



Textbook

Cork in Aerospace: Cultivation to Application

ecoCORK



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Edited by Selim Gürgen

Mehmet Alper Sofuoğlu

Melih Cemal Kuşhan



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Preface

This textbook is produced within a European Union funded project under the Erasmus+ Program KA203: Strategic Partnerships for Higher Education. The project entitled *EcoCork: Educational Development for Sustainable and Eco-friendly Cork Composites in Aerospace Applications*, (#2020-1-TR01-KA203-092763) is conducted by a consortium of six partners; Eskişehir Osmangazi University (Türkiye), University of Aveiro (Portugal), Amorim Cork Composites (Portugal), Catalan Institute of Cork (Spain), Wrocław University of Science and Technology (Poland) and Vilnius Gediminas Technical University (Lithuania).

The motherland of cork is Europe, especially Portugal and Spain. For this reason, cork based products have risen as a commonly shared value in Europe and thereby leading the cork science while shaping the cutting-edge technology in this field. As a natural material, cork provides several advantages to different engineering applications. Sustainability and eco-friendly properties are the most important advantages for the future of our planet. Since the aerospace industry is one of the leading sectors in the world, cork has been investigated from the aerospace perspective in *EcoCork*.

This textbook provides a detailed knowledge about cork science from cultivation to applications. Chapter 1 discusses cork cultivation, harvesting and processing of cork. Chapter 2 focusses on sustainability and eco-friendly properties of cork. Chapter 3 gives a discussion on cork products, cork properties and future trends of cork. Chapter 4 discusses manufacturing and implementations of cork based products. Chapter 5 reviews aeronautical and space applications with cork products.

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CHAPTER 1

Introduction to Cork Science: Cork Cultivation, Harvesting and Processing

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Abstract

This chapter gives an overview of the main aspects of cork science. It describes the essential steps, starting from the specificities of cork forest maintenance, cultivation, and harvesting, and finally, the steps necessary to transform the outer bark into a suitable raw material to develop engineering products. In this scope, the contribution of cork-based raw materials to some of the Sustainable Development Goals (safer and inclusive cities, sustainable manufacturing, and others) will also be addressed. It starts by addressing the cork forest cultivation and maintenance challenges - the different types of cork trees and forests, planned cultivation to keep the material availability and major threats. Then, it is addressed the cork extraction techniques and care - tools, human qualification, the timing between harvestings, and different types and quality of extracted cork. Finally, the use of cork as raw material and its processing, addressing the different treatments and transformations necessary to make it a suitable raw material for structures or products.

Keywords: Cork, forest, raw material, engineering material.

1.1 Cork Forests

The cork oak, or *Quercus suber L.* – its scientific name – is an evergreen oak with a conspicuous thick and wrinkled bark containing a continuous layer of cork in its outer part. The cork oak tree has achieved economic significance due to its bark's properties, aesthetics, and sustainability. Cork oaks can be divided into two distinct agroforestry systems:

- Cork oak woodlands consist of a relatively sparse forest – associated with crops or pasture for cattle grazing – with a small number of trees per hectare (around 50–150 trees per ha). This system, depicted in Figure 1.1, is referred to as montado and dehesa in Portugal and Spain, respectively;
- Cork oak forests, a denser stand in mountainous regions, do not allow agriculture underneath the cork oaks.

The present cork oaks, in their mature state, have mostly resulted from the management by landowners of naturally regenerated stands. However, in some cases, they resulted from artificial seeding complemented by natural regeneration. Therefore, most stands have a heterogeneous spatial distribution and are not the same age.



Figure 1.1 Typical landscape of a montado/dehesa (image courtesy of APCOR© [1]).

The cork oak spreads in the western Mediterranean areas of southern Europe and North Africa, mostly integrating the two types of agroforestry systems – cork oak forests and cork oak woodlands – and normally being used for hunting, and cattle grazing, besides the production of cork.

This semi-tolerant species is well adapted to mild climates such as the Mediterranean one – mild winters and hot and dry summers – and low fertility soils. Cork oak forests play a critical ecological role in restraining desertification and soil erosion, as well as contributing to the maintenance of biodiversity. The cork oak woodlands support a unique and fragile ecology, constituting a habitat for rare and threatened species such as the endangered imperial eagle (*Aquila adalberti*). Alongside Amazonia, Borneo, and the African Savanna, the cork woodlands are one of the 36 most important ecosystems in the world for preserving biodiversity, being home to more than 200 animal species and 135 plant species [2].

The cork oak demonstrates great ecological plasticity. It has the capability of adapting its phenology and physiological activity to changing environmental conditions such as high temperatures and even drought scenarios. It optimally grows from sea level up to 600 m of altitude; however, it is possible up to 2000 m. Concerning the seasonal distribution of rainfalls, it is adapted to higher precipitations from October to March (autumn-winter) and very little to no summer rain at all. The ideal mean annual precipitation is 600-800 mm, but the minimum for a balanced tree development should be 500 mm. Nonetheless, it still survives in years of low precipitation, e.g., under 400 mm. On the other hand, even though precipitations up to 1700 mm are admissible, cork oak is susceptible to water logging.

The ideal mean annual temperature ranges between 13 °C and 16 °C. The absolute minimal temperature for survival is -12 °C, and the minimum average temperature during winter is 4-5 °C. Typical summer temperatures in the Mediterranean can reach more than 40 °C. Nevertheless, an important aspect is the cork oak's good response to temperature increase and optimal temperature of 33–34 °C in cork oak seedlings [3]. In general, the temperatures of -5 °C [3]. Generally, temperatures around -5 °C and 40°C can be considered the minimum and maximum limits. The species is also very tolerant regarding soils; the only exceptions are calcareous and limestone substrates. It allows a pH range between 4.8 and 7.0 and preferably grows in well-drained siliceous and sandy soils. However, growth in poor shallow soils, low on nitrogen and poor on the organic matter is still possible. Furthermore, cork oaks are capable of preventing soil degradation and generating high levels of biodiversity. Cork oaks boost the organic matter of soils by seeking nutrients in the subsoil and returning them to the soil by dropping leaves and branches, making them more productive.

Cork oak woodlands and forests are spread over the western Mediterranean basin (over 2 million hectares). More specifically, in the southern Iberian Peninsula and northern Africa. A geographical representation of cork oaks can be seen in Figure 1.2. Cork oaks are also present in France and Italy. According to Helena Pereira [4], in the 1990s: Portugal had about 713 000 ha, Spain about 475 000 ha, France 68 000 ha, Italy 65 000 ha, Morocco 348 000, Tunisia 90 000 ha, and Algeria, normally referred to as having 440 000 ha, has probably had a decrease to about 230 000 ha.

Two groups of cork oak populations with distinct genetics were identified in two different regions: one in the Iberian Peninsula and nearby French areas and another in North Africa, Provence (France), and Mediterranean islands (Sicily, Sardinia and Corsica). The first group showed higher genetic diversity within its population and lower among-population differentiation than the second.



Figure 1.2 Geographical distribution of cork oak trees: Green regions represent the native range; crosses indicate isolated populations, and the triangles indicate areas where the *Quercus Suber* has been introduced and naturalized [5].

Portugal and Spain have the larger cork oak forests, being also the main producers of cork products. Portugal has the largest area of montado and currently leads the exports of cork products, being the largest manufacturer. Annually, it is estimated production of approximately 374 000 tons of cork products, with most of it coming from Portugal and Spain, which are responsible for 74% of the total (51% and 23%, respectively) [6]. The annual production might vary because of climatic events or natural disasters. For instance, in Portugal, the wildfires in 2003 or the severe drought in 2004.

Besides *Quercus Suber*, there are other cork trees, such as *Quercus Cerris* and *Quercus Variabilis*. The latter fits the oriental climates and is commonly known as Chinese cork oak [7]. The microstructure of the cork from *Quercus Variabilis* is similar to the one from *Quercus Suber*, but the cells are much more corrugated and collapsed. The cells are usually smaller and present in higher numbers per unit of volume, resulting in a denser type of cork. Around 1.2 million ha of forest is composed of *Quercus Variabilis* and circa 50-100 kilotons of processed cork result from it. Nevertheless, the quality difference is significant. Cork from *Quercus Suber L.* presents a much higher quality raw material. Additionally, it presents much higher levels of homogeneity, resulting in planks of higher dimension and regularity. Additionally, it presents much higher levels of homogeneity, resulting in planks of higher dimension and regularity [8].

1.1.1 Botanical Description

The species to which the cork oak belongs - the order of *Fagales* and the family of *Fagaceae* – is thought to contain over 40 varieties and is ultimately divided into four groups: *subcrinita*, *macrocarpa*, *genuine*, and *occidentalis* [9]. Natural hybrids between variations with similar breeding systems also occur, such as the crossing of *Q. ilex* with *Q. suber* [10,11]. They show different botanical forms and may vary in flowering period, the shape and size of the leaves (including flowers and fruits), and the form of the tree itself. The great diversity in terms of morphology and phenotype is largely due to the past transfer of genetic material from one species to another's gene pool, also known as introgressive hybridization. The quality of cork and the offspring of one tree may show a great variation within the same population of trees.

The cork oaks are short-stem trees with thick branches reaching maximum heights of 16 m. Nevertheless, trees grown in less dense stands may have large stem circumferences and crown dimensions (can reach about 500 m² of crown projection), especially in 150–200 years old mature trees. In dense stands, the trees usually have narrower crowns and higher stems, given the fact that the other surrounding trees influence their dimensions. Figure 1.3 and Figure 1.4 show examples of isolated cork oak and a densely forested area. As a result of pruning at a young age and its continuity, many current cork oaks in the managed montado are shaped differently. These typically have a bifurcated stem. The bifurcation starts at a low height, followed by two or three main boughs set with open angles relative to the stem and a circular crown with a flattened top.



Figure 1.3 Isolated cork oak with a larger crown diameter (image courtesy of APCOR© [1]).



Figure 1.4 Cork oaks in a densely forested area (image courtesy of APCOR© [1]).

The species' root system is dimorphic, with a strong and long tap root and thick lateral branches, which may exhibit a great horizontal expansion with numerous superficial roots in open-grown trees. The main root can reach several meters of penetration into the soil. This demonstrates the capability of cork oaks to reach deep aquifers in the summer, making it possible to sustain high leaf hydration and thus maintain its development during periods of high water demand and radiation [12]. The root system is frequently associated with various miccorhyza.

Buds are dark purple, ovoid, and tiny, approximately two millimeters long. The leaves are dark green with a dense white pubescence on the lower face and a dense network of stomata with guard cells extending from the epidermal plane [13]. The leaf form varies between ovoid and oblong with a crinkled or wavy edge. The leaf length and width range between 4 and 7 cm and 2 to 3 cm, respectively. The leaf shape and size vary considerably between trees and the canopy. Figure 1.5 shows the typical leaves in a cork oak tree.



Figure 1.5 Typical leaf shapes (image courtesy of APCOR© [1]).

The physiological activity initiates around February/March with the bud development. Its elongation and generation of new leaves start in early spring up to June. The leaves survive up to around 14 months, ranging from 11 to 18 months [14,15]. Therefore, the leaves tend to fall in springtime (unless heavy winter rains occur, leading to faster defoliation). Because of the leaf falling seasonality, during spring, the tree's crown is still dominated by the fading color of leaves from the previous year, contrasting with other species displaying the newly emerged leaves. When the cork oak is about 15 to 20 years old, the fructification and flowering begin (from April until the end of May). Pollination occurs during spring, and it can either occur with pollen from the same tree or neighboring ones. As a result, the offspring can significantly differ from one another.

The fruits from the cork oak, and the acorns, which can be seen in Figure 1.6, have different shapes and sizes – anywhere from less than 2 cm to over 5 cm in length. The ripening of acorns can happen in annual and biennial cycles [16]. In the first case, the acorn growth period occurs during late summer and autumn, achieving complete maturation by November [17]. As for the biennial ones, these have a vegetative period with minimum growth, followed by an intense growth period in the spring of their second year. The frequency of the latter is influenced by the length of the vegetative period, i.e., shortening caused by intense and long summer droughts. Per decade, a tree typically has 2 to 3 years of high acorn production. Cold weather during the flowering period may induce damage and contribute to acorn production's substantial inter-annual variability [18].

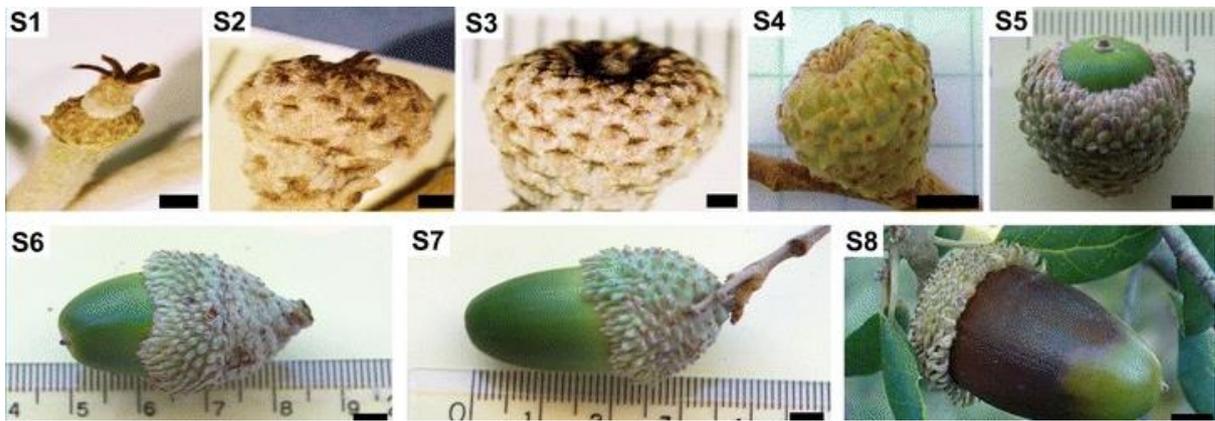


Figure 1.6 Stages of the development of cork acorns until maturing (adapted from [19]).

1.1.2 Silviculture/Agroforestry

1.1.2.1 Stand Regeneration

The majority of cork oaks result from spontaneous acorn sprouting regeneration. Artificial regeneration of cork oak stands is a relatively new practice, having advanced substantially in the 1990s as a result of policies from the EU and incentives for the afforestation of set-aside agricultural lands. Over the last fifteen years, several thousand hectares of cork oaks have been established throughout Portugal and Spain, either through a plantation or direct seeding. However, the mortality rate in the early years is usually high. The reasons are generally related to the lack of adequate soil or preparation of it in order to establish an efficient root system critical for summer; the plant's sensitivity to water stress at their young age; and acorns and young plants are highly appetizing to small rats and cattle, respectively [20–22].

Site preparation entails weeding, often accomplished with a disc-harrow, and enhancing soil properties to facilitate root system development. Preparation techniques may involve ripping or subsoiling to a depth around 60 and 80 cm, particularly in hard rock soils, or plowing and mounding along contours followed by deep plowing and/or disc harrowing. It might encompass the entire area or be limited to the planting line. Typically, a fertilizer based on nitrogen, phosphorus, and potassium is applied at a rate of 40–100 g per plant.

Spring or autumn planting with seedlings grown in a nursery and/or sowing is possible. A diagram with the annual operations is represented in Figure 1.7. The number of trees planted per hectare is less than that of other wood-producing species. Spacings of around four square meters are recommended to balance density and installation costs. Nevertheless, wider (8 m x 4 m) and denser spacings (4 m x 2 m) are also employed.

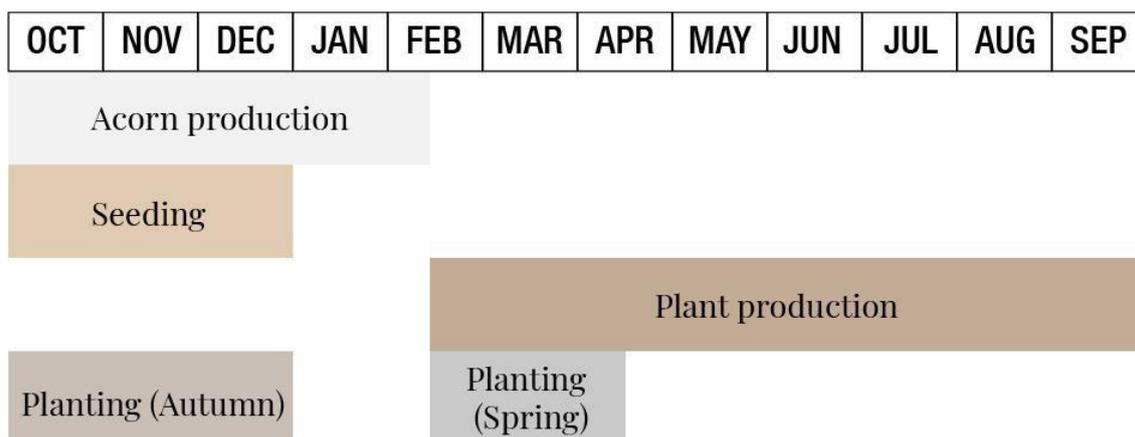


Figure 1.7 Annual afforestation-related events (adapted from [23]).

Due to the high mortality rate in the initial years, the plant is considered established once it reaches an age of 8–10 years. While it is believed that protecting young seedlings with individual tree shelters protects them from browsing and stimulates initial height growth, this technique has resulted in increased mortality rates and young plants with thinner and underdeveloped stems in regions with severe drought and high temperatures [24]. When spring and summer precipitation is insufficient, irrigation should be applied twice or three times during periods of increased stress. Weeding is also suggested during the first years following planting, either around individual seedlings or whole area.

1.1.2.2 Juvenile Stands

This period goes from the tree establishment to the first cork extraction, which typically occurs between 25 and 40 years of age. Typically, 25 years are enough in countries like Portugal and southern Spain. Longer periods are necessary for environmentally stressed and dense stands.

Young trees have extensive ramifications and frequently lack a leading shoot. As a result, executing trimming is critical to obtaining a clear stem of at least 2.5–3 meters high. Usually, three prunings are performed: first between the ages of three and six years to remove all branches from the first 2/3 of the stem, followed by another pruning between the ages of twelve and fifteen years old, and finally, the pruning following the first debarking. Due to the cork oaks' high susceptibility to competition during their first years, weeding should be performed no later than the age of 4–5 years and subsequently every 3–4 years until reaching the age of 10–15 years.

1.1.2.3 Mature Stands

In mature stands, the most critical silvicultural activities are thinning and debarking. Thinning is done to achieve a predetermined spacing factor. The spacing factor is defined as the product of the mean distance between trees and the mean diameter of the tree crown. Even though this empirical rule is not

experimentally confirmed due to the lack of substantial data, it is generally assumed that excessive inter-tree competition reduces cork production. Thus, a spacing factor is recommended to have available spacing necessary for the unconstrained development of the crown. While some forest managers explore applying fertilizers between debarking periods, aiming to increase cork production, the scarce literature on this topic indicates that it has little influence on cork growth or quality.

Since acorns were an economically important crop, cork oaks were pruned to improve fruit yield. This practice is still employed to improve tree vitality and cork yield, which has never been experimentally proven. Weed management may also be performed, depending on the type of cultivation. It is critical that mechanical weeding, like others, is not harmful to the cork oaks' surface root structure.

Cork oak trees can live to be 250–350 years old. However, their phellogen activity declines as they age and their bark thickness. The required cork quality for industrial viability ends by 150–200 years of age. Therefore, the cork oak is a protected species with well-defined regulations about silvicultural operations, debarking, logging, and end of life.

1.1.3 Sustainable Management

From forest to the customer, the entire cork chain depends on consistent and sustainable cork production and, thus, on properly managing cork oak forests. Especially considering the cork oak's overall geographic distribution and extent. According to the World Wide Fund for Nature (WWF), almost 100,000 people in southern Europe and North Africa rely on these woodlands directly or indirectly.

These forests are a model of balancing environmental preservation and sustainable development - the fact that no tree is felled during the cork stripping process is a first in terms of sustainability. Cork oak agriculture provides a wide range of forestry, agricultural, forest grazing, hunting, and economic activities. The cork sector is at the forefront of this sustainable growth, sustaining thousands of employments and allowing families to remain on their land. Cork oak forests are distinct from other forest systems in that the product is not wood (stem) leading to the tree's end of life but the bark that can be harvested multiple times.

Cork growth, a critical element for forest owners and a primary management factor, defines the attributes of the raw material for industrial processing, given that cork is directed toward creating wine stoppers, which require a minimum thickness from the planks. Cork production yields depend on cork and tree growth and management variables such as cork extraction intensity, i.e., the stripped area and the interval between stripping. As a result, the inventory of cork oak forests requires supplementary information about other tree species. Cork production prediction models have been in use for a long time, but cork oak growth and production modeling in stand management has only recently been developed.

The sustainability of cork oak forests and the cork chain is an issue of widespread concern, considering their critical significance in environmental protection against soil erosion and desertification, as well as in the social and economic frameworks of afflicted populations and areas. Cork also has a significant social and cultural impact and legacy that extends well beyond its growth areas. Cork oak sustainable management planning and certification have recently gained prominence in this context.

The primary source of worry for the sustainability of cork oak forests is the montado and dehesa systems, which are experiencing a lack of or insufficient regeneration [25]. Natural regeneration infrequently occurs in these sparse environments, and current stands are largely mature and over-aged. Although an abundance of plantlets may normally be visible near old cork oak trees in the spring as a result of the sprouting of the acorns spread around the region, the majority will perish the following year. Young seedlings require protection, e.g., from the sun, which is not the case in such open, sun-drenched, and heated environments. The opposite is verified in dense cork oak forests, providing the ideal conditions for natural regeneration. The number of young plants is high in these stands despite slow growth due to competition.

Nevertheless, in these conditions, the forest area is tiny compared to the extent of the montado and dehesa systems. To ensure the long-term viability of cork oak stands, it is required to consider artificial regeneration via seeding or planting seedlings grown in nurseries [23]. Cork oak afforestation has been a substantial endeavor in Portugal and Spain, assisted by European Common Agricultural Policy incentives over the last two decades. Following soil preparation, these afforestation initiatives plant trees at a high density of approximately 600 plants per hectare. However, although survival is not always satisfactory, the first 5 to 8 years are critical for tree establishment success.

Another risk to the natural regeneration of cork oak stands is its multifunctional nature, specifically regarding the food chain. For instance, the young plants that have survived the harsh summer conditions are at risk in the presence of cattle. In these cases, farming must be prohibited in regenerating regions until the young trees reach the age of ten and over.

Europe and the rest of the world share a commitment to sustainable forest management. The forests' critical role on the planet has been recognized and progressed in successive international resolutions, specifically their multiple functions (societal, economic, environmental, and cultural) that contribute to society's sustainable development, particularly in rural areas, producing renewable goods and environmental protection. The objective of sustainable forest management is aided by a set of criteria and accompanying indicators that serve as action guidelines. Criteria encompass all forest management areas and serve to evaluate the management's performance. The indicators are quantitative, qualitative, or descriptive measures or parameters that, when measured or controlled on a regular basis, will reveal a criterion's change. The criteria and indicators in Figure 1.8 are consistent with those outlined in pan-European agreements on sustainable forest management. This is a priority because of the environmentally and socially sensitive areas where cork oak forests are found. This

concept begins to germinate and develop at the level of the public and stakeholders. The process of certifying cork oak stands for sustainable forest management has barely begun, and a few cases have already been completed.

Criteria	Indicators
1. Resources and carbon cycles	Forest area, Growing stock, Age structure, Diameter distribution, Carbon stock
2. Ecosystem health and vitality	Soil condition, Defoliation, Forest damage, Deposition of air pollutants
3. Productive functions	Increment and fellings, Services, Roundwood, Non-wood goods, Forests under management plans
4. Biological diversity	Naturalness, Tree species composition, Introduced tree species, Regeneration, Deadwood, Genetic resources, Landscape pattern, Threatened species, Protected forests
5. Protective functions	Soil, water and other ecosystem functions, Infrastructure, Managed natural resources
6. Other socio-economic functions	Forest holdings, Contribution to GDP, Net revenue, Expenditure for services, Occupational safety and health, Forest workforce, Trade in wood, Energy from wood, Accessibility for recreation, Cultural and spiritual values

Figure 1.8 Summary of the existing criteria and associated indicators that establish a framework for sustainable forest management (adapted from [4]).

1.1.4 Threats to Cultivation

1.1.4.1 Diseases

Few serious diseases affect cork oak. Over 300 fungus and oomycota species have been described in cork oak literature. Of these, at least 100 are pathogenic [26]. Fortunately, only a handful are primary infections capable of attacking healthy trees. The majority are opportunistic pathogens that invade oak tissues previously compromised by abiotic or biotic causes [26]. Recently, several species of opportunistic fungus have garnered increased interest due to their ability to colonize oak tissues as endophytes for an extended period of time without causing disease signs [27]. Healthy trees typically manage these endophytes [28]. However, when environmental stressors weaken trees, the initially

contained fungi are capable of colonizing neighboring tissues, resulting in the tree's gradual decline and eventual death [29]. The increased frequency and severity of droughts and rising temperatures favor the most thermotolerant cork oak pathogens. When combined with climate-induced physiological stress, some of these pathogens cause cork oaks to decline and ultimately die [30].

Oak decline is frequently referred to as a multifactorial disease involving various interacting abiotic and biotic factors (e.g., drought, frost, insect pests, and pathogens) that vary in type, intensity, frequency, and even on the site/region [31,32]. However, it has been demonstrated that diseases of the genera *Diplodia* and *Phytophthora* significantly impacted various environments in terms of the decline and mortality of oak trees [33,34].

1.1.4.2 Climate Change

Global warming causes forest loss across the globe [35]. In the Mediterranean, this is verified by increased average temperatures and a general decrease in annual rainfall, which are increasingly irregularly distributed throughout seasons, frequently resulting in longer droughts [36]. Climate change can potentially affect cork oak stands by altering tree growth and mortality, as well as cork production and quality [37,38]. Drought and high temperatures, in particular, have been shown to inhibit cork growth [39]. Adapting forest management practices such as optimizing cork extraction schedules, lowering debarking surfaces, and increasing tree density could boost cork productivity in the face of climate change [40]. Due to the uniqueness of cork oak forests, the promotion of long-term sustainable management techniques and proactive interventions based on afforestation initiatives to preserve biodiversity and ecosystem services should be evaluated at the local or regional level [41].

Cork oak trees are not the only thing affected by the change in the climate. Many of the cork oak pathogens, as well as how these pathogens interact with their host, are also affected. On the other hand, climate change may influence diverse pathogens in distinct ways, and the literature on pathogens' adaptation to climate is still limited [42].

There are many factors that affect how well a pathogen can survive and spread. These include temperature, rainfall, relative humidity, light, leaf wetness, soil moisture, solar radiation, air turbulence, and other factors. In the southern Iberian Peninsula, where the oomycete *Phytophthora cinnamomi* is a significant cause of cork oak decline, the combination of extended droughts and wet seasons, together with lousy site characteristics (infertile soils with low phosphorus levels, poorly drained soils) and a disease-friendly environment (e.g., stands located in south-facing hilly terrain) produce ideal conditions for the pathogen [31]. Given current climate change projections, which include rising mean temperatures and an increase in the frequency of extreme climatic events (e.g., drought, flooding, and storms) in Europe, a proliferation of *Phytophthora* root rots is likely, increasing instability and vulnerability of oak forest ecosystems [43].

Furthermore, severe physiological stress reduces trees' vitality, making them more susceptible to parasites. When combined with continuous dryness, pathogenic endophytes, such as *Brevundimonas mediterranea*, increased infection rates have been related to cork oak loss [32]. The ecological impact of xylariaceous fungi on various forest tree species has obviously risen in the Mediterranean region as a result of unusually dry years [6]. Additional research is needed to determine the effect of increased temperatures and dryness on some cork oak diseases' species-specific characteristics and population dynamics.

1.2 Cork Extraction

Cork extraction, or cork stripping, is an ancient and manual process that involves cutting large rectangularly shaped planks, which are then pulled from the tree, requiring meticulous and experienced hands to avoid any harm to the tree's bark. The procedure takes use of the phellogen's fragility and the freshly developed cork cell layers to remove the bark from the tree without damaging the inner bark or cambium. As a result, this process is purely seasonal, in the late spring and early summer, requiring the cork oak to be physiologically active. On average, the cork oak can be stripped 15 to 18 times throughout its life at nine years intervals, and the first stripping (virgin cork) occurs at the age of 25. At the age of 34, the secondary cork is obtained, and finally, at the age of 43, the reproduction cork is obtained, which contains the ideal properties for making the best quality stoppers.

The process of striping the cork oak is constituted of five stages:

1. Open - The cork plank is separated from the bast by cutting it vertically along its most visible groove with the axe.
2. Separate - The plank is separated by twisting the axe's edge between the plank and the bast.
3. Scribe - A horizontal cut or scribing determines the size of the cork plank being taken from the tree.
4. Extract - The plank is gently removed from the tree so that it does not break. (The larger the plank, the more commercially valuable it is.)
5. Waste removal - At the base of the tree, some cork fragments are left, which are hammered numerous times to eradicate any parasites that may appear.

The industrial requirements for the raw material are determined by the specific application, which is currently oriented mostly toward stoppers production. Thus, a suitable thickness is required (i.e., cork planks with a minimum thickness of 27 mm), and significant flaws such as severe discontinuities (i.e., deep fractures) are nonexistent. These are the main reasons why virgin and secondary cork, obtained from the first periderm and first traumatic periderm, respectively, are not considered for cork stoppers manufacturing.

1.2.1 Cork Stripping Process

The bark is pulled out during periderm activity when the phellogen mother cells and newly created phellem cells are swelled, and the cell walls are thin and weak. First, cut through the bark, then grab and pull it out. A mild force in the radial direction is enough to separate the bark at the level of the phellogenic active zone in this state is possible. The timing of this operation is critical to avoiding damage to the underlying phloem and cambium. As a result, cork extraction is limited to the period of peak phellogen activity, typically occurring between mid-May and early August. The weather determines the debarking period, which may cause operations to be delayed or anticipated. As seen by the creation of shoots and leaves, the beginnings of new spring growth are typically a sign of the tree's physiological activity and a necessary condition for planning the start of the cork-stripping process. One common approach is to evaluate the ease with which cork may be extracted from a few cork oaks. When it is not easily extracted, the bark cannot be removed using conventional methods; if the applied force is excessive, a rupture at the cambium level may occur, resulting in irreversible damage. However, due to the variability of tree physiological status within a stand, it is possible that some trees will not yield cork during the cork extraction operation, i.e., weakened or diseased trees, or that it will be impossible to remove the cork from some parts of a tree, i.e., due to partial crown attack. The knowledge of the cork strippers is critical for successfully completing the operation technically and making the necessary judgments.

Cork peeling is carried out manually. Typically, the work crew comprises two people stripping the same tree simultaneously. Figure 1.9 illustrates the cork extraction process. A stripping axe with a curved cutting blade and a reasonably long wooden arm with a chiseled end is used to separate the cork planks. The cork stripping process begins with a horizontal cut across the tree perimeter at around breast height or slightly higher, followed by two/three vertical cuts depending on the tree perimeter. The cut is made by balancing the axe and adjusting the strength so that it cuts through the cork layer but does not penetrate into the inner bark. The subsequent cutting strokes follow a straight line or around the stem. The cork layer is separated by inserting the axe's arm into the cut and levering it out. The cork plank is next extracted. The cork strip in contact with the soil at the stem's bottom end is removed, leaving a clean, stripped surface. The technique is repeated similarly upward up the tree's stem and main branches until the cork extraction capacity is reached. Ladders, originally made of wood but now usually made of aluminum, are used to access the tree's top branches. Cork stripping is a rather quick process when performed by skilled employees, and a team (2 elements) achieves approximately an average of 900 kg/day [4]. In the case of large trees with short stems and several spreading thick branches, cork stripping is performed by several groups of cork strippers who must work their way up the tree by standing on the branches, as can be seen in Figure 9c. These trees produce a considerable amount of cork, accounting for several hundred kilograms. The Whistler tree, Portugal's largest and oldest cork oak tree, which also happens to be considered the world's largest by

the Guinness Book of Records, weighting 102 tons, was stripped in 2000, yielding 650 kg of cork, while the previous cork harvest in 1991 gave 1.2 tons [44].

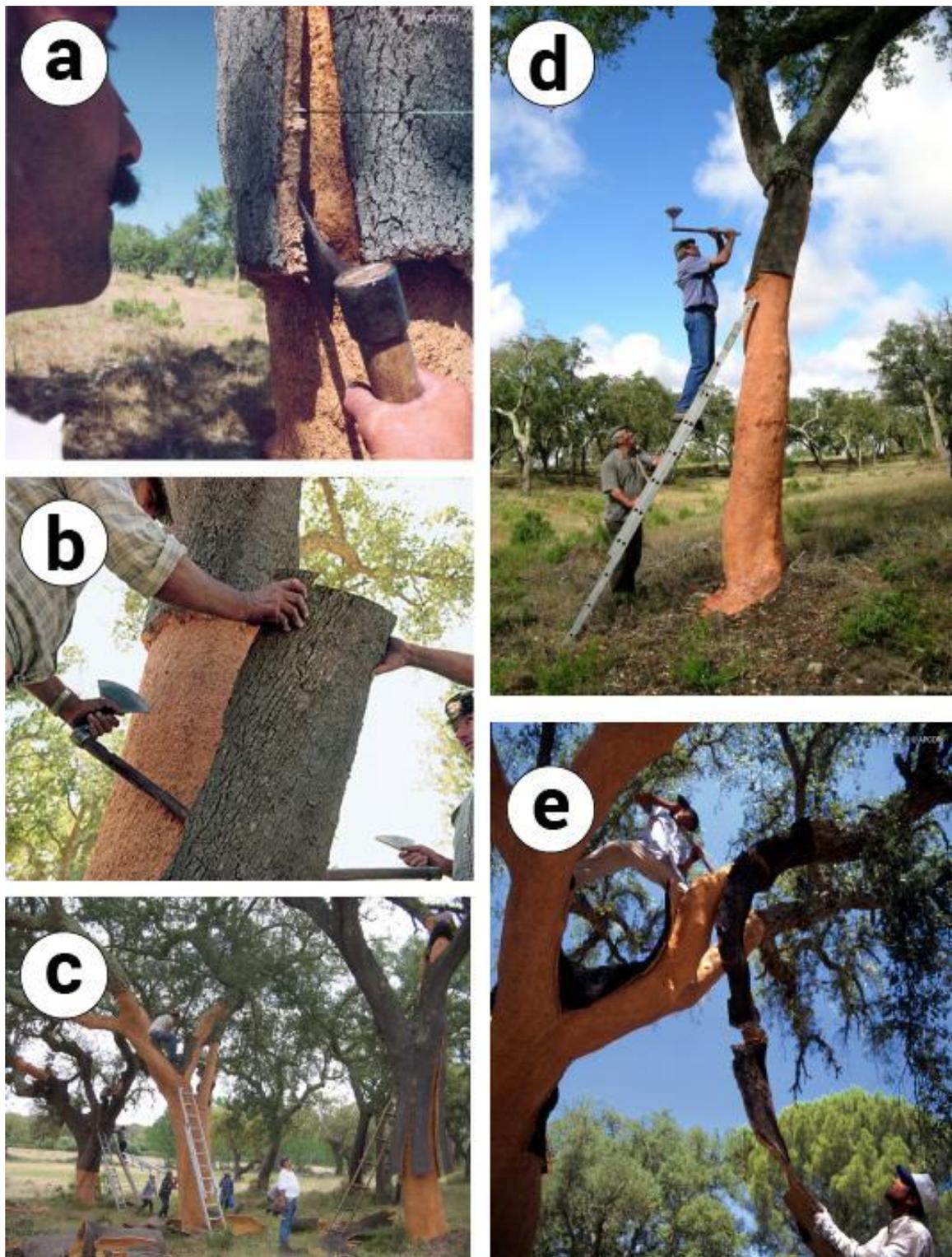


Figure 1.9 a) An axe cuts through the bark - horizontal and vertical lines; b) The axe's arm is used to extract the cork plank; c) Overview of the stripping operation; d) Use of ladders is required for the stripping of the upper part; e) Stripping of the branches (images courtesy of APCOR© [1]).



Figure 1.10 Tractor loaded with cork planks (image courtesy of APCOR© [1]).

Cork stripping is performed by a wide group of workers, most specialized in cork harvesting, approximately 100 in number. In addition to cork strippers, these groups are composed of a manager and individuals who gather and transport the planks to a central location, as well as those who stack them. Figure 1.10 demonstrates how planks are picked from the ground and loaded onto the tractor.

Cork stripping is a spectacular event ingrained in these regions' cultural and social past. It frequently appears in handicrafts such as pottery and hand-painted tiles. There have been some attempts to automate the cork-stripping process. Although more complex approaches, such as using a high-pressure water jet or a laser beam, have been tested, they have been ruled out due to practical or cost constraints. Additionally, some powered hand-carried sawing machines have been proposed for cutting operation and tested in the field [45]. Although limited to vertical and short stem extraction, the results are promising in terms of cutting precision and operational expenses.

Immediately after removing the cork bark, the cork oak stem looks golden brown and smooth. It darkens during the following weeks, ultimately achieving a dark reddish brown color as the phloem's outer tissues swiftly dry, providing the stem with a rough texture, as seen in *Figure 1.11*. After years of weathering exposure, the stem becomes dark greyish brown and even more rough with deep sulci that vary in depth depending on the growing intensity of the underlying layer.

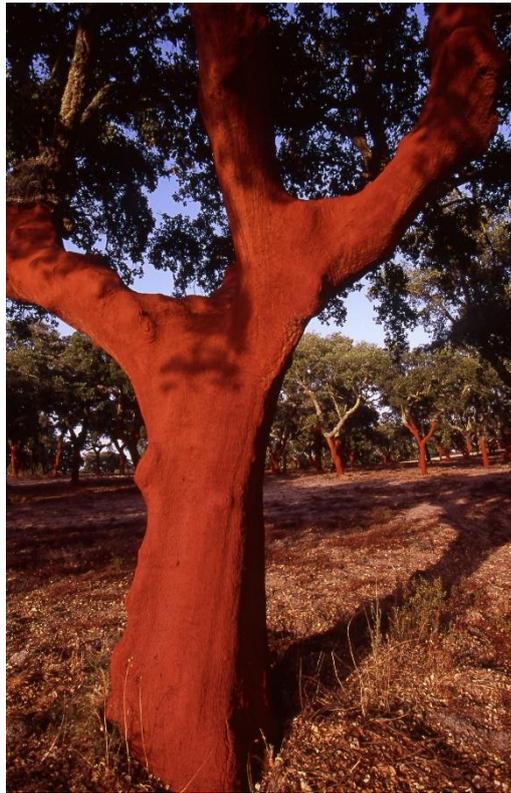


Figure 1.11 Cork oak stem's appearance after the stripping of cork (image courtesy of APCOR© [1]).

