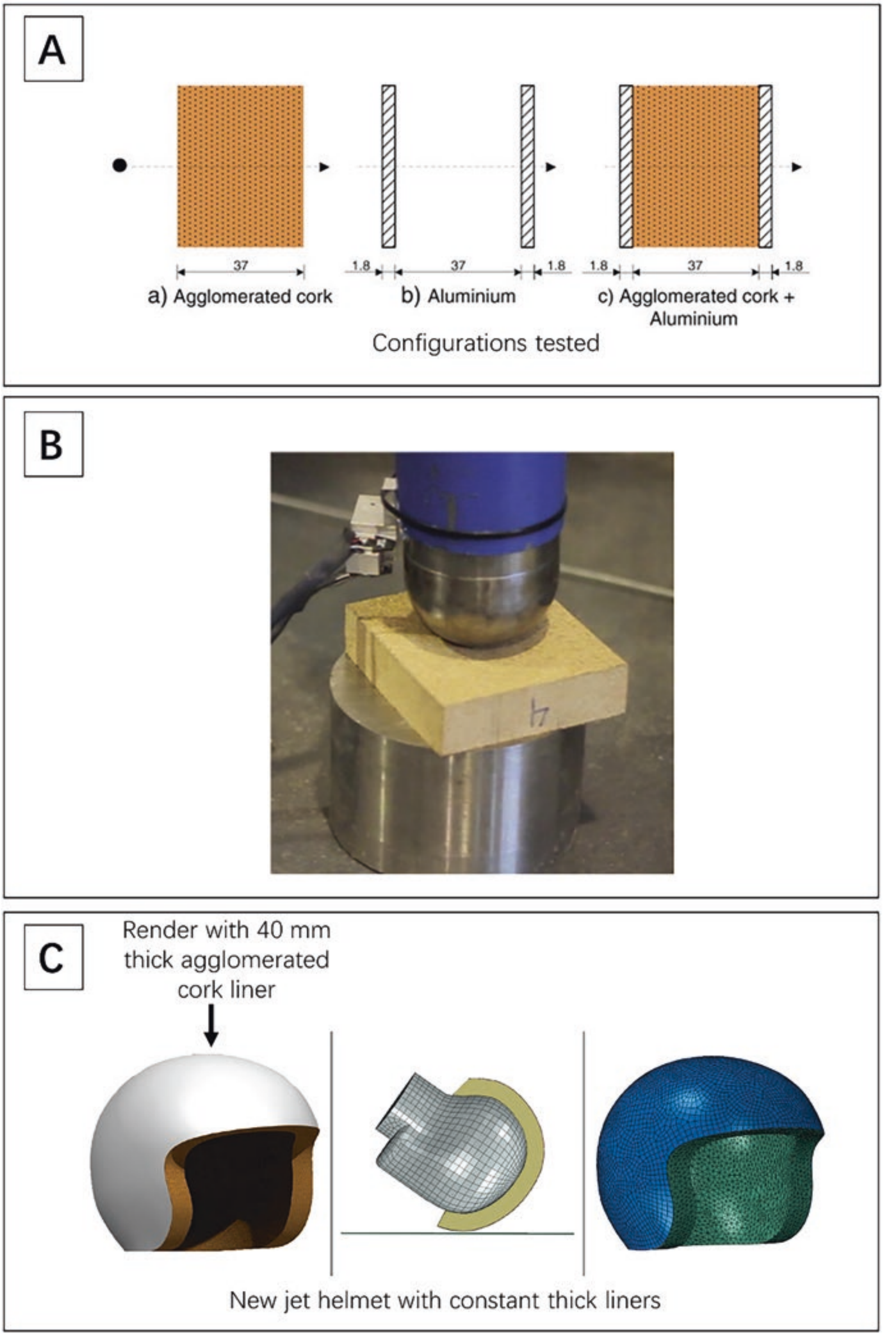


Fig. 6.8 (**a**) Configuration tests for AC-cored structures subjected to ballistic impacts; (**b**) drop tower-based impact test designed by the authors; (**c**) new helmet design [48–50]

6.3 Energy Absorption Performance of Agglomerated Cork Composites: A Case Study

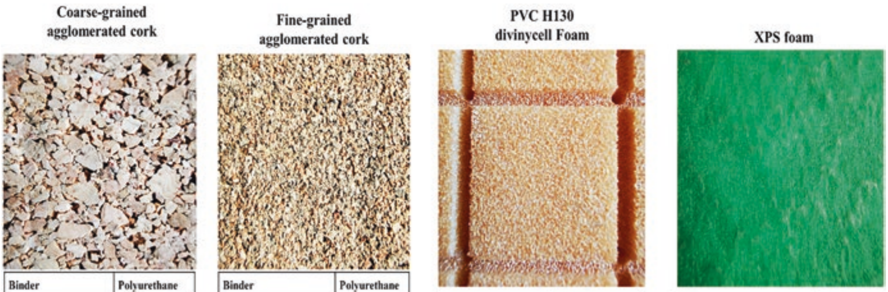
6.3.1 Materials and Method

To investigate the energy absorption properties of cork materials, we selected four materials with different densities: XPS foam (34 kg/m^3), PVC foam (130 kg/m^3), fine-grained agglomerated cork (180 kg/m^3), and coarse-grained agglomerated cork (130 kg/m^3). We prepared samples with dimensions of 80 × 80 mm^2 and adjusted their thickness according to their density to guarantee the same weight for all samples. The thicknesses were 100 mm for XPS foam, 26 mm for coarse-grained cork and PVC foam, and 20 mm for fine-grained agglomerated cork. We performed a low-velocity impact test on the samples using a drop tower device. The impactor had a hemispherical shape with a diameter of 15 mm and a mass of 1.02 kg. We dropped the impactor from a height of 1 m corresponding to an energy level of 10.3 J and measured the impact force damping using a dynamometer placed under the samples. We calculated the EA of the samples from the potential energy difference between the first and second impact of the impactor on the samples. The specifications of the component are detailed in Fig. 6.9. The materials and testing apparatus are illustrated in Fig. 6.10.

6.3.2 Results and Discussion

6.3.2.1 Maximum Reaction Forces

The curves for the selected materials' impact responses are given in Fig. 6.11 and Fig. 6.12 indicates the highest reaction forces (RFs). XPS foam demonstrates a maximum RF of 1398 N which is the least among others while fine cork has 1500 N, coarse cork at 1622 N, and PVC foam with 1690 N. The peak force of the energy-absorbing structures or materials under impact must be kept below the threshold that would cause damage, while still providing a sufficient total EA capacity in the large deformation process. The RF should remain constant or nearly constant to avoid an excessively high rate of retardation. XPS foam is a closed-cell polymer foam with high compression strength and low density. It has a high initial modulus allowing it to deform elastically at lower stresses than other cells but can deform plastically at larger stress levels resulting in greater deformation and high EA. Fine cork has low density and high porosity which enables it to be soft yet strong enough when compressed as well as exhibiting low stiffness. Moreover, although it can undergo elastic and plastic deformation, its deformation is smaller, and EA is less than that for XPS foam. According to the results, fine cork is suitable for anti-impact applications because of the reduced RF as compared to PVC foam and coarse cork. Similarly, coarse cork has a higher RF in comparison to fine cork thereby



Binder	Polyurethane
Density	120-130 kg/m³
Granule size	2-6 mm
Thickness	26 mm
Modulus of elasticity	16-35 MPa

Binder	Polyurethane
Density	170-190 kg/m³
Granule size	0.1-1.5 mm
Thickness	20 mm
Modulus of elasticity	18-50 MPa

Density	120-130 kg/m³
Tensile strength	4.8 MPa
Thickness	26 mm
Modulus of elasticity	175 Mpa

Density	34 kg/m³
Tensile strength	0.380 MPa
Thickness	100 mm
Modulus of elasticity	0.371 GPa

Fig. 6.9 Details of the components

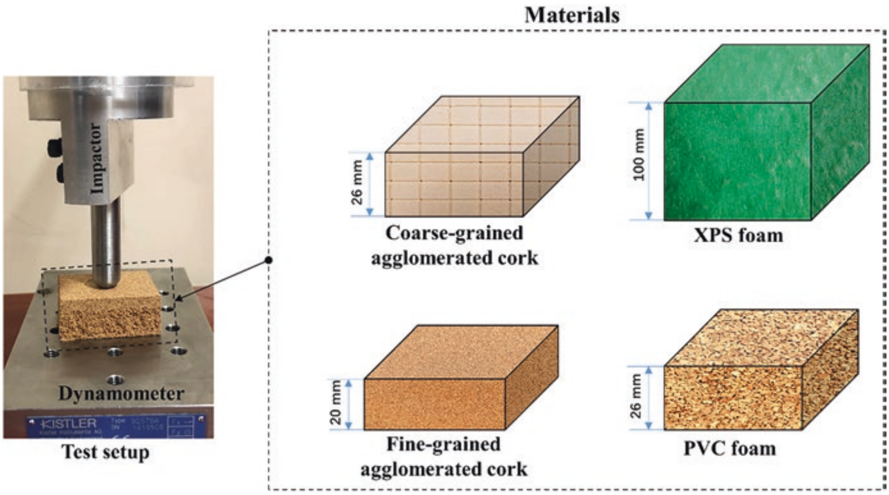


Fig. 6.10 Experimental test setup and specimens

compromising its protective capability. Among the chosen materials, PVC foam has the highest RF.