1.2.1.1 Intensity of Cork Stripping

Cork stripping intensity is defined as the area of removed bark relative to the tree's size. The debarking coefficient is defined by Eq. 1.1 as the ratio between the debarking height and the circumference of the cork oak at breast height, $pbh_{overcork}$ (at 1.3 m of height) [45]:

$$\text{Debarking coefficient} = \frac{\text{debarking height}}{pbh_{overcork}} \quad (1.1)$$

Legislation or good practices procedures restrict the debarking coefficient. In Portugal, the maximum debarking coefficient is regulated by law [4]. It depends on the tree's stage of development: 2.0, 2.5, and 3.0 for the first, second, and successive cork strippings, respectively, as represented in Figure 1.12. The cork cannot be extracted until the tree reaches a circumference of 70 cm (22 cm diameter) at breast height. This is also the limit for extraction in branches. In Spain, the restriction is 60 centimeters around the circumference at breast height (19 cm in diameter). When branches are removed from the cork oak, the debarking height includes the stem height and the branch length measured along the longest debarked branch. The age for production depends on radial growth. However, it is generally accepted that the required diameter is reached at 20 –25 years in typical growing scenarios or 30 – 40 years in less favorable environments.

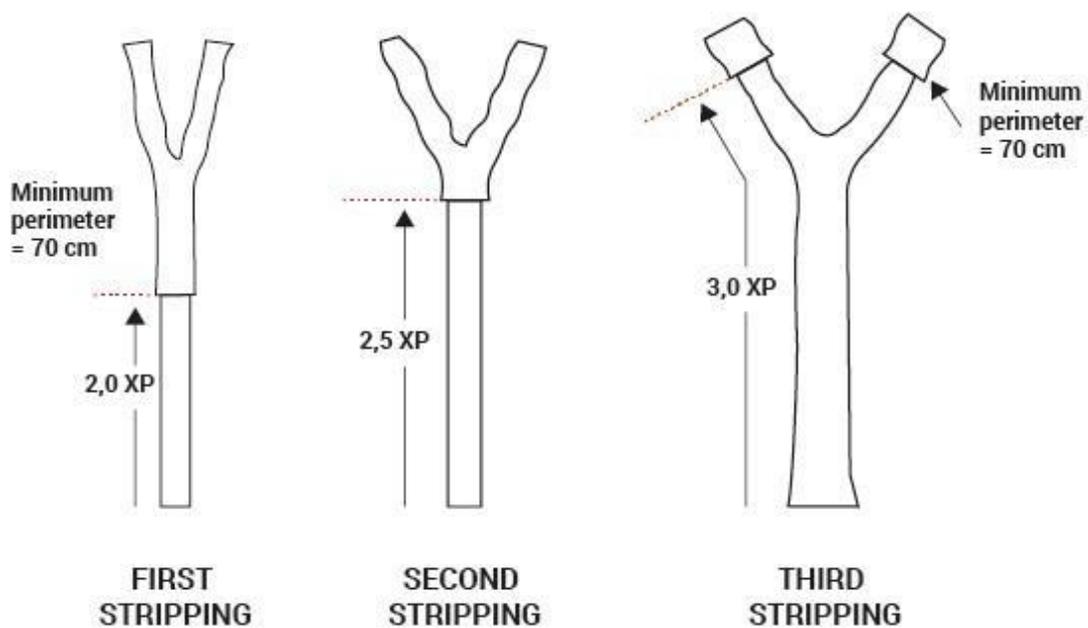


Figure 1.12 Three stripping phases of the life of cork oak (Adapted from [46]).

The intensity limits were established based on experience and empirical common sense regarding the percentage of stem and branch surface that a tree can tolerate losing its periderm without irreparable vitality loss. Cork stripping intensity is connected to the extractions frequency, defined as the number of years between two extractions, referred to as the production cycle. No studies are available that measure the influence of the cork cycle time on tree growth. The cork growth throughout the cycle has been extensively examined, and it appears that the cycle's duration has been dictated by the necessity to attain a specified thickness in the cork plank for subsequent industrial usage. As a result, the duration may vary by region, depending on the annual average of cork growth. In the majority of Portugal and southern Spain, a plank thickness of approximately 3–3.5 centimeters is typically achieved in nine years. However, achieving such a value in Catalonia, Spain, or southern France takes more than fifteen years.

There is a nine years legal limit for the minimum period between extractions in both Portugal and Spain. The age can be determined by counting the rings on a cork cross-section, with the years of extraction being counted as half years, as illustrated in Figure 1.13.

Cork extraction in a stand may occur concurrently in all trees – even-aged cork – or in a subset of trees – uneven-aged cork. Two cork stripping rotations are established in uneven-aged cork stands, the tree and stand cork stripping, depending on the number of distinct cork ages in the stand. To aid in forest management, the year of extraction is registered on the tree by painting in white the last digit on the stem following cork removal – for instance, if extracted in 2005, the number 5 is painted, as illustrated by Figure 1.14. The current management strategy favors even-aged cork management zones and two or three cork ages in large stands.

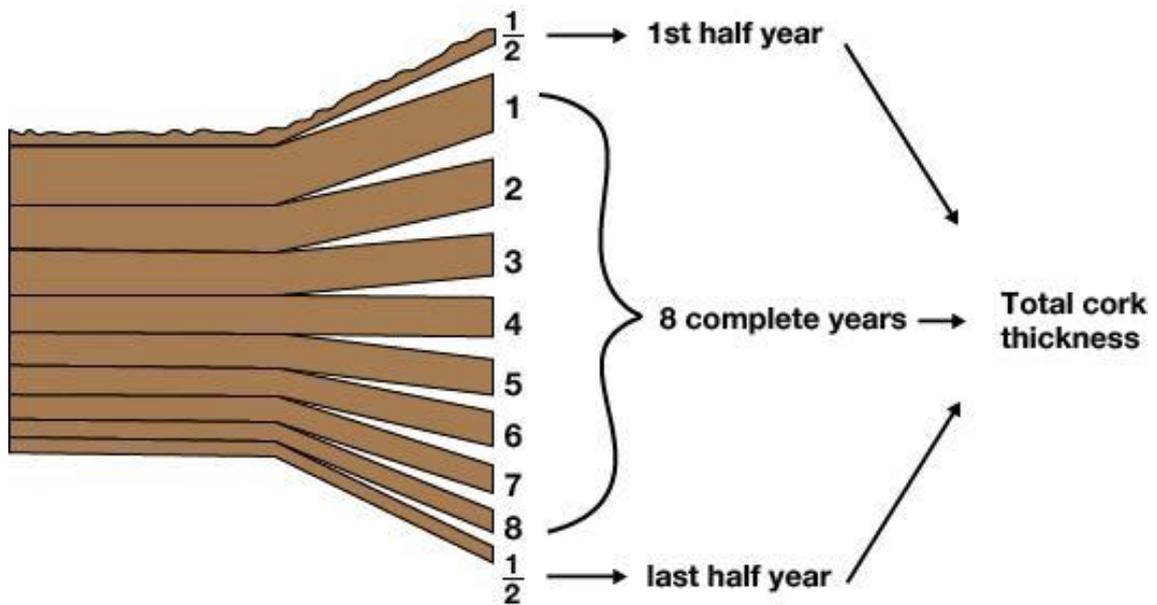


Figure 1.13 Representation of the counting of the rings on a cork section to determine its age (Adapted from [7]).

Historically, fractionated stem cork stripping was also practiced: approximately half of the stem height was debarked in one year, and the remaining area was stripped after 4–5 years. As a result, one tree experienced two cork cycles separated by a 3 – 5 years delay. This practice is currently prohibited or strongly discouraged, as repetitive cutting on the same part of the stem results in wound reactions that form a belt around the stem, resulting in poor-quality cork. These oaks continue to be very characteristic of the montado environment.



Figure 1.14 Indication of the year of cork removal (image courtesy of APCOR© [1]).

1.2.1.2 Effect on Tree Growth

It is acknowledged that the worker involved in the cork extraction must be skilled and careful to cut through the bark without harming the tree. Indeed, a strong and quick cutting stroke is necessary, or the cork will absorb most of the energy but not extremely strong to the point of penetrating the phloem or the cambium. Wounds, such as the ones resulting from cork extraction, provide entry points for infection and biological attack. The tree responds by forming calluses emerging on the stem, sometimes quite prominently, as the boundary line between extractions in fractionated stripping. This phenomenon is facilitated by the repetitive cutting lines in the exact location during subsequent strippings. Cork production decreases in the reaction zones, and the following strippings are technically more challenging, with higher chances of wounding. The effect of tree damage caused by subsequent extractions on its growth was analyzed in [47]. Overall, tree radial development was reduced by around thirteen percent compared to unharmed ones [47]. Cork production decreased by fourteen percent, with a pronounced effect in the two years following extraction [47].

An investigation into the damage caused by the stripping and pruning of cork in four selected sites in the Extremadura region of Spain reported a significant incidence of damage (affecting thirty-one to forty-seven percent of the trees) and noteworthy parallels between damage and holes caused by *Cerambyx* beetle attack and subsequent fungal infection by *Biscogniauxia mediterranea* (Figure 1.15) [48]. The necessity of employing highly skilled labor for cork stripping, disinfecting the cutting instruments between individual tree stripping, and controlling the operation tightly are recurring themes in cork oak management but are not always followed.

The stripping of cork directly physiologically impacts the tree. The region where the cork was removed experiences higher water loss by stem transpiration, while stomata quickly close in the following hours (e.g., no stomatal activity after 24 hours), causing nutritional processes to be disrupted and only reverting to normal after 24–30 days. For this time frame, traumatic phellogen is formed, and several layers of cork cells are formed, protecting the active phloem from losing more water. Because this process necessitates a significant reserve consumption, vascular cambium activity declines, and wood growth ceases during this phase. There are few research findings on the influence of cork removal or its severity on the tree's radial growth. Due to the difficulty of observing annual rings in cork oak, it is impossible to track how cork stripping affects the following growth using stem disc analysis. However, it appears that when a tree starts producing cork, the anatomy of the wood is altered: smaller cells with thicker walls, more fibers, and less parenchyma, wood elements irregularly distributed without the characteristic gradual transition from early wood to late wood [48]. The wood growth reduction in mature trees in the two years following cork stripping is also reported (around fifteen percent in a nine-year production cycle) [49]. However, the removal of cork did not reduce the tree's overall radial growth in very young trees growing in favorable conditions [13].



Figure 1.15 *Biscogniauxia mediterranea* cork oak: a) Characteristic, black stromata erumpent through the bark; b) a sporulating canker on the lower trunk (image from [43]).

1.2.2 Operations Following the Harvest

1.2.2.1 Field Storage

The cork strippers leave the removed cork planks on the ground. They will then be collected by tractor and piled in a yard. In steep areas with limited access, cork planks are transported using a belt tractor or mules (in Spain).

Creating piles is a meticulous process, beginning with selecting the site (flat, dry, and easily accessible by road). The cork planks follow the stem's shape (curved - cork back facing the convex side). These are stacked on top of one another with the cork back facing up and carefully disposed to create a straight and solid outer wall for the pile by using regularly shaped planks. Irregularly shaped and smaller planks are placed in the pile's interior. The piles' dimensions vary but are typically 8 – 10 meters wide, 2 – 2.2 meters high, and 30 – 50 meters long. Figure 1.16 and Figure 1.17 show some examples. The pile is constructed as soon as the planks arrive from the stand. As a result, it contains cork planks of different thicknesses and quality since no segmentation has been made yet. Distinct piles are constructed entirely of cork planks (400 cm² of minimum surface area), besides also a virgin and second cork.

Cork pile masters are skilled professionals that make the pile knowing that prospective buyers will inspect it. Indeed, commercialization of cork and agreement on a price is established following a visual inspection of the pile. While specimens from the pile's core are sometimes taken before making an offer, the planks at sight play a significant role. The price is determined by weight, with the 15 kg standard weighing unit. However, an additional agreement is required about the amount of water the cork contains and the associated weight discount, as specified in the next section. Field storage duration varies and can last a few weeks or, ultimately, up to a year. The arrangements made between producer and client largely determine it, and frequently, the logistics at the industrial mill dictate the timing when the cork is collected. Field storage and pile construction have been recently eliminated, and cork planks are directly delivered to the industrial yard following cork stripping. However, in order to achieve perfect maturation and stabilization, the cork must be left outdoors after stripping. The International Code of Cork Stopper Practices (CIPR) established tight guidelines for this step, including stacking planks beneath non-contaminating materials for no less than six months [50].



Figure 1.16 Collection of the planks in the field (image courtesy of APCOR© [1]).

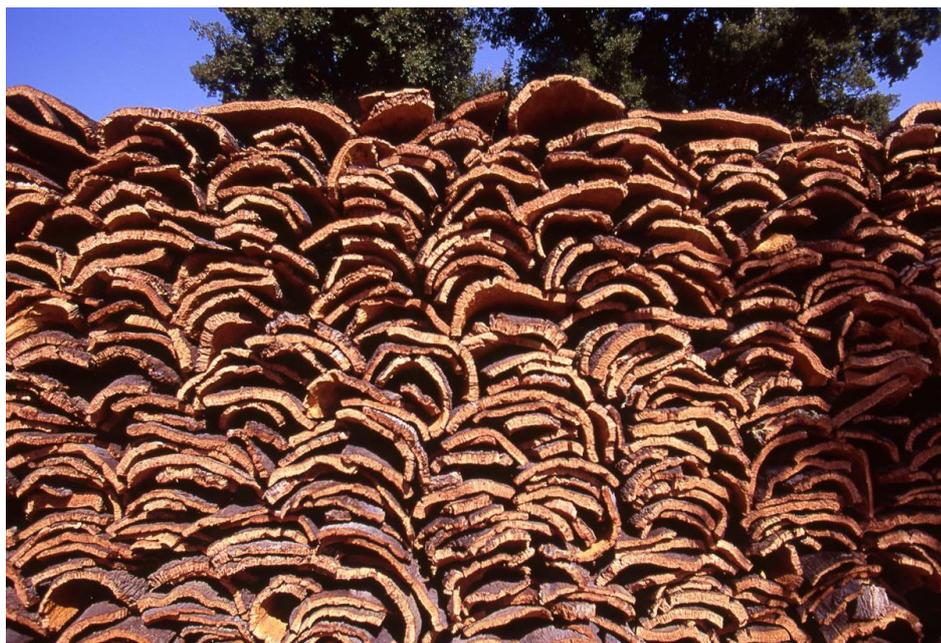


Figure 1.17 Pile of planks (image courtesy of APCOR© [1]).

1.2.2.2 Water Content Variation

Cork presents moisture content during stripping. This is expected given the phellogen's activity and the cells' turgidity in this location. After stripping, cork planks contain about 25% water, but this varies significantly between samples, from having percentages lower than 10% to higher than 50% [51].

The cork plank is damp in the center and dries on the edges. Following separation from the stem, the innermost 1 mm thick cork layer is translucent, as expected from a tissue filled with water. At the time of extraction, cork has a lower water content than wood collected during harvesting (more than 50 % moisture content). The reason is the cork's low hygroscopicity and the current cork cycle's long drying period for the outer layers of the periderm. At room temperature, cork planks quickly lose water. After approximately nine days, field-piled cork planks should have less than 14% water content and can be considered commercial dry cork. Fully equilibrated cork has a moisture level of between 6 and 10%. Storage in field piles does not affect the cork growth ring width or cork planks' porosity.

When negotiating the sale of a cork pile, the price is usually agreed upon (when it is weighed). Cork carried right after stripping or shortly thereafter has a 20% water content discount, which is usually subjected to vigorous debate. Actual water content can be estimated, and the proportion of water to cork weight can be calculated. Using a 25% moisture content at the time of stripping, 14% after nine days, and 10% after one month, 100 kg of dry cork (0% moisture) will weigh 125, 114, and 110 kg, respectively. This suggests that the "discount" to the weight owing to water would be (a) regarding an absolute dry cork, 20, 12.3, and 9.1% of the cork weighed after stripping, nine days and one month, respectively, and (b) concerning air dry cork (the common method) with 10% moisture, 10, 2.3 and 0% of the cork weighed after stripping, nine days and one month, respectively.

1.2.2.3 Yard Storage and Preparation for Processing

Traditionally, industrial mills have a substantial open-air area dedicated to storing cork raw materials on their grounds. The cork plank storage area, or stabilization area, has a slight slope and is cemented to prevent rainwater from accumulating close to the ground. This precaution is intended to avoid the growth of microbes or contamination in the cork planks, which could introduce or accentuate moldy flavors. Manufacturers pay close attention to this issue, as cork stopper taints and off-flavors in wine are critical quality issues.

The cork plank piles in the yards, represented in Figure 1.18, may be arranged in a regular manner (the same way as the field piles) or more randomly organized if erected directly from the truck's unloading, like in Figure 1.19. At the mill, the origin of raw materials is preserved, and storage piles are separated according to their origins as a first step toward tracing the cork within the industrial process.



Figure 1.18 Planks stored in the yard in a regular manner (image courtesy of APCOR© [1]).



Figure 1.19 Planks in the yard after unloading from the truck (image courtesy of APCOR © [1]).

The duration of storage is highly dependent on the requirements of the industrial process in terms of raw-material flow. Historically, prolonged periods of up to two years, then shortened to one year, were performed and stated to be necessary for the chemical and structural stabilization of cork planks. As is the case with a large number of empirical norms, this one as well lacks a scientific foundation. The succeeding operations of boiling in water result in the structural relaxation of stresses, whilst the drying of the inner cork layers and the air oxidation of metabolic products took place in the field,

keeping in mind that the latter are limited to the few cell layers close to the phellogen. Currently, good official practices recommend a storage term of six months. However, raw material is frequently processed with shorter storage periods due to economic and logistical factors related to cork production's seasonality and the raw materials' extremely expensive cost. Storage duration has no effect on the variations of cork ring width, cork porosity, and mechanical properties of cork stoppers [52] - the latter study addressed durations from zero to six months.

The preparation for industrial processing takes place at the storage yard and entails gathering the cork planks in pallets for boiling them in water. During this procedure, planks with an obvious extreme low quality are separated and defined as waste raw cork planks, as well as cork planks with moldy inclusions and yellow stains. Several planks from the lowest portion of the cork oak stem have the cork collar placed into the soil at the tree roots' junction, referred to as the footer. This section is cut from the plank at the height of around twenty centimeters to avoid microbial attack from the soil. This procedure also begins in the field prior to pile construction.

1.2.2.4 Types of Raw Cork

Virgin cork, formed in the oak's first periderm, can be seen on young trees like the one represented in Figure 1.20a, prior to the first extraction of cork or on unstripped branches of mature cork oaks. Thus, the first extraction of cork at the age of 25 years old results in virgin cork. Because of its uneven structure and excessive hardness, this cork is unsuitable for cork stoppers production. This cork is also used for various purposes, such as flooring and insulation.

Following the initial cork extraction, the new traumatized periderm develops until the subsequent extraction (secondary cork). This second stripping occurs nine years after the previous one and results in a less stiff cork with a more uniform structure which can be seen in Figure 1.20b. However, secondary cork frequently exhibits deep fissures, making it also more suitable for agglomerates as well as for use in construction and other products. The reproduction cork, represented in Figure 1.20c, is contained in the following periderm – when the tree is about 43 years old – as well as any others that may develop afterward. This is the raw material that the industry will use to manufacture stoppers. The cork oak will produce excellent cork every nine years from this point forward for roughly a century and a half.

Virgin cork is obtained from young trees that just started producing mature trees whose cork can be stripped from an elevated height due to tree radial expansion. In this situation, a strip of virgin cork is placed into the stem's highest part until the desired height limit is reached.

Figure 1.21 depicts a young tree following cork stripping, with the boundaries between cork extractions visible: virgin cork located in the upper portion, second cork from the next lower region, and the exposed inner bark in the remaining lower portion of the stem.

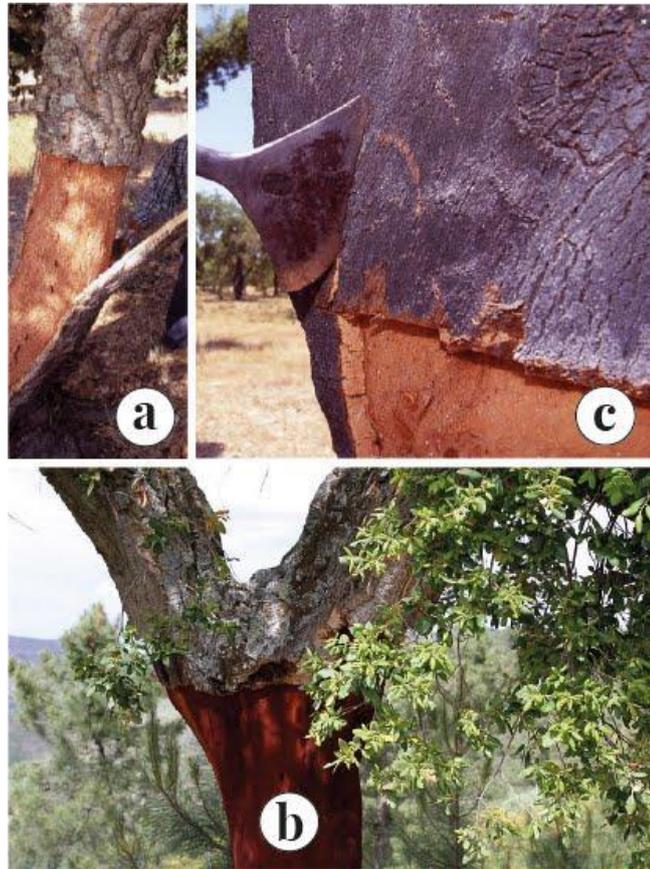


Figure 1.20 Three types of raw cork: a) virgin cork (image courtesy of APCOR© [1]); b) secondary cork (image by Gerd Eichmann [53]); c) reproduction cork (image courtesy of APCOR© [1]).



Figure 1.21 In this stem is possible to visualize, from top to bottom, the virgin cork, the secondary cork, and the exposed phellogen after the stripping of the cork (image from [54]).

Virgin cork may also be obtained from pruned branches or young trees that have been removed during thinning operations. Because cork oaks are pruned in the winter, the cork layer firmly adheres to the inner bark. The cork is removed manually with a small axe or mechanical debarking equipment. Cork is obtained in either instance in pieces ranging in size from a few centimeters to lengthier strips (approximately 20 centimeters), although it includes a significant amount of the inner bark. This variety of cork is referred to as corkwood (also known as winter cork). This raw material has a lower industrial value since it must be thoroughly cleaned following grinding to remove wooden mater from the cork granules.

Overall, the possible types of cork (raw material) to be obtained from exploiting these trees are summarized in Table 1.1, along with its main characteristics and industrial applications.

Table 1.1 Cork types obtained from the exploitation of oaks and their respective characterization and use (adapted from [3]).

	Origin	Characteristics	Main use
Virgin cork	First cork extraction of young trees	It contains deep fractures and a distorted structure	Trituration for agglomerates
	Increase of cork stripping height from stem and branches during the juvenile and first age of mature trees		
	From branches of pruned felled trees (obtained manually with an axe)	It contains a large portion of inner bark and wood. (Also called winter cork)	Trituration for expanded agglomerates
Secondary cork	Second cork extraction	It contains deep fractures	Trituration for agglomerates
Reproduction cork	From third extraction onwards	May be obtained either by stripping of the standing tree or by axe removal after felling. In the latter, it contains portions of inner bark	Planks for production of stoppers
	Under-aged cork from tree fellings		Refuse, pieces and very thin planks for trituration for agglomerates

1.2.2.5 Industrial Requirements

The industry produces a variety of goods with varying degrees of cork incorporation and technological transformation. Still, the economic feasibility of the entire sector is mainly defined by the manufacturing of natural cork stoppers, mainly for wine bottling. Nowadays, the suitability of cork as raw material for this application largely determines its commercial value and the forest manager's goals.

When determining the suitability of raw material for processing, the plank's thickness is the critical variable. Therefore, it is common for the potential industrial client to pay close attention to the thickness distribution of the cork planks when inspecting the field piles. The planks thickness obtained from various trees within the same stand and between stands within the same region varies significantly. The decisive factor is the fraction of cork planks with an appropriate thickness (minimum of twenty-seven millimeters) for manufacturing stoppers. The thinner planks are used to make cork discs for technical stoppers, such as those used on champagne bottles.

The plank's thickness is determined by environmental circumstances, tree genetics, and the length of the cork's cycle: thicker cork layers are obtained with longer intervals between extractions. This is a management variable that foresters can use to optimize production value considering industrial requirements. Additionally, consideration is paid to the cork planks' quality in terms of cork tissue homogeneity. Excessive porosity caused by lenticular channels, visible in Figure 1.22, and other discontinuities such as cracks or insect galleries significantly reduce stoppers' production output and quality, which might result in quality rejections. In this situation, such planks are considered waste and processed to obtain cork granules for the purpose of producing cork agglomerates.

The dimensions of raw cork planks vary according to the size of the tree and operational factors related to the stripping of the cork oak. They are roughly rectangular, with a height of 1–1.8 m and a width of 0.4–0.8 m. Cork planks used to make stoppers had an average height of 1.19 meters and a width of 0.47, resulting in a mean area of 0.37 m² [47]. Comparable dimensions in cork planks destined for disc production revealed an average height of 0.75 meters and a width of 0.35 meters, resulting in a mean area of 0.19 m² [56]. Pieces with a surface area smaller than 400 cm² do not fit into the category of planks and are piled separately for use in the production of granulates.

After boiling in water, cork planks are classified according to their thickness and quality. The primary criterion is its suitability for stopper manufacturing.

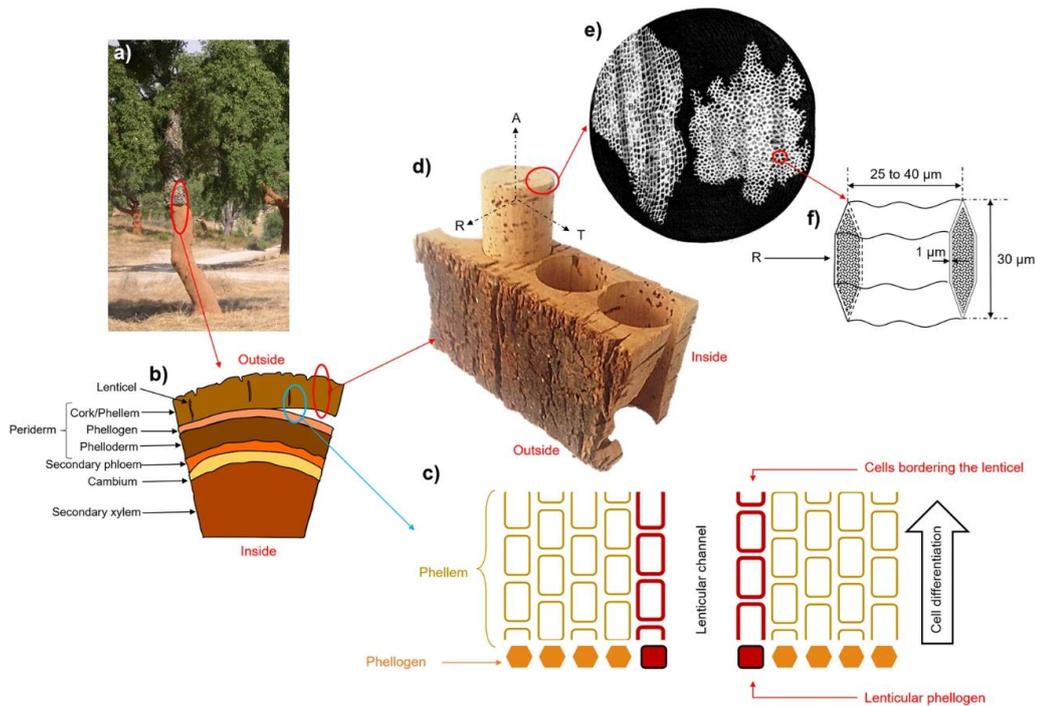


Figure 1.22 Lenticular channels crossing the cork layer: (a) Cork oak after harvesting; (b) Cross section of cork oak; (c) Phellogen region with cellular differentiation. (d) Cork stopper production from the bark (A – axial direction, R – radial direction, and T - tangential direction). It is possible to observe the lenticular channels aligned with the radial direction; (e) First observation of cork cells by Robert Hooke in 1665. (f) Phellem cell typical shape and dimensions (from [55]).

1.2.3 Cork Defects and Implications

The porosity caused by lenticular channels, a natural and important physiological feature that allows communication between the tree's living cells and the external environment, cannot be considered a defect. However, when in excess, as explained previously, it can compromise the plank's quality in a way that it can no longer be used for stoppers as it can increase the permeability of fluids and therefore contaminate the wine or cause leakages.

Cork occasionally also contains traits of biological or external origin that correlate to structural flaws and have a degree of impact on the raw material's quality depending on their type and amount. These can be classified as follows:

- **Insect galleries:** the cork oak can suffer attacks from insects that develop galleries in the cork tissue (phellogen layer), as seen in Figure 1.23. Ants – the most common being the *Crematogaster scutellaris Oliv.* – live in the cork oak bark and dig channels that run randomly through the plank. Apart from occasional contaminants such as sand particles, insect excrement, and fungal hyphae, the galleries are completely empty [57]. Additionally, coleopterons (*Coroebus undatus F*) lay eggs in the cork back cracks, and the larvae, which grow to a fair size of three centimeters, feed on the phellogen. These areas that have been attacked by such insects are not suitable for stopper manufacturing.



Figure 1.23 Insect galleries caused by ants (image from [58]).

- Nails: the defect known as “nail”, represented in Figure 1.24, consists of the presence of lignified cells in the cork tissue, with thick walls, often almost without an open lumen and a lignocellulosic chemical composition. They occur due to the inactivity of some phellogen cells, leading to the regeneration of a new phellogen portion. Because of that, they present higher toughness, density, and low elasticity [6].



Figure 1.24 “Nails” in the cork plank (image from [58]).

- Deep sulcus: deep sulcus may occur on the plank back, as shown by the examples in Figure 1.25. They run vertically, penetrating the cork tissue. The groove lines indicate tissue failure as a result of the growth tangential stress and are thus more prevalent in trees with a high radial growth rate (typical for secondary cork).



Figure 1.25 Planks with deep sulcus (image from [58]).

- Stains: planks might show stains, such as yellow and marble ones, resulting from microbial attacks. *Armillaria Mellea*, saprophytic basidiomycetes that grow on soil and lignocellulosic materials, causes yellow stains, as seen in Figure 1.26. Cork cells protect the tree from pathogen invasion. The cork becomes grey, and the surrounding tissues reveal a white-yellow discoloration and a distinct moldy odor. The polar extractives replace lignin and polysaccharides in cork's chemical composition. The discoloration is more common closer to the soil at the stem's base. As a result, stained corks are not used in the fabrication of wine stoppers. As for the marble stain, a fungal attack (*Melophia opiospora Sacc*) causes a bluish staining cork in the exterior layers and around lenticular channels. Aside from the perforation location, the cork cell wall stays intact, and the hyphae do not impact the cork's properties [57]. Such cork is not used to make cork stoppers. Instead, it might find added value being used for decorative purposes because of its marble-like random stain distribution and dark contour lines.



Figure 1.26 Example of yellow stain in a piece of cork (image from [59]).

- Wetcork: This is a cork defect that results in exceptionally high humidity levels (400-500 %) and whose cause is unknown. However, Natividade [6] suggests that it is caused by the loss of cell impermeability, which in turn results from abnormal suberin deposition in the secondary layers of the cell walls. This defect happens mainly in the most recent annual layers, adjacent to the belly of the planks and in the region adjacent to the stem's base. The main drawback is the excessive shrinkage that cork suffers in the affected region after drying (sometimes even leading to the collapse of cells), which impairs its sealing capacity and dimensional stability; therefore, it is not suitable for the production of stoppers [60]. An example of wetcork in a cork plank can be seen in Figure 1.27.



Figure 1.27 Example of a plank affected by wetcork (image from [58]).

1.2.4 Cork Planks Quality Classification

1.2.4.1 Thickness Classes

The thickness of the planks is the primary aspect in defining the final application of natural cork, impacting its industrial processing and commerce. The industrial approach is to classify cork planks according to their thickness, as specified by standards and illustrated in Table 1.2.

Table 1.2 Classes of thickness for planks used in the cork industry (adapted from [4]).

Commercial class	Thickness (mm)
Extra thin	9 - 22
Thin	22 - 27
Half standard	27 - 32
Standard	32 - 40
Large	40 - 54
Extra large	>54

The classes were created with the potential for further processing in mind. The thickness classes most suitable for stoppers' production are 27-32 mm, and thus, cork manufacturers aim to produce cork planks in this thickness range. The Cork plank's thickness is determined by the length of the cork production cycle and the cork's annual growth rate. In the largest cork-producing locations, a 9-year cork production cycle is adequate to fulfill the primary industrial raw material requirements.

The overall plank thickness is measured from belly to back. Hence, when determining the industrial suitability of a plank, the exterior layer of the back must be considered. Although prices vary significantly amongst cork plank caliber classes, generally, planks' price (per kilogram) in the 27-32 and 32-40 millimeters ranges is the same and serves as a guideline for other classes. Plank prices in the 22-27 millimeter range are almost 1/2 of this reference value, less 1/3 of the price of planks thinner than 22 millimeters, and nearly 2/3 of planks in the 40-54 mm range of thickness.

1.2.4.2 Quality Classification

Cork planks are commercially categorized into multiple classes based on their quality. This visual inspection of the cork plank's transversal and radial portions and its belly surface are used to determine its quality. The first quality parameter is associated with the porosity provided by the lenticular channels, which vary in number but primarily in area. A high-quality plank contains a minimal amount of lenticular channels. Second, the presence of flaws and their potential impact on processing. The

classification of a single cork plank is based on the integrated notion of this potential yield in high-quality natural cork items such as stoppers and discs.

Cork planks are classified based on their quality into 6 classes (1st to 6th) and an additional refuse class. The evaluation is manual and highly depends on the operator. Thus, a high degree of subjectivity is involved, and the classification may vary between operators. While it is common and easy to distinguish between very good and terrible cork, this is not true for middle-quality cork. As a result, significant variations exist between the classifications established by various experts. A study using a reference catalog of 480 cork samples classified by five independent specialists [61] revealed only a 5.3% correlation in the classification of the individual samples (but with a 100% match regarding top and bottom qualities - 1st quality and refuse).

This six-quality (and refuse) categorization of cork boards is no longer utilized in practice. Rather, additional aggregated quality classes are employed: a current classifying system uses a 1st–3rd assortment to represent high-quality corks, a 4th–5th assortment to represent medium-quality corks, and a 6th class to represent low-quality corks. Another possibility, and probably the most used, is to narrow down the quality classification of planks into only 2 categories: a 1st-5th assortment representing cork planks suitable for cork stoppers production and a 6th class comprising planks of lower quality and performance for stopper production.

The relationship between quality grading and image-based porosity quantification was examined, and the porosity and pore size increased as the grade class increased. This is true for both the tangential and transverse or radial sections. However, within each class, there is considerable diversity, and the differences in mean values between contiguous classes are statistically insignificant. Table 1.3 represent different parameters for porosity in cork planks of varying quality classes.

Table 1.3 Average porosity-related parameters for different quality grades of cork planks (observations in the tangential section). Average of 40 samples per class (Adapted from [4]).

	Quality class				
	1st	1st - 3rd	3rd	4th - 5th	6th
Porosity coefficient (%)	3.3	4.5	6.0	6.7	12.4
No. of pores/ 100 cm ²	568	584	785	860	815
No. of pores > 0.8 mm ² /100 cm ²	47	84	111	121	176
Average pore area (mm ²)	0.58	0.83	0.81	0.79	1.57
Maximum pore area (mm ²)	19.7	23.1	21.1	26.3	82.0

The division into only three classes enables more differentiation and consistent grading. For example, the porosity coefficient can be employed to categorize planks by establishing the following class limits: high-grade planks have a porosity lower than 6%, and medium-quality planks must have a porosity of less than 10%. The dimensions or shapes of the objects seen in the image of the cork surface can be employed to distinguish lenticular channels from other defects, such as insect galleries [62].

1.2.4.3 Integrated Value-Index of Cork

Given that the plank value is determined by a combination of thickness and porosity-related quality, a combined variable has been recommended to indicate the cork value based on the relative commercial value of various combinations of thickness range and quality classes. This can be used to evaluate the production value for a certain cork stand, considering the planks' thickness and quality distribution [4]. The following quality index was proposed (Eq. 1.2):

$$Q = \sum_{k=1}^{n_k} Q_k P_k = \frac{\sum_{i=1}^{n_t} Q_i}{n_t} \quad (1.2)$$

Where Q_k denotes the index price for cork of class k , p_k denotes the proportion of cork sampling units in cork of class k , n_k denotes the number of quality classes, Q_i is the index price for the sampling unit extracted from tree i , and n_t denotes the total number of trees sampled.

The index prices are linked to the most valued cork-quality class, as illustrated in Table 1.4, with an example established by a panel of experts. Clearly, the figures may need to be updated to reflect changes in the cork market or to reflect unique trading and processing conditions.

Table 1.4 Index prices for industrial corks of different thicknesses and qualities (adapted from [4]).

Thickness (mm)	Quality class			
	1st - 3rd	4th - 5th	6th	Refuse
14 - 18	22	10	8	8
18 - 22	31	13	8	8
22 - 27	50	30	13	8
27 - 32	100	60	28	8
32 - 40	100	60	28	8
>40	66	33	17	8

1.3 Post-Harvest Treatments

After the raw cork planks are received at the mill, they are held in ambient conditions and then go through a procedure known as preparation, which entails boiling in water, trimming, and classifying planks. A complete scheme of the preparation process is represented in Figure 1.28.

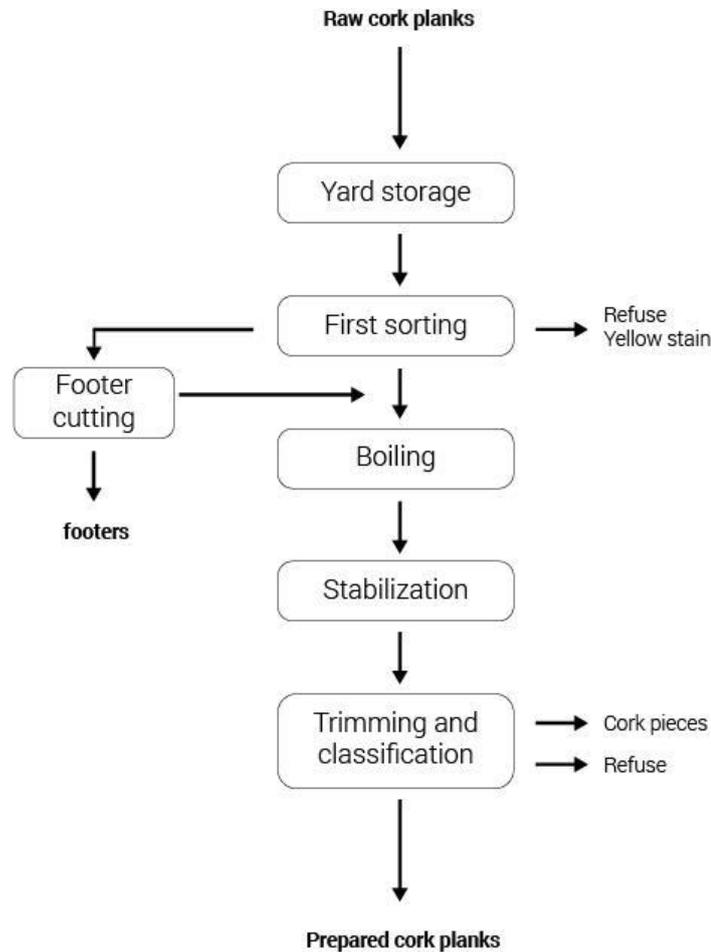


Figure 1.28 Scheme of the preparation of the raw cork planks in the mill (adapted from [4]).

1.3.1 Boiling in Water

Boiling cork in water is a one-hour process applied to all reproduction cork planks used to create stoppers and discs. The method has seen significant modernization in recent years. The plank piles were stacked in tanks of great capacity, boiling water using a furnace usually fuelled with wood. The process was repeated for subsequent batches using the same water, and to replenish the amount absorbed into the cork or evaporated, clean water was also introduced. Every four to five days, the tank would be emptied, cleaned, and refilled with water. Under these conditions, the water would quickly become very dark brown with excessive foam, and the suspended and dissolved particle concentrations in the effluent wastewater were elevated. For example, after one operation day, dissolved solids amount to 0.24% and solubilized phenolics amount to 0.04% of cork plank mass [63].

The current cork boiling technique and equipment have undergone significant evolution. The planks are now stacked on stainless steel pallets, and the water treatment takes place in a closed stainless-steel autoclave. The simplified schematic represented in Figure 1.29 depicts the boiling operation. The water is heated to 95°C and circulated within the autoclave using heat exchangers. Filters in the water lines remove suspended solids. The empty autoclave is loaded with cork pallets, and water is added after closure and circulated during the 1-hour procedure. Finally, the autoclave is drained, the door is opened, and the pallets are removed. The autoclave's truncated pyramidal bottom avoids solid deposition. The autoclave is mainly automated and computer-controlled, including loading and unloading. In some situations, steam at 110–120°C may be used to expand thin planks to manufacture discs for champagne stoppers.

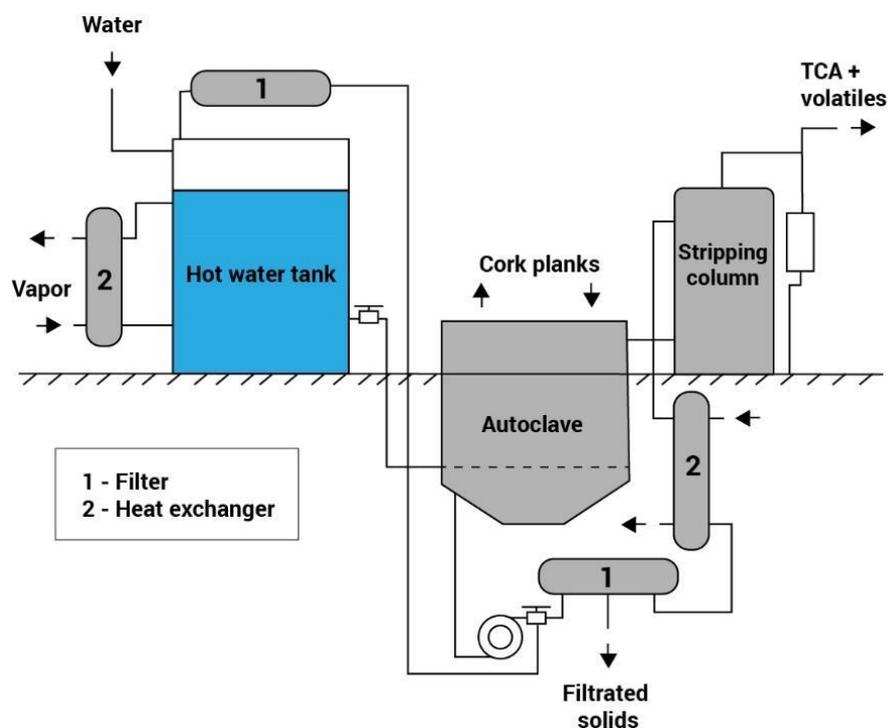


Figure 1.29 Diagram representing an autoclave for cork boiling with water circulation and stripping of volatiles (adapted from [4]).

To avoid the entry of chlorinated substances into the cork, which could result in wine contamination and taint, the water used is not chlorinated. In other circumstances, as in the system depicted in the schematics in Figure 1.29, a stripping column is used to extract and concentrate volatiles from hot water. Boiling water extracts and concentrates 2,4,6-trichloroanisole (TCA) and chlorophenols, which contaminate the wine.

The effluent waters are a waste problem due to their average chemical oxygen demand (COD) and biochemical oxygen demand (BOD) concentrations of 7.4 and 1.3 g/L, pH values of 4.8–5.1, and high toxicity due to the presence of phenolic and polyphenolic compounds at concentrations of 9 g/L (phenol) and 0.5 g/L (as caffeic acid), respectively [64,65]. There have been several proposed

processes, including ultrafiltration [66], combined flocculation, flotation, and ultrafiltration [67], fungal degradation and detoxification [64], ferric chloride flocculation [65], chemical oxidation with Fenton's reagent [68]. Several of the significant phenolic pollutants found in cork wastewaters, such as esculetin (6,7-dihydroxycoumarin) [69], gallic acid [70], ellagic acid [71], and acetovanillone, have been investigated as model compounds for treatment [72].

1.3.1 How the Boiling Affects the Cork

The primary goal of the water boiling procedure is to alter the planks' mechanical properties so they can be flattened, facilitating future cutting processes. The combination of heating and water results in a significant weakening of the cork shortly after boiling. This alleviates growth stresses, reducing corrugations in the cell walls and increasing the homogeneity of the cellular structure.

Cork expands in dimension due to the cell wall straightening: the thickness of cork planks increases by roughly 15%, relating to the cells' radial expansion, whilst the expansion is around 6% in both tangential and axial directions [73]. It is reasonable to predict that the expansion of different corks with boiling varies significantly, as this value depends on the cellular corrugations due to internal stresses, which are extremely variable properties. Even though the typical figures for cork plank radial expansion are typically between 11 and 15%, individual values ranging from nearly zero to over 40% are also obtained. As measured by the porosity coefficient, cork's porosity diminishes as the temperature of the water rises [74]. Thus, water boiling of cork improves the quality of the planks in practice by increasing its size and decreasing the lenticular channels' diameters. Additionally, the curvature of raw cork planks is virtually removed, becoming practically flat, as presented in Figure 1.30, which eases the manufacturing of stoppers and the introduction of automated equipment in the manufacturing process.



Figure 1.30 Cork planks after boiling.

At temperatures below 100°C, the dimensional change in cork caused by boiling is irreversible. This means that repeated soaking and drying of cork, as occurs during stopper washing and bleaching, has no effect on its dimensions.

Because the extraction duration and cork-water surface area are too limited, boiling cork extracts a tiny quantity of the water-soluble compounds corresponding to less than 2 % of cork's water extractives. Therefore, despite frequent assertions, the extraction of chemical compounds from cork is not the purpose of the boiling process under the conditions employed in the industry. The same holds true for what is referred to as microbiological sterilization of the plank.

The frequency of water renewal and volatile stripping are not meant to maximize material extraction but rather to avoid contaminating planks from boiling water, progressively concentrating on potentially harmful substances.

1.3.2 Post-Boiling Process

After the water is boiled, cork planks rest - air dried for a few days (two/three days), a process called stabilization. Pallets are stacked on top of one another to assist the planks flattening. Typically, enormous stacks of boiled planks were built, and the drying lasted for several weeks. This has been altered in recent years, with shorter stabilization times being used to avoid microbial growth that could jeopardize the cork stopper's harmless nature with respect to wine. Immediately after boiling, the plank's moisture content decreases from around 40% to 70%. After two days, the moisture content should drop to about 14–18 %, regarded as the sufficient working moisture content in the industry.

Following drying, each boiling cork plank is examined individually by an experienced worker responsible for trimming and cutting the plank into more uniform pieces for additional processing. The first measure is to remove defective sections (or the entire plank) for it to be processed into stoppers or discs:

- moist cork planks are separated for kiln drying or long-term air drying;
- yellow stained planks or with various moldy areas are excluded from manufacturing and sent for trituration;
- parts containing insect galleries are rejected and removed for trituration;
- planks, or portions of it, having a high percentage of defects such as cracks, among others, are discarded and withdrawn for trituration;
- planks, or portions of it, excessively thin for production (thinner than 13mm), are discarded and withdrawn for trituration.

Trimmer/classifier cuts the planks by hand with a knife. The purpose is to sort through the rejected planks and separate the unsuitable pieces for further processing as solid cork from the raw planks.

Additionally, if the plank is heterogeneous in thickness and quality, it will be separated into smaller, homogenous planks, allowing for either stopper punching or disc manufacture. Additionally, large planks are divided, allowing workers to handle them more readily manually. Measurements of raw cork planks demonstrate an average area of 3745 cm², with dimensions around 47 cm in horizontal and 119 cm in vertical directions. In contrast, measurements of subsequently prepared planks reveal average dimensions of 34 and 70 centimeters in the horizontal and vertical directions (average plank area 1674 cm²), respectively [75]. This procedure loses 5% of initial raw material as small cork bits.

A loss of cork raw material was measured experimentally during the cutting of planks for further processing compared to thin planks to be used in manufacturing cork discs [56]. The wasted material accounts for around 19.5% of its initial mass, while the between-plank yield varies between 0 and 50%, depending on the individual planks' shape and quality characteristics.

Trimming the planks straightens the edges and creates more appealing cross-sections while classifying the planks by caliber and quality class. Operations such as trimming are minimized in stoppers and disc manufacturing to prevent raw material losses. The specific mill requirements determine separation into the thickness and quality classes: it is common to divide it only into three caliber classes, 14 to 22, 22 to 27, and higher than 27 millimeters, and 2 quality classes, the 1st–5th class as the primary raw material assortment for the production of stoppers and discs, and a sixth lower-value quality. When the cork plank is the final mill product, greater attention is given to ensure that the edges and thickness are uniform, and the quality categorization is more explicit, e.g., as 1st–3rd, 4th–5th, and 6th, or according to customer demands.

1.3.3 Wet Cork Processing

The planks with wet cork sections are separated and dried to a moisture content of 14% or less, which is the standard for cork. This can be accomplished through natural air drying over a period of 1–2 years or through forced hot air drying in kiln chambers. Adapted from wood drying kilns, these have been implemented in more modern units, using drying cycles with increasing air temperature. Conditions vary by mill: one example is a 96-hour drying period at a final temperature of 90°C; another is a two-week drying period at an 80°C final temperature.

Following drying, the planks are launched into the processing line and run through the standard operational circuit for the manufacturing of stoppers or discs.

1.3.4 Second Boiling

When the cork is sufficiently dried to moisture contents in the range of 5 to 8% (which denotes equilibrium) between boiling the cork planks and processing them into stoppers or discs, the advantages of a greater amount of moisture on the material's strength and machining capabilities are

lost. This is typically the scenario if the boiling planks are not processed at the preparation mill or if they are put in storage for more than two to three weeks.

In this situation, the planks are subjected to a second boiling operation following the same technique as stated previously but for a shorter duration of 30 minutes. Due to the fact that the internal stresses of the cork were already eased during the initial boiling, as mentioned above, no further expansion of the cork occurs.

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CHAPTER 2

Sustainability, Carbon Footprint and Potential Products of Cork

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Abstract

This chapter discusses the significance of cork material in connection to sustainability and the green economy, as well as its existing and future use beyond the well-known cork stopper. It will also explore the connection between cork consumption and the Sustainable Development Goals (SDGS) of the United Nations as well as the challenges posed by climate change. The chapter consists of three sections: (i) Cork and sustainability, (ii) the carbon footprint of cork goods, and (iii) the possible applications of cork. The first section focuses on sustainability and cork and describes the ecological services provided by the cork forest. The second section will concentrate on the carbon footprint (concept, calculation and values for different cork products). In the third unit, an overview of cork's many uses and applications will be provided. At the conclusion of the chapter, the understanding of cork as a sustainable material, the concept of cork's carbon footprint and the various steps for its calculation, an introduction to the various applications of cork material, and the characteristics that make cork suitable for the aerospace industry are explained.

Keywords: Cork, sustainability, cork ecosystem, environmental services, climate change, carbon footprint, life cycle.

Nomenclature

CO₂ eq Carbon dioxide equivalent

GHG Greenhouse gas

LCA Life cycle assessment

SDGS United Nations Sustainable Development Goals

2.1 Cork and Sustainability

2.1.1 Cork Ecosystem

Ecology

In terms of ecology, the cork oak or *Quercus suber* L. is native to southwest Europe and northwest Africa. It is suitable for this climate:

- short summer
- an abundant and evenly distributed rainfall
- very mild winters
- dry periods tempered by atmospheric humidity
- very permeable, moist, and deep siliceous soils

The cork oak grows in warm, humid and sub-humid conditions from sea level to 2000 m. This optimum growth reaches an altitude of 600 m [1]. This is the case of Mediterranean climate zones with an annual mean temperature of 13-18°C, humid winters, high-temperature summers, and with an average annual precipitation that does not exceed 900 mm. The tree is very sensitive to water logging. The precipitation in Mediterranean zones is concentrated in late autumn and winter, improving the adaptability of cork oak trees. This species is also well adapted to mild winters and hot and dry summers. The best soil conditions suitable for the growth of cork oak are siliceous and/or sandy soils and well-aerated and drained soils [1]. So, this species is also tolerant to poor and shallow soils.

Some years ago, cork oaks were introduced in the United States, and in several countries, from Australia to Bulgaria and South America, without success. Some aspects, such as seed conservation or problems in the growth of young plants, have been responsible for not obtaining adult trees. The long cycle life of the tree doesn't help either. However, it is possible to find it in many parks all over the world because of its high ornamental value.

Cork oak forest covers a worldwide area of over 2.1 million hectares. It covers a big area in Europe, mainly Portugal and Spain but also in France, Italy, and the northern African countries of Morocco, Algeria, and Tunisia. According to forest inventories for the cork oak areas: 713,000 ha in Portugal, 475,000 ha in Spain, 68,000 ha in France, 65,000 ha in Italy, 348,000 ha in Morocco, and 90,000 ha in Tunisia. The distribution map of cork oaks and cork production is shown in Figure 2.1.

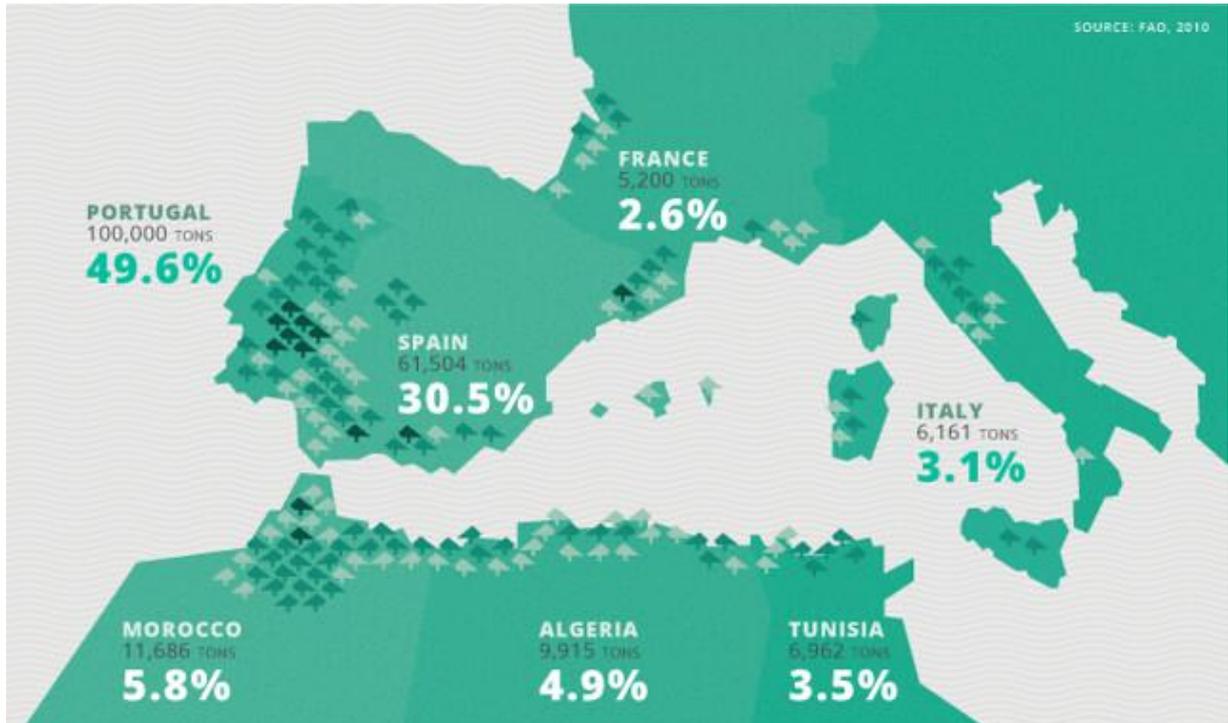


Figure 2.1 Distribution of cork oak and tones of cork production.

(<https://www.amorimcork.com/en/cork-and-wine/raw-material-and-production-process/>).

Biodiversity

Cork oak landscapes represent an important ecosystem due to their rich biodiversity, safeguarding a wide range of habitats for flora and fauna [2, 3]. This is the reason that the Mediterranean is known as one of the 35 global “hot spots”. Biodiversity is the variety of life in all its forms, levels, and combinations: ecosystem, species, and genetic diversity [4].

In brief, cork oak ecosystems are described as multifunctional ecosystems with a tree cover layer dominated by cork oak (*Quercus suber* L.) frequently associated with holm oak (*Quercus ilex* and *Q. rotundifolia*), wild olive trees, and pines [1, 5] and with a herbaceous species [6]. The temporal dynamics of these systems have been reported by several authors [7-9].

The cork oak landscapes are a reservoir of biodiversity and home to a variety of species, some of them endangered, such as the imperial eagle (*Aquila adalberti*). It is also the habitat of great natural biodiversity of wild fauna (about 24 species of reptiles and amphibians, more than 160 bird species, and 37 mammal species). Also, the Mediterranean Basin is the region of the world with the third highest number of endemic plant species. Specifically, in cork oak woodlands, plant biodiversity can reach a level of 135 species per square meter. These include various types of aromatic, medicinal and culinary plants. The undergrowth includes shrubs and bushes such as lavender or strawberry trees.

Social and economic impact

The landscape of cork oaks is one of the best examples of a balance between conservation and development for the benefit of both people and the environment. This non-natural ecosystem is the consequence of centuries of ongoing management and focused silviculture activities that have molded the trees and cork oak environment. As a result of some practices such as grazing, clearing or plowing for agriculture, cork oak forests were gradually transformed into open woodlands.

Nowadays, cork oak ecosystems include a mosaic of four types of patches: forests, oak savannas (or montados in Portugal and dehesas in Spain), shrublands, and grasslands (Figures 2.2 and 2.3). “Montado” is the Portuguese term used to describe landscapes where mixed farming centered around extensive oak woodlands interspersed with areas of shrubs and/or grasslands. As mentioned above, oak savannas and grasslands are maintained as a result of the long-term human presence and related activities in this area [10, 11].



Figure 2.2 Oak savannas or montados in Portugal and dehesas in Spain (<https://gosuber.es/>).



Figure 2.3 Forest in Catalonia.

The cork ecosystem is one example of sustainable forestry exploitation and represents an important source of income derived mostly from cork stoppers production. Despite the high market value of cork stoppers (representing almost 70% of cork market value), other agricultural and silvicultural practices have been taking place in parallel to the harvesting of cork. Cattle breeding, herbal, fungi, and medicinal plants recollection, production of honey, and ecotourism are some activities that also take place in cork oak landscapes [12,13]. There are thousands of direct (jobs in the field of forestry) and indirect jobs related to this ecosystem.

Environmental impact

Cork oak landscapes as a natural barrier against desertification and its roles in fire resistance are other aspects to take into account. Due to the fact that they collect approximately 26.7% of total precipitation, cork oaks protect against erosion and enhance the rate of rainwater infiltration. Cork oak trees carry a substantial amount of soil nutrients from the lower to the top soil levels making them accessible to other plants. Lastly, its porosity and organic composition give it a high capacity for water retention.

In short, the cork oak is one species that should be preserved, taking into account its ecological and economic importance. On the one hand, cork oak forests support one of the world's highest levels of forest biodiversity, second only to the Amazonian Rainforest. In this sense, cork oak forests are hotspots of biodiversity and constitute unique ecosystems that are recognized for their ecological value [14]. Well-managed cork oak landscapes avoid quickly being overgrown by Mediterranean matorral species which increases the risk of fires and loss of habitats and biodiversity [15]. On the other hand, the extraction of cork and the high added value of cork stoppers are responsible for thousands of businesses in different levels of its production (forest, industry, and/or laboratory). The cork industry contributes to avoiding the abandonment of cork oak forests because it provides employment in different forestry areas.

2.1.2 Environmental Services

As a natural-resource management strategy, the concept of environmental services has gained a considerable lot of attention over the past decade. Moreover, this has been progressively integrated into environmental policies [16]. Simultaneously, payments for environmental services continue to garner significant interest from both academics and conservation practitioners [17].

The first step in doing environmental services is to quantify and economically analyze the direct and indirect environmental services benefits associated with the cork oak forest area. The different environmental services offered by an ecosystem are classified according to other studies [18] in four

categories: (a) provision of goods and services, (b) regulation, (c) support, and (d) cultural services. So, ecosystems offer multiple functionalities, such as provision of food, water, fuel, materials, solar protection, water regulation, fire prevention, recreational use, and nutrient cycles among many others.

This document takes as an example a study carried out by Dr. Jesús Rives and his colleagues, a methodology is presented to perform this type of service: “The value of the environmental services of cork oak forests in Catalonia Evaluation of the environmental services of the ecosystem” [18]. In agreement with this study, an example of a methodology used for the determination of environmental services is presented in Figure 2.4.

In the case of quantification and economically analyzing the direct and indirect environmental benefits associated with cork oaks in Catalonia, the first step is to select the forest sample as representative as possible and then, select the criteria. In this step is important to consider some aspects such as:

- Main activity cork extraction and the possibility of other complementary activities
- Field in operation
- Representative field dimensions at the Catalan level (between 200 and 1,000 ha)
- Mature forest structure - representative of the diametrical classes
- No significant recent disturbances
- Distributed in different areas
- Available in updated PTMGF and with digital mapping.

The information on the selected fields are presented in Table 2.1.

Table 2.1 Characterization of selected fields [18].

Area	Albera- Salines	Gavarres	Selva-Gironès	Montseny	Montnegre
Total surface (ha)	201,7	937,9	269,9	479,2	481,0
Altitude min and max (m)	155-395	75-325	325-704	475-980	91-357
Average slope(%)	40%	30%	20-80%	25%	20%
Average temperature (°C)	2,3-28,2	2,5-30,7	1,6- 28,3	-2,0-25,0	2,7-29,0
Rainfall(mm)	580,8	819,0	900,0	850,0	750,0

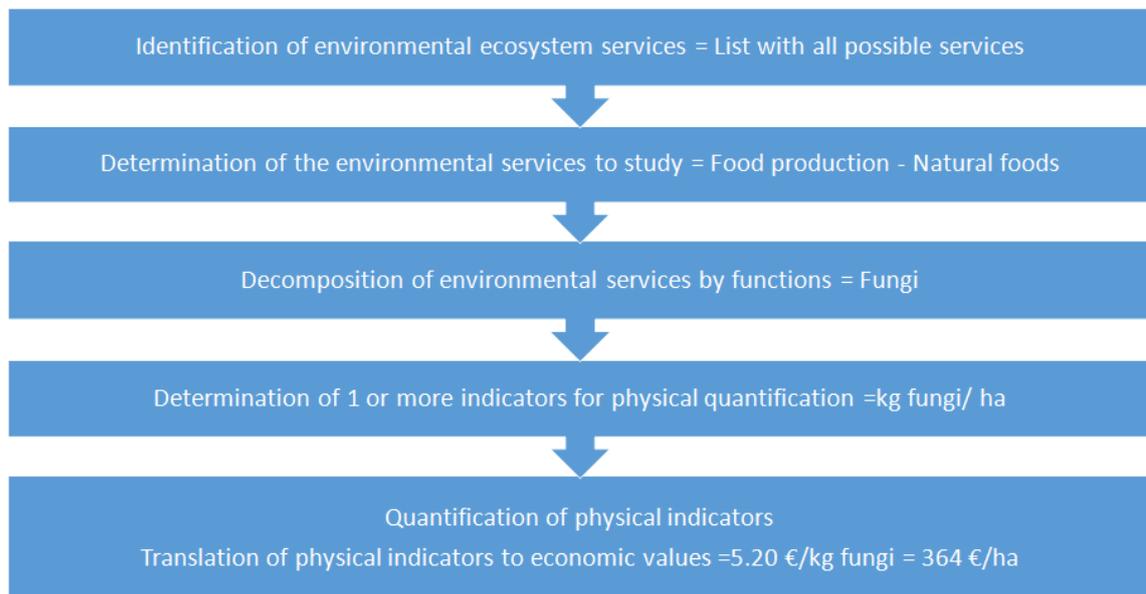


Figure 2.4 Methodology for the determination of environmental services [18].

PROVISION SERVICES		
Food supply		
Natural foods	Fungi	Kg / ha
	Wild fruits	
	Chestnut	
	Pine nuts	
	Honey	
	Aromatic and medicinal plants	
Forest resources		
Wood	Fungi	t / ha
	Quercus suber	
	Pinus pinaster	
	Pinus insignis/radiata	
	Eucalyptus	
	Other woods	
Cork	Cork (virgin cork, reproduction cork)	t/ha
Pineapples and resins	pineapples and resins	Kg/ha
Other forestry products	Biomass	m3/ha
	Firewood	t/ha
	Decorative bushes	units/ha

REGULATION SERVICES		
Cycles		
Soil training and protection	Amount of soil eroded	T eroded soil/year
	Soil erosion rate	T eroded soil/year/ha
Pollination	Amount of ropaloceros through the BMS	Number of individual/ha
	Number of species of ropaloceros through the BMS	Species/ha
	Number of swarms	number swarms/ha
	Bee population	Bees/ha
Climate regulation	Amount of carbon accumulated	Totals t CO2/ha
Prevention		
Fire prevention/control Pollination	number of fires in the last 100 years	Ha burned
	number of fires in the last 20 years	Number fires
	Road density, property management and fire protection	m/ha
	Amount of water for the fire	m3/ha
	number of traps	number of traps

CULTURAL SERVICES		
Functions of human well-being		
Recreational activities	Number of visitors	n ^a visitors/year
		n ^a concerted visits/year
Turism and ecoturism	number of annual overnight stays	days with occupation
	total rural tourism places	n ^a placces
Scenery	N ^o of visits	n ^a visits/year
Education/interpretation	environmental education activities	n ^a students/year

Figure 2.5 Examples of the different environmental services offered by an ecosystem are classified in four categories: (a) provision of goods and services, (b) regulation, (c) support, and (d) cultural services [18].

The second step is the identification of environmental ecosystem services to study and the decomposition of these services by functions. So, the different environmental services offered by an ecosystem are classified into four categories, as mentioned previously. Examples of each service and some functions of each of them are presented in the following Figure 2.5.

The next step is the determination of one or more indicators for physical quantification and the quantification of each.

2.1.3 Sustainable Management

Cork ensures the economic, social, and ecological sustainability of oak woodlands [11]. This sustainability must be characterized in terms of three aspects: natural, social, and economic, in accordance with the diversification of forest functions [19] and cork applications.

The sustainable management of cork production is predicated on the fact that cork barks can be peeled from the stem without jeopardizing the viability of the tree since it regenerates a new cork layer. The extraction of cork for the production of cork stoppers necessitates the periodic removal of cork from the bark to a degree deemed compatible with the preservation of the tree in excellent physiological condition and the production of this end product. This sustainable management of cork due to its cycle life of cork oak is represented in Figure 2.6.

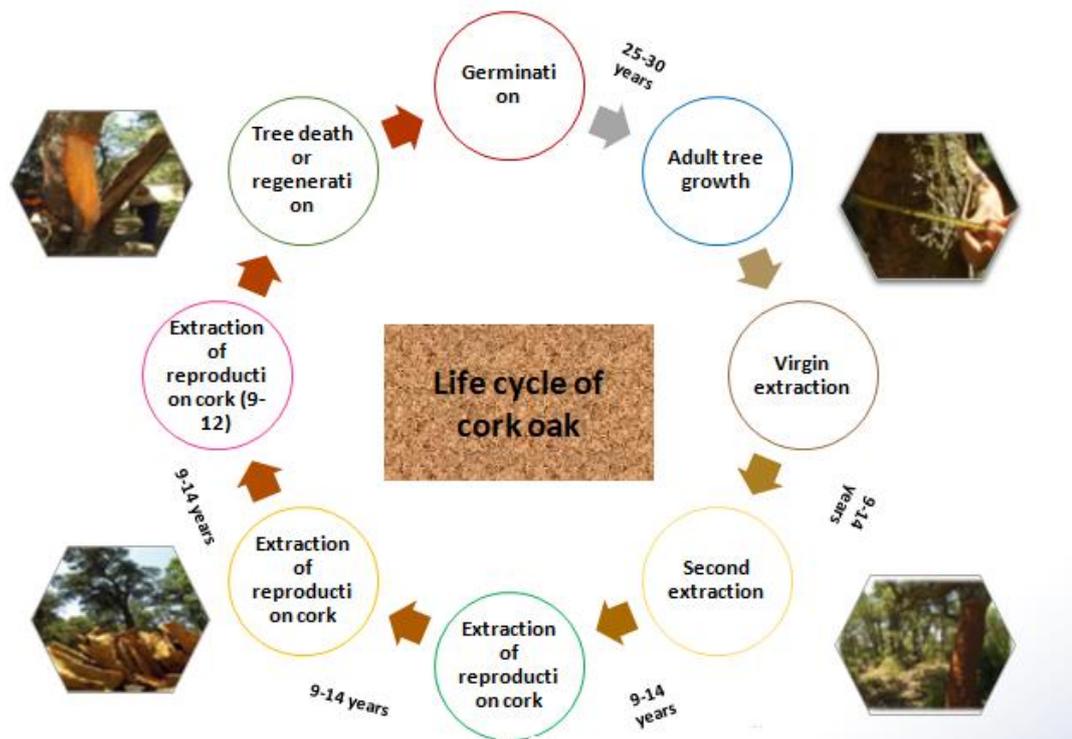


Figure 2.6 Cycle life of cork that shows how cork bark is obtained from the germination of the seeds to the tree dead (ICSuro).

As we can see in this Figure 2.6, the cork's first stripping is done when the tree is from 30 to 40 years old or when the tree is adult (it depends on the region). This first obtained bark is named virgin cork. Then, after 9 to 14 years, depending on the region, the tree is stripped again obtaining the second bark or second cork. These first cork planks are not suitable for cork stoppers production due to their mechanical properties and visual characteristics. And then, the cork oak is removed periodically at 9 - 14 year intervals getting another material named: reproduction cork. These last barks are useful for cork stoppers manufacture. This process is continuous until the tree is 150 to 250 years old. These conditions allow obtaining the commercial grade cork.

The cork stripping is done manually, and this process is shown in Figure 2.7. Therefore, cork stripping is a manual process that requires some expertise to avoid wounding the tree: without reaching and damaging the vascular cambium below the phellogen. This competence of the cork strippers is required to correctly execute the operation and make the correct selection regarding the beginning of the cork oak stripping.



Figure 2.7 Cork stripping process (ICSuro).

Utilizing an axe with a curved cutting blade and a relatively long wooden arm as a lever to separate the cork planks, the process of stripping is carried out. First, the stripper makes long cuts on the cork: horizontally around the tree perimeter and some vertical cuts. Then, the planks or cork layers are separated by inserting the axe's arm into the cut until the cork plank is extracted [1]. Usually, the cork team is constituted of two cork strippers, and the process is carried out rather fast and with an average yield of about 900 kg of cork in a working day [20]. Nowadays, there is an alternative mechanized process for cork harvesting.

Figure 2.8 shows the visual aspect of the virgin cork, the second cork, and the reproduction cork after the harvest. Virgin and secondary cork planks present some differences in the visual aspect in comparison with reproduction corks. These differences are due to the development of the tissue named periderm and its regularity. The surface of both first cork barks is irregular and presents lignocellulose structures. That is the reason that both barks are not suitable for natural cork stoppers production.

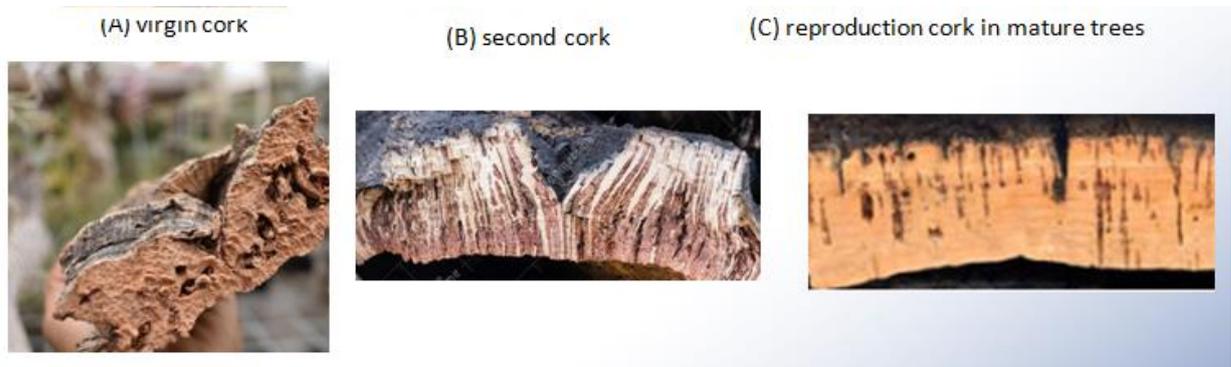


Figure 2.8 *Quercus suber*: (A) virgin cork; (B) second cork; and (C) reproduction cork in mature trees (ICSuro).

The cork extraction process is done only when the cork oak is physiologically active or during the period of periderm activity: when the phellogen mother cell and the recently formed phellem cell are turgid, and the cell walls are thin and fragile. By applying moderate force, the cork layer at the level of the phellogenic active zone can be easily separated [1] in this state. This stage corresponds to late spring and early summer. After cork stripping, the phellogen dies, and a new one is formed.

These conditions mentioned above are essential to guarantee that the tree is not harmed because it is possible to generate points of infection during the stripping. In this case, a biological attack could produce the death of the tree.

But how is possible cork bark regeneration? When we look at a cross-section of a tree stem (Figure 2.9), we can differentiate two meristems or a group of undifferentiated cells with cell division capacity (cambium and phellogen). Both meristems are able to produce tissues on both sides. In the case of the cambium, it is responsible for the formation of the xylem or wood (in the inner part) and phloem or principal food-conducting tissue in the vascular plants (in the outer part). This is the typical structure of woody plants. And in the case of the phellogen, is responsible for the formation of the phelloderm and phellem (or cork) in the inner and the other part, respectively. The periderm is the sum of phelloderm, phellem, and phellogen. Phloem and periderm composed the bark [1].

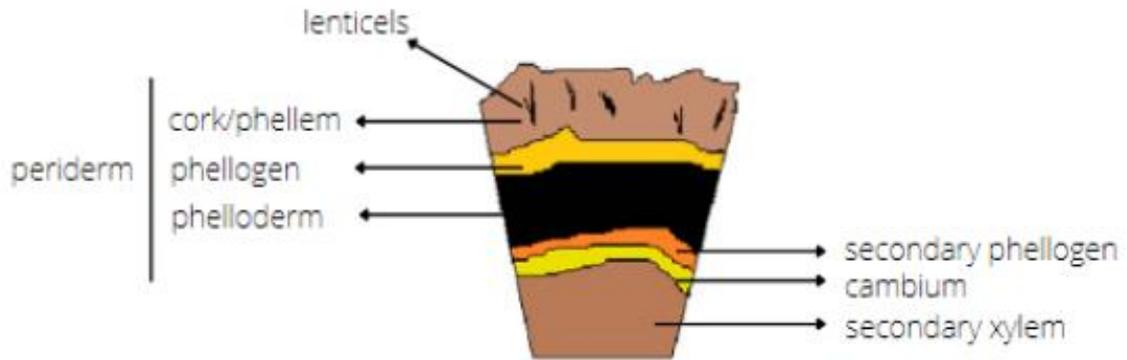


Figure 2.9 Cross section of cork oak stem (ICSuro).

The periderm is a protective tissue and, in some species, is only functional during a period of time. In the case of *Quercus suber*, the successive deaths and subsequent regenerations of the periderm are responsible for cork production. Also, cork oak periderm has some special characteristics related to its development, regularity, growth intensity, and longevity, and as mentioned above, its regeneration capacity after removal has made this species very unique.

After its extraction, cork can be used in multiple applications. Nowadays, natural cork stoppers are the most valuable and produced product in the cork industry. Cork stoppers represent 70% of the total revenue generated by the cork industry. According to APCOR registration, natural cork stoppers or stoppers for still wine accounted for 60% of the market, while other types of corks accounted for 21%, such as sparkling wine stoppers, represented 19%.

Cork that is not suitable for the cork stopper industry: virgin cork or low-quality cork are used to produce cork granules that are classified according to their density and grain size [21]. The absence of defects such as excessive discontinuities, i.e., deep fractures, are unsuitable for cork stoppers production for this reason, virgin and second cork are not used for this activity. These cork granules can be used as a final product in several applications taking advantage of their properties which are characterized by their lightweight, elasticity, and impermeability to gases and liquids.

The cork plank quality is an important factor in deciding the end use of this raw material. This quality is evaluated by a visual check of the cork planks. As mentioned above, the classification of cork planks is done by a specialized operator taking into account subjective criteria that are different according to their end use of them. In the case of cork quality of cork stoppers production, the principal characteristics considered are mainly porosity, the thickness of raw cork, and some defects such as insect holes or tangential cracks.

2.1.4 Climate Change's Effect on the Cork Ecosystem

The species of cork oak provides ecological, economic, and social benefits. Since the 1950s, however, the phenomenon of decline in certain cork oak forests has been recognized. In addition, prior research indicates that this decline has accelerated in the thirty years since the 1980s [22]. The capacity of Mediterranean forests to respond to systematic changes, such as enduring intense human influences or climate change, is limited. However, the causes of this situation are not yet clear.

Biotic and abiotic factors such as climate change or some human management could lead to a consistent oak forest loss, particularly in the Mediterranean Basin. For example, as a result of some practices such as clearing, grazing, or plowing for agriculture, cork oak forests were gradually transformed into open woodlands [15].

Kim et al. [5] suggested some hypotheses of *Quercus suber* decline. According to this study, some natural agents such as the increase of annual mean temperature, drought periods, rainfall extremes or the decrease of 57 mm in the average annual rainfall during the last two decades have been suggested to be causes of forest degradation. These environmental changes could lead to an increase of tree vulnerability to insects and pathogens and/or a physiological decline of the trees [23] because the survival and development of pathogens increase when the temperature rises in winter.