6.3.2.2 Energy Absorptions

As seen from Fig. 6.13 which shows the EA capacities of selected materials. XPS foam has the best performance in absorbing energy (9.07 J). Then fine cork absorbed more energy (8.04) after XPS foam and this was obtained while it was less thick than PVC foam. Fine cork has smaller grains and high porosity, and this makes it easier to deform after impact and absorb more energy through elastic and plastic

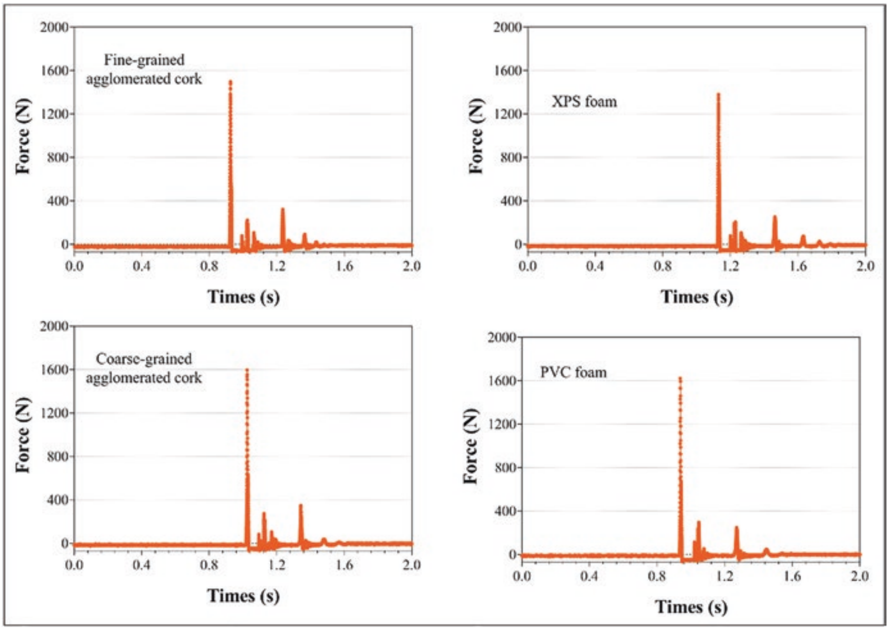


Fig. 6.11 Reaction force curves for the specimens

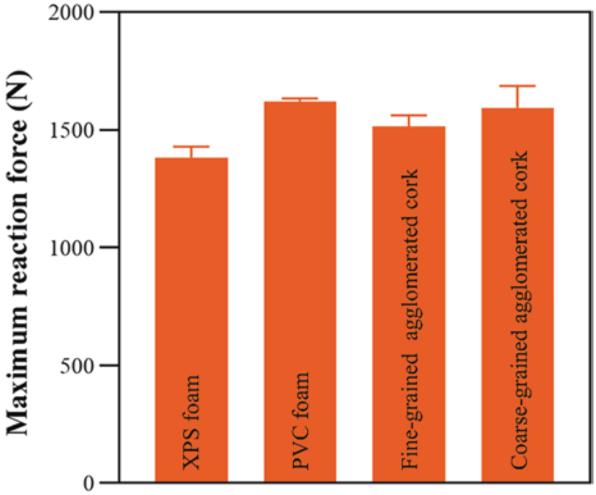


Fig. 6.12 Maximum reaction forces for the specimens

deformation. Coarse cork has larger grains and less porosity, which makes it more resistant to deformation than fine cork. Coarse cork can withstand more loads before failure but absorbs less energy from a sudden impact.

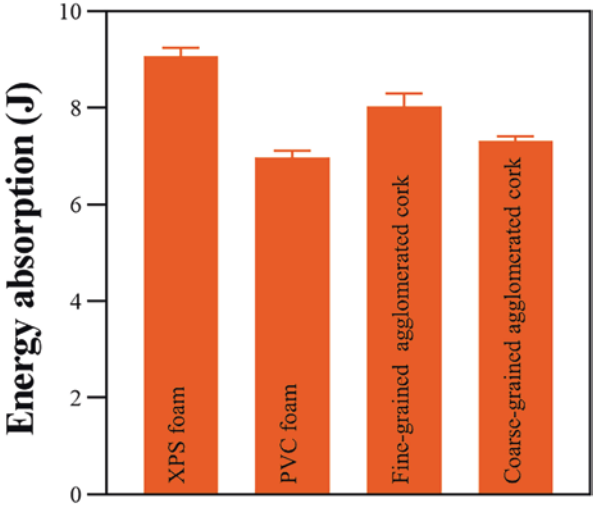


Fig. 6.13 Absorbed energy by the specimens

6.4 Conclusions

In this chapter, we investigated the energy absorption (EA) properties of cork materials. First, the studies conducted by researchers were reviewed, and it was shown how they used cork materials in different structures for anti-impact and energy-absorbing purposes. The review of their studies showed that although cork materials cannot be used alone in most applications due to their poor mechanical properties, by their high EA capabilities, they can be used as an auxiliary part of the main structure to absorb energy. In the second part of the chapter, the energy-absorbing capacity of two types of cork composites (fine and coarse agglomerated cork) is compared with two types of synthetic PVC and XPS foam. All were subjected to an impact test device, and their EA values were calculated. The results demonstrated that, despite having less thickness, fine cork has better performance than PVC foam, which shows that the impact resistance of cork material is inherently high. With smaller grains and higher porosity, fine cork can deform easily upon impact and absorb less energy in impact time. The results of the second part of the chapter indicated that cork materials are promising candidates for use in energy absorption structures, and fine cork can perform better results than coarse cork. The energy-absorbing structure should be light, possessing a high specific energy absorption (SEA) capacity, which is vital important for vehicles energy absorber components and personal safety devices. Since cork has a cellular structure, it has a low weight, and this has made it a high SEA.

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References

1. Tarlochan F (2021) Sandwich structures for energy absorption applications: a review. Materials 14:4731. https://doi.org/10.3390/ma14164731
2. Farley GL (1983) Energy absorption of composite materials. J Compos Mater 17:267–279. https://doi.org/10.1177/002199838301700307
3. Ha NS, Lu G (2020) A review of recent research on bio-inspired structures and materials for energy absorption applications. Compos B Eng 181:107496. https://doi.org/10.1016/j.compositesb.2019.107496
4. Lu G, Yu T (2003) Energy absorption of structures and materials. Woodhead Publishing Limited, London
5. Gladysz GM, Chawla KK (2015) Cellular materials. In: Voids in materials. Elsevier, Amsterdam, pp 103–130
6. Novak N, Vesenjak M, Nishi M et al (2021) Mechanical behavior of cellular materials – from quasistatic to high strain rate impact response. In: Explosion, shock-wave and high-strain-rate phenomena of advanced materials. Elsevier, London, pp 109–154
7. Gibson LJ (1989) Modelling the mechanical behavior of cellular materials. Mater Sci Eng A 110:1–36. https://doi.org/10.1016/0921-5093(89)90154-8
8. Baroutaji A, Arjunan A, Niknejad A et al (2019) Application of cellular material in crashworthiness applications: an overview. In: Reference module in materials science and materials engineering. Elsevier, Amsterdam
9. Habib F, Iovenitti P, Masood S et al (2019) Design and evaluation of 3D printed polymeric cellular materials for dynamic energy absorption. Int J Adv Manuf Technol 103:2347–2361. https://doi.org/10.1007/s00170-019-03541-4
10. Aroso IM, Araújo AR, Pires RA, Reis RL (2017) Cork: current technological developments and future perspectives for this natural, renewable, and sustainable material. ACS Sustain Chem Eng 5:11130–11146. https://doi.org/10.1021/acssuschemeng.7b00751
11. Ana Carina P, Han B, Helena P, Joost V (2012) Cork and sustainability: discussing the sustainable use of the material from a design perspective. J Shanghai Jiaotong Univ Sci 17:360–363. https://doi.org/10.1007/s12204-012-1287-8
12. Leal S, Nunes E, Pereira H (2008) Cork oak (Quercus suber L.) wood growth and vessel characteristics variations in relation to climate and cork harvesting. Eur J For Res 127:33–41. https://doi.org/10.1007/s10342-007-0180-8
13. Silva SP, Sabino MA, Fernandes EM et al (2005) Cork: properties, capabilities and applications. Int Mater Rev 50:345–365. https://doi.org/10.1179/174328005X41168
14. Şen A, Quilhó T, Pereira H (2011) The cellular structure of cork from Quercus cerris var. cerris bark in a materials' perspective. Ind Crop Prod 34:929–936. https://doi.org/10.1016/j.indcrop.2011.02.015
15. Chanut J, Wang Y, Dal Cin I et al (2022) Surface properties of cork: is cork a hydrophobic material? J Colloid Interface Sci 608:416–423. https://doi.org/10.1016/j.jcis.2021.09.140
16. Pereira H (1988) Chemical composition and variability of cork from Quercus suber L. Wood Sci Technol 22:211–218. https://doi.org/10.1007/BF00386015
17. Pintor AMA, Ferreira CIA, Pereira JC et al (2012) Use of cork powder and granules for the adsorption of pollutants: a review. Water Res 46:3152–3166. https://doi.org/10.1016/j.watres.2012.03.048
18. (1981) The structure and mechanics of cork. Proc R Soc Lond A Math Phys Sci 377:99–117. https://doi.org/10.1098/rspa.1981.0117
19. Pereira H, Emília Rosa M, Fortes MA (1987) The cellular structure of cork from Quercus suber L. IAWA J 8:213–218. https://doi.org/10.1163/22941932-90001048
20. Crouvisier-Urion K, Chanut J, Lagorce A et al (2019) Four hundred years of cork imaging: New advances in the characterization of the cork structure. Sci Rep 9:19682. https://doi.org/10.1038/s41598-019-55193-9