In the case of the increase in the temperature, the annual mean temperature in the Mediterranean region is expected to rise by 2 to 4.5°C, according to the IPCC report. During a hot summer, an increase in air temperature could hinder tree growth due to increases in respiration rates and drought stress imposed by the rising demand for evapotranspiration [5]. Furthermore, environmental phenomena such as periods of severe drought, rapid fluctuation of soil water levels, water logging, and/or prolonged flooding could be implicated in cork oak declines. These phenomena may be particularly important in initiating decline syndromes [24].

This decline phenomenon is associated with an increase in the number of trees with 'sudden death' symptoms that are related to infection by the fungus *Phytophthora cinnamomi* [25, 26]. Other reasons that lead to a cork decline are the presence of beetles in barks or an invasion by the opportunistic stem, and root disease fungi are other reasons [26].

The human impact is another factor to take into consideration. Some human activities such as industrialization, urbanization, overexploitation, or wildfire can cause environmental deterioration of some Mediterranean countries. Some consequences of them are climate change or major environmental problems such as soil decline, sedimentation, the loss of biodiversity or water and air pollution. In the late 19th and early 20th centuries, excessive tannin extraction following bark stripping was one of the primary causes of the long-term decline of cork oak woodlands [27].

Mediterranean forests have a long history of grazing. Some scientific evidence has shown that livestock grazing is an ecological factor that can serve the conservation of Mediterranean forests if properly used. Masson et al. have found that grazing in the French cork oak forest can result in the control of flammable shrubs. In the past, other studies blamed domestic animals for their destruction. These suggested that overuse and exploitation of cork oak forest might reduce its regeneration rate below the sustainable level in the Mediterranean basin [28, 29]. According to Costa et al. [20], the abandonment of traditional land management practices has resulted in significant land use transformations, such as the replacement of agricultural land uses and native oak woodlands with shrublands and fast-growing Eucalyptus and pine (*Pinus pinea* L.) plantations.

2.2 Carbon Footprint of Cork Products

2.2.1 Introduction to Carbon Footprint

Climate change is the main problem for the future of nature and humanity, and we need significant reductions in net greenhouse gas (GHG) emissions to mitigate future problems and set the world on a sustainable path to the future. Total net anthropogenic GHG emissions have continued to rise during the last decade, as have cumulative net CO₂ emissions since 1850. The forestry sector offers significant mitigation opportunities while providing food, wood, and other renewable resources, as well as biodiversity conservation. Natural resources can be renewable or non-renewable, depending on whether they can be extracted more than once and replace themselves naturally, and they have the potential to make the aeronautics industry more efficient.

Life cycle Assessment (LCA) and Carbon Footprint are increasingly popular tools for the environmental assessment of products that take under consideration their entire life cycle. The difference between an LCA and a Carbon footprint relates to the impact categories studied. A Carbon Footprint is concentrated on one environmental impact category: greenhouse gas emissions (CO_{2eq}¹). Carbon footprint analysis is a subset of an entire life cycle assessment of a product, activity, or process. LCA identifies the inputs and outputs of matter and energy throughout the useful life of a process, product, service, person, or organization, depending on the scope of the study. This analysis, together with the Carbon Footprint, allows for the standardization of data, the performance of analyses and comparisons, and the determination of the environmental impact of the object of research in the same unit (CO_{2eq}) regardless of the context.

¹ CO₂ equivalent, abbreviated as CO₂ eq, is a metric measure used to assess emissions from other greenhouse gases based on their global-warming potential (GWP) by converting levels of other gases to the equivalent amount of carbon dioxide with the same GWP.

To evaluate the environmental performance of different products, we can use the LCA and translate the results in CO_{2eq} (carbon dioxide equivalent) as a carbon footprint. We can define the Life Cycle Assessment methodology as the assessment of the environmental impacts associated with a product, process or service throughout its life by inventorying material resources, energy inputs, and environmental issues through the raw materials obtention, fabrication, use and disposal of the product or service (cradle to grave approach) (Figure 2.10).

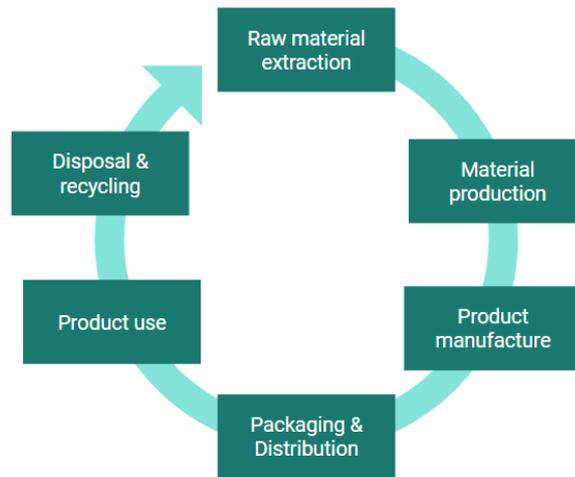


Figure 2.10 Life Cycle Assessment (LCA) (ICSuro).

Cork material is intimately related to the preservation of biodiversity, the cornerstone of sustainable development, as well as the reduction of greenhouse gas emissions and CO₂ sequestration. Cork regenerates after each stripping, allowing the cork tree to withstand the loss of a significant amount of bark, typically more than 50 percent of the total trunk and branch surface. The fact that corks are created from the bark of living trees has prompted policymakers to favor their use over less natural alternatives. There are some life cycle assessment studies that are focused on cork oak forest management and their relationship with the environment [30-33].

The carbon footprint for the cork sector must be considered at all its different stages, from forest management (not only cork harvesting), through the manufacturing processes and product distribution, to the product end-of-life (namely disposal, incineration, recycling, etc.). Also, the biogenic carbon sequestered into forest-based products (cork, wood, etc.) is usually not included because they are released into the atmosphere during the processing and end-of-life stages by decomposition, incineration, or biological degradation. The biogenic carbon sink and emission delayed in the forest (wood, cork bark, roots, and foliage) is held within the cork product during the product's use until the end-of-life stages (considering that incineration with or without energy use, landfilling with anaerobic cork degradation, and composting are end-of-life stages depending on the possibilities of each territory and public services for collection and management of waste and by-products).

2.2.2 Carbon Fixation of Forests

According to the United Nations' most recent IPCC (Intergovernmental Panel on Climate Change) report from 2022, it is "unequivocal that human impact has warmed the atmosphere, ocean, and land." In the 21st century, global warming will reach 1.5°C and 2°C unless carbon dioxide (CO₂) and other greenhouse gas emissions are drastically reduced in the following decades. From a physical scientific standpoint, limiting human-caused global warming to a predetermined level implies limiting cumulative CO₂ emissions and achieving net-zero CO₂ emissions, in addition to significant reductions in other greenhouse gas emissions. Although humans are responsible for the combustion of fossil fuels, the assimilation and medium-term storage of carbon in forests can help to the reduction of carbonic gas emissions from fossil fuels.

The *Quercus suber* woods are outstanding ecosystems because they are the consequence of long-term, traditional human management practices and a symbiotic relationship between humans and the environment. Cork oak woodlands, like all forests, contribute to climate change mitigation by removing (CO₂) from the atmosphere through photosynthetic activity and storing it in their perennial tissues during the natural growth process and in the soil as organic matter. The cork oaks are long-lived trees; they are able to store carbon for very long periods of time, and their exceptionally tough bark can last long after the cork oak has died. The same is true of cork products, as they are extremely durable and can be used for extended periods of time, as well as in a landfill (the cork material is not easily degraded), storing the majority of the carbon contained in the cork bark (biogenic carbon) harvested from the cork oak forest, thereby contributing to the reduction of the greenhouse effect caused by CO₂ gas.

Carbon sequestration in forest ecosystems is assessed by the equilibrium between photosynthetic carbon absorption and ecosystem respiration-emitted carbon dioxide (including the decomposition of organic matter in the soil, which provides the essential nutrients for life). Hence the significance of gauging the ecosystem's balance or net production.

Cork forest ecosystem absorbs between 2 to 14 tons of CO₂/ha/year, according to different studies [34-38], and this amount depends on the type of ecosystem (grassland or forest) and climatic conditions.

ICOS (Integrated Carbon Observation System) was developed by the European Union to aid global efforts to quantify the carbon balance. The annual carbon retention capacity of montado or Portuguese cork oak forests has been evaluated through research conducted in Portugal. For instance, in central Portugal (Herdade da Machoqueira), a 50-year-old cork oak (*Quercus suber*) open woodland with an understory of semi-deciduous shrub species and native grassland can retain up to -388 g C m⁻² year⁻¹ [37] (i.e., 14.2 tons of CO₂ per hectare per year). However, the occurrence of adverse conditions, such as a dry year, can result in significant decreases (about 45%) in carbon sequestration.

The carbon stock in cork oak forests depends mainly on the location of the cork oak forest because this affects the tree density per hectare, the period of cork extraction, and the growth rate. The annual variation of carbon sequestration also depends on the climatic conditions in a given year.

The following table shows the results of the net carbon sequestration (fixation minus emission or net ecosystem exchange rate) of the cork oak forest according to various studies, and it also presents the variation of the net exchange of CO₂ depending on the climatic conditions as well as the final average. Carbon fixation results in studies are often reported in units of gCm⁻² year⁻¹, these have been converted to standard values of ton CO₂ ha⁻¹year⁻¹; In addition, when the studies report ranges of values, these have been transformed into a mean value in Table 2.2.

Table 2.2 Net Ecosystem Exchange rate (ton CO₂/ha·year).

	Author	Ton CO ₂ /ha·year	Ecosystem	Period	Location
1	Pereira [34]	-3.1	Holm oak and cork oak woodland	2003-2006	Alentejo, Portugal
2	Garcia [82]	-2.9	Cork oak forest	2005	Catalonia, Spain
3	Costa-e-Silva et. al. [37]	-14.2	Cork oak woodland	2011	Central Portugal
4	Spampinato et al. [38]	-5.0	Cork oak woodland	2017	Calabria, Italy
5	Montero et al. [35]	-1.9*	Cork oak woodland and forest	2004	Spain

*Result of the quotient of total biomass annual increment (1.031.232 tons CO₂eq) divided by cork oak distribution area in Spain (541.179 ha according to data from INIA-CSIC).

The biomass measurement, reported as dry weight, quantifies the quantity of carbon fixed in forest ecosystems as well as the comparable amount of carbon dioxide (CO₂) removed from the atmosphere. The carbon fixed in plant tissues (wood, leaves, etc.) accounts for around half of the biomass, while the carbon dioxide equivalent is calculated by multiplying the carbon content of the biomass by the ratio of the molecular weights of anhydride carbon to elemental carbon.

The use of cork is closely related to CO₂ sequestration. Periodic cork extraction causes cork oaks to produce between 250% to 400% more cork [39] than they would if the cork was not removed (after cork removal, the tree quickly starts to produce new bark to protect itself), therefore increasing the fixation of CO₂. The sustainable management and exploitation of the cork oak forest, due to the commercial exploitation of this material, promotes the formation of more cork, and thus more CO₂ is sequestered [40]. Additionally, these cork products can have a useful lifetime of years (such as cork stoppers) or tens of years (such as flooring and other construction materials). In fact, there are still no in-depth studies on the influence of recycling cork stoppers in increasing the useful life of cork, for example, the initiatives in the application of recycled and granulated cork stoppers in urban applications as those promoted by the Catalan Cork Institute Foundation. In the end-of-life phase, biogenic carbon emissions were also taken into account. Specifically, in the event of incineration, all of the cork products' biogenic carbon was regarded to be emitted back into the atmosphere (after the use period of the cork products). In the case of landfilling, just 2% of the biogenic carbon contained in the items is typically regarded to be released, with the remainder remaining permanently retained in the landfill site [41]. The lengthening of its useful life allows its characteristics of carbon neutrality to be extended until the instant of its decomposition or energetic use.

The harvesting period of cork takes place in the summer (May to August) and is carried out after the tree has reached 0.7 m (Portugal), 0.65 m (Catalonia and Andalucia), or 0.60 m (Extremadura) in the perimeter at 1.3 m from the ground. In the same tree, two consecutive debarking are separated by a minimum of 9 or 14-year intervals (depending on the territory). The first cork harvest (cork bark extraction) can take place when the trunk diameter is large enough. The first bark extracted is called virgin cork, and because of the irregularities on the exterior surface, it is usually shredded and used for construction purposes. Nowadays, this first cork is destined for the cork granulation industry in the production of granules that will be agglomerated for the production of black cork products utilized as insulation in construction.

After the first cork stripping, between 9 and 14 years, the second cork harvest takes place. This cork of the second extraction is named secondary cork (*matxot* in Catalan, *segundero* in Spanish, *secundeira* in Portuguese), and since its characteristics are not optimal for cork stopper production (the use of the highest value-added), it is sent to the granulation industry for the production of white granulated cork for insulation and other agglomerated cork products.

The third cork stripping and subsequent strippings produce more uniform cork planks. Reproduction cork is used for the fabrication of natural cork stoppers for the still wine industry for the closing of wine bottles and natural cork discs for the assembly of agglomerated cork stoppers (called technical corks) for sparkling wine. The sparkling wine bottles have internal pressure and technical corks to more efficiently seal the bottles. The cork obtained through the pruning of the cork tree's branches and uneven trunks yields a cork byproduct known as deadwood cork (*suro pelut* in Catalan or *falca* in Portuguese), which is a mixture of several cork varieties, inner bark, and wood. After the cork has been separated from the wood, it is deemed to be of inferior quality (virgin and second cork) and is shredded and agglomerated for use in the creation of construction materials.

It is considered that 150 -200 years are the maximum exploitation age for a cork oak tree [37]. The tree density of a cork forest varies widely depending on the region (50–150 trees per hectare), and an average density of 100 trees per hectare can be assumed for LCA analyses throughout the cork-producing phase. The forest cork output can vary greatly depending on the territory, which indicates varying climatic and ecological circumstances, which in turn influence the tree density, the development rate of the cork trees, and the intensity of cork stripping. For example, we can calculate the production of 1.49-3.48 tons of total raw cork per hectare in the Catalan forest [42].

There are two main management models or ecosystems of cork oak stands agrosilvopastoral systems (mainly in Portugal and Southern Spain) and forest systems (i.e., Catalonia and Southern France). They originate at different impact levels, which tend to be significantly lower in forest systems [41]. The environmental hot spots in the two models are distinct. In the forest system, they are associated with cleaning, road maintenance, and worker and cork transport. In agro-silvopastoral systems, they are fertilization, pruning, and cleaning. The two allocation criteria of environmental impacts significantly affect the results obtained for virgin cork in agrosilvopastoral systems and for virgin and second cork in forest systems. Comparing the impacts found for virgin and second cork in Portugal and Catalonia reveals that the impacts in Catalonia are significantly lower due to the less intense management procedures described above. Both Portugal (Alentejo region) and Catalonia maintain their cork oak forests differently. In Portugal, cork oak stands are intensively maintained agrosilvopastoral systems characterized by low tree density. Forest systems in Catalonia have a higher tree density, fewer automated operations, and no fertilizing. Due to these distinctions, cork produced in Portugal tends to have greater environmental repercussions than cork produced in Catalonia [41].

The Cork Carbon Footprint Model (CCFM), developed for the Portuguese cork sector [33], can be extrapolated to other cork territories such as Spain. This proves that the cork sector is a carbon sink; this means that the cork sector as a whole retains more CO₂ than it emits to the atmosphere in the manufacture of cork products. Figure 2.11 shows that carbon taken by the forest for biological purposes is greater than the greenhouse gas emissions (GHG) of the entire sector, including biogenic

carbon. Also, the figure shows that the most GHG emitting processes are the manufacturing of agglomerated products, mainly due to the resins that are mixed with cork granules during agglomerated cork production. With this figure, it becomes clear that cork oak forests and the cork products obtained with cork harvesting have the potential to mitigate the greenhouse effect by reducing carbon emission in the atmosphere.

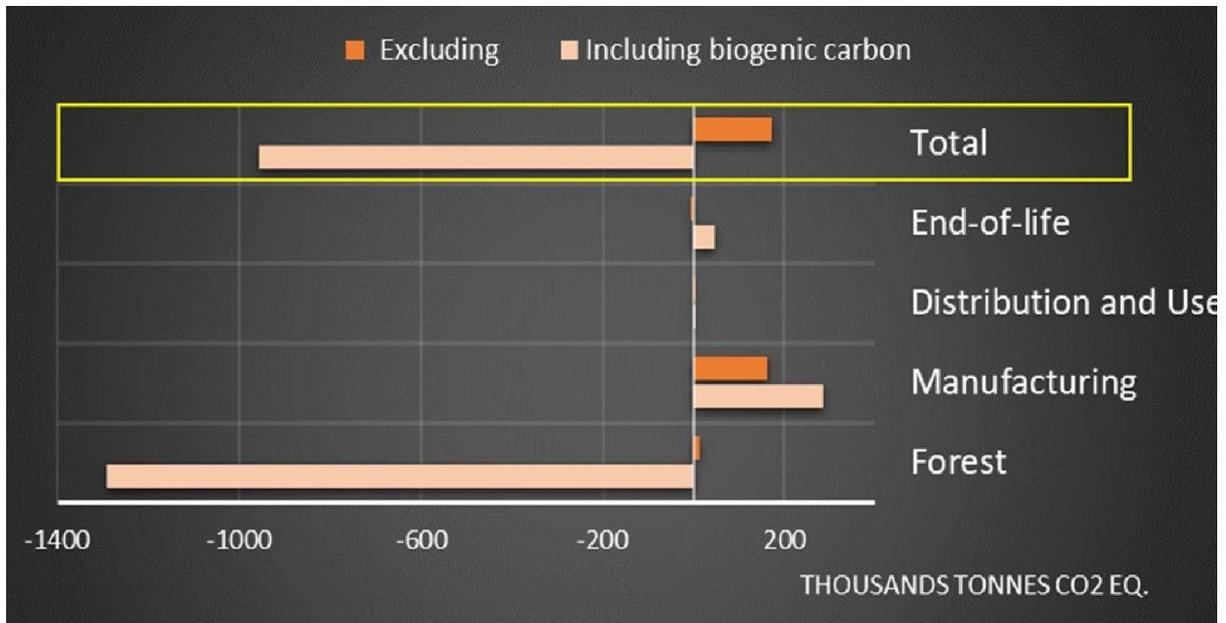


Figure 2.11 Cork carbon footprint by sector stage calculated by the Cork Carbon Footprint Model [43].

2.2.3 Life Cycle of Cork Products

The development and deployment of Product Category Rules (PCR) could be advantageous in the case of cork products since it would allow the comparison of different studies and aid in the avoidance of miscalculations by providing a standardized methodology. In fact, at the time of writing this document, the Spanish Technical Committee for Standardization (CTN 56 SC5), in charge of the standardization of cork products and led by the Catalan Cork Institute Foundation, is developing a PCR to standardize the methodology for calculating the environmental footprint of different types of cork stoppers. We can find in the literature a few LCA studies searching on the environmental effect of the main cork products. For example, natural cork stoppers, champagne cork stoppers, and cork floating floors. Currently, in Catalonia is being updated an integrated environmental analysis of some cork products [44].

Through the application of LCA, it is possible to evaluate all the materials used, the fossil and renewable fuels consumed, and all the resulting emissions in order to find the most influential phases that may be modified to reduce the total environmental impact of cork product manufacturing. The data on the major hotspots of the manufacturing process (boiler and forest management) may be

examined by the industry in order to implement improvement measures and reduce the final environmental impacts, as well as the end-of-life strategy. Since these two processes are the most impactful across all categories of effect evaluated. The cork industry could achieve a better environmental performance by focusing on those two aspects. In the case of forest management, for instance, an alternative approach could be implemented by altering the frequency of activities such as clearing of the spontaneous vegetation or fertilization; however, this must be thoroughly studied so as not to reduce forest productivity, which would be detrimental to the carbon footprint.

As indicated earlier, the sequestered carbon remains in the biomass of the cork oak tree and later in cork products until it is released into the atmosphere through burning or decomposition. Consider the forest stage (including cork oak management activities), the manufacturing stage (including the various processes for the production of cork products), the use stage (including the transportation of used cork products to distribution locations), and the end-of-life stage (including the management strategies of recycling, composting, incineration or power generation and landfilling). Also describes CO₂ sequestration at the forest stage (during the growth of the cork oak trees). Considering the biogenic CO₂ emissions and storage (CO₂ stored in the cork material itself), it is vital to note that the end-of-life destination has a considerable impact on the results, as it can considerably alter them. It is not possible to assume that all of the biogenic carbon present within the system loop persists. Considering that recycled cork stoppers may be utilized in the creation of other agglomerated cork goods (i.e. building), Demertzi [33] calculates that 30% of the raw material is included into the finished product. In the event of recycling, 30% of the carbon included in natural cork stoppers is believed to remain in the system without being released into the atmosphere, whereas 70% of the biogenic carbon contained in natural cork stoppers is released into the atmosphere (due to cork dust combustion). When biogenic carbon is included in the calculations, CO₂ sequestration in the forest stage is considered a negative emission since it decreases the quantity of CO₂ in the atmosphere.

According to the standard ISO 14067:2018 *Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification*, when biogenic carbon is stored in a product for more than 10 years, it should be documented and valorized but should not be included in the carbon footprint.

The percentages used for the final destinations of the various cork products should be based on the main final destinations of municipal solid waste and recycling strategies. Recycling would significantly increase useful life in the cork sector as a whole. It must be taken into account that 440 tons of cork stoppers were collected in glass treatment plants in Spain in the year 2020, according to ECOVIDRIO (non-profit entity responsible for managing the recycling of all glass packaging waste in Spain). As a whole, in Spain, the wineries adhering to the Integrated Waste Management System declared 3,700 tons of cork stoppers, according to ECOEMBES (a non-profit corporation that

supervises the waste recycling put in the yellow and blue bins). Therefore, the cork and wine sectors have a high potential for recycling cork stoppers and increasing their useful life through other applications and thus increasing the time until biogenic carbon passes definitively into the atmosphere.

Depending on the effect category assessed, many end-use management solutions, such as landfilling, incineration, energy production, composting, and recycling, might be selected. Some alternatives can give the greatest environmental outcomes for climate change, ozone depletion, and acidification, while others can provide the best environmental outcomes for photochemical ozone generation and mineral and fossil resource depletion. In most categories of environmental effect, the landfill option does not provide the optimum performance.

However, when the biogenic carbon dioxide emission is evaluated for the climate change category, the recycling option is shown to be the most efficient since the majority of the biogenic carbon would be nearly permanently retained in the cork products and would not be released into the atmosphere. CO₂ sequestration in cork products for different applications is based on previous determinations of the carbon content of different cork materials. Knowing the amount of biogenic carbon in different types of materials allows engineers, architects, designers, and other technicians to estimate in an easy way the amount of CO₂ sequestered in the cork products when using them in very different applications. On the other hand, and from a broader perspective, we can consider that cork products, given their physical-mechanical characteristics, tend to be substituted for plastic materials which are much more energy-intensive in their manufacture and come from sources of energy and non-renewable matter. These calculations are a current issue and have an increasing importance when comparing materials bearing in mind the need to achieve carbon neutrality. An example of these calculations can be found in Gil's work [31] (Table 2.3).

Table 2.3 CO₂ content of different cork products [31].

Product	g CO ₂ /product	g CO ₂ / g product
Sparkling cork stopper (agglomerated with 2 discs of cork)	16.5	1.90
Still wine cork stopper (natural cork stopper)	10.6	1.89
Agglomerated cork stopper for still wine	9.3	1.90
Micro agglomerated cork stopper for still wine	7.9	1.47
Expanded cork slab (40 mm wide)	-	2.27
Expanded joint (12 mm wide)	-	1.93

Natural cork stoppers have a 100% cork; in fact, for a stopper to be considered a "cork stopper" it must contain at least 65% cork in mass in their formulation [45]. Other cork-based materials also have considerable carbon content, from about 55% to about 65% (w/w), and this corresponds to high carbon sequestration in these materials. Given this aspect and due to the fact that cork materials have quite long useful lives, which can be extended after a first use through recycling, these are materials of choice for so-called "green" and sustainable applications.

2.2.4 Carbon Footprint Values

The cork industry is distinguished by a wide range of cork products. Figure 2.12 depicts the most representative cork products manufactured from the various cork types: black agglomerated cork construction products and granules (from deadwood cork and virgin cork), white agglomerated cork construction products and granules (from deadwood and second reproduction cork), natural cork stoppers and discs, and agglomerated cork stoppers and construction materials (from reproduction cork). These products represent 97.6% of the total cork products sold in Portugal [46], in Spain almost 100% of cork products manufactured are cork stoppers. The remaining part of the cork material includes mainly raw material and decoration products, composites as well as cork sheets used in fashion products and nowadays there is no available data regarding the GHG emissions during their manufacturing.

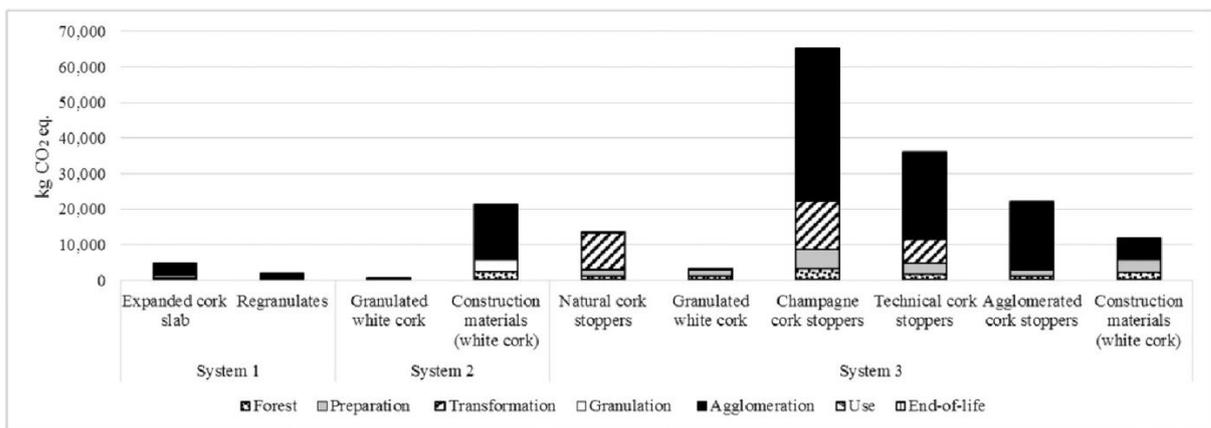


Figure 2.12 Carbon footprint output of the model for the most representative final products of the cork industry, excluding biogenic carbon and forest sequestration [48].

The total carbon footprint of the cork sector can be substantially reduced if we take into account the carbon sequestration in the forest stage. It is known that 79% of the carbon sequestered in the forest stage is stored wood, roots, and foliage of the cork tree, while the rest 21% is conserved in raw cork [48]. If we consider the best conditions for carbon sequestration in the forest (14.2 tons CO₂ ha⁻¹ year⁻¹

¹⁾ and an average productivity of 1.5 tons per hectare, we have that -9.5 kg of CO₂ is absorbed for every kg of cork extracted. This calculation of forest carbon fixation can be valued together with the result of the carbon footprint calculation to better understand the positive impact of the use of cork material.

Obtaining a carbon sequestration value that is as close to reality as possible is important from the perspective of carbon farming. Carbon farming can be defined as a green business model that rewards land managers for adopting improved land management practices that increase carbon sequestration in living biomass, dead organic matter, and soils by enhancing carbon capture and/or reducing the release of carbon into the atmosphere, while adhering to ecological principles that are beneficial to biodiversity and the natural capital as a whole. The financial incentives may originate from public or private sources and may reward land managers either for their management techniques that increase atmospheric carbon sequestration or for the amount of carbon sequestered. Carbon farming would be a new source of income for land managers, who might, in many cases, also reap the benefits of more fertile and resilient land in general. Moreover, carbon farming approaches frequently generate co-benefits for biodiversity, improve ecosystem services, and assist land managers in becoming more climate change resilient

2.3 Potential Uses of Cork

2.3.1 Main Properties of Cork

Cork is a natural substance extracted from the outer bark of the cork oak. The cork oak (*Quercus suber* L.) is an indigenous species to the woods of the western Mediterranean region. Cork is a peculiar substance. It is lightweight and water-repellent, making it a suitable material for floats. It is used to stopper bottles since it is compressible and impervious to liquids. [34]. Its extremely low thermal conductivity makes it an excellent insulator for ablative insulators used to shield spacecraft from high temperatures, and its energy absorption capacity is also utilized in other aerospace applications. But why does cork material have these properties?

In the 17th century, Robert Hooke sliced a tiny piece of cork, placed it under his microscope, focused sunlight on it with a thick lens, and viewed the specimen via the eyepiece. Hooke compared what he observed to a honeycomb. Cork's structure was composed of numerous small, empty chambers divided by thin walls. The compartments were referred to as "pores or cells." He estimated that there were approximately twelve hundred million of these cells per cubic inch of cork. Hooke had discovered the microscopic structure of cork. He believed that the microscopic structure of cork was responsible for its macroscopic qualities. And what he predicted was true, but he was unaware that there was another factor that explained the multiple properties of cork [49].

The qualities of a material are determined by the chemical properties of its constituents, as well as their relative amounts and distributions (Figure 2.13). As with other cellular materials, the chemical components of cork are situated on the cell faces and cell edges, forming a three-dimensional network of a solid matrix that surrounds the air-filled hollow cells. Many of the cork's unique traits are directly related to its chemical composition, while others, like its mechanical behavior and interaction with fluids, are the result of both the cell-level structural features and the chemical structure of the cell wall. Thus, the physical and mechanical properties of cork are a result of the cellular structure and chemical composition of the plant wall (suberin, lignin, and polysaccharides).

This subchapter summarizes the knowledge about the main properties of cork and also refers to its chemical composition and structure.

Structural characteristics

Cork's macroscopic cellular structure is widely established and well known, but its microscopic structure remains poorly comprehended. After growing, cork cells are devoid of cytoplasm and become empty. It is generally acknowledged that the cell wall is a convoluted structure made of the primary wall, which is primarily formed of cellulose, the secondary wall, which is assembled from lamellar depositions of suberin and, to some extent, lignin, and the tertiary wall, which consists of polysaccharides. The resultant structure is composed of a collection of hollow cells. Cork is a substance with anisotropy. The cross-section of the radial direction (surface perpendicular to the direction of bark growth) resembles a honeycomb with polygonal cells with four to nine sides [1]. The tangential and axial cross sections are morphologically comparable, and the structure resembles that of a brick wall (prismatic cells) [2].

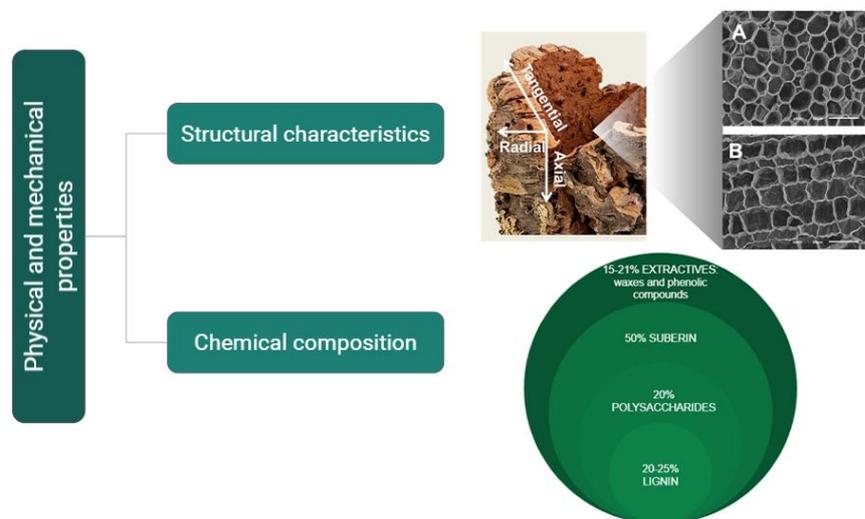


Figure 2.13 Schematic representation of physical and mechanical properties of cork: structural characteristics and chemical composition. SEM micrographs taken from a small cork cube (a) tangential section and (b) radial section [50].

Cork comprises a noteworthy number of properties that are unique within naturally occurring materials. It is estimated that in 1 cm³ of cork, there are 15 to 40 million cells. Each cell measures about 40µm on average, of which 10µm corresponds to the cell wall.

Chemical composition

The composition of cork began to be studied by Brugnatelli in 1787. Suberin is the main compound of cork, and it was identified by Cheureul in 1807. From then until today, the composition of cork and its macromolar structure are still being studied, and there are still no clear models.

Cork's chemical composition is dominated by the presence of suberin as the primary structural cell wall component and by its close association with other components, primarily lignin and non-lignin aromatics. The chemical composition of the cork is substantially different from the other parts of the tree tissue. Its specificity results in some gaps in the knowledge of the structure of the chemical composition of cork. In addition to its composition and the chemical properties of its constituents, a more comprehensive chemical understanding of cork necessitates knowledge of their distribution within the cell wall, known as cell wall topochemistry, and their eventual interaction.

The methodology used in determining the chemical composition, as well as other aspects, such as the origin, the physiological state, or the number of specimens, can condition the results. For this reason, if it is talked about the chemical composition of cork is given the rank of each family of compounds. The structural components of the cell wall are by order of relative importance suberin (50% approx.), lignin (20-25%), and the polysaccharides (about 20%), cellulose, and hemicelluloses; the extractive (14-18%), which include lipid and phenolic substances and inorganic components (1-2%) [1] (Figure 2.13).

- Suberin is a polymer composed of fatty acids, alcohols, and glycerol, namely long-chain aliphatic chains connected by ester bonds and mostly glyceridic anchoring sites. Suberin is the primary structural component of the cork cell wall (constituting more than fifty percent of its solid mass) [34,51]
- Lignin is a cross-linked aromatic polymer that contributes to the structural rigidity and compression resistance of cells. Lignin is composed of three phenylpropane monomers: p-hydroxyphenyl (H), guaiacol (G), and syringyl (S) [34,52].
- In the development of the cork cell wall, polysaccharides play a minor role. The structural polysaccharides of plant cell walls consist of cellulose and hemicelluloses [34].
- Extractives are molecules of low or medium molecular weight that can be extracted from cells without changing the cellular structure of the material or its mechanical properties [14].

- Inorganic components of lignocellulosic materials are usually the ash content, which represents the solid residue after total combustion.

In the cell wall, the suberin, lignin, and hemicellulosic fractions form a spatially stable and chemically resistant assemblage, making their fractionation very challenging regardless of the technique employed. Pereira [34] depicted the building of the cork cell wall schematically (Figure 2.14). The lignin matrix of the middle lamella binds the cells together and reinforces the structure as a whole. The lignin and aromatics layers between the suberin lamellae also impart structural solidity to the cell walls, serving as a sort of scaffolding for the flexible aliphatic component. The lumen side of the cell is lined with the cellulosic tertiary wall.

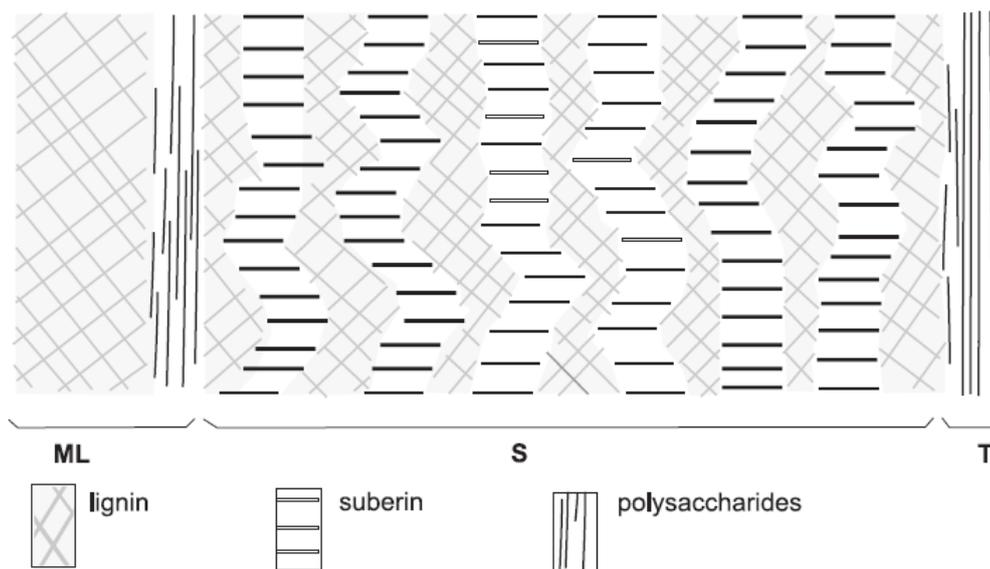


Figure 2.14 Schematic representation of cork cell walls in *Quercus suber* showing the location of the structural components [34].

Cork properties

Cork possesses a remarkable combination of qualities, including low density, very low permeability to liquids and gases, low conductivity, chemical stability, durability, high compressibility with good recovery, and low conductivity. As stated previously, the characteristics of cork's cellular structure (cell arrangement, cell size, and cell wall corrugations) and the chemical composition of the cell walls explain these qualities. Many cork's qualities are influenced by its water content, and heating treatments alter cell size and chemical content. The cork mass itself seems uniform and devoid of cell-type distinction. The only distinguishing macroscopic characteristic of cork is the natural presence of lenticels. The lenticular channels traverse the cork layers from the exterior to the interior tissue of phellogen and are filled with non-suberified material of a deeper hue [34].

The high amount of gas, the low water adsorption power, and the cellular measurement, among other characteristics, make the cork have great versatility and that it can be used for multiple purposes. The physical, mechanical, and thermal properties of cork can be summarized in ten points or the decalogue of cork [89].

1. Low density and lightness [1].

Cork is a light material that floats on water. This is the result of its cellular structure formed by hollow and closed cells with a small solid fraction that is concentrated in thin cell walls, without any intercellular communication channels. The density of the air-dried cork tissue is low, on average in the range of 150-160 kg/m³ but with values that may go from below 120 to over 200 kg/m³. The density of cork will vary due to the following structural features: the size of the cells, the proportion of earlycork (cells formed in the first period of growth) and latecork (the cells formed at the end of the growing season), the corrugation of cells, the extent of the porosity derived from lenticular channels and the presence of woody inclusions. This one feature has been widely used in all floatation elements.

2. Impermeability and waterproofing [1].

As cork cells are about 90% occupied by air, it could be thought that a liquid can fill that empty space. The hydrophobic behavior of cork in contact with water vapor and liquid water results from its structure with hollow cells without intercellular communication and a cell wall containing suberin as the major chemical component. The presence of suberin, lignin and waxes in the cell wall make cork an impermeable material to liquids, which prevents its deterioration. However, its gas impermeability is not absolute, since it allows a slow diffusion of gases. Cork stoppers are watertight and they have an oxygen transfer rate from 0.004 to 0.14 mg/day after one year of bottling [54-56]. The high gas content has low conductivity, the small size of the cells eliminates the gas convection, the low solid fraction and the low adsorption power due to the numerous cell walls make cork have a low heat transmission. The heat waves dissipate and spread over its surface and make it a good thermal insulator. At the same time, it is breathable and non-flammable, which makes it a unique climate regulator. The heat conductivity (λ) and the thermal diffusivity (α) of cork with a density 140-170 kg/m³ is 0.040-0.045 W/m·K, 1×10^{-7} - 1.5×10^{-7} m²·s⁻¹ respectively. When cork is heated, there are chemical and physical changes that affect the cell wall mass, their composition and the cellular dimensions. These changes influence the properties, namely the mechanical properties, to an extent that depends on temperature and time of treatment. The mass loss of cork is relatively small (about 6% of the initial mass) until 200°C, but increases afterwards until complete carbonization at about 450°C.

3. Low sound transmission and acoustic insulation [57-59].

Cork presents a near-zero Poisson's ratio (about 0.2) for NR/NR [57], low density and high porosity. The cork properties make the most of the sound waves being adsorbed and transformed into heat

energy. Cork acoustic impedance is $1.2 \times 10^5 \text{ kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ for a 120-200 kg/m^3 natural cork [58]. Cork is very absorbent of sound for low and medium frequencies. It is a good insulating property for acoustic percussion; for this reason, it can be used in laminate flooring [59].

4. High resistance to movement and high coefficient of friction [34,58].

Cellular structure causes suction effects. The resistance to movement offered by cork against a surface is a property of interest in especially two cases: the extraction of cork stoppers from bottles where the cork moves against a glass surface, and the use of cork products as surfacing materials, sometimes with anti-slippery objectives [34]. This property is very important in cork stoppers to ensure the correct closure of the bottles and their maintenance over time. The coefficient of friction is 0.35-0.76 for cork-glass [58].

5. Buffering capacity and shock–energy absorbing capacity (damping).

The cellular structure allows the deformation by flexion of the cell walls, as in the previous cases, the propagation of mechanical waves can dissipate on the surface. The collapse stress of the cork cells is low, so that the peak stress during impact is limited while large compressive strains are possible, absorbing a great deal of energy as the cells progressively collapse. The total energy of compression to a strain of 83% is approximately $3.4 \times 10^6 \text{ J}/\text{m}^3$ and $2.2 \times 10^6 \text{ J}/\text{m}^3$, respectively for the radial and non-radial directions. The part corresponding to the deformation until the end of the collapse plateau represents about $1.5 \times 10^6 \text{ J}/\text{m}^3$ [34]. This property is very important for some applications such as the cushioning capacity in "seismic" joints, automobile industry shoe soles or mats.

6. Compressibility, elasticity, and flexibility [1,60].

The cells high air content and its near-zero Poisson's ratio allows the cork to be compressed to almost its half without losing flexibility, and to regain its shape and volume when it is no longer pressed. Cork does not fracture under compression either across cells or across cell walls. The dimensional recovery after unloading is considerable and the residual strain is small even from initial strains within the collapse region and densification regions. Cork only fractures if stressed in tension (also on the tension side in bending) and under shear forces. Pores have a dominant effect in the tensile strength of cork and fracture initiates always at the vicinity of a pore. Cork is an approximately elastic cellular material that combines an interesting set of mechanical properties. In the mechanical behavior of cork, two characteristics have an important function: the ability of cell walls to buckle and strongly collapse without cell wall fracture and the presence of lenticular channels. The modulus of elasticity of cork is a range of values between 10 MPa and 20 MPa are reported in the various studies for the compression of cork in the different directions. In cork the dimensional reversibility is not total due to the viscous component of the deformation. Cork only resembles to an elastic behavior and within it is a

viscoelastic material [60]. These characteristics are totally related to the cork's energy absorption capacity.

7. Wear, stability, and inert [34,50,59].

The lignin and polysaccharides in its cell wall provide rigidity. And these components give the cork resistant to passage of time. Cork is a dead tissue. Furthermore, cork is neither toxic nor allergenic and does not produce undesirable reactions in contact with the skin or other tissues. Cork is a material resistant to surface wear that withstands without significant fracture or abrasion the repeated rubbing of objects against it [34]. Cork presents resistance to most solvents including mild acidic and basic solutions [50]. It does not rust due to the action of air or humidity [59]. These are the reasons why cork-based products, mostly cork agglomerates, are used for flooring in areas subject to intense use, such as hospitals, schools or airport halls.

8. Hygroscopic and biosorbent [61-69].

Cork is hydrated depending on environmental conditions. Cork swells when it absorbs water. Because of its structural anisotropy, the dimensional variation is not the same in the three directions. The corrugation of the cell wall, as a structural aspect, has to be taken into consideration to understand the dimensional variation of cork. Within, the straightening of the cell walls may overlay to the swelling due to water adsorption to the cell walls. The absorption of water by the cork appears to proceed by two mechanisms: diffusion of the water molecules along the cell walls and the penetration into the cell lumen. The intake of water by cork therefore depends on two aspects: the chemical composition of the material and the presence of lenticular channels. The equilibrium moisture content of cork after air drying and equilibration in in-door conditions is on average 7%, ranging from about 5 to 10% with very low air RH or humid conditions, respectively. For instance, cork oak wood has an equilibrium moisture content at approximately 20% for a RH 80%. The maximum moisture content that can exist in a material depends on its density. For instance, the maximum moisture content of a cork with a density of 160 kg/m³ would be 545%, while for a density of 190 kg/m³ it would be 446% [34]. Moreover, several researchers have shown the potential of cork to remove emergent pollutants such as polycyclic aromatic hydrocarbons [61-63], phenanthrene [64], methyl orange [65], ofloxacin [66], biphentrin [67] ibuprofen, carbamazepine and clofibrac acid [68] or heavy metals [69].

9. Natural, recyclable and renewable.

Cork is a natural material because it is the outer bark of an oak tree. Cork oak tree can regenerate cork bark after each harvesting. It permits an equilibrium balance between agroforestry management and human activity. It can be easily incorporated into a circular economy. As natural material, it can be recyclable in the compostable bin. Moreover, it can be reused, i.e. used cork stoppers can be collected and / or crushed. The cork in these stoppers can form new products (but not new stoppers).

10. Electrical insulator [69,70].

Another important application of cork is as an electric insulator, since it is a dielectric material. Cork exhibits a complex pattern of polarization mechanisms where three different relaxation processes can be distinguished, although they are merged or partially superposed. The loss factor of cork has been reported at about 0.1 with a weak dependence on frequency in the range 10^2 -10 kHz but increasing to nearly 0.3 for high strain amplitudes [69, 70]. This is a high loss (rubber has a loss coefficient of 0.08) and gives cork good damping and sound-absorbing properties, and a high friction coefficient, as already discussed.

2.3.2 Cork Applications

Due to its unique combination of valuable physical properties, cork has a wide range of traditional applications. Cork stoppers have the highest added value and the largest market share, primarily for still and sparkling wine [59]. According to the 2018-2019 APCOR yearbook [46], the main product of the cork industry is the cork stopper (72%) destined for the wine industry. The annual production of cork is approximately 201 thousand tons. However, only 25% of the annual production of cork is suitable for the manufacturing of natural cork stoppers (cork stoppers made with a single piece of cork). This means that 75% of harvested cork is unsuitable for this application, and so it is manufactured into agglomerated cork closures or other surplus products made of this material. Natural cork stoppers are punched directly from the best quality cork bark, the reproduction cork. Other cork stoppers, such as agglomerated with or without discs, micro agglomerated or technical cork stoppers for still and sparkling wine, are made by-product cork from natural cork manufacturing. The agglomerated cork stoppers manufacturing also has some waste like defecting odors, planks, or dust. There is some cork that has never entered the cork stoppers manufacturing process, such as virgin cork (first harvesting cork), cork planks with alterations, or cork forestry residue. The cork used for the rest of the applications is the so-called low-quality cork: unstopable cork, cork by-product, or cork waste (Figure 2.15).

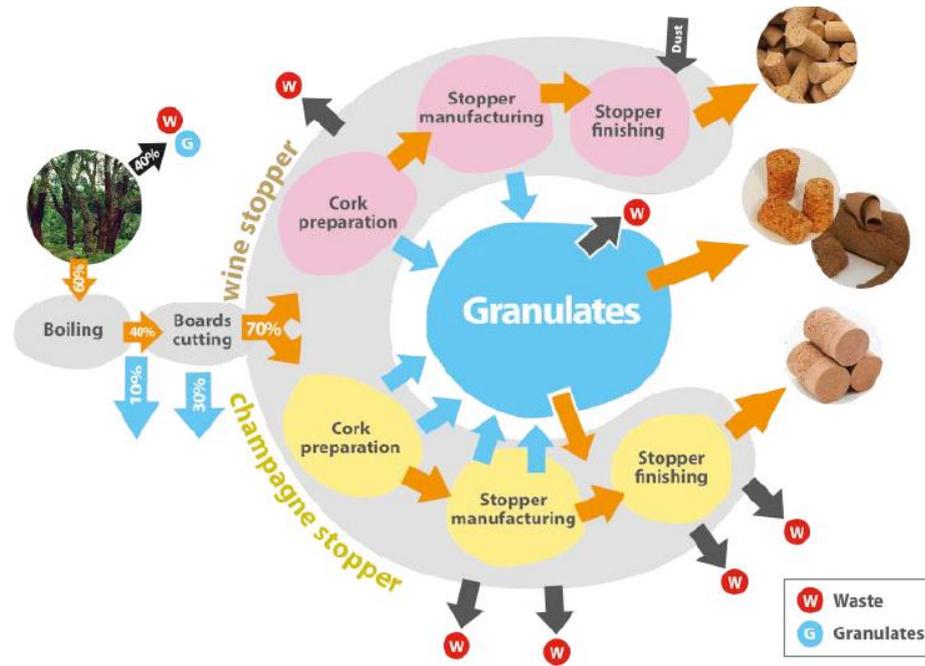


Figure 2.15 Diagram of the cork flows in the manufacturing of still and sparkling wine stoppers [59].

2.3.3 Cork in Construction

Cork construction solutions are the second destination in order of importance within the sector. Cork products are primarily used in construction for thermal insulation and energy absorption, but they also play an important role in decoration and light pavements. Floors, expansion joints, chambers of air, and external coatings are common uses of cork in buildings. It can even be used in a mix with concrete for driveways or exterior pavements. So the cork enables a range of applications based on anti-vibration, thermal and acoustic capabilities (Table 2.4).

One of the main products in this field is agglomerated cork or agglomerated cork panels. The agglomerates are made by process of agglutination of cork granules with a specific particle size and/or a predetermined density through a specific action of compression, temperature, and binding agent, giving rise to different types of agglomerates.

In this way, the type of cork (particle size and density), the type and proportion of glue, and the agglutination conditions (temperature, time, and/or pressure) are factors that affect the result of the final agglomerated product. Each of the combinations of the above conditions will give rise to different agglomerate cork products. Thus each agglomerated process provides an agglomerated product with different characteristics. Each producer has standardized production processes defined in the different technical sheets.

Table 2.4 Cork products used in construction applications and their underlying properties [72].

Uses	Products	Examples	Required properties
Covering (floors, walls and ceilings)	Agglomerated cork composites	Cork tiles for flooring	Wear resistance and resilience
	Cork in emulsion projected	Roofs, facades and floors	Wear resistance and non-moisture absorption
	Rubber – cork composites	Underlay for flooring	Wear resistance and non-moisture absorption
	Expanded cork agglomerates	Underlay for ceilings and interior wall and roof panels	Shock absorption and non-moisture absorption
Thermal and acoustic insulation	Agglomerated cork composites	Cork-epoxy agglomerates	Low thermal conductivity coefficient
	Cork in emulsion projected	Roofs, facades, walls and floors	Acoustic and thermal resistance
	Expanded cork agglomerates	Roof panels and interior wall	Adequate mechanical resistance and non-moisture absorption
	Granulated cork	Fillings material for empty spaces between double walls and floors	Durability, vibration shock absorption and fire resistance
Vibration insulation	Agglomerated cork composites	Sandwich-type structures	Shock absorption
	Expanded cork agglomerates	Expanded corkboards with high density	Vibration absorption
	<i>Rubbercork</i>	Structural joints	Bumping absorption
Expansion joints	Agglomerated cork composites	Structural joints	High compressibility
	<i>Rubbercork</i>	Expanded corkboards	High recovery

Agglomerated cork boards or planks are the many cork products used in contraction (Figure 2.16). Cork agglomerates can be grouped and divided in many ways. It is widely accepted the division of agglomerates products (no agglomerated stoppers) according to whether or not binders and additives are used in the manufacturing:

- **Expanded agglomerate or thermo expanded agglomerated cork.** Expanded agglomerated is a cork board without any additive. It is made of agglutinated raw cork granules or cork of very low quality. The binding power of suberin itself is used, which has the ability to bind at

high pressures and temperatures. This process provides boards of different thicknesses and shapes depending on the mold used. Normally the process ends with diametric and shape corrections. This product is natural and of plant origin since no synthetic agents are used (Table 2.5).

Table 2.5 Properties of expanded agglomerate cork board [59].

Properties	Values
Density	105 a 130 kg m ⁻³
Thermal conductivity	0.040 W m ⁻¹ k ⁻¹
Acoustic absorption (500, 1000 and 4000 Hz)	0.33, 0.49, 0.98
Compressive strength (MOR)	0.14 a 0.20 MPa
Usage temperatures	-180 a +140 °C
Fire resistance category	Euroclass E

- **Composites:** A cork composite is a cork board with additives. It is made of agglutinated cork granules with natural or synthetic resins. This product can be manufactured with different properties and shapes. The resulting material is a compound of cork and other materials that originate a different new compound with the properties and characteristics of both products. Depending on their function, different composites can be distinguished: anti-vibration, acoustic, shock-absorbing, etc. (Table 2.6).

Table 2.6 Properties of a kind of cork composite (rubber-cork) [72].

Properties	Waterproofing	Acoustics
Density (kg m ⁻³)	>900	550-650
Thermal conductivity (W m ⁻¹ k ⁻¹)	0.018	0.075
Thermal resistance ((m ² K W ⁻¹)	0.019	0.027
Compressive strength (MPa)	>1.3	>0.6



Figure 2.16 Agglomerated cork boards. The second board starting from the top, is thermoexpanded cork board. The others are examples of cork composites.

Currently, cork is also beginning to be used in urban planning. Cork composites are used to manufacture street furniture (highway sound barriers and building cladding) and pavements for tracks and playgrounds. At the same time, innovation in the industry is bringing the use of cork closer to the manufacture of flooring where weight is a determining factor, such as in train cars or aeronautics.

2.3.4 Textile and Mobility

Cork has been used in the fashion and textile industry for centuries. One of the benchmark products in this field is cork soles, both natural cork and agglomerated or sandwich type. Currently, cork as a textile solution can be found as natural cork, agglomerates, or in combination with other natural fibers. It fills a very broad market niche: footwear, leather goods, furniture, upholstery, clothing, mats for practicing sports, and box binding (Figs. 2.17-2.18).

Different options can be distinguished among them: cork textile (sine sheets of natural cork or agglomerated cork, cork with cotton, polyester or gelled polyurethane for footwear, wall cladding, leather goods, gift and novelties, and cork paper (wall cladding and lamps).

Like leather or suede, cork provides a sophisticated look and a luxurious touch. Cork is easy to clean (simply by wiping with a damp cloth) and is highly resistant to water and stains. It can be an eco-friendly solution for fabrics. As a detail, Lady Gaga (singer) wore a cork dress in 2014 after a concert in Lisbon, and Cristiano Ronaldo (footballer) appeared in front of the press with Nike sneakers made of cork in 2018.



Figure 2.17 Example of cork products used in different textile applications (<http://www.articor.com/es/>).



Figure 2.18 Peugeot 208 Natural with cork composite in the roof [81].

Due to its potential for impact energy absorption, this material has been used in a wide variety of applications, including road helmets [73-75], passive safety mechanisms [76-78], and other types of armor subjected to dynamic compressive loading. Cork and its agglomerated variants are viewed as an expressive alternative to polymeric foams [73-75,79,80] due to their aforementioned properties.

There are some examples of cork in mobility in the automotive market, like the Peugeot “208 Natural”. In this car, a cork composite is used for the roof.

Cork has been used in space exploration. Furthermore, cork has been used by NASA in space crafts. The role of cork in aerospace could be as the ablative insulator in covering space vehicles. These thermal insulation systems are essential for the launch and operation of all spacecraft, whether manned or unmanned.

There are several examples of the use of ablators that contain cork. The Jupiter C spacecraft demonstrated ablation's effectiveness as a thermal protection method in 1957. Scout, the first solid fuel launch vehicle, used cork/fiberglass heat shields and cork-insulated fins to launch the first American satellite Discover I. Pathfinder utilized a heat shield with a phenolic honeycomb filled with cork and silica bead-filled epoxy for its 1997 Mars entry. The space shuttle incorporates cork into a number of its components, including the solid rocket boosters and the external tank's insulation. Accidents involving the space shuttle necessitated a re-examination of its components, including its complex thermal insulation system; one of the components, an ablator made of silicone resins and cork, was retained. In one patent description, such an ablator is described as having a mass composition of 7.22–7.98% ground cork. The Atlas V rocket that launches the New Horizons probe for the NASA mission to Pluto is encased in a cork fairing. The conical surface of the European ARD (Atmospheric Reentry Demonstrator) is coated with a cork powder and phenolic resin composite [34].

According Reculosa [83] examined the cork/phenolic resin ablator sold under the brand name Norcoat*-liège at temperatures as high as 2500°C. The Norcoat*-liège HPK F1 Space Grade contains roughly fifty percent cork particles, thirty percent phenolic resin, and twenty percent fungicide and mineral fireproofing agent. The fundamental point is that the composite's original cellular structure is preserved after thermal treatment.

2.3.5 Pharmacy and Cosmetics

Cork and its by-products can be an important source of multiple bioactive compounds, such as phenolic acid, terpenoids, and tannins [84]. These bioactive have a variety of relevant properties: antioxidant, anti-inflammatory, anti-aging, purifying activity, or free radical capture. In this way, cork can be used as a promising ingredient in the cosmetic industry. In fact, there are already some examples of the use of cork as a smoothing tensor (SUBERLIFT), as an active oil (DIAM OLÉOACTIF), or as a peeling agent (ACTISCRUB). Recently the Biogründel company has developed SUBERCHEM, and Quimivita has just launched to the market a new peel agent made by cork EXFOBREEZE with the collaboration of the Catalan Cork Institute Foundation. SUBERCHEM is a cork extract rich in polyphenols and obtained through Green extractions. Phenolic compounds are substances with a growing interest thanks to their antioxidant, antimicrobial, antibacterial, antiallergic, anticancer, and anti-inflammatory properties, and even some antisecretory and antiulcerogenic

properties [84]. In this sense, some studies, the high antibacterial activity that cork presents is demonstrated, reducing the activity of bacteria such as *Staphylococcus aureus* and *Escherichia coli* by 96.93% and 36%, respectively [85], and it is also stated that cork has an antitumor potential obtained by different extraction methods in human promyelocytic leukemia cells [86].

As it has been said throughout this chapter, cork has multiple properties, and therefore, it can have a wide variety of applications. The majority of cork's applications have endured for centuries and are largely the same as they were centuries ago, but each year new fields of application for cork emerge.

2.3.6 Others

Nowadays, the green awareness of the people and sustainable development goals has put the cork back in the spotlight. Cork is a natural and eco-friendly material, and it can be a good candidate to be a part of a new biobased material to reduce plastic, for example.

In 2017, 3DSpider Print and Catalan Cork Institute Foundation developed a dual cork coin. The purpose of the study was to develop a new cork-based additive product suitable for printing, extrusion, injection, and other manufacturing processes. This item is a mixture of cork granules and plastic biopolymer (as utilized in 3D printing). The new material, 3DCORK, is ecosostenible because it is PLA-based and contains more than 20% cork [89].

Cork is also a good candidate for the treatment and purification of wastewater. As it has explained, cork is a good biosorbent of pesticides, heavy metals, polycyclic aromatic hydrocarbons (PAHs) and recalcitrant products. There are several examples of cork wastewater treatments: wetland (LIFE ECOCORK and [90]), wet walls [87], green walls [88 and 91] or water purification by photobioreactors (LIFE SPOT).

Many things can be made with cork, and with cork, only someone has to cover them.

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CHAPTER 3

Sectors for Cork Products, Cork Properties and Future Trends for Cork

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Abstract

Cork is a versatile and sustainable material with a wide range of uses in many industries. It is naturally waterproof, fire retardant, and environmentally friendly. Over the years, its use has grown exponentially as cork products have become increasingly popular in the home, commercial, and industrial consumer markets. There are several sectors that utilize this material including construction, flooring, insulation, and sealing solutions. As consumer preferences have shifted towards more sustainable products, the demand for cork has skyrocketed, and the sector is expected to further expand in the near future.

Keywords: Cork, cork products, cork properties, automotive, aerospace, aviation, isolation.

3.1 Introduction

Natural cork, the main product of the unique forest ecosystem in the world of cork oak trees, is a material with unique properties that can be reused in any form, non-toxic, durable and wear resistant. Cork effectively binds atmospheric carbon dioxide, which is essential, especially concerning global warming. The world of science and business values cork for its extraordinary physical and mechanical properties that can be synergistically used for the sustainable development of the economy and industry. Another article [1] discusses cork cultivation and its micro and macrostructure.

Cork is one of the most versatile natural materials. It has a wide range of applications, from simple bottle caps to specialized aviation heat shields. It is light, compressible, elastic, durable, chemically and biologically resistant, non-toxic, flame-retardant, practically impermeable to gases and liquids, shows good thermal and acoustic insulation, and is also an excellent vibration and electric insulator. The unique cork properties result from its honeycomb-like cellular structure [1]. The cork's low density results from the cell system and the lenticular tubules located between them. The mentioned dimensions of cells vary slightly depending on the cork oak bark age and the period of its collection [1]. The value of cork density determined in this way is in the range of 120–240 kg/m³, and the average density of a dried cork is assumed to be 150–160 kg/m³ [2]. Due to the low density, the cork

share significantly influences the weight reduction of the structures containing it. The cellular structure, ensuring a specific distribution of stresses acting on the cork cells under load, prevents cracks in the material. Cork retains its properties regardless of the humidity and temperature of the environment. It is always soft but elastic, pleasant to the touch, and wear-resistant [3].

Cork is distinguished by many exciting properties, such as flexibility, high physical stability, compressibility, resistance to long-term load cycles, and thermal, electrical, and acoustic insulation [2]. High thermal insulation is determined by a small value of the thermal conductivity coefficient of natural cork $\lambda = 0.040\text{--}0.045 \text{ W / (m}^\circ\text{C)}$ [2], and acoustic insulation - acoustic resistance of $1.2 \cdot 10^5 \text{ kg / (m}^2\text{s)}$ [2], enabling the reduction of sound intensity by 31–36 dB, depending on the material thickness [4]. On the other hand, the plug's electrical insulation strongly depends on both the material's moisture content and the temperature. This coefficient at 25°C with a water content of 3.5% equals $1.2 \times 10^{-14} \text{ S/m}$, while for a completely dry cork at the same temperature, it is $2.9 \times 10^{-10} \text{ S/m}$. However, the radical reduction in the insulation capacity of this dielectric material is mainly caused by the increase in temperature - the electrical conductivity of the plug, e.g., in the range of 25–100°C, increases by three orders of magnitude. The binder content in the cork agglomerate material increases the conductivity up to four orders of magnitude [2]. It should be emphasized that the use of materials of natural origin (e.g., cork, wool) in place of highly processed insulation materials, such as expanded polystyrene or polyurethane, disposed of by incineration, significantly reduces (by 98%) the negative impact on the environment. The cork is not susceptible to changes in volume, even due to sudden temperature changes. It is also flame retardant - it does not burn with a flame but with charcoals. It exhibits anti-slip properties and high resistance to surface wear [2], [5] (it does not deteriorate because of repeated rubbing against the neck of the bottle, despite the relatively high friction coefficient of 0.5) [6], [7]. Natural cork is chemically inert, it is a barrier to liquids and gases, and in contact with them, it does not absorb odors [2], [3], [8].

Due to the high suberin content, the cork shows antibacterial and antifungal properties, thus preventing the penetration of these microorganisms, e.g., into a bottle blocked with it [9]–[12]. Cork is a hydrophobic material with a surface energy of 18 mN/m, and low adhesion force characterizes it from other materials [2], [4]. The hydrophobic nature of cork can be changed because of plasma modification of the surface under atmospheric pressure (Atmospheric Pressure Plasma Torch - APPT) or low-pressure conditions (Low-Pressure Plasma Chamber - LPPC) [13]. Plasma treatment can only affect the outer surface of the cork without changing its properties. The reactive groups formed due to these treatments on the cork surface allow for its more permanent connection with other materials [14], [15]. The adhesive properties of the cork surface are also enhanced by the silanization process [16]. One of the most critical features distinguishing cork from other natural materials and enabling its broad application is its high ability to absorb energy, even under relatively low stresses. The average value of the energy absorbed during compression of the plug to the level of 83% of the initial volume

in the radial or non-radial direction is $3.4 \cdot 106 \text{ J/m}^3$ and $2.2 \cdot 106 \text{ J/m}^3$ [2]. The already mentioned flame retardancy and the ability to slow down fire spread are significant cork features. The cork burns without flames and, very importantly, does not emit toxic gases [2]. Cork is a flexible, anisotropic cellular material with specific mechanical properties, mainly due to its susceptibility to gradual bending, deformation, and thickening of its cell walls under load [3].

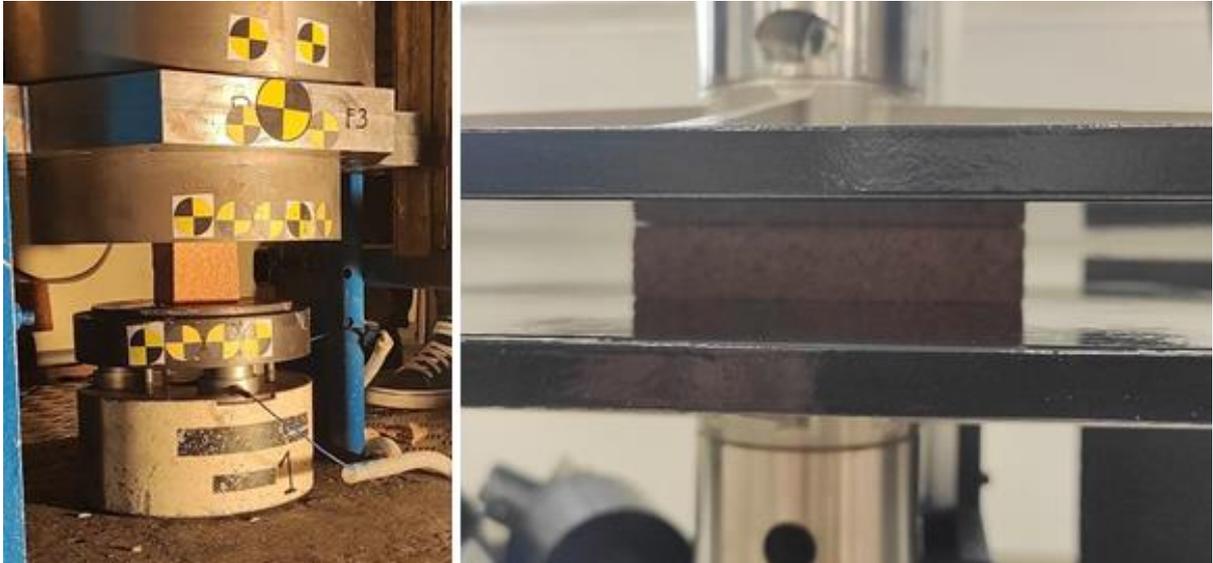


Figure 3.1 Cork samples in compression test.

The behavior of the cork under quasi-static compression is illustrated by the stress-strain linear plot with an extensive plateau ending when the cork's cellular structure is wholly compressed and densified (Figure 3.1) [2]. The slope of the curve in the plateau region determines the values of the plug's modulus of elasticity (prepared in a specific way) within the range of 6–20 MPa, depending on the load direction. In the case of radial direction loads, these values are higher than those of loads in the axial and tangential directions [2], [17]. Heating the cork at 100–150°C for 24 hours deprives it of moisture and significantly increases its compressive strength. However, more prolonged heating, longer than 24 hours, reduces its strength due to thermal degradation of the structure [17]. The extraordinary flexibility of the cork is evidenced by its behavior in the compression test. After compressing the NL10 plug (density 135 kg/m^3) to 80% of its original thickness, it returns within 0.5 min, after unloading, without buckling symptoms, to approximately 80% of its original size. The mechanical properties of cork cannot be characterized by one value of the Poisson's ratio [18], [19] or Young's modulus [30] because its grades differ, especially in density, cell dimensions, and porosity [2].

3.2 Sectors for Cork Production

In recent years, cork industry has gained new fields of industry. Cork as a material has fascinating properties which can significantly improve current designs. Fields of cork material applications are as wide as,

- Stoppers for Still and Sparkling Wines and Spirits
- Automotive and railways
- Micro mobility
- Energy
- Aerospace
- Sports
- Architecture and design applications, including Floors and wall coverings
- Construction and Infrastructure such as Cork Underlayment
- Expansion Joints and Insulation Corkboards
- Fashion

At this point, it should be noted that the successful introduction of cork material in existing products could be considered only by its presence on the market. Prototype or custom solutions not in mass production cannot be regarded as valid applications of the cork materials because they are public or private founded research programs or overpaid, highly customized products. Therefore, the discussion of the currently introduced cork materials is limited to the products offered on the market. In this paragraph, cork material is considered as raw cork and derivative cork materials such as polyurethane-based cork conglomerate, etc.

In most cases, the application of cork material is strongly connected with its specific outstanding properties. Cork material as bulk material is relatively expensive. That is the main reason why designers chose these materials only with care about special requirements that must be met. That is why cork applications are unique and non-obvious. It is not common that cork material is the primary material for engineering equipment. Cork usage is a secondary material, which other materials cannot substitute in particular applications.

Insulation properties of the cork are worse or better enough to compare by cost with commonly used polymer foams such as polystyrene, ABS, or XPS polymer foams. Raw cork panels' fire resistance properties do not withstand any fire protection standards. Only conglomerates with fire self-extinguishing additives could be considered fire-resistant material. Noise suppression properties are relatively high concerning other materials. For some properties, such as Mechanical properties, it is

hard to compare cork materials with different materials. Ashby diagrams characterize cork materials with respect to others. That is why it is hard to write general clue about fields of cork materials. At this point, it should be mentioned that cork has some unique properties which are very important for its choice in various designs. Most natural material users have good feelings when touch devices are covered with cork. Moreover, moisture and sweat absorption by cork materials are highly recommended for long-time device handling purposes. Outstanding properties in attenuation of electromagnetic waves or good atmospheric re-entry ablation prove that cork material has no advantage over polymeric composite of metal-based materials in engineering. However, a few very specific properties allow use in specific and demanding applications.

In the Aerospace industry introduction of cork material in current applications, occupied by other usually polymer-based materials, is difficult to achieve. One of the most trivial results of changes in the aerospace industry is the certification and recertification cost of any new design. Replacement of currently used materials at this point is not a priority for planes manufacturer and operators. Moreover, supply-chain stability in aerospace production is one of the most important factors during the flying vehicle's production. Cork, as a natural material, is harvested in the cork forest. Each year production of cork and its price may significantly vary.

As mentioned before, cork materials exhibit excellent attenuation of electromagnetic waves. This property is used to reduce radio signatures of flying objects, primarily planes, to avoid detection by enemy air defense systems. This property is strongly related to the microstructure of the cork. Lignin and suberin are elongated channels that trap magnetic radio waves, which do not reflect radio waves to the radiation source (radar systems).

One of the future trends of cork material in aerospace is related to sound suppression systems in propulsion. Current propulsion systems generate unpleasant noises, which require additional sound suppression systems. For jet engines, engine nacelles are shaped to reduce noise. Redesign jet engine nacelles with accompanying sound suppression material, where cork may be considered might be the next cork application.

One non-trivial property of cork material is the low environmental impact of cork panel erosion. Any exhaust of non-flammable, hot, or cold gases with any particles which could erode material might be covered by cork material. It has good thermal insulation properties, capable of eroding with small quantities of material. Obviously, after a specified time, these covers should be replaced.

Cork is assumed as heat protection shielding material for a test mission, where spacecraft will re-enter the earth's atmosphere. During the re-entry, each spacecraft experience high thermal loads due to air friction against the spacecraft structure. During the Space Shuttle era, space shuttles were covered with ceramic panels. One of the hypotheses is that cork material might be used for re-entry shielding. Low

burn regression and high thermal insulation properties in high temperatures have great potential for cheap and non-complicated manufacturing heat shields for re-entry.

Cork material, recognized as a green and sustainable material, is widely used in the fashion industry. In this field, trends play significant roles, which is why the quantity of applications will vary in the following years. Fields of application in the fashion industry are decorative cork fabric, liners, shoe making material. In this sector of the economy, where manufacturing companies make strong declarations about ecology and sustainable materials usage, it is expected that cork material with other natural-based materials will be more present.

The usage of the cork in architecture is widespread. Due to its attractive structure and positive experience for human hands, cork is very common in any type of architecture, from household accessories to major decorative roles in large buildings and artistic installations.

Throughout architectural applications, large quantities of cork materials are used for floor and wall panels. These two products consume the highest quality of cork material in architecture. In this application, cork is expensive and has high-standard features.

One of the potential cork applications is chemical absorption from the air. Cork, due to its internal microstructure, can absorb chemical substances. Many organic substances are very toxic to humans. The source of harmful carbon-based substances comes from using coal in private fireplaces, gasoline, and diesel engine exhaust, including vehicles, and other types of devices such as power generators, lawnmowers, and other house garden tools with combustion engines. An additional source of harmful organic substances is intensive agriculture, landfills, and large quantities of organic waste compost with decay processes.

In open environments, filtrating systems use is not possible, which is why bulks of cork might be used for trapping harmful substances. Moreover, in this case, cork might come from recycling, but it requires that actual cork cells are not covered by any binder layer and are exposed to the surrounding atmosphere.

Natural, renewable, and recyclable cork material with valuable properties finds various applications. About 70% of the obtained cork is used as bottle stoppers. Still, it is more and more commonly used in producing composite materials intended mainly for the construction industry (approx. 22%) [3], [4], [20]. It is expected that it will expand its use in other areas of the economy in the future.

3.2.1 Cork Agglomerates for General Use

Cork composites are prepared from agglomerates of various granulation, usually 0.5–30 mm grain size. The granules used are usually waste from the production of plugs. The granules are mixed with a reactive prepolymer and pressed at room temperature or mixed with a polymer binder and pressed at

an elevated temperature under pressure to produce cork composites [4]. The intended properties of the finished product depend on the dimensions of the cork granules, its mass fraction in the composite (up to 90% by mass), the type of binder (polyurethanes, phenol-formaldehyde resins, etc.), and the packing density of the agglomerates used in the production process.

The blocks of cork agglomerates produced are laminated, shaped according to the planned dimensions, and smoothed (Figure 3.2). They are used to obtain panels, boards, shoe inserts, etc. [2], [4]. Agglomerates for wall coverings [4] and floors are produced similarly but with a suitable binder or variable pressure in the pressing process. The obtained material is more durable and odorless. Its abrasion resistance can be increased by applying a protective polymer layer one or more times in multi-layer products. A separate, important group of cork composites is the so-called rubber stopper, a mixture of cork granules and rubber. The composition ingredients are mixed (compounded), and the final product is shaped and polished. The produced composites are used as a material for gaskets in cars and glands for oil tanks because they are impervious to liquids and do not undergo transverse expansion due to the low value of the Poisson's ratio of the plug [3], [19].



Figure 3.2 Cork Stools, Bicycle Cork Chop Grips, POMM iPad Case, Fiskars Garden Shears, Baby blocks, Cup holders and stoppers [21]–[24].

3.2.2 Thermal and Sound Isolation

Cork agglomerates for thermal and sound insulation in construction (Figure 3.3). Cork is characterized by small thermal conductivity, sound propagation speed, and acoustic impedance, making it suitable for use as a material for thermal and sound insulation. The cork composites used in this way contain 90–95% cork weight in a polyurethane matrix. The mixed components are usually heated to about 100°C for a specific time to agglomerate them. This type of material is widely used in thermal and sound insulation construction. It is also used by NASA and ESA space agencies as thermal and anti-vibration shields for rocket components [2]. According to the Portuguese Cork Association, Peugeot 208 Natural, presented in 2014 in Sao Paulo, had cork implemented in the roof and dashboard. The material ensured better thermal and acoustic insulation.



Figure 3.3 House isolation created from agglomerate cork.

The construction industry is the second largest area where natural cork is used in soundproofing walls, suspended ceilings, wallpaper, plinths, floor coverings in buildings, and insulation in industrial cold rooms (Figure 3.4). The previously used composites with a synthetic foam core and cladding carbon reinforcement have relatively low acoustic insulation. In response to the growing need to reduce noise, an innovative composite with a layered structure was developed, consisting of a natural cork and carbon fiber spacer. Such a composite shows the synergy of the advantages of the constituent materials. It retains its strength properties and low weight, suppresses noise more effectively than traditional insulation materials (by 250%), and is much more durable and durable [3], [25]. The so-called black agglomerates are made of granules of natural cork without a binder in a closed autoclave at high temperature (approx. 300°C) and high pressure (approx. 540 kPa) [26], [27]. As a result of the thermochemical degradation of the cork cell walls, suberin is released (acting as a natural binder). The degradation waste is agglomerated, and the intermediate product used to produce cork boards is formed [3], [28], [29]. It is a reusable material and, at the same time, completely natural, without chemical additives. Industry of means of transport Cork, thanks to its very low density (0.24 g/cm³) and good insulation, is often used by the industry of means of transport as a material for components of motor vehicles and various types of rolling stock.



Figure 3.4 Flooring industry with implemented agglomerate cork.

3.2.3 Sound Isolation Case

As mentioned before, cork is produced from the bark of a Cork Oak tree. It is a natural raw material with unique properties such as low weight, impermeable to liquids and gases, flexible, compressible, and good thermal and acoustic insulation. In its natural form, cork is also an excellent fire retardant, although cork dust is highly flammable (because the cell structure has been broken down). Moreover, it is completely biodegradable, renewable, and easy to recycle. The case study by Kłusak and Grygny [30] presents the application of a rigid spacer of cork type to make cork composite and its application in firefighting vehicles.

The following manufacturing methods were used to produce composites and mass comparison of the samples:

- HLU (Hand Lay Up) lamination, - VB (Vacuum Bagging) vacuum bag, manual laminating with the use of vacuum
- spraying of staple fiber and SU resin (Spray-Up)
- VI infusion (Vacuum Infusion)
- CCBM (Closed Cavity Bag Molding) resin injection under a reusable silicone diaphragm
- LRTM (Light Resin Transfer Molding resin injection into a closed mold)

Soric material has been used so far in producing 10 mm thick composites. The study aims to build a composite that will be lighter than a composite with a Soric spacer and will not create technological problems during processing. During the tests, it was decided to make a composite with a cork core and an SBC-type spacer for comparison. The composite made of the SBC spacer turned out to be very dimensionally unstable because large thickness deviations were obtained in different cross-sections of the samples. It became technologically challenging to process and was omitted in further works [30].

As part of attempts to produce a cork composite by various methods, it turned out that 1 m² of the material made with a cork spacer weighed 6.2 kg and was 1.3 kg lighter than a composite with a non-woven polyester interlayer of the type Soric. As a result of replacing the synthetic Soric spacer with a cork spacer during the production of elements for the new composite construction, it was possible to reduce the weight of the manufactured structure [30].