21. Gil L (2009) Cork composites: a review. Materials 2:776–789. https://doi.org/10.3390/ma2030776
22. Soares B, Reis L, Sousa L (2011) Cork composites and their role in sustainable development. Proc Eng 10:3214–3219. https://doi.org/10.1016/j.proeng.2011.04.531
23. Gil L (2015) New cork-based materials and applications. Materials 8:625–637. https://doi.org/10.3390/ma8020625
24. Castro O, Silva JM, Devezas T et al (2010) Cork agglomerates as an ideal core material in lightweight structures. Mater Des 31:425–432. https://doi.org/10.1016/j.matdes.2009.05.039
25. Gürgen S, Fernandes FAO, de Sousa RJA, Kuşhan MC (2021) Development of eco-friendly shock-absorbing cork composites enhanced by a non-Newtonian fluid. Appl Compos Mater 28:165–179. https://doi.org/10.1007/s10443-020-09859-7
26. Silva JM, Devezas TC, Silva A et al (2010) Exploring the use of cork based composites for aerospace applications. Mater Sci Forum 636–637:260–265. https://doi.org/10.4028/www.scientific.net/MSF.636-637.260
27. Gul J, Saleemi AR, Mirza S et al (2010) Thermal and mechanical characteristics of cork filled insulation for aerospace applications. Plastics Rubber Composit 39:28–32. https://doi.org/10.1179/174328910X12608851832010
28. Santos Silva J, Dias Rodrigues J, Moreira RAS (2010) Application of cork compounds in sandwich structures for vibration damping. J Sandw Struct Mater 12:495–515. https://doi.org/10.1177/1099636209104538
29. Caniato M, Orfeo S, Kaspar J, Di Monte R (2013) Green cork-based innovative resilient and insulating materials: acoustic, thermal, and mechanical characterization. J Acoust Soc Am 133:3453–3453. https://doi.org/10.1121/1.4806128
30. Paulino M, Teixeira-Dias F (2011) An energy absorption performance index for cellular materials – development of a side-impact cork padding. Int J Crashworth 16:135–153. https://doi.org/10.1080/13588265.2010.536688
31. Tay YY, Lim CS, Lankarani HM (2014) A finite element analysis of high-energy absorption cellular materials in enhancing passive safety of road vehicles in side-impact accidents. Int J Crashworth 19:288–300. https://doi.org/10.1080/13588265.2014.893789
32. Alcântara I, Teixeira-Dias F, Paulino M (2013) Cork composites for the absorption of impact energy. Compos Struct 95:16–27. https://doi.org/10.1016/j.compstruct.2012.07.015
33. Walsh J, Kim H-I, Suhr J (2017) Low velocity impact resistance and energy absorption of environmentally friendly expanded cork core-carbon fiber sandwich composites. Compos Part A Appl Sci Manuf 101:290–296. https://doi.org/10.1016/j.compositesa.2017.05.026
34. Miralbes R, Ranz D, Ivens J, Gomez JA (2021) Characterization of cork and cork agglomerates under compressive loads by means of energy absorption diagrams. Eur J Wood Wood Product 79:719–731. https://doi.org/10.1007/s00107-020-01625-7
35. Ferreira Serra G, Fernandes FAO, Alves de Sousa JR et al (2022) New hybrid cork-STF (Shear thickening fluid) polymeric composites to enhance head safety in micro-mobility accidents. Compos Struct 301:116138. https://doi.org/10.1016/j.compstruct.2022.116138
36. Le Barbenchon L, Girardot J, Kopp J-B, Viot P (2019) Multi-scale foam : 3D structure/compressive behaviour relationship of agglomerated cork. Materialia (Oxf) 5:100219. https://doi.org/10.1016/j.mtla.2019.100219
37. Paulino M, Dias FT, Gameiro CP, Cirne J (2009) Hyperelastic and dynamical behaviour of cork and its performance in energy absorption devices and crashworthiness applications. Int J Mater Eng Innov 1:197. https://doi.org/10.1504/IJMATEI.2009.029364
38. Coelho RM, Alves de Sousa RJ, Fernandes FAO, Teixeira-Dias F (2013) New composite liners for energy absorption purposes. Mater Des 43:384–392. https://doi.org/10.1016/j.matdes.2012.07.020
39. Kaczynski P, Ptak M, Wilhelm J et al (2019) High-energy impact testing of agglomerated cork at extremely low and high temperatures. Int J Impact Eng 126:109–116. https://doi.org/10.1016/j.ijimpeng.2018.12.001

40. Sanchez-Saez S, García-Castillo SK, Barbero E, Cirne J (2015) Dynamic crushing behaviour of agglomerated cork. Mater Des 1980–2015(65):743–748. https://doi.org/10.1016/j.matdes.2014.09.054
41. Sanchez-Saez S, Barbero E, Garcia-Castillo SK et al (2015) Experimental response of agglomerated cork under multi-impact loads. Mater Lett 160:327–330. https://doi.org/10.1016/j.matlet.2015.08.012
42. Gameiro CP, Cirne J (2007) Dynamic axial crushing of short to long circular aluminium tubes with agglomerate cork filler. Int J Mech Sci 49:1029–1037. https://doi.org/10.1016/j.ijmecsci.2007.01.004
43. Sousa-Martins J, Kakogiannis D, Coghe F et al (2013) Behaviour of sandwich structures with cork compound cores subjected to blast waves. Eng Struct 46:140–146. https://doi.org/10.1016/j.engstruct.2012.07.030
44. Barbenchon LL, Viot P, Girardot J, Kopp J-B (2022) Energy absorption capacity of agglomerated cork under severe loading conditions. J Dyn Behav Mater 8:39–56. https://doi.org/10.1007/s40870-021-00316-5
45. Sheikhi MR, Gürgen S (2022) Deceleration behavior of multi-layer cork composites intercalated with a non-Newtonian material. Arch Civil Mech Eng 23:2. https://doi.org/10.1007/s43452-022-00544-z
46. Sheikhi MR, Gürgen S, Altuntas O (2022) Energy-absorbing and eco-friendly perspectives for cork and WKSF based composites under drop-weight impact machine. Machines 10:1050. https://doi.org/10.3390/machines10111050
47. Sheikhi MR, Gürgen S (2022) Anti-impact design of multi-layer composites enhanced by shear thickening fluid. Compos Struct 279:114797. https://doi.org/10.1016/j.compstruct.2021.114797
48. Sanchez-Saez S, Barbero E, Cirne J (2011) Experimental study of agglomerated-cork-cored structures subjected to ballistic impacts. Mater Lett 65:2152–2154. https://doi.org/10.1016/j.matlet.2011.04.083
49. Fernandes FAO, Jardin RT, Pereira AB, Alves de Sousa RJ (2015) Comparing the mechanical performance of synthetic and natural cellular materials. Mater Des 82:335–341. https://doi.org/10.1016/j.matdes.2015.06.004
50. Fernandes F, Alves de Sousa R, Ptak M, Migueis G (2019) Helmet design based on the optimization of biocomposite energy-absorbing liners under multi-impact loading. Appl Sci 9:735. https://doi.org/10.3390/app9040735
51. Ivañez I, Sánchez-Saez S, Garcia-Castillo SK et al (2020) High-velocity impact behaviour of damaged sandwich plates with agglomerated cork core. Compos Struct 248:112520. https://doi.org/10.1016/j.compstruct.2020.112520

Chapter 7
Experimental Behavior of Cork-Based Structures Under Impact Conditions

Anand Pai and Marcos Rodríguez-Millán

7.1 Introduction

Cork agglomerate is primarily composed of cork granules obtained from the bark of the cork oak tree (*Quercus suber*). The bark of the cork oak tree, primarily found in Europe's Mediterranean region, is used to make cork agglomerate. The cork bark is picked carefully, with the outer layers stripped away while the inner bark is preserved. The base material for cork agglomerate is then made from this inner bark, which has been chopped into tiny granules or particles [1]. These cork particles are mixed with a natural binder, typically a high-quality adhesive or resin derived from suberin, a natural substance found in cork, to make cork agglomerate. The mixture is then subjected to high pressure, compressing it to form blocks or sheets of varying thicknesses. The resulting material exhibits a characteristic honeycomb structure, imparting cork agglomerate with unique properties. On the other hand, expanded cork, also known as black agglomerate or insulation cork, offers distinct characteristics. Expanded cork is a lightweight agglomerate structure with exceptional water resistance and low thermal conductivity. The manufacturing process for expanded cork involves exposing cork bark granules to compression and superheated steam. The steam heats the granules, expanding them by up to 30 vol. % and activating the natural resins that bind the granules together. This traditional process, which has been in use since the late 1800s, causes the cell walls to stretch and lose thickness during expansion, resulting in the unique properties of expanded cork [2].

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Cork agglomerate has excellent insulation properties (such as thermal, vibration, and acoustic insulation) because of closed cellular structure. Moreover, cork cores have a high energy-absorbing capacity as well as good dimensional recovery under impact [3]. Therefore, due to these properties, cork-based materials have potential industrial applications in ballistic and energy absorption applications, including their use in safety devices, protective equipment, and other applications where energy absorption is essential. This chapter presents the energy absorption capacity of cork-based materials over a wide range of impact velocities, from low to high-velocity impacts.

7.2 Cork-Based Structures at Low-Velocity Impacts

As a cellular material, cork has been used as a core material in multilayered sandwich laminates [4] to absorb energy due to compression. Cork layers have also been deployed as facing layers to impart thermal resistance. While thicker cork layers have been employed in cores, thinner layers have qualified as the facing materials in many laminates [5].