For the experimental tests, the samples were produced with a cork spacer, a PVC foam spacer, and a Soric spacer, as well as solid laminate structures. Composite materials tested were used to construct unique car bodies, including crew compartments for personnel transport and service. Comprehensive tests of composites were carried out following the R1 requirements of PN-EN 45545-2: 2013 and included the following characteristics [30]:

- test of reaction to fire - fire propagation according to ISO 5658-2
- response to the fire test. Testing the intensity of heat, smoke, and mass combustion rate according to ISO 5660-1: 50 kW/m²
- testing the smoke production of materials and the toxicity of their combustion products according to ISO 5659-2: 50 kW/m² PN-EN-45545-2: 2013 Annex C

The tests were conducted on composite materials produced in various technologies, including sandwich-type sandwich composites. The tests carried out as part of the expert opinion covered horizontal flammability (following ECE-R 118 Annex 6), fusibility of materials (following ECE-R 118 Annex 7), and vertical flammability (following ECE-R 118 Annex 8). The tests were performed for the following five structures [30], [31]:

- structure no. 1: composite made by infusion consisting of four-way fabrics weighing 600 g / m², 6 mm Core-cork cork spacer, and flame-retardant vinyl ester resin
- structure no. 2: composite made by infusion consisting of four-way fabrics weighing 600 g / m², a synthetic Soric 6mm spacer, and a flame-retardant vinyl ester resin
- structure no. 3: composite made by infusion consisting of 9 layers of a four-way fabric weighing 600 g / m² and a flame retardant vinyl ester resin
- structure no. 4: Composite made by hand lamination, consisting of 600 g/m² four-way fabrics, 6 mm Core cork spacer, and flame-retardant polyester resin
- structure no. 5: A composite made by hand laminating, consisting of four-way fabrics weighing 600 g/m², a synthetic Soric 6 mm spacer, and a flame-retardant polyester resin

In conclusion, all the samples (5 structures) met the requirements of the regulations, which gives an excellent opportunity to select the appropriate structure depending on the required mechanical strength [32]–[35]. According to the PN-EN ISO 527-4 norm, samples made with a cork spacer with a

thickness of 30 mm obtained a lower value of the deflection profile at maximum stress than with PVC foam [34]. The following materials received the results: plug deflection profile with a maximum stress of 17.2 mm; PVC foam 26.67 mm. The structure using cork as the spacer material showed greater stiffness, even by 35%, compared to the foam spacer [30].

The use of plug-in cabins and firefighting structures is justified for several reasons. The cork allows for a significant reduction in the weight of the manufactured elements, which translates into lower fuel consumption in the operated fire trucks. The decrease in weight also allows for transporting more specialized rescue equipment without the risk of exceeding the permissible axle loads of the car. Car cabins have been soundproofed with specially installed mats and secured with a stiffening layer. It was decided to replace other used spacer materials using cork processing methods and, in one operation, by the infusion method, to make a car cabin. Such a cabin with a cork spacer turned out to be lighter while maintaining the required mechanical strength. The cabin obtained increased acoustic insulation without performing any additional operations, which reduced the number of man-hours needed to soundproof the cabin. The cabin was also made with a layout and materials that met the fire resistance requirements according to the ECE R 118 regulations [30], [31].

3.2.4 Sandwich like Structures

Lightweight panel structures are a good choice for quick rearrangements of vehicle passenger space. It might be used for temporary walls, floors, and ceilings. These kinds of panels usually are sandwich structures. Outer panels are made of side skin material ensuring rigidity and carrying most loads, while inside, the core material is lightweight. Core material glued to skin panels prevents buckling. At this point, it should be noted that neither skin panels nor core material can withstand even a small portion of loads that properly glued sandwich material can, mostly due to loss of stability, usually referred to as buckling.

Figure 3.5 shows aluminum skin panels with different overall thicknesses and core materials. Nowadays, core materials are divided into natural or synthetic core materials such as wood, plywood, hemp, straw, or cork. The bottom left panel (Figure 5) is created with balsa wood core material perpendicular grain direction to the panel surface. Two other panels are created with synthetic cores that have aluminum honeycomb and foam cores. The rest of the panels has cork cores. It is essential to mention that in sandwich structures volume of core material may be up to 95% of the material. Thus, ensuring a high usage degree of eco- and sustainable materials for cores is crucial. Skin panels, usually made of aluminum, have a low ecological impact due to their high recycling capability. Using natural materials for this purpose makes it possible to create high-performance, lightweight structures with a low carbon footprint.



Figure 3.5 Sandwich panels with balsa wood, cork, aluminum honeycomb, and synthetic foam core material.

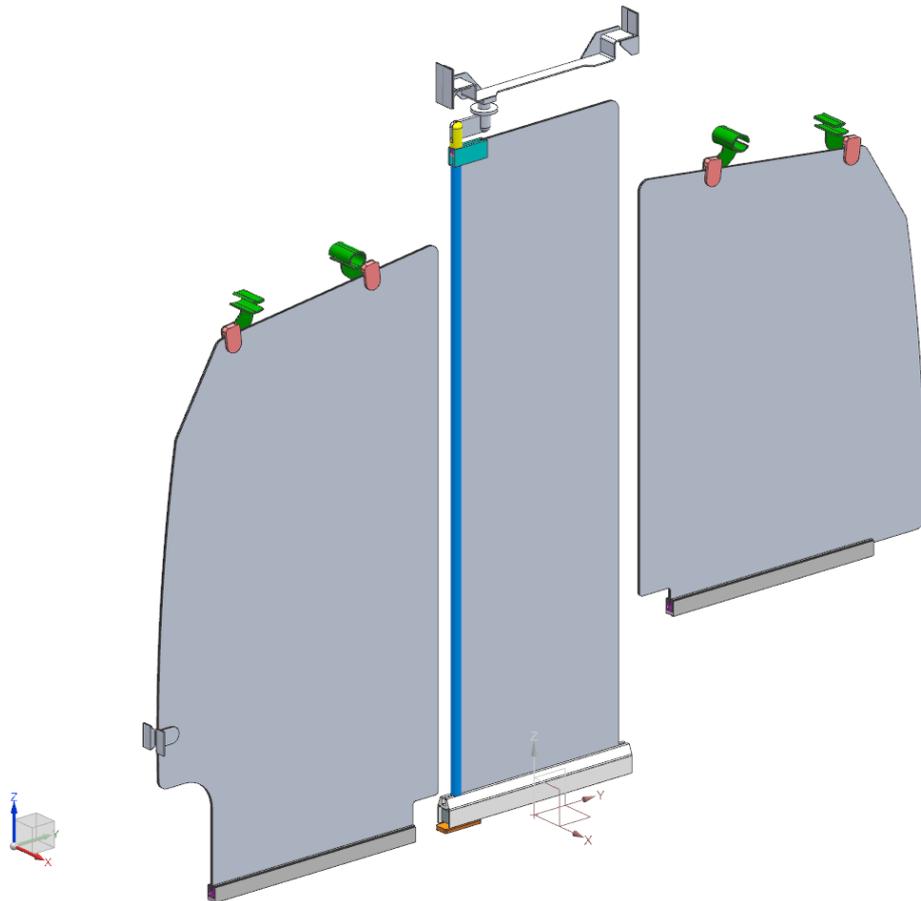


Figure 3.6 Train temporary walls model.

Among sectors where cork-cored panels might be used, it is necessary to discuss and review general requirements and good practices in a specific sector. In the rail industry, where safety requirements are shifted to the long endurance service, temporary installations for interior rearrangement are common practice. Requirements for wide-body passenger planes are very demanding, and due to high passenger concentration and short evacuation time, it is impossible to use moving, temporary walls. For the automotive sector, temporary rearrangements of the interior are very rare and are very custom solutions. In the marine industry, ships and yachts are designed just for one purpose, and only minor changes are introduced.

In the presented case scenario temporary train wall for interior rearrangement is shown (Figure 3.6). This kind of wall can be disassembled and placed in a new position during journey train preparation, changing passenger distribution in the interior. The original concept considered two materials for these walls: highly modified plywood with gloss surface paint and glued double-layer glass. After consideration, a change of materials for cork core sandwich material is assumed to be a possible choice.

One of the advantages of cork core sandwich material is its high sound damping property. It is much better than highly modified plywood or glued double-layer glass, mostly due to using two combined materials with significant changes of density that work as a bandpass filter. With a similar mass scenario, sandwich panels have significantly higher stiffness than the previously mentioned materials with higher thickness. The disadvantage of sandwich panel structures is complex mounting, which requires using inserts for handling compression forces coming from bolt/screw connections. High fire resistance was considered at the same level as plywood, whereas glass panel has outstanding fire-resistant properties.

Finite Element Analysis (FEA) allows determining stress in material and deformation of examined geometry against applied loads. Usually, FEA requires the following steps: cleaning off original geometry by removing unnecessary features from geometry, preparing discrete model (convert, by default infinite continuous, geometry into discrete elements), applying interaction mechanisms such as contacts, ties, or gluing connections, use boundary conditions and forces, setup simulation parameters. Figure 3.7, top left, shows a prepared discrete model with hidden boundary conditions and force, while the other examples in Figure 3.7 show results of static case scenarios, which assume hard push against other train vehicles. Figure 3.7, top right and bottom left, are deformation plots, which will occur under assumed loads. It should be noted that the scale is in millimeters, and the deformation scale is magnified ten times for better visualization of deformation directions. Figure 3.7, bottom right, presents max principal stress (MPa) in parts that are subjected to mentioned above loads. Without wider considerations and explanation, which is out of the scope of this book, presented results should be treated as qualitative and not quantitative.

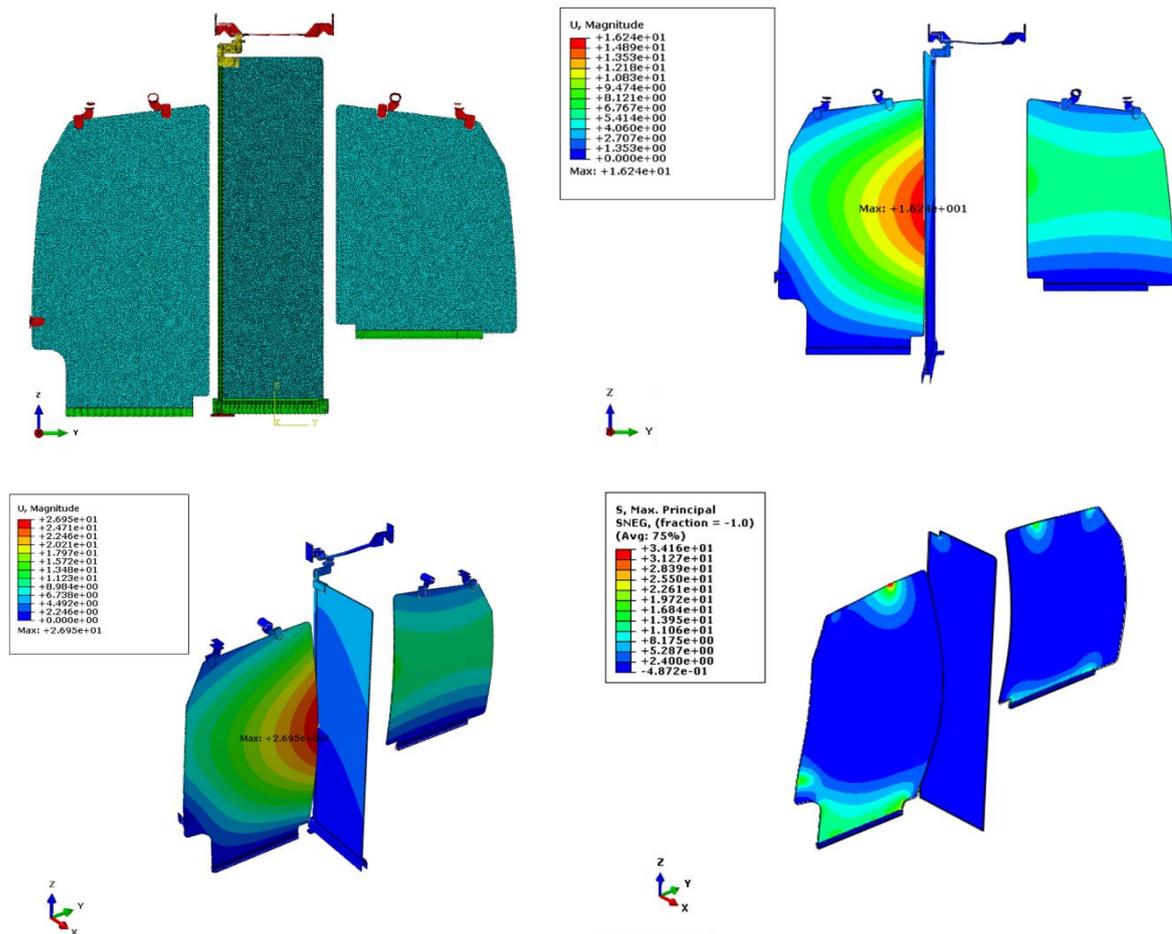


Figure 3.7 Top left - Train temporary walls discrete model; top right - Front view of train temporary walls deformation under in motion direction hard push load case scenario [mm]; bottom left - Isometric view of train temporary walls deformation under in motion direction hard push load case scenario [mm]; bottom right - Isometric view of train temporary walls principal stress under in motion direction hard push load case scenario [MPa].

One interesting property of cork material in sandwich structures is the excellent support role for skin panels carrying most loads. In 4-point bending tests in the middle of the specimen pure bending stress state is present. Researchers must determine the structure's overall strength and assess the damage mechanism in a certain combination of panel and core material concerning thicknesses and adhesion film used. As shown in Figure 3.8, the test results show good cork properties against applied loads. The first foam panel (top) suffered local damage due to local overload of the core, which collapsed and allowed excessive skin deformation. In contrast, the second foam panel suffered shear forces in the adhesion zone between foam and skin. In the case of cork, where results require much deeper consideration, it might be said that cork has good adhesion properties with various skin materials and good capabilities for supporting skins that prevent from local damage. In most cases, the whole structure has a wide range of influence.



Figure 3.8 Post experiment analysis of damage mode and mechanisms for cork and synthetic core materials sandwich panels.

Shown example of skin panels is one of the most interesting, economically, and structurally justified cases of advanced cork material usage. Combining high strength and stiffness skin materials such as aluminum or epoxy/polyester based composited in small volume with a high volume of core material, which can be, i.e., cork, sandwich material, is achieved. This allows the design of smart, lightweight, and high-strength structures with a low carbon footprint and is ready to market.

3.2.5 Automotive

Cork is used for making various seals, especially in cars, and for the interior finishing of vehicle cabins. Its flexibility, resistance to heat and impacts, and pleasant touch texture are used [5], [36]. The transportation industry has a growing demand for materials with a high strength-to-weight ratio [37]. Due to its low density, high strength, independent level of moisture, and temperature changes, cork is used as a core material in sandwich structures. The so-called sandwich, where the core material is cork agglomerate, and thin multi-layer facings are made of highly rigid materials, such as steel, aluminum alloys, polymers, or various fiber composites [3], [27], [38], [39]. The research on aluminum-cork sandwich composites produced in industrial conditions (Carbon Fox), with potential use for walls and floors in the railway industry. Figure 3.9 shows an example of a product made using the technology of producing composites from prepregs in the company mentioned above.

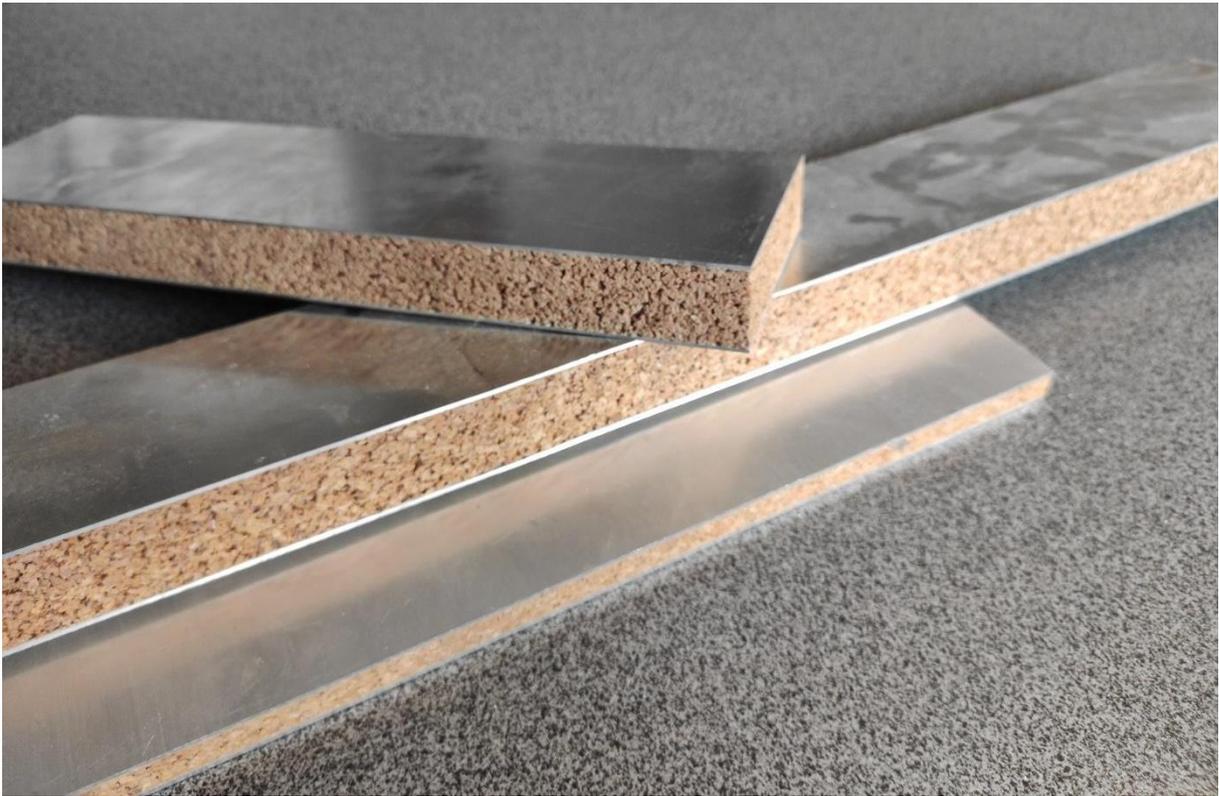


Figure 3.9 Detail view of aluminum skin, cork core sandwich material with different thicknesses.

Car body element, the rocker panel for a rally car, is composed of carbon and aramid fibers in an epoxy resin matrix, with a core cork spacer (solution based on patent application P-413342). The cork spacer was used to increase product stiffness while maintaining the required weight, impact strength, energy absorption, and service life and reducing production costs. The unique use of cork in the space vehicle industry should be mentioned. The quality of insulating materials plays an essential role in rocket engines because the structure of their components is subjected to high temperatures, creating a risk of a gas explosion during the launch and return of rockets to Earth. Due to its properties, cork is usually used to obtain nozzles and thermal shields critical for rocket safety.

3.2.5.1 Case Study

This chapter introduces a reader to the case study, in which the authors present the approach to use the cork-composite in the automotive sector. The research aimed to improve the safety of vulnerable road users (VRU) by developing and implementing a frontal protection system (FPS), which mitigates injuries during an accident with a vehicle.

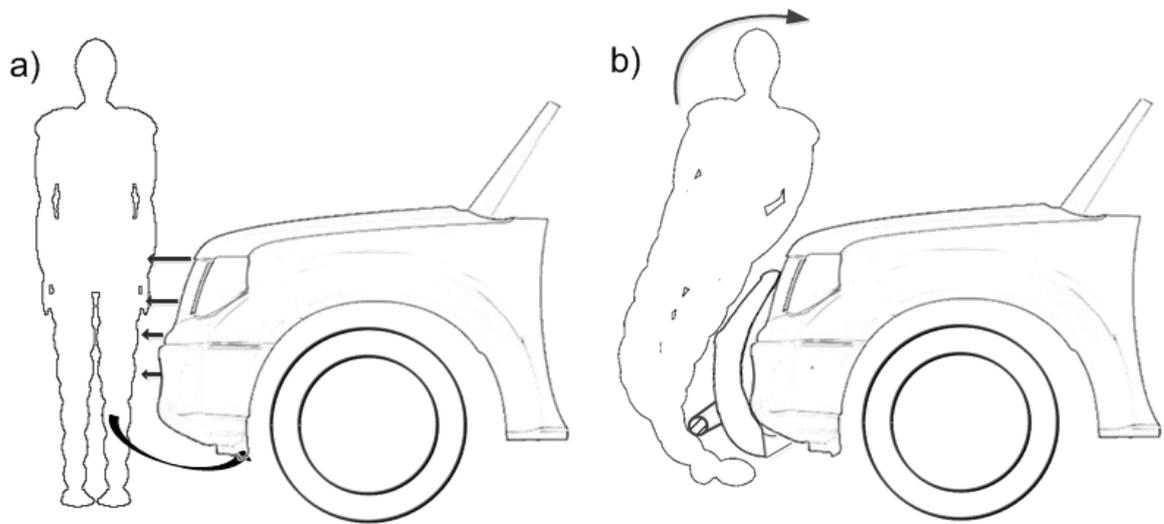


Figure 3.10 Schematic diagram of pedestrian kinematics after a collision with an SUV: a) without a safe FPS; b) with a safe FPS fitted to the vehicle – based on the author's patent [40].

Due to the trend for the purchase of SUVs in Europe and their more frequent participation in accidents involving pedestrians and cyclists (SUVs are commonly used in cities), the authors identified a need for a safe frontal protection system (Figure 3.10) [41]–[43]. The designed FPS provides pedestrians and cyclists with appropriate, supported by numerical tests, kinematics after collision with a vehicle while at the same time contributing to the reduction of injuries through the use of appropriate energy-absorbing materials, i.e., natural materials (cork) and composites (carbon fiber). As a part of the research, multivariate numerical models and a physical prototype were created and tested. This implementation of the combination of cork with carbon fibers allowed the authors to substitute steel and aluminum alloys in the FPS. It should be emphasized that the development of the new FPS not only enhanced VRU safety but also improved the design of the vehicle front-end (Figure 3.11).



Figure 3.11 The proposed design of the frontal protection system.

As a subsequent stage, a thorough 3D scan, using a Leica P20 scanner, of the vehicle with the front belt removed was performed in order to recognize the mounting elements for the frontal protection system. Measurements were taken from two scanner positions and combined in Leica Cyclon software [44]. The registration – i.e., the scanning merging procedure effect – is depicted in Figure 3.12 (with the reflection intensity marked). The quality of the obtained point cloud in the case of optical methods depends, among others, on the reflectivity of the object's surface. The scanned structural elements are relatively black, which results in missing points in the cloud of points representing the body geometry. The influence of this property is especially visible when comparing transparent windows or headlights with the more light-absorbing front-end structure.

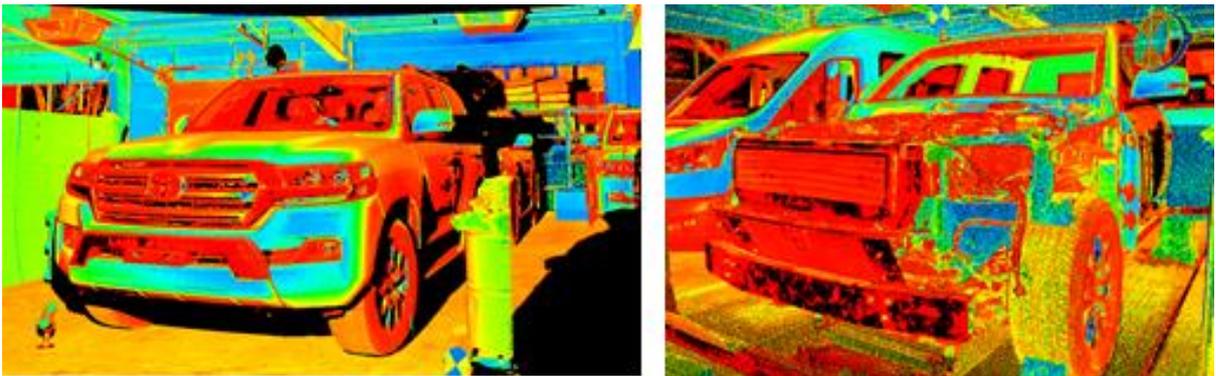


Figure 3.12 Cloud of points of Toyota Land Cruiser vehicle with disassembled front belt (with marked shade intensity).

The final result of the measurements is the combined point cloud from all scans, which is the basis for recreating the vehicle front-end geometry. The obtained scanning tolerance after combining the point cloud was approx. 1 mm. An exemplary view of the cloud of points obtained from the scanning is shown in Figure 3.13. It is the design basis for modeling the frontal protection system. Further design works were carried out in CATIA v5 software.



Figure 3.13 Toyota Land Cruiser cloud of points with FPS models (left) and FPS rendering (right).

Various types of cork oak were tested, i.e., natural cork, agglomerated cork composite with polyurethane, and cork filled with non-Newtonian liquid [45]. Due to the minimization of head injuries during multiple impacts (especially in motorcyclists), different configurations of the arrangement of different types of cork connected with glue (cork composites) were also investigated. Finally, a material model (FEM) was also developed, which will be validated during experimental tests. For the sake of FPS safety properties, the use of cork material for energy-absorbing FPS filling was the most reasonable choice. However, two types of reinforcement (covering the cork material) were considered: carbon and glass fibers. The carbon is composed of structures almost entirely chemically similar to graphite. They are characterized by high resistance to high temperatures and chemicals and good thermal and electrical conductivity. In addition, carbon fibres' advantages include low density, high strength, and the ability to dampen vibrations.

Moreover, what is important in the context of the automotive market, carbon fiber has an attractive appearance (Figure 3.14). S-2 glass / SC-15 glass fiber technology was also considered [46]. The properties of glass fibers differ from those of pure glass material because they are characterized by high tensile strength and flexibility, thanks to which they do not break at high bending angles. However, the properties of composites with glass fibers are inferior to materials reinforced with carbon fibers. Therefore, it was finally decided to use carbon fibers on the FPS prototype. The disadvantages of carbon fiber-reinforced polymers (CFRP) include the high material price and a more complicated production process than glass fiber reinforcement [47].

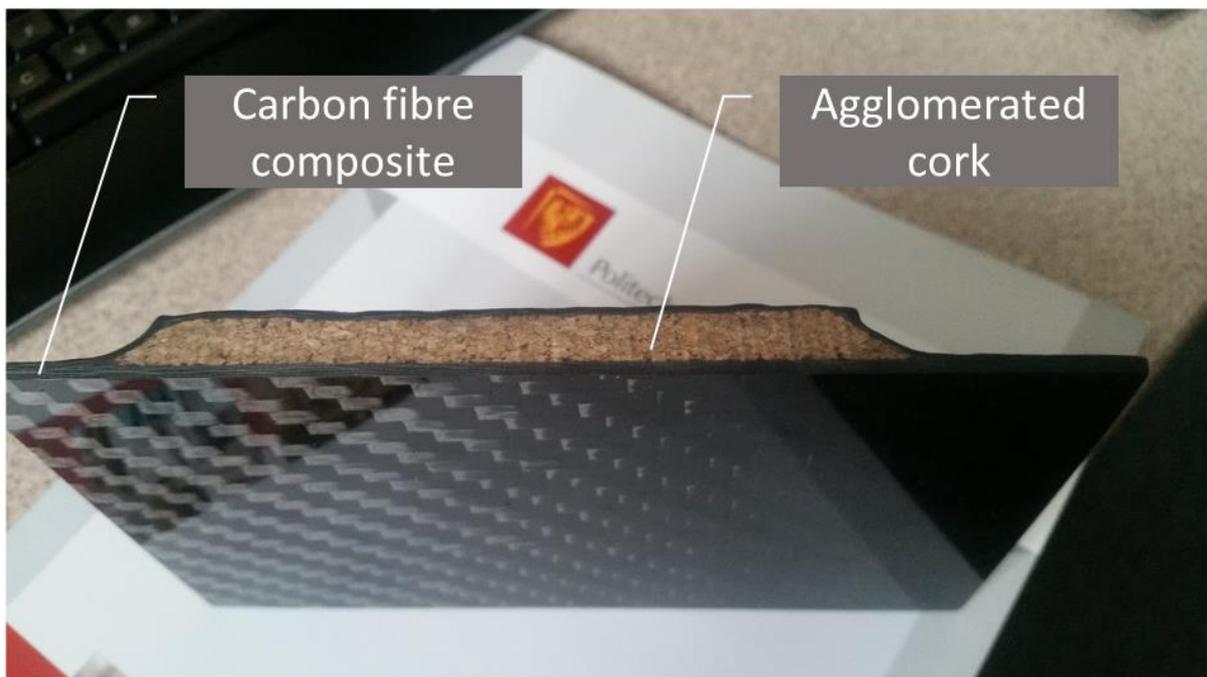


Figure 3.14 The cross-section of the frontal protection system made of agglomerated cork as a core and carbon fiber twill weave.

The market demand requires not only a product with appropriate safety features but also an attractive design. Thus, the authors chose the twill weave structure, which is the most common weave type for carbon fiber parts – sometimes referred to as a 2x2 weave [48]. The pattern goes over two intersecting warps to create a woven fabric with a diagonal pattern (Figure 3.5).

Type-approval tests demanded for the FPS, i.e., Regulation (EC) 78/2009 [49] based on impactors, do not include the full kinematics of vehicle impact with a pedestrian. Thus, our approach involved a kinematic analysis of a pedestrian hit by a vehicle equipped with a composite frontal protection system. We used an ellipsoidal pedestrian dummy from the MADYMO v7.5 library. Numerous independent institutions have confirmed this dummy is widely used in pedestrian safety tests and its biofidelity. Based on the results of tests [50], [51], the contact point between the dummy and the ground was defined as 0.55. Throughout the whole simulation, the dummy was in the field of acceleration $g = 9,81 \frac{m}{s^2}$. The vehicle's initial velocity was 40 km/h without applied braking deceleration.

The boundary conditions that define the constraint of the vehicle's front-end were considered the worst computational case [52]. Screw-nut connections were mapped using beam elements and Node Sets that are available in LS-DYNA code. The whole numerical setup is depicted in Figure 3.15.



Figure 3.15 A discrete model of the vehicle front-end with the mounted FPS and MADYMO 50th-percentile male dummy model.

By analyzing the course of the simulation presented below, a significant improvement in kinematic and biomechanical parameters of the dummy can be observed in relation to the vehicle not equipped with FPS (Figure 3.16). The greatest deflections in the knee have been significantly reduced, which is also confirmed by the tests of biomechanical criteria. The head and upper body remain stationary for a certain moment under the force of inertia, but the given rotation makes it possible to project the head onto the vehicle's hood. We can observe a reduced deflection of the dummy's cervical vertebrae, which reduces the likelihood of serious injury [53]. The course of the dummy kinematics makes it possible to

use other systems that improve pedestrian safety – including a lifting mask with an additional gas cushioning, such as an airbag to protect the head. The rotation given to the pedestrian also causes the pedestrian not to experience the maximum acceleration of the whole body in a short time. In addition, the head acceleration does not exceed the standard parameter, among others HIC (critical value 1000 – in the simulation <100) [54], [55].

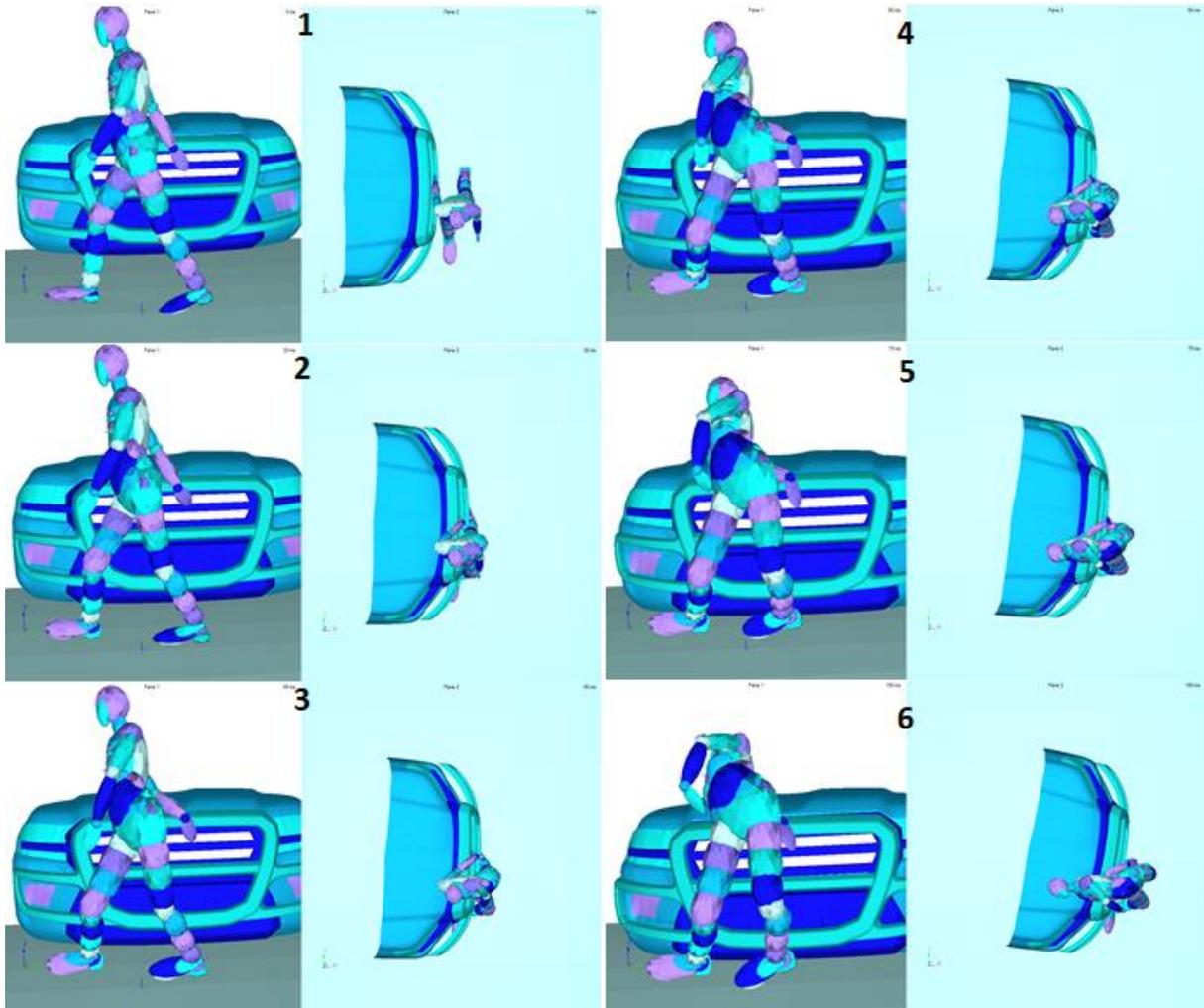


Figure 3.16 Numerical simulation of LS-DYNA and MADYMO pedestrian impact at 40 km/h – successive 0-100 ms shots shown at 15 ms intervals.

Assessing the FPS's effectiveness in ensuring pedestrians' protection included a positive kinematic validation. An assessment of the pedestrian's post-impact trajectory was sufficient at the designing stage of the FPS. The next stage of the work involved the optimization criterion was for FPS to meet the type-approval requirements established in Regulation (EC) 78/2009 of the European Parliament and Council for legform impactor to frontal protection system test as described in [56]. The final design of FPS mounted on a Toyota Land Cruiser vehicle and Ford Transit is depicted below (Figure 3.17).

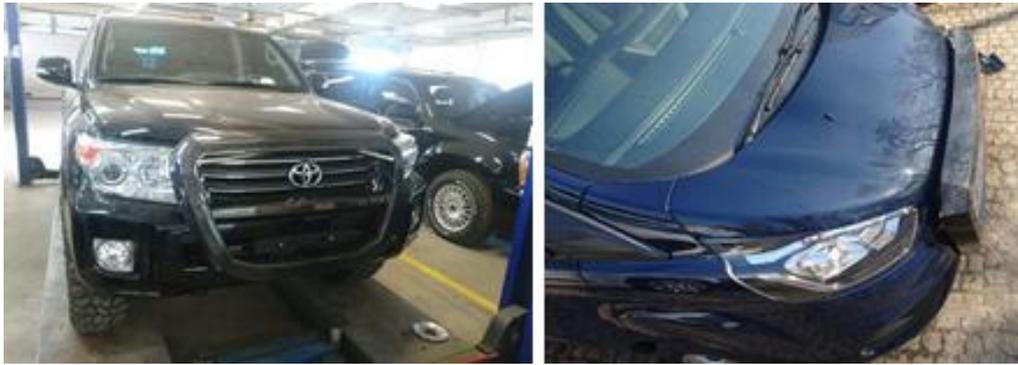


Figure 3.17 Frontal protection system made of cork and CFRP mounted on Toyota Land Cruiser (left) and Ford Transit (right).

Remarks

The study aimed to improve the safety of pedestrians and cyclists by developing and implementing systems based on natural energy-consuming materials. In this case study, a cork-cork FPS was designed and numerically tested. The carbon fiber composite is increasingly used in the automotive industry due to its low mass density and high strength. Thanks to that, FPS made of carbon fiber may efficiently protect the front elements of the vehicle. Additionally, the cork-core energy-absorbing capabilities can reduce injuries sustained by a pedestrian during an accident. Combining cork material and carbon fiber is a good solution when selecting the material for the elements to protect the car and the pedestrian. Thus, it has been proven that the combination of cork and carbon fiber is a perfect solution when choosing the material for the elements to protect both the car and the pedestrian – cork ensures the absorption of mechanical energy, thanks to which the injuries suffered by humans are relatively small. In contrast, carbon fiber due to its strength, protects the front part of the vehicle.

3.2.6 Energy Absorbing Technology

Current trends in the continuous search for eco-friendly and cost-efficient materials led to numerous studies by various research groups [3], [57]–[65]. Currently, most personal safety gear utilizes energy-absorbing liners that are made of synthetic cellular materials such as expanded polystyrene (EPS) and expanded polypropylene (EPP) with the combination of different densities within different pads, absorbing impact energy through permanent deformation. Under compressive loading, cellular materials can undergo large strain deformation while maintaining their low-stress level almost constant until densification [66]. In the work of Fernandes et al. [67], a commercially available, EPS-based motorcycle helmet certified by the European standard R22.05 [68] is employed as a reference (Figure 3.18). The idea was to compare the helmet validation results with EPS as linear and with agglomerated cork as a liner. The tests were conducted with cork agglomerates AC199, AC216, and EC159 (AC - agglomerated cork, EC – expanded cork).