Agglomerated cork specimens with varying thicknesses and two impact energies were studied by Sánchez-González et al. [1] to determine their multi-impact behavior. The impactor had a circular-flat tip with a total mass of 4.134 kg. The specimens featured a 50 mm × 50 mm cross-section and three varied thicknesses. A total of 36 tests were done in this study. The authors investigated the maximum contact force, maximum strain, and absorbed energy with the structures. The maximum contact force and maximum strain decreased by increasing thickness of the structures for all the impact energies. The maximum strain showed a rise with each subsequent impact when the impacting energy created stresses in the plateau area and stayed virtually constant in the densification stage. A large amount of the impact energy, from 70 % to 80 %, was absorbed for both impact energy levels. The absorbed-energy percentage rose marginally at greater impact-energy levels. The maximal strain and force had a comparatively modest dispersion of 7.5 %, while the absorbed energy had a scatter of 9 %. Thicker specimens revealed the maximum strain values of roughly 25–30 % with an impact energy of 35 J; hence, no specimen showed the densification stage. The increase in strain for the lowest impact energy examined between the first and third hits was 31%, i.e., double the amount seen in thicker specimens.

Gomez et al. [6] investigated the low-velocity impact response of woven carbon/epoxy laminates with an agglomerate cork core. A steel projectile of 7.5 mm diameter was made to strike the laminates at two velocities: 91 and 151 m/s, respectively. For a comprehensive investigation into the impact phenomenon, two impact velocities were carefully chosen to examine the process in detail. The first velocity was selected to ensure that perforation of the front facesheet did not occur, while the second velocity was explicitly aimed at producing perforation of the front facesheet perforation. By utilizing this approach, the model can thoroughly analyze the penetration process, focusing on factors such as damage evolution and energy absorption through various mechanisms.

Sergi et al. [7] studied the impact behavior of bio-based sandwich structures having an agglomerated cork core and intraply flax/basalt hybrid facesheets when subjected to puncture impact. For comparison, a series of impact tests were conducted on three agglomerated cork samples with varying densities and three polyvinylchloride (PVC) foams with similar densities. The results guided the selection of one specific agglomerated cork variant (NL25) and one PVC foam variant (HP130) for further analysis. Finite element analysis (FEA) was carried out on the selected core materials, and complete sandwich composites were subsequently fabricated based on these findings.

Wang et al. [8] studied the impact response of sandwich structures with different core materials. The structures were made of aluminum facesheets with five different cores: low-density balsa wood, high-density balsa wood, cork, polypropylene honeycomb, and polystyrene foam. The structures were subjected to a hemispherical steelhead projectile impacts at three different impact energies: 43, 85, and 120 J, respectively (Fig. 7.1).

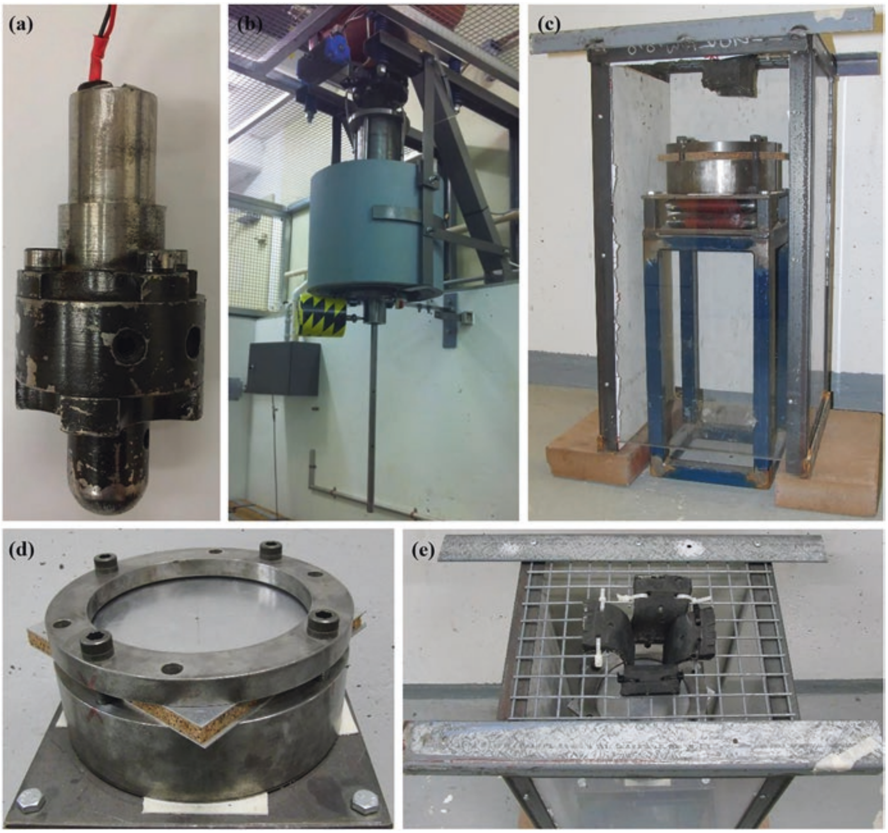


Fig. 7.1 Experimental setup for the drop weight test [8]

The sandwich structure with a high-density balsa core (Balsa HD) had the highest peak force at all three impact energies (43, 85, and 120 J), according to the results of the impact tests. The peak force of the sandwich structures with low-density balsa (Balsa LD), high-density balsa, and cork cores remained almost constant when the impact energy was increased to 120 J. At the impact energies of 43 and 85 J, the Balsa HD core sandwich structure absorbed the highest specific energy. However, the Balsa LD core panel outperformed the Balsa HD core panel at the impact energy of 120 J. The sandwich structure with a polystyrene foam core (PS foam) absorbed the lowest energy (74.3 J) at the impact energy of 120 J. The specific energy of the PS foam core panel was also the lowest at all three impact energies. For the sandwich panels with a cork core, the local indentation on the top surface was lower than its global bending deformation, except at the lowest impact energy. The depth map of the cork and PS foam core sandwich structures on the front facesheet showed a rhombus shape, indicating that the sandwich panel underwent significant deformation due to the different clamping forces between the sample's corners and sides. Figure 7.2 shows the cross-section views of sandwich panels after a 120 J impact.

Sarasini et al. [9] studied the impact response of green sandwich panels with agglomerated cork in the middle and flax/epoxy facesheets on the outside. The study used a CEAST/Instron 9340 instrumented drop-weight impact testing system for low-velocity impact tests. The impactor was a hemispherical one, measuring 20 mm in diameter. The experimental setup involved using samples with varying mass compositions, including a dropped body with a total mass of 3 kg for flax/epoxy facesheets and 8 kg for the remaining samples. The experimental findings indicate that agglomerated cork exhibits a distinct rebound phase when subjected to low-velocity impact tests, occurring at a perforation energy level of 25 %. The material experiences reduced damage upon impact at lower velocities. At a perforation energy level of 25 %, it was observed that the cork specimens exhibited no discernible damage on either of their surfaces. An indentation was observed at 50 % of the perforation energy, which subsequently increased in depth to 75 % of the perforation energy. The resulting cross-sectional views of the damaged region are depicted in Figs. 7.3 and 7.4.

Sheikhi et al. [10] investigated multilayer composites made of cork and warp-knitted spacer fabrics (WKSF) for energy-absorbing applications. WKSF is a three-dimensional textile structure with high porosity and thickness. Combining cork and WKSF can create lightweight, eco-friendly composites with high energy absorption capacity. The authors designed and fabricated eight different configurations of composites with a laser cutting machine. They used a low-velocity drop-weight impact machine to measure the energy absorbed by the manufactured composite structures. The impact tests used a 5 kg cylindrical steel rod with a hemispherical tip as the projectile. The velocities at which the impacts were conducted varied between 2.5 and 4 m/s. The composites under study were made of cork sheets measuring 3 mm in thickness and WKSF with a thickness of 10 mm. The composites were cut into square shapes with 100 mm × 100 mm dimensions to prepare the specimens for testing. They measured the composites' specific energy absorption and life cycle