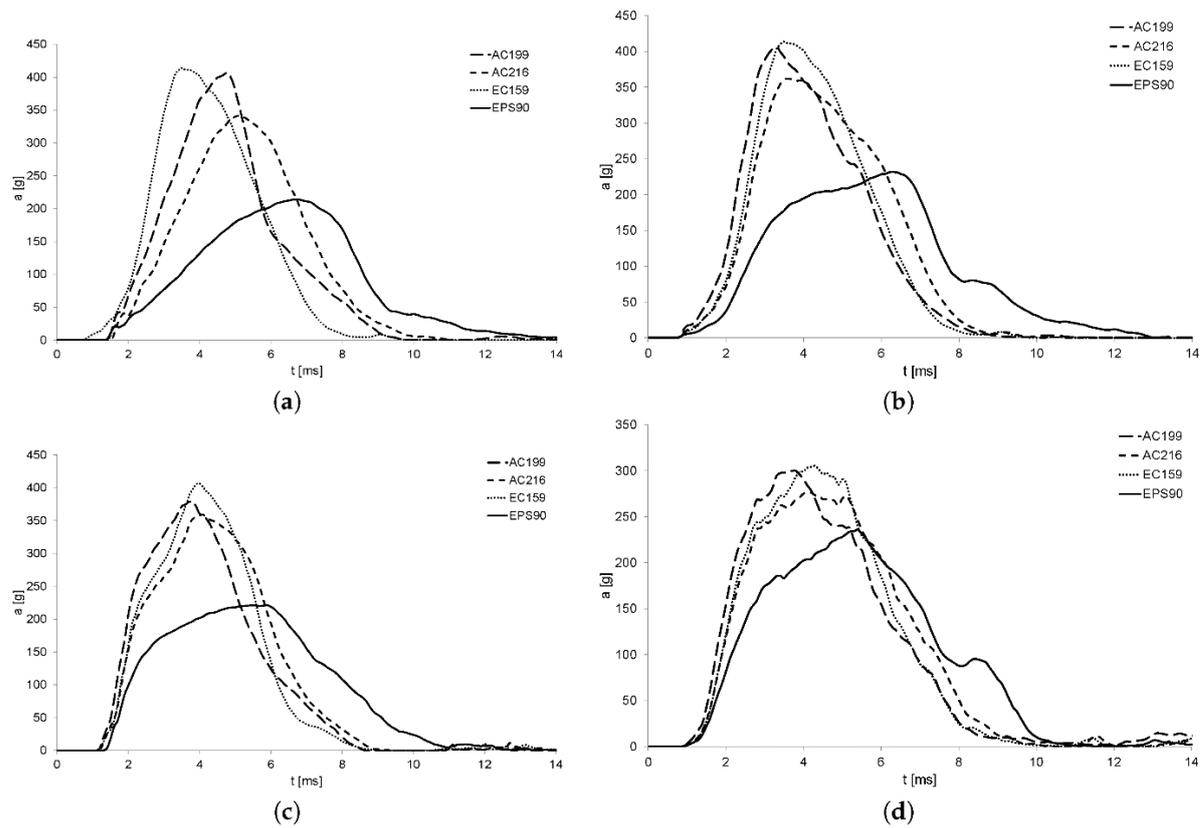


Figure 3.18 Acceleration measured in the headform's COG - ECE 22.05 test conditions: (a) Impact point B. (b) Impact point P. (c) Impact point R. (d) Impact point X adapted from [67].

It is noticeable that cork agglomerate AC216 stood out from the other proposed configurations. For the investigated acceleration-time curves, the curve characteristic is wider and has lower peak accelerations. Additionally, AC216 was the best material regarding the response to a second impact, even better than EPS90. What is more, AC216 has a greater capacity to withstand impact energy. Thus, it is believed that the helmet used in this analysis energy-absorbing it at a thickness higher than necessary for AC216. The further step of the research was to modify the geometry of the liner. According to the authors, the best case was a 40 mm thick AC216 liner with 15 mm holes in a circular pattern characterized by an angle of 30°, and a spacing of 45 mm. This helped to reduce 0.907 kg from the structure. The research was summarized by collaborating with CMS, a Portuguese helmet company. The product was enriched with a cork liner responsible for energy absorption (Figure 3.19).

The Portuguese company Nexx s developed a cork-based helmet for winter disciplines similar to CMS. The energy-absorbing technology is used as a part of inside cushioning. The shell is created by an impact-resistant advanced thermo-resin shell, plush anti-sweat, anti-allergy inner lining (which is removable), with a PC Lexan visor. Additionally, the producer offers a cork shell design [69].



Figure 3.19 Cork-based motorcycle helmet concept (left) and a helmet with cork shell design (right) [69].

3.3. Conclusions

Cork is a remarkable natural raw material with a unique combination of synergistically reinforcing properties. It is suitable for various applications, from typical bottle stoppers to sophisticated thermal insulation shields for engines and rocket tanks. The aim of the module was to present in a technically credible way how various properties of cork material create and drives the sector of cork production. In the module, the knowledge about the characteristic combination of cork's properties was presented, which led to certain applications of cork material. Beginning with the characterization of cork material with respect to other materials and underlining its advantages/disadvantages, the reader shall have knowledge about the proper application of cork material in accordance with real-world requirements and particularly a case study – an original cork-based frontal protection system for an SUV. The cork-core energy-absorbing capabilities can reduce injuries sustained by a pedestrian during an accident. In this module, we introduced the reader to a set of properties that makes cork unique and exceptional material. Further, the path was turned into an explanation based on examples of why cork is the right choice in the material selection process for the presented application.

Cork is a remarkable natural raw material with a unique combination of synergistically reinforcing properties. It is suitable for various applications, from typical bottle stoppers to sophisticated thermal insulation shields for engines and rocket tanks. The knowledge in modern materials engineering enables the continuous expansion of the application area of cork and its composites, and research on innovative cork applications is also continued. Cork is a precious gift of nature that must be treated with respect and used as widely as possible, sustainably, and ecologically.

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CHAPTER 4

Manufacturing and Implementation of Cork-Based Composites in Aviation

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Abstract

It is vital to examine the most significant positive and negative properties of cork-based composites to determine the use of natural cork-based composites in aviation and their rational implementation in the structural elements. This research provides a broader approach to cork material manufacturing processes and the application areas of cork-based sandwich structure composites in aeronautics. Cork composite applications for gaskets and other sealing materials are presented in this chapter. To understand more about the characteristics of the material, the two main testing approaches were performed: vibration and bending. The results of the conducted vibration testing suggest the possibility of replacing polymethacrylimide foam with a renewable cork-based material in laminated composite structures. The test was performed employing the modal analysis, thus comparing the vibration-damping characteristics of the material. As could be seen from the obtained bending test results, the material with the highest strength rate was composed of the largest cork-based granules. The withstand force was three times higher than the composite material with polymethacrylimide foam filler. Integrating renewable materials such as cork into the sandwich-structured composites allows to implement and seek the higher level of sustainability in the aviation industry.

Keywords: Cork, sandwich-structured composites, sealing materials, vibration and bending testing.

4.1 An Overview of Cork-Based Sandwich-Structured Composites

4.1.1 Definition and Types of Sandwich-Structured Composites

Sandwich-structured composites fabricated of several layers of different materials attached are widely used in aeronautics where lightweight and rigid structures are required [1]. Sandwich-structured composites, in which two face sheets are attached to the core, are most commonly used in aeronautics [2] (Figure 4.1).

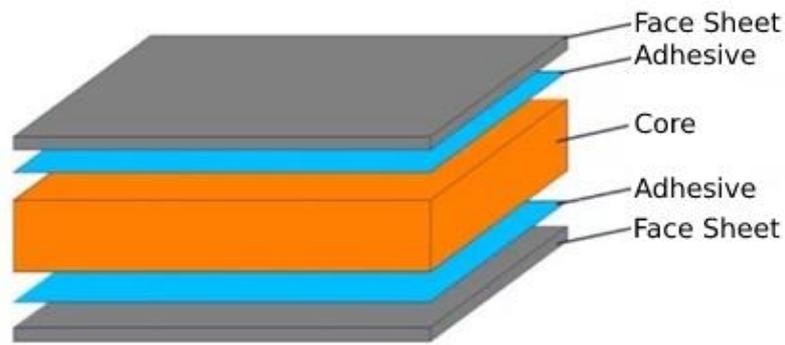


Figure 4.1 A sandwich-structured composite [3].

Such a structure allows for high stiffness characteristics while maintaining a low mass.

Sandwich-structured composites may be fabricated out of multiple layers, having two or even more core layers between which the face sheets are allocated [4]. For instance, sandwich multi-layer panels used in construction consist of two face sheets (Figure 4.2). These layers are separated by a double core layer separated by an additional layer.



Figure 4.2 A multi-layered construction panel fabricated out of three metal tinplates [5]. Two core layers are sandwiched between tinplate layers.

Such multi-layered structures with a cork-based core and composite materials, wood or metal layers could be used as decorative panels having ecological and good sound insulating properties. Even though a multi-layered structure, to some extent, differs from a sandwich structure, its manufacturing and implementation properties are identical. Therefore, if necessary, the paper will focus only on sandwich-structured composites, noting the technological or structural differences of multi-layered structures.

4.1.2 Properties, Advantages and Disadvantages of the Most Significant Cork-Based Sandwich-Structured Composites in Aeronautics

To define natural cork-based composites used in aeronautics and most rationally used structural elements, it is vital to examine these composites' most significant positive and negative properties.

The advantages of natural cork-based composites:

- A. The most compelling advantage of this composite is that it is environmentally friendly and easily recyclable [6]. It is a profound quality, especially nowadays, as more attention is drawn to the machinery materials which could be utilized without polluting the environment, or even better if they could be recycled or reused. It is an overpowering feature relevant for aeronautics as most of the composite materials currently used in this field are complicated to dispose of or recycle for reuse.
- B. Due to the relevant softness and elasticity, cork-based sandwich-structured composites have good noise and vibration-dampening properties [7].
- C. Notwithstanding the organic nature of the cork-based sandwich-structured materials, a high level of fire resistance is another worth mentioning property [8]. Thus, making them suitable for the interior finishing of aircraft and glider cockpits/cabins.
- D. Cork-based composites have aesthetic properties - they are pleasant to touch. This property is considered when applying it as the interior finishes [9]. Moreover, these materials could be decorated with various patterns transferring images onto them by using modern technologies (for instance, laser engraving).



Figure 4.3 Laser-decorated cork-based panels [10].

While applying the laser cutting technique, cork-based composite panels could be cut through with the patterns. Such cut-through elements could be used for the aircraft cockpit/cabin interior decoration (Figs. 4.3 and 4.4).



Figure 4.4 A laser cut through cork-based composite panels [11], [12].

- E. These composites are moisture-resistant and do not absorb water.
- F. Cork-based composites have good thermal insulation properties [13].
- G. Cork-based composites are well-treated by conventional machinery methods in the general machinery manufacturing process (Figure 4.5).

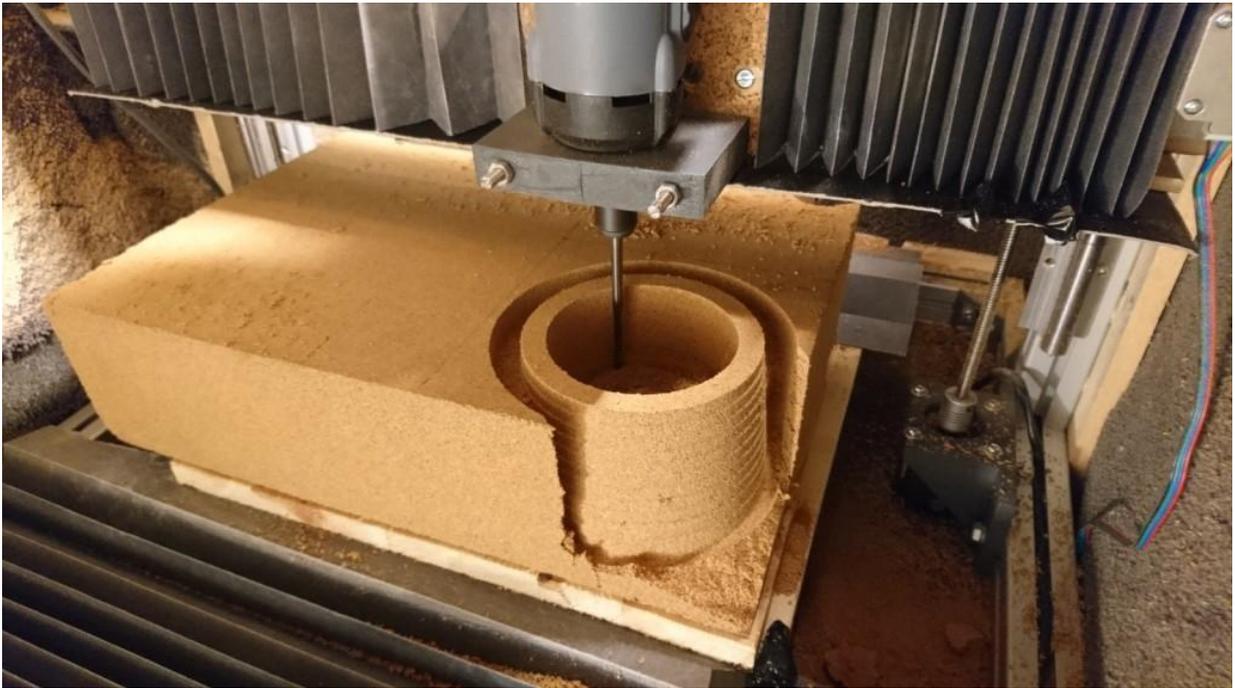


Figure 4.5 Cork milling with a finger milling cutter [14].

Disadvantages of the cork-based composite materials:

- A. Like most other natural materials, cork-based composites have sensitive mechanical properties. They depend on the type of cork oak, growing conditions, climate, and even the location where the bark was harvested. The outer part of cork oak bark is brittle and woody and is characterized by high density. The density of the bark decreases as it approaches the trunk, and it gains elasticity. Therefore, the bark density ranges from 60 kg/m^3 to 250 kg/m^3 —the elasticity and hardness of the bark change accordingly [15].

It is a formidable obstacle for applying these materials in aeronautical structures, as the stability of the mechanical strength is an essential condition for ensuring static strength, fatigue strength, and stable technological properties. This obstacle could be overcome by grinding the cork bark into tiny granules and mixing them.

- B. The organic nature of cork-based composite materials determines their low resistance to mold and other fungal damage [16]. There is a risk that they can be a medium for insects to feed and reproduce.
- C. Many types of solvents, cleaners, and other chemicals are used in aeronautics. Their effect on cork-based composite materials has not been sufficiently examined yet.

4.1.3 Application Areas of the Cork-Based Sandwich-Structured Composites in Aeronautics

Following the defined advantages and disadvantages of natural cork-based composite materials, it is possible to estimate which aircraft structural elements could be manufactured using sandwich-structured or multi-layered composites.

Small aerodynamic and massive inertial loads affect ultralight, light, glider wingtips, fairings, and undercarriage wheel wells [17]. These structural elements do not have a decisive effect on these aircraft's strength or cyclic fatigue characteristics. They usually are multi-layered or sandwich-structured.



Figure 4.6 The part of the glider wing with four winglet types [18].

When designing such structural elements, it is sufficient to analyze whether honeycomb or foam fillings could be replaced with cork-based materials. Probably, the application of these materials will not have an adverse effect on the mass of the structure. However, it will considerably reduce pollution when these structural elements are no longer adequate for use and are destined for disposal. For instance, easily removable and replaceable glider wingtips (winglets) quite often damage gliders when landing in outdoor areas. In addition, the market offers various winglets adapted specifically for various flight conditions [19]. Thereby, gliders use several types of winglets (Figure 4.6) or are forced to change them in case of infringement. Such elements are complex to utilize in an environmentally-friendly way. The application of cork-based materials would propose a partial solution to this problem.



Figure 4.7. A motor glider [20]. An open engine compartment can be seen at the top of its fuselage, whereas an undercarriage wheel well could be observed at the bottom of the fuselage. These structural elements could be manufactured using cork-based sandwich-structured composites.

The cork-based filler is a good material for manufacturing model aircraft or small UAVs. They are affected by light loads, and good elasticity properties may prevent damage typical of such aircraft when they land.

It would be sufficient to manufacture sandwich-structured undercarriage wheel wells or retracted engine compartment doors from two-layers aluminum alloy sheets, filling the gap between them with cork-based material (Figure 4.7). Thus, a light and strong structure could be obtained, and all the components (aluminum sheets and cork-based materials) would be recyclable.

Bulkheads are usually installed inside the fuselages of business class aircraft, separating the passenger cabin from the cockpit and ensuring a separation for isolated spaces. Such bulkheads are commonly decorated with wood (Figure 4.8).



Figure 4.8 The fuselage of a business class aircraft [21]. A bulkhead decorated with wood at the rear part of the aircraft can be seen. On the right side, a folding table is installed between the chairs.



Figure 4.9. A sandwich-structured panel is filled with cork material, and the wood layers are adhered to both outer sides [22].

Such bulkheads must be light, fire resistant, and have noise reduction and thermal insulation properties. It is sufficient to manufacture these bulkheads using wood sandwich panels, where the inner filler is fabricated from cork-based material (Figure 4.9).



Figure 4.10 A sandwich-structured panel [23]. One side is covered with plywood, the other with a metal sheet. The inner filler is produced out of granulated cork material.

The exterior of the bulkheads could be covered with metal or plastic sheets. The wood layer could be applied to one side only. Thus, the bulkhead is quickly adapted to the cabin interior design and specific requirements of separate aircraft compartments. For instance, if there is a compartment right behind the passenger cabin, one side of the bulkhead could be made of wood, whereas the other could be covered in metal sheets or specific plastic (Figure 4.10). The wooden side of the bulkhead adds luxury, while the metal side facing the galley is easy to clean and is mechanical damage-resistant.

Such bulkheads ensure good sound insulation and are characterized by having low mass. It is sufficient to use such sheets to manufacture business-class aircraft furniture. (For instance, the table's surface is shown in Figure 4.8). Striving for a luxurious impression, they are produced massively. Using cork-based sandwich-structured panels makes it possible to manufacture furniture of massive appearance and low mass.

The surfaces of the bulkheads and furniture could be covered with specifically decorated cork-based material layers. As cork-based materials are easy to treat by applying various methods, it is possible to obtain surfaces that brighten the interior.



Figure 4.11 The surface of the wardrobe door is covered with patterned cork-based material [24].

Figure 4.11 shows a wardrobe door decorated with a layer of cork-based material with geometric patterns. Contemporary ways of treating materials offer a wide range of surface decoration options. They can be used for business-class aircraft interiors too.

Aiming to improve sound insulation properties, it is sufficient to apply multi-layered cork-based fillers, the layers of which could be fabricated from various dense cork-based materials [25]. Such sheets effectively suppress sound in a wide frequency range. The noise reduction in the business class aircraft cabin could be achieved via coverage of the decorative cabin surfaces with cork-based material panels. They could be sufficiently thin and compiled out of several different layers of cork-based materials of different densities. Therefore, the mass of the decorative panels would increase; however, the noise generated by the air entering the aircraft and the cabin ventilation system would be reduced.

Soft, pleasant to touch, and “warm” cork-based materials are suitable for manufacturing aircraft control panel hand levers (Figure 4.12).



Figure 4.12 Hand levers manufactured out of the cork-based material

A - A hand lever fabricated out of the granulated cork [26]

B - A hand lever made out of continuous cork.

Such hand levers have been used in light aircraft for a long time. They can be manufactured out of hot-pressed cork-based granules (Figure 4.12A) or by mechanically processing continuous cork-based material (Figure 4.12B).

While combining cork-based materials with rubber layers of various elasticity, effective anti-vibration damping sheets are obtained (Figure 4.13). The sheets could be both: sheet-type and doubly-curved products. They are efficient when fixing the pilot and passenger seats on light aircraft or other structural elements of the cabin, thereby reducing the vibrations caused by engines and propellers transmitted to them.



Figure 4.13 An anti-vibration sheet with a cork-based core covered with a porous rubber [27].

4.2 Cork-Based Sandwich-Structured Composites Manufacturing Methods

When reviewing the manufacturing methods of cork-based sandwich-structured composites, it is noteworthy to consider the geometrical properties of such structures. It is vital to distinguish between flat sandwich panels and sandwich elements of singly-curved or doubly-curved surfaces.

4.2.1 Manufacturing Methods of Flat Sandwich Panels

4.2.1.1 Manufacturing of Flat Sandwich Panels under Mechanical Compression

While applying mechanical compression for the sandwich-structured panels, flat panels with face sheets consisting of pre-made sheets of metal, wood, plastics, or other materials are the best option (Figure 4.14). Composite sheets of glass, carbon or polymerized plastic reinforced with other fibers may successfully be used for this too. A smooth and solid surface of sufficient dimensions and the ability to compress the panel are needed for the manufacturing process.

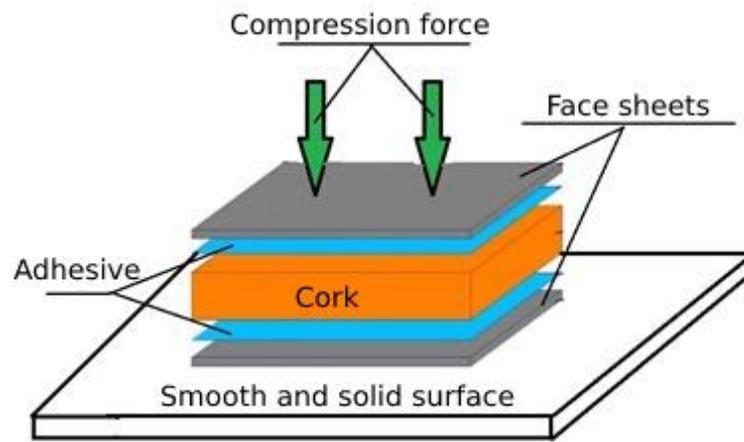


Figure 4.14 A schematic diagram of a flat sandwich-structured panel manufacturing process.

A face sheet with an adhesive coating is placed on the surface. Then, a cork-based core is placed, the adhesive is applied, and the structure is covered with another face sheet. The panel is compressed, and after the adhesive has hardened or polymerized, a flat sandwich-structured panel is obtained, which has to be cut according to the contour required.

Any mechanical compression equipment (a press, specialized compressor, and others) may be used to compress the panel. Small panels could be compressed with heavy objects. In order to distribute the compression force evenly, sand-filled bags or bags filled with any other loose and relatively heavy material are used. Applying compression force from above with another smooth and solid force application plate is highly recommended for evenly distributed panel compression. It is very convenient to use film adhesive to manufacture such panels. Not only does it simplify the manufacturing process, but it also makes it more convenient and "cleaner". It is crucial to ensure that air cavities are not formed in the adhesive coating when applying liquid adhesive, as it may damage the panel's external appearance or even cause a partial detachment of the layers resulting from the temperature change. It is also necessary to ensure that there is no local *over-compression*, which is best prevented by applying a compression force to the panel with force application plates on both sides. The cork-based filler is neither hard nor solid. Therefore, it is essential to control the compression force, especially when manufacturing small-dimension panels.

4.2.1.2 Manufacturing of Sandwich-Structured Panels under Vacuum Compression

It is convenient to use a vacuum for the compression in the cork-based sandwich-structured panels manufacturing process. Therefore, an evenly distributed and not excessive compression could be obtained, and it is also easier to avoid forming air bubbles in the adhesive layers. The manufacturing process of such panels is shown in Figure 4.15.

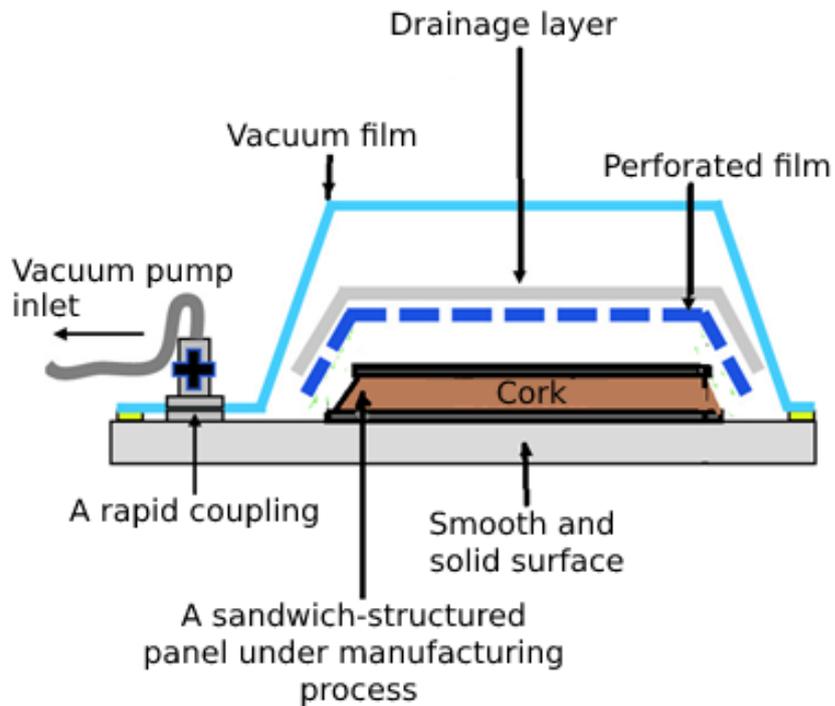


Figure 4.15 A schematic diagram of the manufacturing process of flat sandwich-structured panels with a cork-based core under vacuum compression.

Therefore, the panels are manufactured as follows:

1. A face sheet is placed on a sufficiently smooth, solid surface of sufficient dimensions. Suppose a liquid adhesive is used in the manufacturing process of a sandwich-structured panel. In that case, it is obligatory to cover the panel with an anti-adhesive layer beforehand (usually with silicone-based compounds/pastes) to prevent the release of glue from sticking to the manufacturing process plate.
2. The face sheet is covered with adhesive, and the cork-based core is placed.
3. The upper face sheet is covered with adhesive.
4. On the adhesive layer, another face sheet is placed.
5. Everything is coated with a specialized perforated film. The perforated film is applied only when layers of the panel are glued with adhesive. If the film adhesive is used, it is not obligatory to apply the perforated film. Therefore, the film adhesive layer is not thick and does not protrude over the edges of the panel when compressed.

6. Perforated film is coated with a uniquely thick, air-permeable material. It is a drainage layer that prevents the formation of internal air bubbles between the vacuum film and the surface of the manufactured panel.
7. At a distance of about 50÷150 mm from the edges of the panel on the manufacturing process plate, a special adhesive tape is glued around the entire manufactured panel, and everything is covered with a vacuum film. The vacuum film must adhere well to the adhesive tape, as this will determine whether a sufficient vacuum will be obtained when the vacuum pump is connected.
8. Standard slots are made in the vacuuming film for rapid coupling with the vacuum pump insert, and the coupling is inserted.
9. After verification, the bag is connected to the vacuum line (pump) through a rapid coupling.
10. The vacuum is turned on. At this stage, it is essential to slowly produce a vacuum under the vacuuming film by controlling the tightness and formation of folds along the perimeter of the manufactured panel.
11. The vacuum is kept activated until the adhesive dries or polymerizes.
12. As the adhesive has hardened, the vacuum is turned off, and the vacuum film and the drainage layer are removed. The panel is removed from the manufacturing process plate and is cut according to the required dimensions.

This way, high-quality sandwich-structured cork-based panels are manufactured without applying mechanical compression. However, a vacuum pump and several auxiliary materials are required for this process.

4.2.2 Manufacturing Process of Singly or Doubly-Curved Panels

Most sandwich-structured panels used in aeronautics are fabricated from singly-curved or doubly-curved surfaces [28]. Such items are manufactured using a slightly different technology than flat panels. This technology is also used in the manufacturing process of flat sandwich-structured items when the face sheets are made of fiber-reinforced composite materials, which are formed during the manufacturing process of sandwich-structured products [29]. For the fabrication of these products, a mold used as a contact surface forming the work area is necessary. Usually, such panels are manufactured in two stages. The first stage is shown in Figure 4.16.

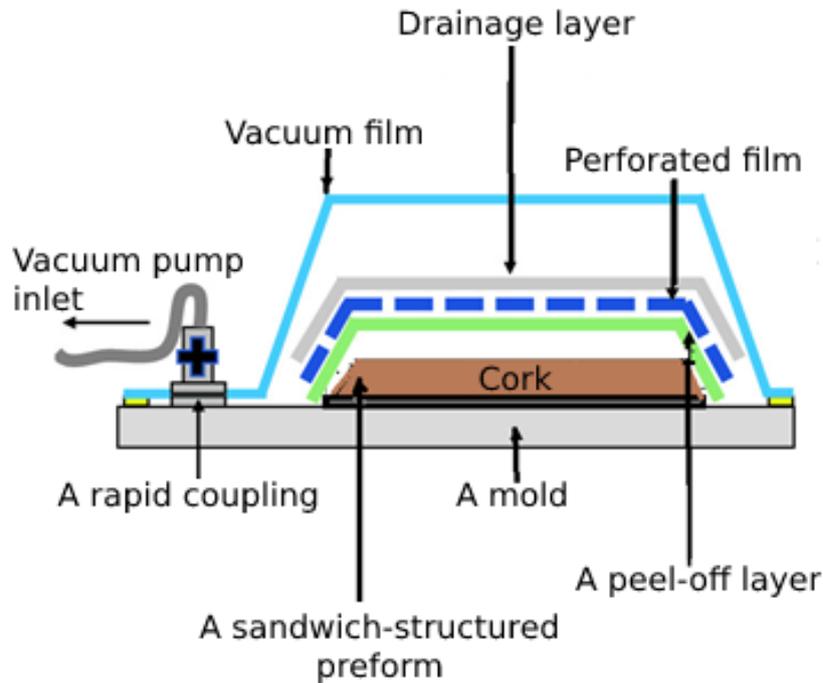


Figure 4.16 A schematic diagram of the first stage of the manufacturing process of a sandwich-structured panel when it is formed using composite materials.

Let us analyze the manufacturing process of this stage:

1. Before the first stage manufacturing process, it is vital to perform a visual inspection of the mold, drawing particular attention to the surfaces on which the quality sheet will be formed. If necessary, the minor scratches of the mold are polished. In case of severe damage, the mold is coated and then polished.
2. The work area of the mold is covered with an anti-adhesive coat and then polished. These actions are taken following the technological instructions provided by the layer manufacturer.
3. If the product is painted, the work area of the mold is covered with a particular decorative layer (Gelkaut).
4. A specialized adhesive tape is applied around the entire perimeter of the model to seal the vacuum film.
5. After the Gelkaut dries to a slightly sticky state, the face sheets of the composite are laid, soaking each one with resin. While laying the composite layers, it is vital to maintain the direction of reinforcement specified in the construction and technological documentation.

6. The core material is placed (cork-based material) as the layers are formed. When placing the core material (sometimes the core is made out of several sheets, then it is necessary to talk about sheets) and then vacuuming, it is essential to control that the sheet of this material occupies the correct position in the mold and does not move during the vacuuming process. This process requires certain skills and an understanding of how the surface deforms after applying the vacuum and starting to soak air from the vacuuming film. It is noteworthy that when manufacturing the doubly-curved surfaces in the mold, the radius of the surface change is relatively small.
7. On a formed surface, a specialized peel-off layer is placed. It helps to absorb excess resin and simplify the preparation of surfaces for the next molding stage.
8. Everything is covered with a unique perforated film.
9. On a perforated film, a drainage layer is applied. It prevents the formation of internal air bubbles between the vacuum film and the surface of the manufactured panel. It absorbs the excess resin that inevitably occurs with such a manufacturing technology.
10. A molded panel is covered with a vacuum film. The vacuum film must adhere well to the adhesive tape, as this will determine whether a sufficient vacuum will be obtained when the vacuum pump is connected.
11. Standard slots are made in the vacuuming film for rapid coupling with the vacuum pump insert, and the coupling is inserted.
12. After verification, the bag is connected to the vacuum line (pump) through a rapid coupling.
13. The vacuum is turned on. At this stage, it is essential to slowly produce a vacuum under the vacuuming film by controlling the tightness and formation of folds along the perimeter of the manufactured panel.
14. The vacuum is kept activated until the adhesive polymerizes.
15. As the adhesive has hardened, the vacuum is turned off, and the vacuum film, the drainage layer, the perforated film, and the peel-off layer are removed.

After a visual inspection and assurance that the product meets the requirements, the second manufacturing stage could be implemented.

The second stage of the manufacturing process involves molding another face sheet of a sandwich structure. The sequence of the actions of this stage is slightly different from those taken in stage one. The schematic diagram of the second stage is shown in Figure 4.17. A technological process of the second stage is analyzed in greater detail below.

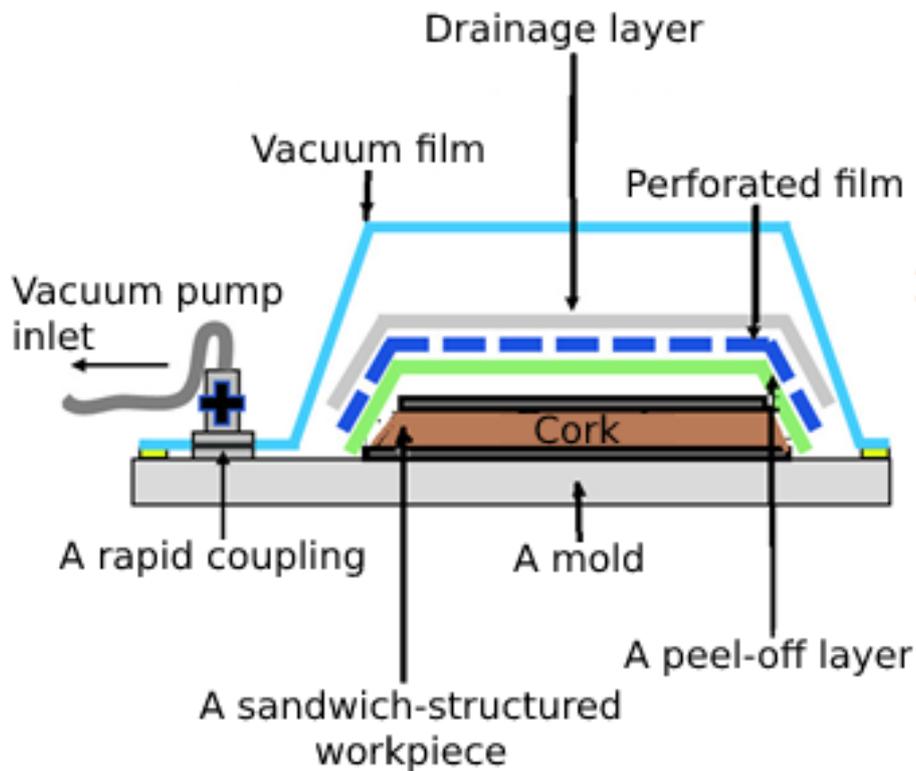


Figure 4.17. A schematic diagram of the second stage of the manufacturing process of a sandwich-structured panel, when it is formed using composite materials.

Before the implementation of the second stage of the sandwich-structured composites manufacturing process, its surfaces, after the removal of the peel-off layer, are lightly ground with at least 100-grit sandpaper. The following steps are taken:

1. The layers covering the core of the composite are laid. Each layer is soaked in resin. During the first stage, when forming the composite layers, it is essential to maintain the direction of reinforcement of the layers specified in the construction and technological documentation.
2. On a formed surface, a specialized peel-off layer is placed. The peel-off layer has the same function as in the first stage.
3. The following steps are identical to steps 8-12 taken in the first stage.
4. The manufactured surface is removed from the mold. Its quality is verified.
5. The surface is cut according to the dimensions given in the drawing, and after verification, it is ready for further use.

4.2.3 Peculiarities of the Mounting Point of Sandwich-Structured Panels

Cork-based sandwich-structured panels have several construction peculiarities. One of them is the complicated structure of the mounting points. This peculiarity is common for all light core-based sandwich-structured materials. The core materials are very light and have very low contact stress. The face sheet materials are usually characterized by having good mechanical properties (as well as relatively high contact stress). However, these materials are very thin. It is common to fasten various assemblies to sandwich-structured elements. Therefore, the reception of local loads in such structures is usually very complicated and requires unique structural solutions.

There may be several mounting options. Each of them uses a specific mounting method.

4.2.3.1 Reinforcement of Sandwich-Structured Panels at the Mounting Points of Other Structural Elements

If a structural element is exposed to a higher load, it needs to be bonded with the surface of a sandwich panel or any other sandwich-structured surface. In this case, a replacement of the core material with a heavier material of better mechanical properties at the local mounting point is needed. A slot of a sandwich structure with such an insert is shown in Figure 4.18.

Such a structure is fabricated as an ordinary flat or singly-curved or doubly-curved surface. In the local mounting points, the core material is removed, and sufficient dimensions of the core are inserted. The insert is manufactured from a material with better mechanical properties. To simplify the manufacturing process, the insert can be formed into a recess of the required shape made in the core by filling resin mixed with a filler (chopped carbon fiber, other special resin fillers) that improves mechanical properties.

When another structural element subjected to extremely low loads is bonded to a sandwich-structured panel, it may be sufficient to increase the thickness of the face sheet to which it is bonded by applying more layers of reinforcing material locally or simply by bonding it with a larger reinforcing patch from the outside. The schematic diagram representing such reinforcement is shown in Figure 4.19.

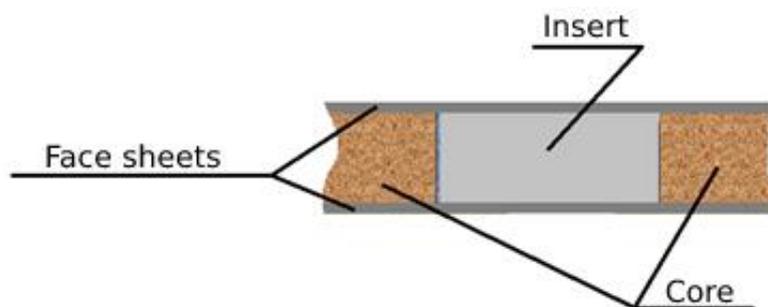


Figure 4.18 An insert slot in a sandwich-structured panel with an eco-cork core.

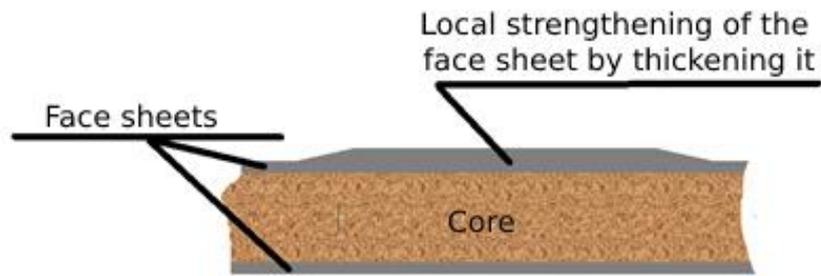


Figure 4.19 A slot diagram of the local external reinforcement of the sandwich-structured panel.

4.2.3.2 Reinforcement of Sandwich-Structured Panels at the Mounting Points of Other Structural Elements when These Elements Are Screwed

Commonly, sandwich-structured panels or other panels are fastened to other assemblies, which must be removed from time to time. The best option for that is screw connections. However, at this point, two challenges may be encountered:

- A. With screw connections, it is relatively easy to overload the core material when tightening the screw nut. This problem becomes prominent when the core material is cork-based. Such a core has a high elasticity rate and is easily deformable. Therefore, when tightening the screw, it becomes easy to crash the core, damaging the face sheets.
- B. Under heavier loads, an unreinforced core material at the mounting points may be torn out by the screws.