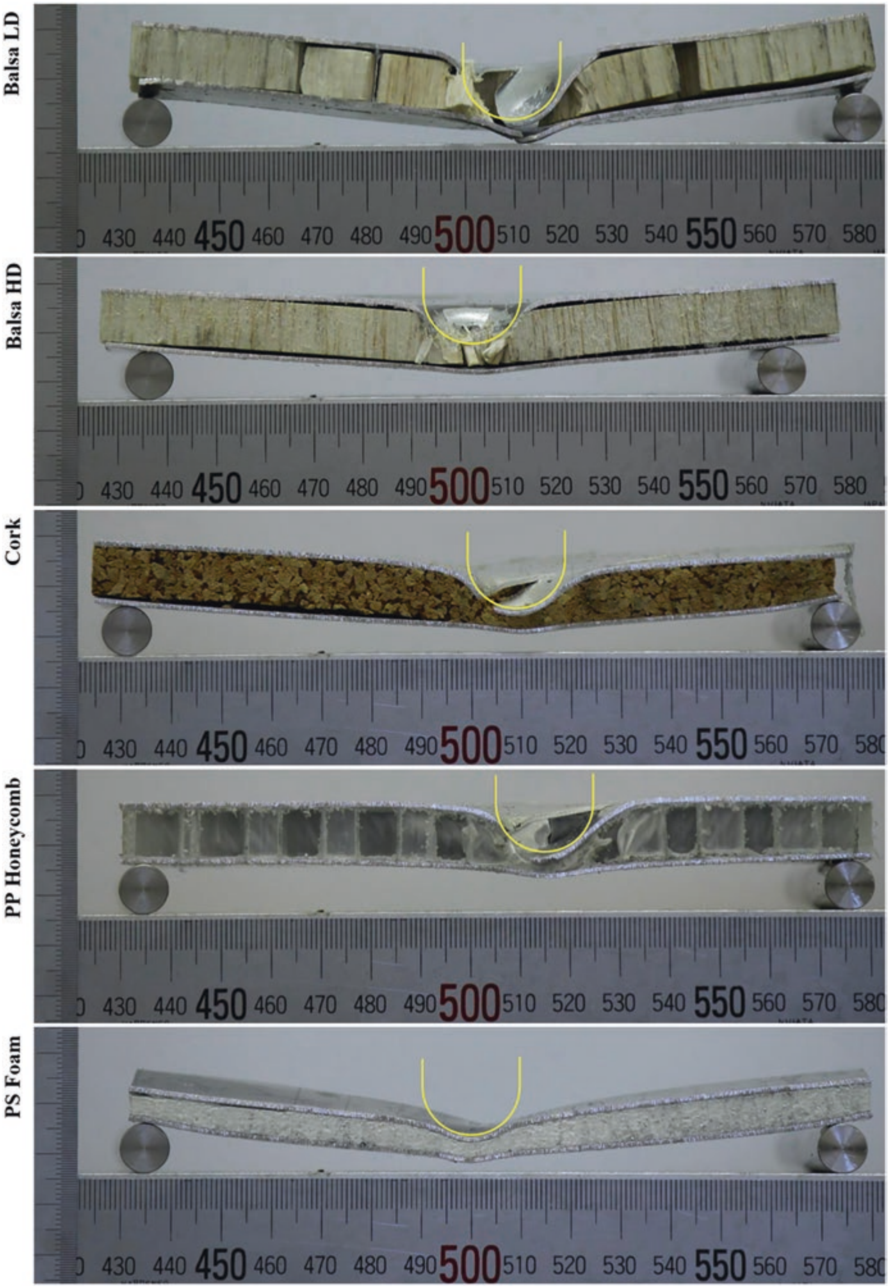


Fig. 7.2 Cross-section views of sandwich panels after a 120 J impact [8]

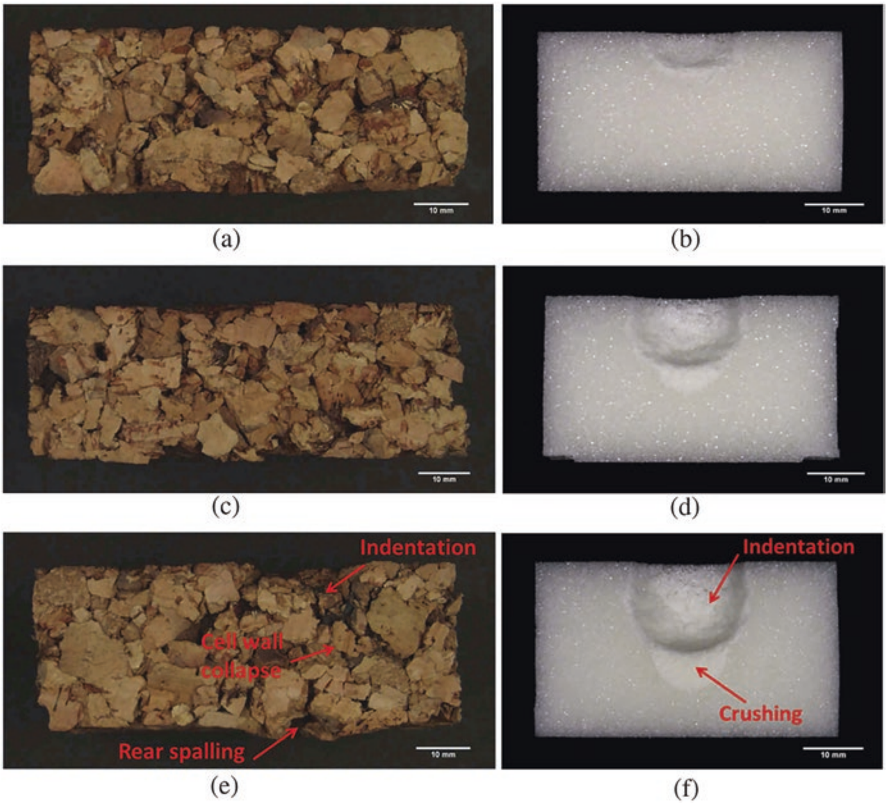


Fig. 7.3 Cross-section views for cork and synthetic foam specimens from 25% to 75% perforation energy [9]

assessment, to understand their environmental impact. The results show that the cork–WKSF composites have a high energy absorption capacity, especially at low-impact velocities. The cork layer reduced the peak impact force and the backface deformation, while the WKSF layer dissipated the impact energy through its deformation. Therefore, they concluded that the top layers of cork are more effective than the top layers of WKSF in absorbing the impact energy. Also, the cork at the top layer can spread the impact energy to distant areas and compress the WKSF layer below. The WKSF at the top layer transfers much of the impact energy to the lower layers. Therefore, the distant areas of WKSF at the top layers are not used effectively to reduce the impact energy. The life cycle assessment reveals that cork-WKSF composites have a lower environmental impact than conventional composites made of synthetic materials.

Gabriel Serra et al. [11] examined the combined effects of shear thickening fluid (STF) and cork agglomerates on low- and high-energy impacts. Cork-STF impregnated fabric, cork-STF with bulk STF as an interlaying agent, cork-STF with bulk STF encapsulated between cork and TPU, and cork-STF filled polymers were made

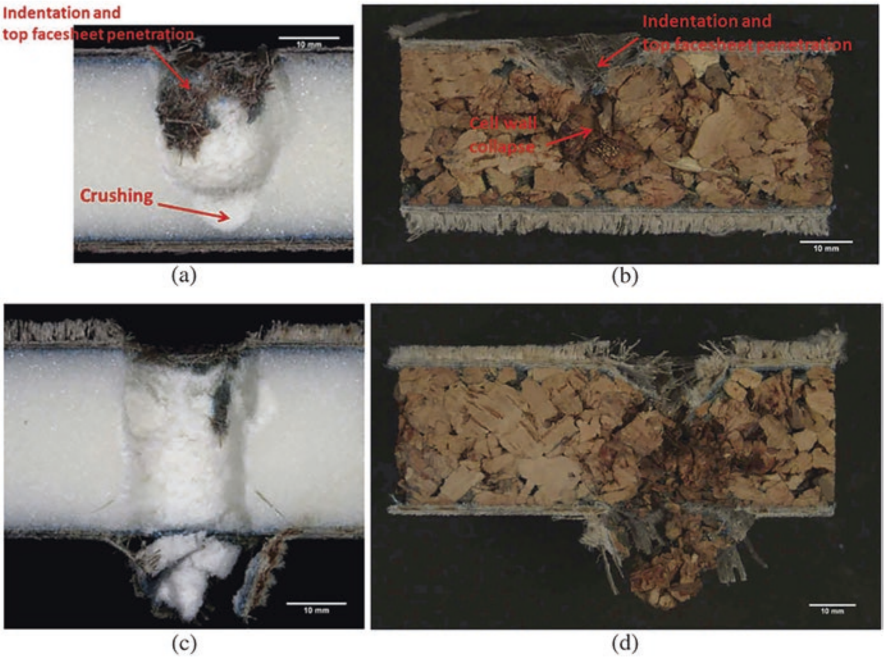


Fig. 7.4 Cross-section views for cork and synthetic foam specimens at 75% perforation energy [9]

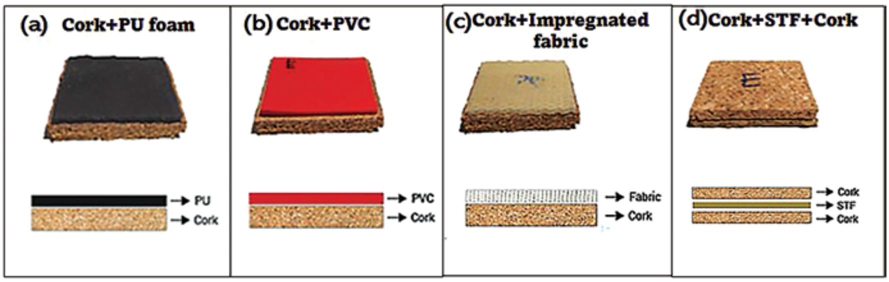
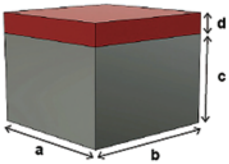
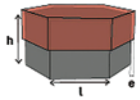


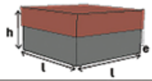
Fig. 7.5 Specimen configurations used in the impact tests [11]

so that the impact response of these structures could be studied. The specimens are shown in Fig. 7.5 while Fig. 7.6 shows the details of them.

The results suggested that the proposed solutions have promise for incorporation into future versions of helmets for high-risk drivers. The findings indicate that the bulk application of STF exhibits superior performance under conditions of complete restriction and high-impact energies. The study found that when STF (C30-STF-TPU) samples were encapsulated and subjected to impacts of 100 J, there was a reduction in peak acceleration of 8.50 %. Additionally, the encapsulated samples exhibited smoother deceleration at higher deformation magnitudes for a given







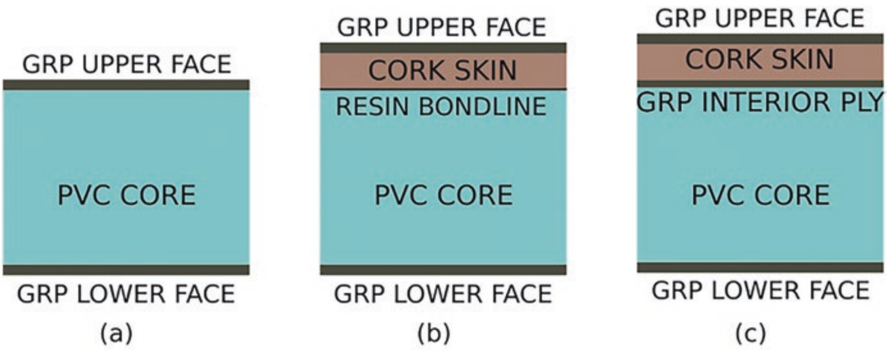
	Sample's visual configuration	Sample code	Dimensions (mm) a	b	c	d
Individual		C10	50	50	-	9.65
		BF10	50	51	-	10
		C30	59	59	-	30
		C60	59	59	-	60
Combined samples (placed over cork)		C5-C5	51	51	5	5
		C5-STF-C5	51	51	5	5
		C10 + IF	50	50	10	4.10
		C10 + PVC	52	51	9.65	3.30
		C10 + BF3,3	45	45	9.65	3.30
		C60 + BF3,3	50	50	60	3.30
		C60 + PVC	46	46	60	3,30
		C60 + IF	49	49	60	4.10
		C50 + BF10	50	50	51	10
		C50 - F - C10	60	60	51	10
Encapsulated samples		Sample code	l	e (wall thickness)		h
		C20	20	-		20
		C20 + TPU	20	1		20
		C20-STF-TPU	20	1		20
		C30 + TPU	60	1		30
		C30-STF-TPU	60	1		30

C = Cork; BF = Black Foam; STF = Shear Thickening Fluid; IF = Impregnated Fabric; Number after a letter stands for the thickness of the sample, ex: C10 = 10 mm cork.

Fig. 7.6 Samples configurations and dimensions [11]

amount of energy absorbed per unit volume. The PU foam specimens, specifically BF10 and C50 + BF10, exhibit favorable outcomes concerning their maximum strain energy density and maximum strain. On the contrary, it has been observed that the peak acceleration was relatively high, and the impact time was comparatively low compared to other low-energy impact samples. The cork and impregnated fabric composites exhibited superior resistance for low- and high-energy impact scenarios. The C10 + IF and C60 + IF samples had the highest values for strain and impact duration, and the C10 + IF and C60 + IF samples had the highest strain for the specified levels of absorbed energy. In addition, the composite material under investigation exhibits the lowest weight among the samples tested, indicating a favorable balance between its density and capacity to absorb energy.

Sutherland et al. [5] evaluated six different configurations of cork-skinned sandwich composites and compared them with a baseline of glass-reinforced plastic (GRP)/PVC foam sandwich laminate typically used in marine structures (Fig. 7.7). According to the results, laminates 5 and 7 have the highest perforation resistance, with an increase in perforation energy of roughly 40 % and 60 %, respectively, compared to the baseline laminate. Notably, the laminates featuring core cork skin exhibit greater weight than the simple PVC core, which serves as the baseline. Also, laminates 5 and 7 have an additional GRP ply, contributing to their overall weight.



Candidate sandwich laminates.

Laminate	Core	Cork skin	Interior ply	Upper plies	Thickness (mm)
1 (baseline)	PVC	None	–	3	24.8
2	PVC	2 mm 'Thin'	–	3	26.8
3	PVC	4 mm 'Thick'	–	3	28.8
4	PVC	2 mm 'Thin'	1	2	26.8
5	PVC	2 mm 'Thin'	1	3	27.6
6	PVC	4 mm 'Thick'	1	2	28.8
7	PVC	4 mm 'Thick'	1	3	29.6

Fig. 7.7 Specimen configurations and associated nomenclature [5]

In addition, the best weight-saving solution for boosting perforation resistance is to use a laminate made up of two upper-face GRP plies, a thin core cork skin, and one interior GRP ply (referred to as laminate 4). The results in this study indicate that the proposed concept could enhance the perforation resistance of laminates. Both the quasi-static indentation and impact loading rates are improved, but the laminate becomes heavier as a result.

Fernandes et al. [12] carried out an approach to analyze the possibility of cork use in motorcycle helmets. The researchers first developed a finite element model of a commercially available motorcycle helmet to evaluate its safety performance. Additionally, they aimed to establish a direct comparison between cork agglomerates and polystyrene as liners. A novel helmet model with a generic geometry was subsequently created to test the viability of using agglomerated cork as a liner material for different types of helmets. Different iterations of helmet liners were developed by manipulating their thickness and selectively removing portions of the material. Subsequently, the liners' performance is evaluated through double-impact testing. The findings from the conducted tests suggest that agglomerated cork liners can serve as a highly viable substitute for synthetic liners. The material in question exhibits a remarkable capacity for energy absorption and can withstand repeated impacts while maintaining its performance integrity. The authors concluded that using agglomerated cork in protective equipment can enhance its effectiveness and ability to endure multiple impacts. Therefore, it is considered that there is a great field to be analyzed by linking it with individual safety terms such as the minimization of brain injury.

7.3 Cork-Based Structures at High-Velocity Impacts

The ballistic evaluation of cork-based materials has not been studied less than with low-impact velocity tests. Generally, the ballistic tests performed in the literature have employed a pneumatic launcher with spherical projectiles.

Sanchez-Saez et al. [13] investigated the impact behavior of structures composed of agglomerated cork cores subjected to high-velocity loading. The study involved testing three distinct specimens: an agglomerated cork, two thin aluminum plates spaced apart, and a pair of thin aluminum plates separated by a core made of agglomerated cork as depicted in Fig. 7.8. The goal of this study is to investigate the response of agglomerated cork and the influence of the cork core on its ballistic limit, residual velocity, and energy absorption. The ballistic tests were conducted utilizing a Sabre Ballistics model A1G+ gas gun. In this study, a sample size of 55 specimens was subjected to impact velocities ranging from 130 to 680 m/s. The impact was induced by spherical steel projectiles measuring 7.5 mm in diameter and weighing 1.7 g. Figure 7.9 shows the ballistic curves for the specimens. From the chart, inserting a cork agglomerate core between two aluminum plates leads to a ballistic limit increase of 7.7%. The agglomerate cork's absorbed energy decreases significantly as the impact velocities increase, ultimately leading to the complete perforation of the spaced aluminum plates. In contrast, the reduced absorbed energy by the aluminum plates spaced apart exhibits a comparatively smaller magnitude. The amount of energy absorbed by the aluminum plates changes noticeably due to the cork core. The addition of the cork core enhances the structure's ability to absorb energy by about 30% when tested with an impact energy of 300 J.

Amaro et al. [14] investigated the ballistic performance and damage resistance of composites reinforced with Kevlar/epoxy and a cork powder matrix. The production of cork stoppers generates a significant amount of cork powder, considered the primary waste product of cork processing. This waste material accounts for

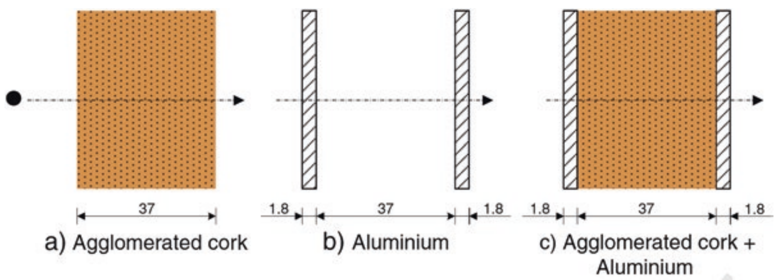


Fig. 7.8 Specimen configurations used in the impact tests [13]

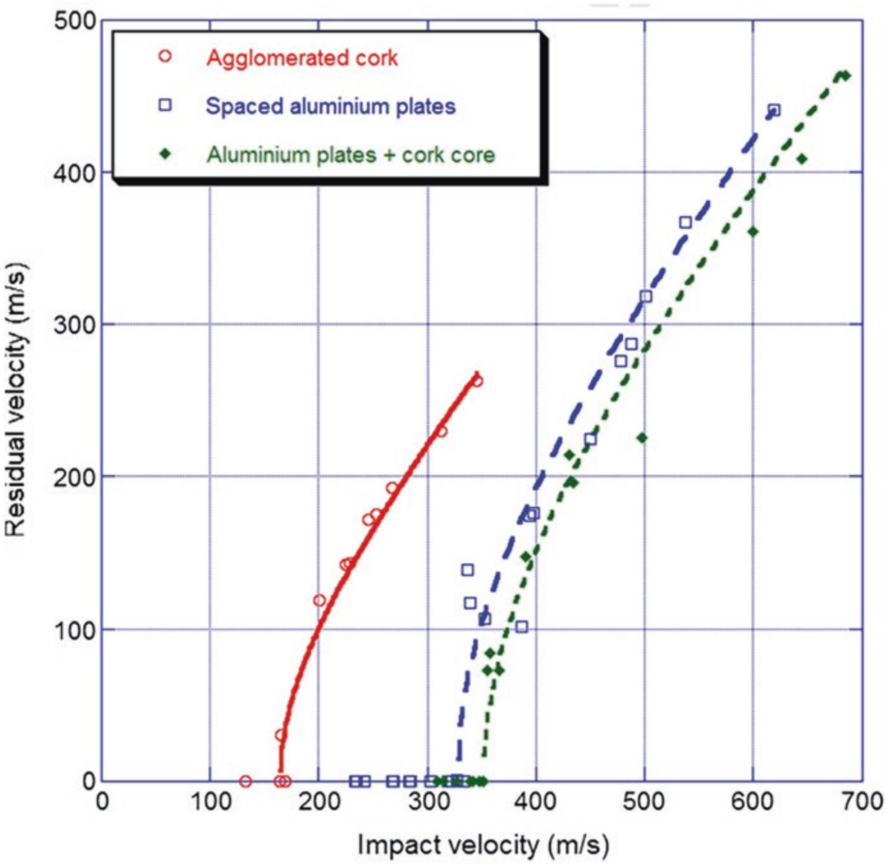


Fig. 7.9 Ballistic curves for the specimens [13]

approximately 25–30% of the raw cork material used in production. Reducing resin content in composites by incorporating cork powder is an indisputable fact, leading to enhanced environmental sustainability. The cork powder utilized in the study was supplied from the residual material generated during the concluding sanding process of cork stoppers. The material was procured from the industrial premises of Amorim Cork S.A., located in Valada, Portugal. High-velocity impact tests were conducted on bidirectional Kevlar woven laminate plates, each with a surface area of 100×100 mm^2. A 7.5 mm diameter spherical projectile made of steel was used in the impact experiments. Ultrasonic inspection, more specifically the C-scan mode, was used for the damage assessment of the impacted samples. The findings indicate that Kevlar laminates with neat resin exhibit a minimum perforation velocity of approximately 206.35 ± 4.20 m/s. On the other hand, Kevlar laminates with resin filled with cork powder demonstrate a minimum perforation velocity of roughly 209.71 ± 4.63 m/s. The incorporation of cork particles results in a reduction of damage areas, particularly at velocities that fall below the minimum perforation threshold. The observed trend in the absorbed energy as a function of the impact energy is comparable between the two plate types (Fig. 7.10). The plates located below the perforation site are observed to effectively absorb the kinetic energy of the projectile, primarily through the occurrence of damage. The absorbed energy exhibits an asymptotic decrease when the impact energy exceeds the perforation point.

Resin envelops the cork granules, forming closed cells that contain air. According to the authors, these cells can deform under an impact force, allowing them to absorb the force without suffering damage. Because of the large number of open through-cut cells and the inability of the resin to allow cell deformation, smaller granules exhibit comparatively lower levels of improvement compared to larger ones. As a result, the capacity of the system to absorb energy is limited. The response of the cork/resin composite is subject to the influence of the number of closed cells present in the granules.

The damaged areas on the specimens are depicted in Fig. 7.11 based on the C-scan. It is observed that the extent of damage is greater at velocities approximating the minimum perforation velocity. When the damaged areas on the laminates made with plain resin are compared to those made with cork powder mixed into the resin, a clear trend shows that the latter has less damage in all cases. The cork additives exhibit a remarkable energy absorption capacity. As previously mentioned, the

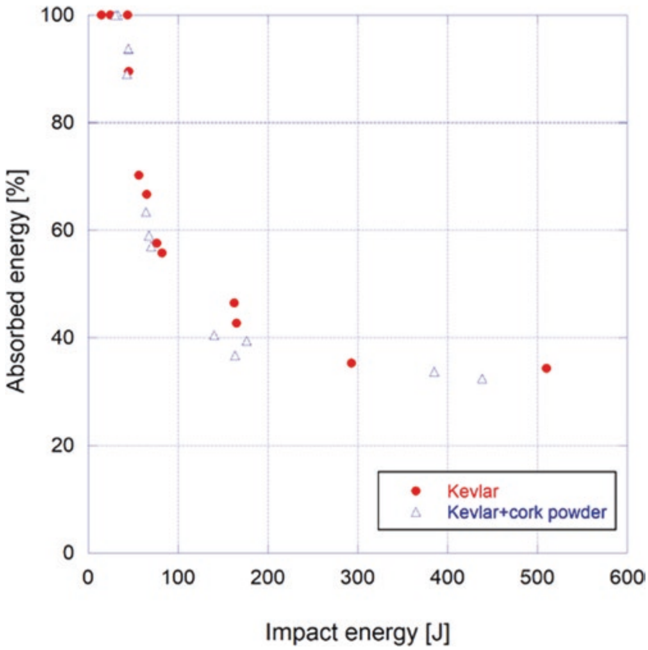


Fig. 7.10 Energy absorbed by the specimens [14]

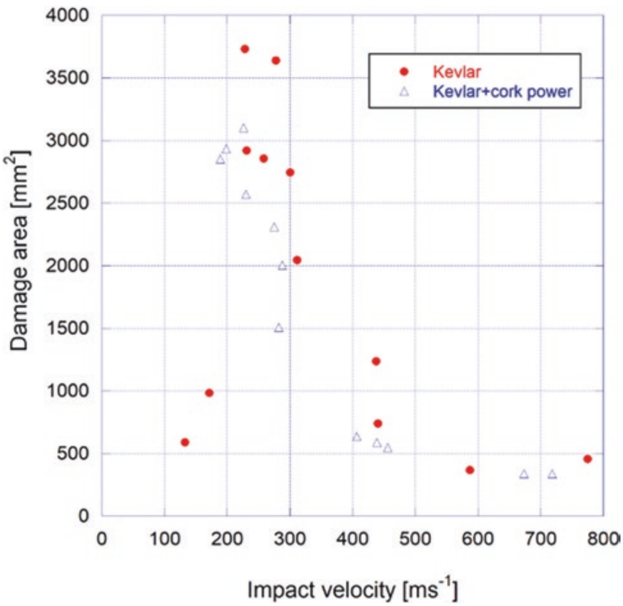


Fig. 7.11 Damage area vs impact velocity [14]

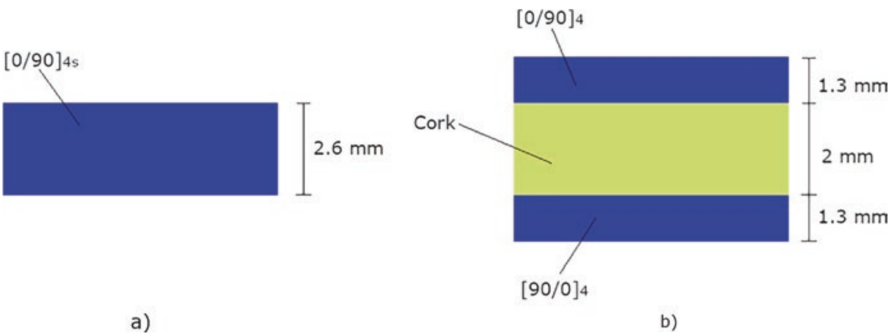


Fig. 7.12 Configurations of (**a**) monolithic laminate plates and (**b**) composite sandwich plates [15]

behavior of the cork/resin composite is subject to the number of enclosed cells present in the cork granules.

An experimental investigation was conducted by Ivañez et al. [15] to investigate the ballistic impact behavior of monolithic laminates and composite sandwich plates with an agglomerated cork core. The plates were subjected to ballistic tests to determine the benefits of incorporating a cork core using monolithic plates as shown in Fig. 7.12. A total of six configurations were designed in this study. A saber ballistic gas gun was used to conduct the ballistic tests. The propellant gas used during the tests was high-pressure helium. The study employed steel projectiles with a radius of 6.25 mm and a mass of 7.98 g. The results show that cork as a core material in sandwich structures improves the ballistic properties of composite materials. The study also included the ballistic limit values and residual velocities. Cork integration into the sandwich plates cannot alter the ballistic behavior significantly. The specimens subjected to the 40 J impacts exhibit greater disparities. However, the difference is lower for the 25 J impacts. A decrease of 25% in ballistic limit of monolithic laminates is observed concerning the reference laminate when subjected to an impact of 40 J as shown in Fig. 7.13.

Sarasini et al. [9] conducted high-velocity impact tests on green sandwich structures composed of agglomerated cork and flax/epoxy laminates. The experimental procedure included high-velocity impact tests using a Sabre Ballistic A1G+ gas gun. A 7.5 mm diameter spherical projectile made of tempered steel was utilized in the tests. The impact energy was systematically increased until the target was fully perforated. The results show that agglomerated cork has an energy-absorbing capacity no less than Rohacell. Significant differences in residual velocities are observed when the impact velocity approaches the ballistic limit of the cork sandwich (Fig. 7.14). As impact velocity increases, the observed differences gradually approach a limit of 7%.

Sergi et al. [16] conducted ballistic impact tests on bio-based sandwich structures having agglomerated cork cores. Density of cork agglomerates was studied by designing specimens as NL10 ρ = 0.14 g/cm^3, NL20 ρ = 0.20 g/cm^3, and NL25 ρ = 0.25 g/cm^3, and comparing them with commercial polyvinyl chloride (PVC) foams such as HP130 ρ = 0.13 g/cm^3, HP200 ρ = 0.20 g/cm^3, and HP250 ρ = 0.25 g/cm^3. They used thermoplastic polypropylene skins reinforced with LINCORE® HF T2 360 intraply flax/basalt hybrid fabric from Depestele Group and made by hot compression molding (P400E by Collin GmbH). Specimens of 100 mm^2 were impacted by a 1.7 g spherical projectile with a 7.5 mm diameter in the ballistic tests.

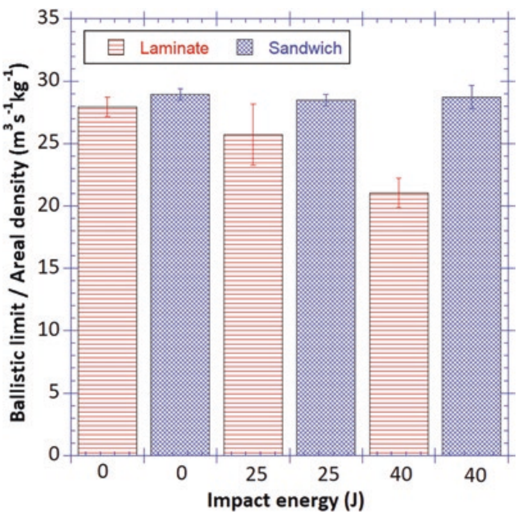


Fig. 7.13 Ratio of ballistic limit and areal density for the specimens [15]

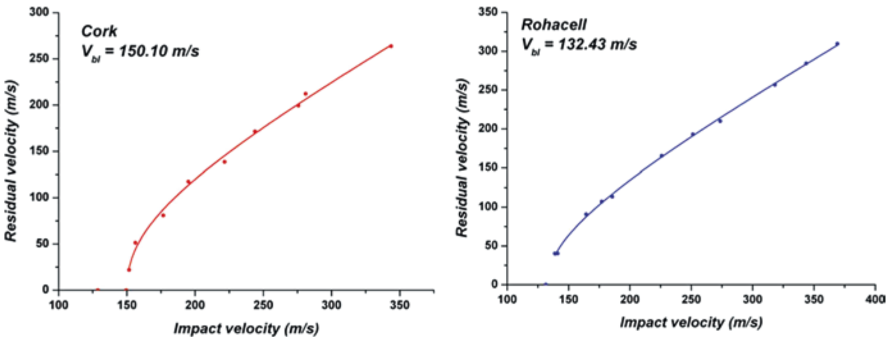


Fig. 7.14 Ballistic curve for cork and Rohacell [9]

Table 7.1 Ballistic limits for different configurations [16]

Specimen	Ballistic limit (m/s)
PP_NL10	171.6
PPC_NL10	165.1
PP_NL25	187.0
PPC_NL25	177.6
PP_HP130	171.1
PP_CHP130	172.3

PVC foams offer better anti-impact properties than the agglomerated corks; however, their performance changes when bound to skins (Table 7.1). The higher ballistic resistance of PVC foams is due to their higher inherent strength and the early separation of agglomerated cork plugs from the polyurethane binder due to a poor interface between the cork granules and the binder. As density increases, both core types show an increase in the ballistic limit; however, the trend differs. PVC foams experience a linear increase in ballistic limit with density, while agglomerated corks display a decreasing rate.

As shown in Fig. 7.15, agglomerated cork and PVC foams have different damage modes. Agglomerated cork exhibits an intergranular fracture while PVC foams show a cylindrical plugging damage mode. Both core types show a progressive decrease in damage area extent with increasing impact velocities due to a decrease in impact reaction time and damage localization. Two main factors contribute to the conoid intergranular fracture of agglomerated cork: the weak granule-binder interface, which acts as a preferential path for crack propagation because it consumes less energy, and the low solid mass volume fraction, which is about 10% in natural cork and slightly higher in agglomerated cork due to the polymeric binder. PVC foams have a lower damage threshold than agglomerated cork, with a 77.3% lower damage threshold than the projectile dimension. This is due to high elastic deformation in compression, which is recovered after the projectile leaves the sample.

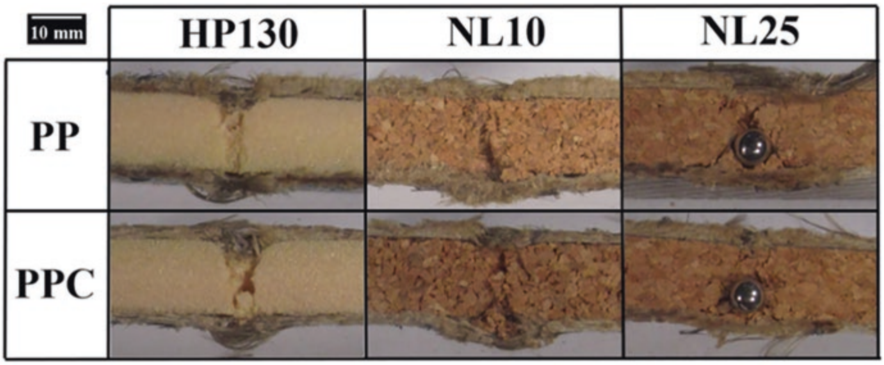


Fig. 7.15 Damage of the six sandwich configurations at 175 m/s impact velocity [16]

Agglomerated corks have lower back damage, decreasing between 72.2% and 84.4% as impact velocity increases. The fiber–matrix interface improvement provided by the maleic anhydride coupling agents to composite skins is negligible. Agglomerated cork improves impact performance when embedded between the two skins. Ballistic resistance is lower than synthetic PVC foam, and the ballistic limit does not increase linearly with density.

7.4 Conclusions

This chapter reviews the efforts in the literature to determine the mechanical behavior of cork-based sandwich panels under low- and high-impact conditions. Most studies use a drop-weight impact machine to analyze cork-based sandwich panels under low-velocity impacts. Some of these studies compare the energy absorption performance between cork and other materials such as balsa wood or polymeric foams. Generally, the studies of cork-based materials at low impact velocity conclude that they are promising materials for energy absorption. These properties make it an excellent candidate to replace the synthetic foams traditionally used in hulls. Regarding the study of cork-based materials for ballistic protection purposes, the works are generally limited. Most of the studies on high-velocity impact behavior of cork-based materials investigate the structures against spherical projectiles made from steel. There is still a big gap in this field since the energy absorption capacity of cork-based materials has not been investigated for other types of projectiles simulating explosive fragments such as Fragment Simulating Projectile (FSP) or projectiles with different tip geometries (conical, hemispherical, and flat). It is possible to mention that cork-based materials are good candidates for core sections in sandwich structures as well as liners in protective equipment.

References

1. Sánchez-González M, Santiago Beltrán R, Lanzo Palacios R, Prades C (2023) Analysis of cork quality and cork tree health in stands of western Spain. For Ecol Manag 539:121012. https://doi.org/10.1016/j.foreco.2023.121012
2. Walsh J, Kim H-I, Suhr J (2017) Low velocity impact resistance and energy absorption of environmentally friendly expanded cork core-carbon fiber sandwich composites. Compos Part -Appl Sci Manuf 101:290–296. https://doi.org/10.1016/j.compositesa.2017.05.026
3. Sergi C, Sarasini F, Tirillò J (2021) The compressive behavior and crashworthiness of cork: a review. Polymers 14:134–134. https://doi.org/10.3390/polym14010134
4. Sergi C, Sergi C, Sarasini F, Barbero E, Barbero E, Sanchez-Saez S, Tirillò J (2021) Assessment of agglomerated corks and PVC foams cores crashworthiness under multiple-impact events in different loading conditions. Polym Test 96:107061. https://doi.org/10.1016/j.polymertesting.2021.107061
5. Sutherland LS, Soares CG (2022) Impact resistance of cork-skinned marine PVC/GRP sandwich laminates. Thin-Walled Struct 180:109830. https://doi.org/10.1016/j.tws.2022.109830
6. Gómez A, Barbero EJ, Barbero E, Sanchez-Saez S (2021) Modelling of carbon/epoxy sandwich panels with agglomerated cork core subjected to impact loads. Int J Impact Eng:104047. https://doi.org/10.1016/j.ijimpeng.2021.104047
7. Sergi C, Boria S, Sarasini F, Russo P, Vitiello L, Barbero E, Barbero E, Sanchez-Saez S, Tirillò J (2021) Experimental and finite element analysis of the impact response of agglomerated cork and its intraply hybrid flax/basalt sandwich structures. Compos Struct 272:114210. https://doi.org/10.1016/j.compstruct.2021.114210
8. Wang H, Ramakrishnan KR, Shankar K (2016) Experimental study of the medium velocity impact response of sandwich panels with different cores. Mater Des 99:68–82. https://doi.org/10.1016/j.matdes.2016.03.048
9. Sarasini F, Tirillò J, Lampani L, Barbero EJ, Barbero E, Sanchez-Saez S, Valente T, Gaudenzi P, Scarponi C (2020) Impact behavior of sandwich structures made of flax/epoxy face sheets and agglomerated cork. J Nat Fibers 17:168–188. https://doi.org/10.1080/15440478.2018.1477084
10. Sheikhi MR, Gürgen S, Altuntas O (2022) Energy-absorbing and eco-friendly perspectives for cork and WKSF based composites under drop-weight impact machine. Machines 10:1050. https://doi.org/10.3390/machines10111050
11. Gabriel Serra F, Fernandes FAO, de Sousa RJA, Noronha E, Ptak M (2022) New hybrid cork-STF (Shear thickening fluid) polymeric composites to enhance head safety in micro-mobility accidents. Compos Struct 301:116138. https://doi.org/10.1016/j.compstruct.2022.116138
12. Fernandes FAO, de Sousa RJA, Ptak M, Migueis G (2019) Helmet design based on the optimization of biocomposite energy-absorbing liners under multi-impact loading. Appl Sci 9:735. https://doi.org/10.3390/app9040735
13. Sanchez-Saez S, Barbero EJ, Barbero E, Cirne J (2011) Experimental study of agglomerated-cork-cored structures subjected to ballistic impacts. Mater Lett 65:2152–2154. https://doi.org/10.1016/j.matlet.2011.04.083
14. Amaro AM, Reis PNB, Ivañez I, Sanchez-Saez S, García-Castillo SK, Barbero EJ, Barbero E (2020) The high-velocity impact behaviour of kevlar composite laminates filled with cork powder. Appl Sci 10:6108. https://doi.org/10.3390/app10176108
15. Ivañez I, Sánchez-Saez S, Garcia-Castillo SK, Barbero E, Amaro A, Reis PNB (2020) High-velocity impact behaviour of damaged sandwich plates with agglomerated cork core. Compos Struct 248:112520. https://doi.org/10.1016/j.compstruct.2020.112520
16. Sergi C, Sarasini F, Russo P, Vitiello L, Barbero E, Sanchez-Saez S, Tirillò J (2022) Experimental and numerical analysis of the ballistic response of agglomerated cork and its bio-based sandwich structures. Eng Fail Anal 131:105904. https://doi.org/10.1016/j.engfailanal.2021.105904

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