The resolution to this problem is placing/pouring the inserts in the places of the screws, as shown in Figure 4.18. and by slotting holes in those cavities.

The schematic diagram of such an assembly is shown in Figure 4.20.

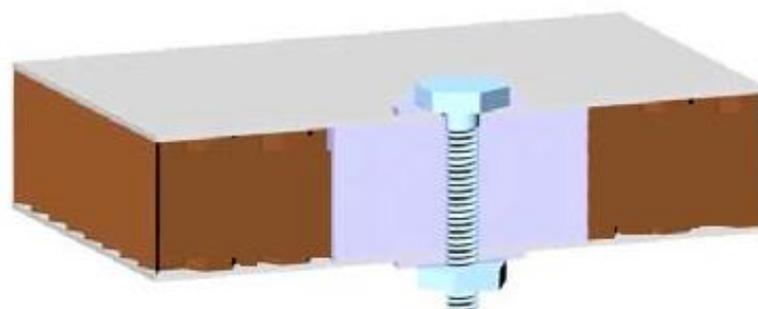


Figure 4.20. A slot in the insert of the sandwich-structured panel for the screw connection [30].

However, such a decision is only sometimes enough. It is relatively common that the mounting points are affected by heavy loads. The screw connection has to be easily disassembled and reassembled due to operational and other requirements [31]. Sometimes there are also requirements to ensure the hermeticity of such a connection. As typical for closed aeronautical structures, the screw has to be tightened from one side without using a nut.

In such cases, a more oversized insert is bonded with adhesive into the core, and after drilling a hole, a special bushing is bonded with adhesive. The scheme of such a connection is shown in Figure 4.21. Certified custom-manufactured aircraft bushings are primarily used in aeronautics (Figure 4.22). Bushings can be custom-designed and manufactured for specific connection points if necessary.

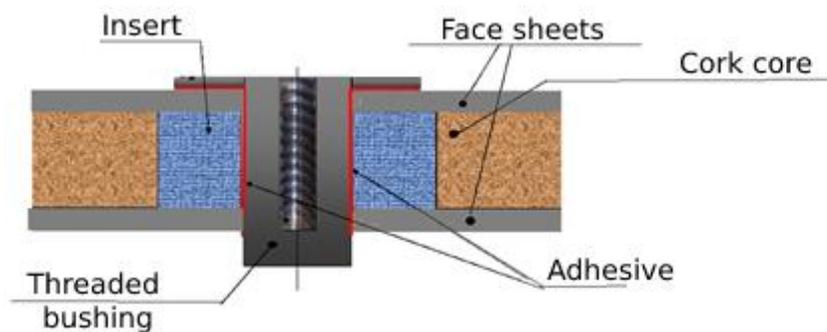


Figure 4.21 A threaded bushing bonded with adhesive into a sandwich-type structure [32].



Figure 4.22 Samples of standard bushings of sandwich-structured panels [33].

4.2.4 Features of Sandwich-Structured Panel Edge Closures

Sandwich-structured or multi-layer panel edges have to be sealed in unique ways. It has to be done to insulate the core at the edges. Furthermore, the panel edges are usually attached to other structural elements. However, the mounting methods mentioned above could not be used in this case.

When the structural elements are manufactured to be used in the load-affected structures, the connection usually requires an edge where the face sheets are joined, and there is no core material between them. The transition has to be smooth, without any sudden stiffness changes. Therefore, the core side slopes are created. The angle of the side slope should be as small as possible. It is usually 30 degrees or even less (Figure 4.23).

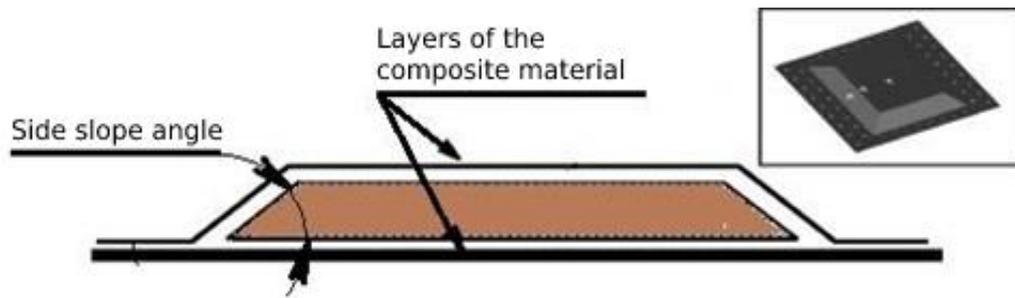


Figure 4.23. Edge closures of the sandwich-structured panel by creating side slopes at the core [34].

The smaller the slope angle, the smoother the change in stiffness at the edges of the panel is. A smaller slope angle is desired when manufacturing the panels using the vacuum mentioned above methods. In case of a bigger (close to 90 degrees) slope angle while vacuuming the panel at the edge of the core, zones where the vacuum does not compress the composite panel, are inevitably formed. Consequently, aesthetic surface defects appear, and the strength of load points deteriorates significantly.

Sometimes, a sandwich-structured panel with a cork-based core has to be sealed by cutting it steeply. In such a case, the core could be kept intact too. Therefore, the panels are sealed by manufacturing various bulkheads for the aircraft cabin. In such cases, the methods of sealing the panel's core with various profiles are used. The schematic diagram of these methods is shown in Figure 4.24.

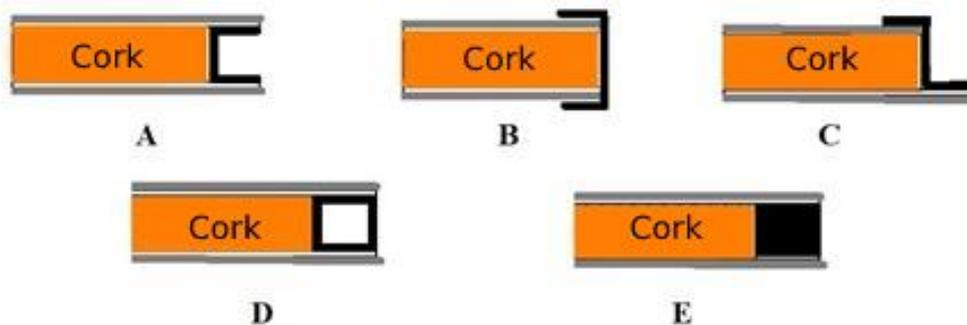


Figure 4.24 Sealing methods of the sandwich-structured panel with cork-based cores when it is necessary to cut them steeply. A “U” form profile inside of the face sheets; B “U” form profile outside the face sheets; C “Z” form profile; D closed hollow profile; E solid square or rectangular bar.

In all these cases of sealing a sandwich-structured panel, the sealing elements (profiles and rods) are bonded using adhesive to the face sheets and the core. Screw or rivet connections are less common. If the sealing elements must be invisible from the outside, the sealing with a “U” form profile inside of the face sheets (Figure 4.24A) or with a closed hollow or solid profile (as shown in Figure 4.24D and Figure 4.24E) is used.

Sometimes a sandwich-structured panel needs to be “framed” in specific zones across the perimeter. It is often done for aesthetic reasons, less commonly due to the structural features of the connections. In such cases, the best options are to use the sealing methods shown in Figure 4.24B and Figure 4.24C.

Let us analyze the manufacturing process of sealing presented in Figure 4.24A. First of all, the core material is removed mechanically from the zone where the sealing profile is planned to be bonded by adhesive. While completing this step, it is noteworthy to avoid damaging the face sheets of the panel and not to leave core residue in the removed areas. The inner surfaces of the face sheets are ground and coated with adhesive. The adhesive-to-be profile is cleaned and prepared for bonding with adhesive according to the appropriate technology for the profile material. The profile is inserted, the excess adhesive is removed, and after the compression, the product is left until the adhesive hardens. As soon as the adhesive has hardened, the compression is relieved, and the excess of the adhesive is removed.

When working on the aircraft cabin interior, connecting steeply cut sandwich-structured panels is often vital. For the sealing of the edges, it is rational to use such connections, which simplify more complex profiles.

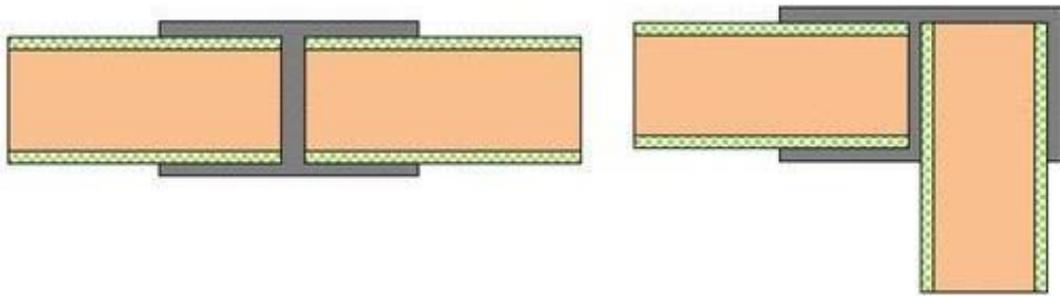


Figure 4.25 A connection of flat panels via profiles sealing their edges.

Figure 4.25 shows the means for connecting two flat panels with profiles and options for sealing and connecting elements of the panel edges. Therefore, the joint mass is reduced, the connection is made cheaper, and the aesthetic image is obtained.

4.3 Cork Composite Applications for Gaskets and Other Sealing Materials

Gaskets are among the most common and time-tested applications for cork rubber composite. The application of cork composites for their sealing properties in aviation is widespread and proven practical. The gaskets made from cork rubber composite can be used with various fluids and gasses in different aircraft systems [35].

4.3.1 Most Common Fluids used in Aerospace Industry

1. Gasoline (AVGAS 100LL):

AVGAS 100LL is the standard fuel used with most piston engines for propeller aircraft and helicopters. *Avgas* is a conventional gasoline used in the automotive industry, just with the addition of tetraethyl lead (TEL), which raises the octane number of the gasoline to 100. Furthermore, the added TEL number is reduced compared to AVGAS 100, hence the name – “Avgas 100LL (Low Lead) [36].

2. Kerosene (Jet fuel):

JET A-1 is the most widely used type of kerosene fuel that is primarily used for jet engines for aircraft and helicopters [37]. There are fundamental differences when comparing kerosene to gasoline or diesel, mostly the flash point, energy density, and chemical composition. Jet engines can generally work in a wider variety of fuels, which is one of the most fundamental reasons why cheaper kerosene-based fuel is used.

3. Engine oil:

Various engine oils are used depending on the engine type and its characteristics. The most commonly used oils for four-stroke piston engines for propeller aircraft are mineral oils described in SAE J-1966, like Aeroshell 80 (for temperatures between -17°C and 21°C), and semi-synthetic oils described in SAE J-1899, like Aeroshell W15W50 and equivalent.

Jet engines commonly use thinner oils because of the higher engine rotation. The most commonly used standard - MIL-PRF-23699F, Eastman Turbo Oil 2380 is one of the examples.

4. Hydraulic fluid

The primary purpose of this type of fluid is to transfer energy (in the form of pressure) from one place to another. Because of this, the fluid is usually not consumed in the operation process. However, the requirements for the properties of hydraulic fluid are incredibly high. For example, the standard operating pressure for hydraulic systems is 3000 Psi (206.8 Bar) [38]. Another essential characteristic is the flow rate, which can reach up to 3 liters per second in some aircraft systems. This requires the hydraulic fluid to perform at high pressures and high flow rates while remaining liquid, preferably keeping the laminar flow, not evaporating, and not changing its properties under immense stress, as indicated in the SAE AS1241 standard.

All these properties are achieved by blending mineral oil and different chemical elements, usually non-disclosed for commercial reasons. However, in a standard aircraft maintenance and repair organization, hydraulic fluid is considered the most erosive and chemically aggressive fluid used in aviation (Table 4.1).

Table 4.1 Standard aviation fluids pressures and operating temperatures.

Type of fluid	Standard operating temperature	Standard operating pressure
Gasoline (AVGAS 100 LL)	-58°C to 60°C	≤ 1000 psi
Kerosine (JET-A1)	-47°C to 80°C	≤ 1500 psi
Engine oil (piston engine)	-17°C to 82°C	≤ 65 psi
Engine oil (jet engine)	-40°C to 350°C	≤ 45 psi
Hydraulic fluid	-40°C to 100°C	≤ 3000 psi

4.3.2 Fluid Sealing Technologies

Because of the different chemical and mechanical properties required for sealing materials used in aerospace applications, quite a few solutions have been developed. The most common solution are sheet gaskets, solid material gaskets, envelope gaskets, kammprofile gaskets, and O-rings (Figure 4.26). However, cork-rubber composite sealing technologies have only proven effective in the form of sheet gaskets [39].



Figure 4.26 Cork-rubber sheet gaskets [40].

The properties of cork-rubber gaskets depend on a few factors, such as cork grain size, density, chemical composition, and rubber-to-cork ratio (Table 4.2). Adjusting these characteristics makes it possible to create a composite with the required parameters for a specific application. However, it is unreasonable to expect the possibility of making a “perfect” composite that would perform well in all the environments found in the aerospace industry. Different fluids, temperatures, and pressures will affect the composite in various ways; therefore, a unique cork-rubber gasket design is required for each system.

Table 4.2 Cork/rubber composites and their properties [41].

Material	Description	Density (kg/m ³)	Hardness (Shore-A)	Compressibility% (400 psi)	Traction resistance (Mpa)	Temperature resistance (°C)
TS2050 (D205)	Cork/SBR blend. Suitable for all engine and gear oils and coolants.	830*	60-80	15-35	2*	-30°C to 90°C
TS4600 (GT46)	Cork/SBR blend. Suitable for all engine and gear oils.	>640	70*	25-45	>1.03*	-30°C to 110°C
TS1521	Cork/SBR blend. Suitable for most lubricant fluids.	550-750	50-70	35-50	>0.8	-30°C to 110°C
TS1400	Cork/NBR blend. Suitable for fuels, bio- fuels, oils, and coolants.	1100*	75-90	10-22	>3.5	-30°C to 125°C
TS7100	Cork/NBR blend. Suitable for fuels, biofuels, and oils.	900*	60-75	20-45	2.5*	-30°C to 110°C

Cork-rubber composites have many advantages, such as sustainability and using cork industry by-products, such as cork shavings and cut-offs, to produce high-quality aerospace products. Cork has exceptional temperature resistance, vibration dampening, and sealing properties. However, as a material, cork could be better at operating in a high-pressure environment. Therefore, it is generally

not used in hydraulic systems where operating pressures are over 3000 Psi [42]. The most common materials for hydraulic system sealing are still purely synthetic, like peroxide-cured Ethylene Propylene Diene Rubber (EPDM), fluorocarbon, or silicone [43].

4.3.3 Time-Tested Aerospace Applications

During the early era of the aviation industry, the first aircraft primarily had piston engines with propellers, and the standard material for engine and fuel system gaskets was cork (Figure 4.27). The technology of other synthetic materials was not advanced enough to replace it. As time passed, new materials started replacing the cork in gasket manufacturing. However, as the modern era industry moved towards sustainability and eco-friendliness, aerospace engineers turned their heads back to cork gaskets. This time is implementing the advanced technology of making cork composites with different materials, such as rubber or silicone, to produce the gasket with desired properties.



Figure 4.27 Cork gasket (left) and silicone gasket (right) [44], [45].

One more factor why the aviation industry uses so much cork for various systems is because the changes and implementation of new technology in aviation are much slower and more conservative when compared to the automotive industry. Even though the first engines used for automobiles and aircraft used mostly cork as gaskets, when new materials appeared, automotive engineers were much faster to implement the changes. Meanwhile, the aviation industry takes much more time to properly test and certify new technological designs. Therefore, there was no rush to replace something that was working fine. By the time synthetic sealing materials had evolved and had been tested thoroughly enough, the industry shifted to sustainable solutions. Therefore, aircraft continue to use these time-tested gaskets for oil and fuel systems.

4.4 Tests of Sandwich-Structured Composite Materials with Cork Fillers

4.4.1 Spectrum Analysis of Sandwich-Structured Composite Materials with Cork Fillers

The Purpose of Analysis: Find resonance points and evaluate/compare a dynamic (damping) property of different laminated cork materials (additional compare with laminated polymethacrylimide foam material).

Objects for Analysis: In the current analyses, four different objects (3 types of cork and 1 type of polymethacrylimide foam materials) were under investigation (Figure 4.28):



Figure 4.28 Objects of research (1-3: laminated cork material; 4: laminated polymethacrylimide foam materials). The dimensional of object 30x30x3 mm for 1-3 objects and ~ 25x30x3mm for object 4.

Analysis Type: the current analysis is based on the modal analysis. Modal analysis studies the dynamic properties of objects in the frequency domain. Modal analysis helps to determine the vibration characteristics (natural frequencies and mode shapes) of a mechanical structure or component, showing the movement of different parts of the structure under dynamic loading conditions, such as those due to the lateral force generated by the electrostatic actuators [43]. The natural frequencies and mode shapes are essential parameters in designing a structure for dynamic loading conditions [46].

The modal analysis is performed by a vibration FFT (Fast Fourier Transform) spectrum analysis. The key focus of this research is to find resonance and compare a damping property of an investigated object. There are several steps to follow as guidelines to help achieve a successful current analysis. The following is a general list of these steps:

1. Collect data from the measuring: velocity of object vibration under impact from the impulse (excluding low environment vibration). Conduct additional testing if further data is required.
2. Make an FFT spectrum analysis for each object for comparison.
3. Analyses spectral data – evaluate the overall values and specific frequencies corresponding to object material.
4. Reporting of obtained results and comparing damping properties of the objects.

4.4.2 Test Bench and Measurements Conditions

The present experimental measurements were conducted to establish the resonance points of research objects to compare their damping property. The measurements were performed via Two Sample Measurement Design and based on a One-Sample Statistical Method with Estimating Uncertainty in Repeated Measurements of data processing.

The test bench for the experimental research is shown in Figure 4.29. It includes a metal base with rubber protection from environment low-frequency influence, research objects, and a laser scanning system for measuring the vibration of object surface under Integrated Electronics Piezo-Electric (IEPE) impulse hammer impact signal.

The measuring tests include measuring objects' vibration and outer surface deformation (velocity/displacement) of objects from impact with an impulse hammer. The time of one measured by the PSV Sensor Head is firmly 4 seconds. During this time IEPE impulse hammer generate an impulse on a metal base with a force shown in Figure 4.30a, and velocity is measured by PSV Sensor Head on a metal base, shown in Figure 4.30b, during tests.

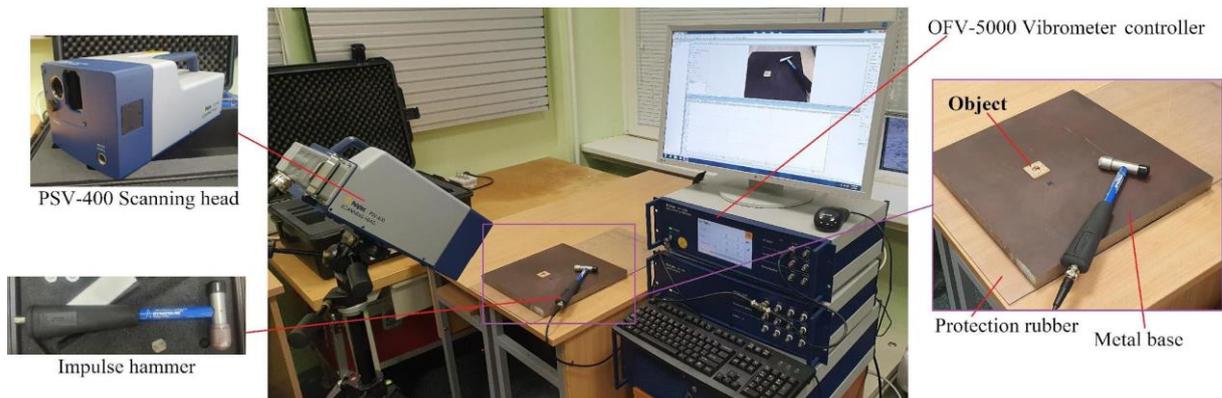
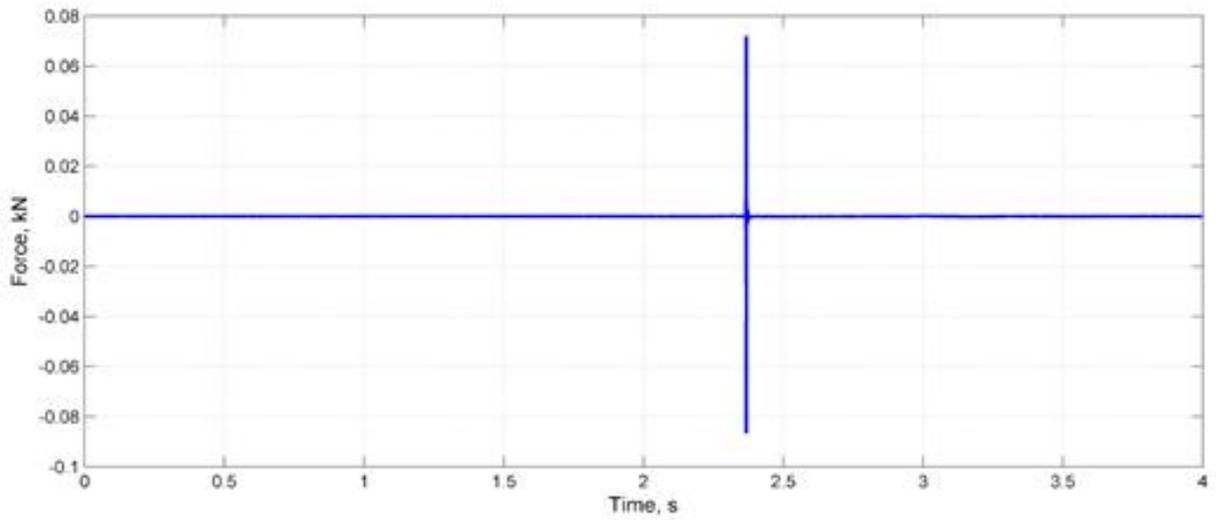


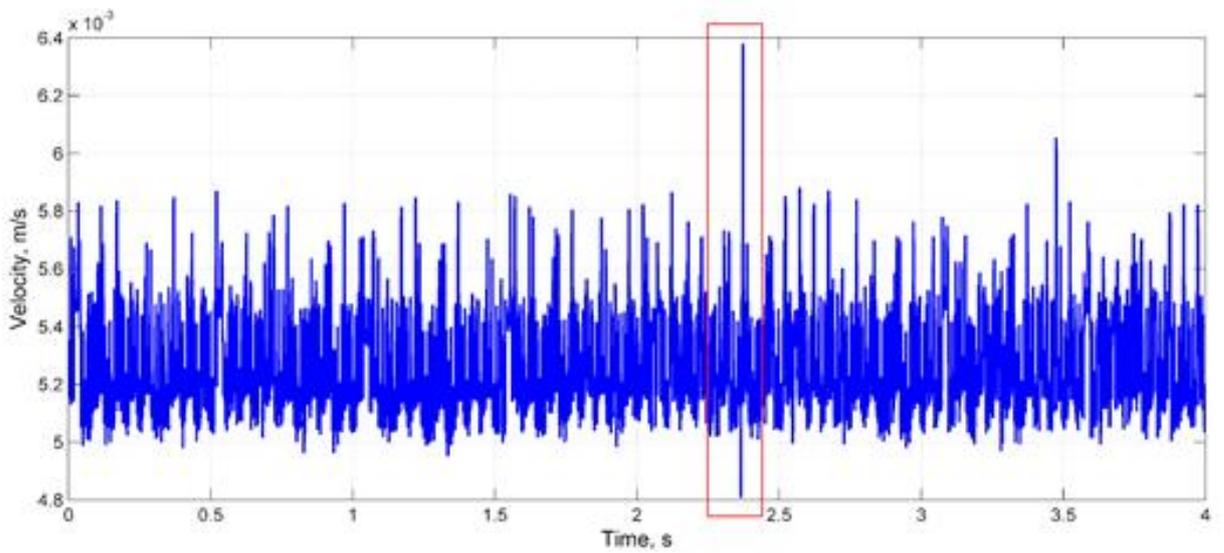
Figure 4.29 The test bench for measuring [47].

For decrease during measurements was accepted and presented averages of several measurements. The main result obtained from tests is the frequency response of materials based on spectrum analyses using the Doppler Effect to establish the resonance points better and compare a material damping property.

On the established objects was created a grid with 25 points created a close surface for measuring (Figure 4.31a). The points were scanned by a laser, and while measuring all time, a scan status was in Optimal conditions, which means that a grid of points and focus of laser is optimal for this type of reflective material. Additionally, the frequency domain includes a bandwidth 1.6 kHz with a step resolution 0.25Hz (Figure 4.31b).

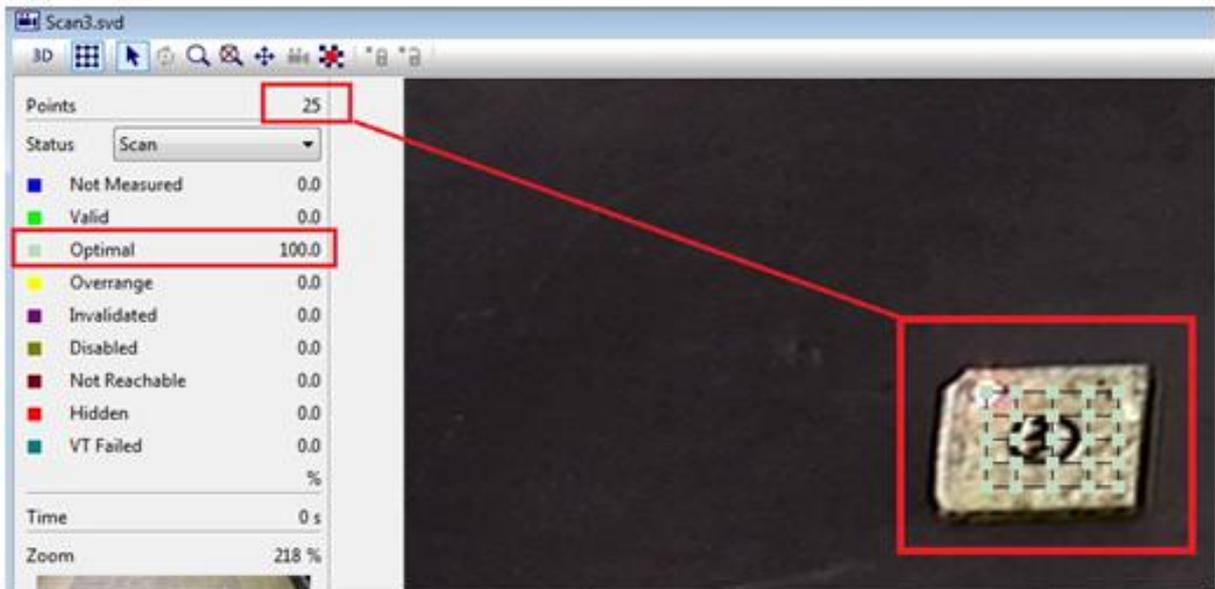


a)

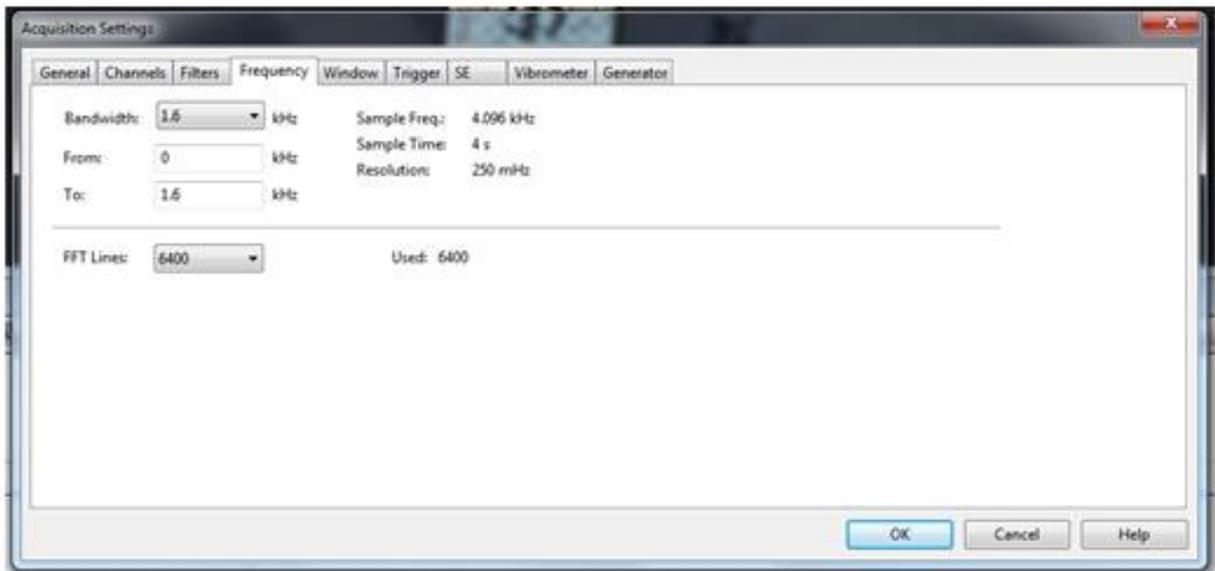


b)

Figure 4.30 Example from measuring: a) signal from IEPE impulse hammer; b) velocity measurement from PSV sensor head.



a)



b)

Figure 4.31 Setup of measuring: a) point of measuring; b) frequency condition.

This means that obtained results from spectrum analysis will be up to 1600Hz and displayed each 0.25Hz (Figure 4.32).

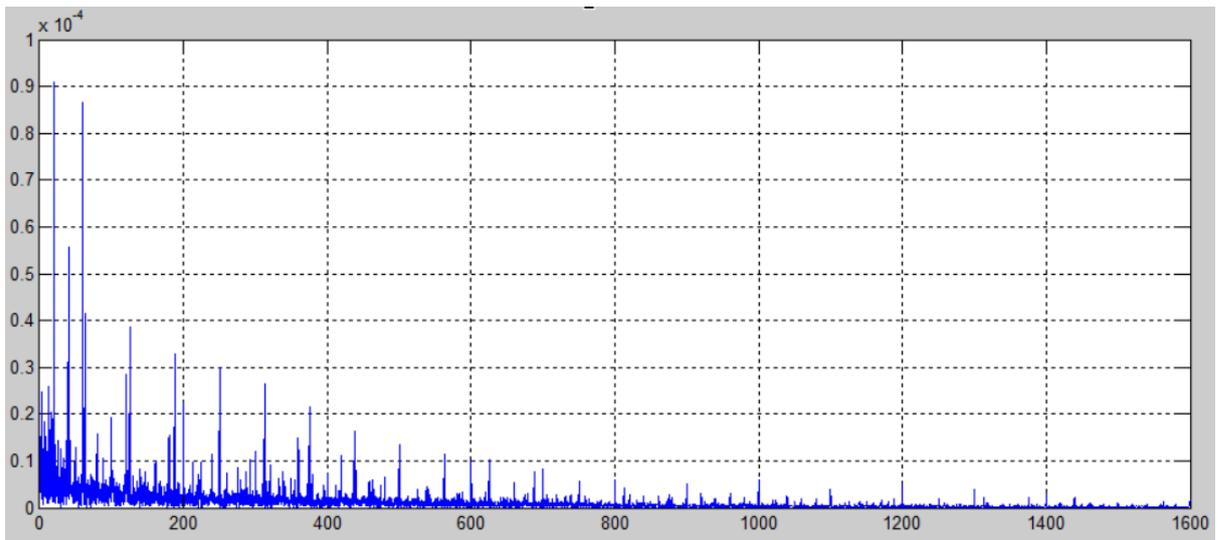


Figure 4.32 The obtained results from spectrum analysis.

The results of measuring by modal analysis are presented next (Figs. 4.33-4.37). However, the leading interest for analysis is the frequency range up to 500 Hz since the main resonant modes were observed in this frequency range. **Note: The frequency response graphs are presented in the velocity domain since, in this spectrum analysis, the resonance points are more visible than in acceleration and displacement graphs.*

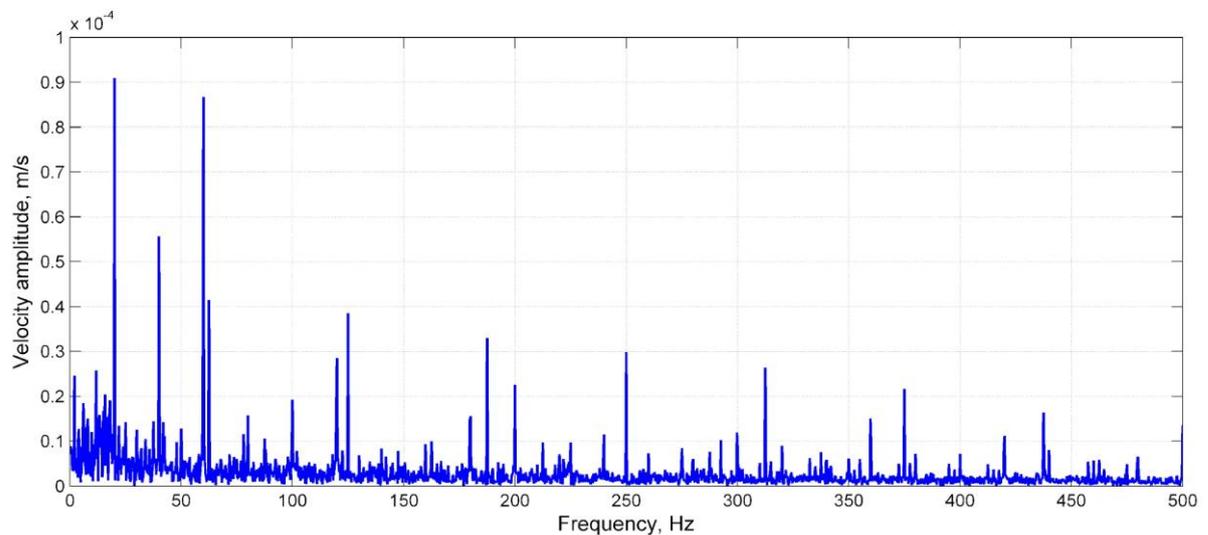


Figure 4.33 Graphs of spectrum analyses – frequency's response of the first object.

** Additionally, a video of shape mode on the first resonance point - 20Hz (+.gif) is presented in a separate file*

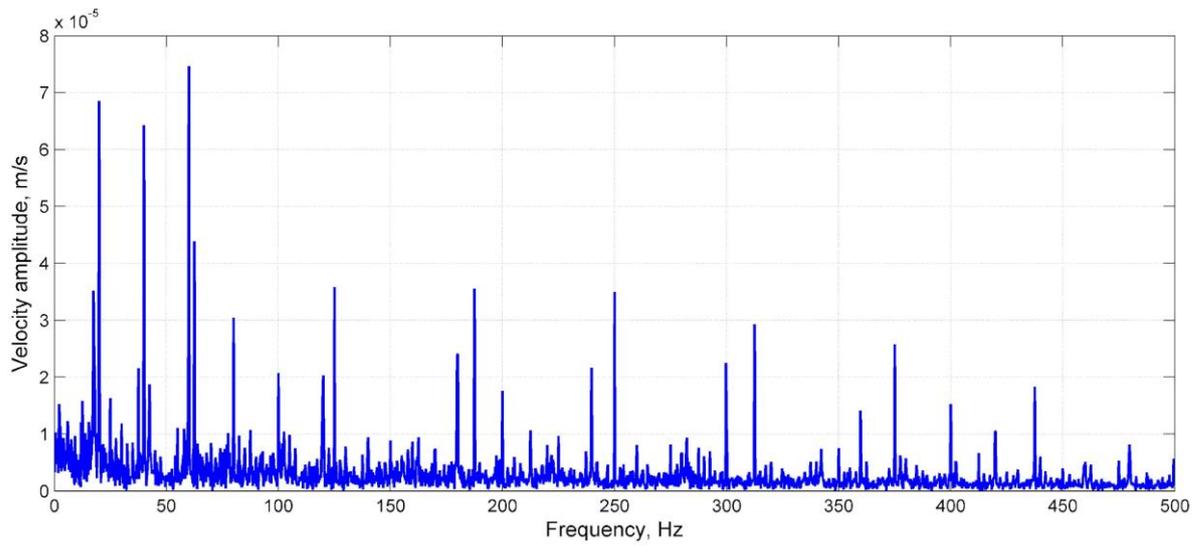


Figure 4.34 Graphs of spectrum analyses – frequency's response of the second object.

**Additionally, a video of shape mode on the first resonance point - 20Hz (+.gif) is presented in a separate file.*

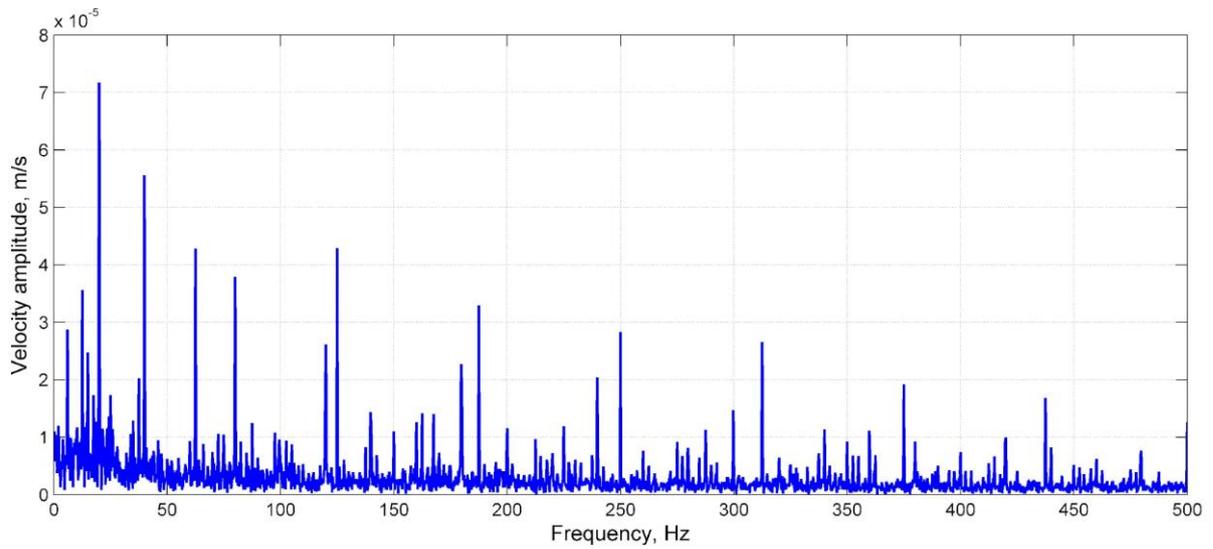


Figure 4.35. Graphs of spectrum analyses – frequency's response of the third object.

**Additionally, a video of shape mode on the first resonance point - 20Hz (+.gif) is presented in a separate file.*

4.4.3 First Analysis Conclusion

The first analysis includes a comparison of Cork materials frequency response (Figure 4.36):

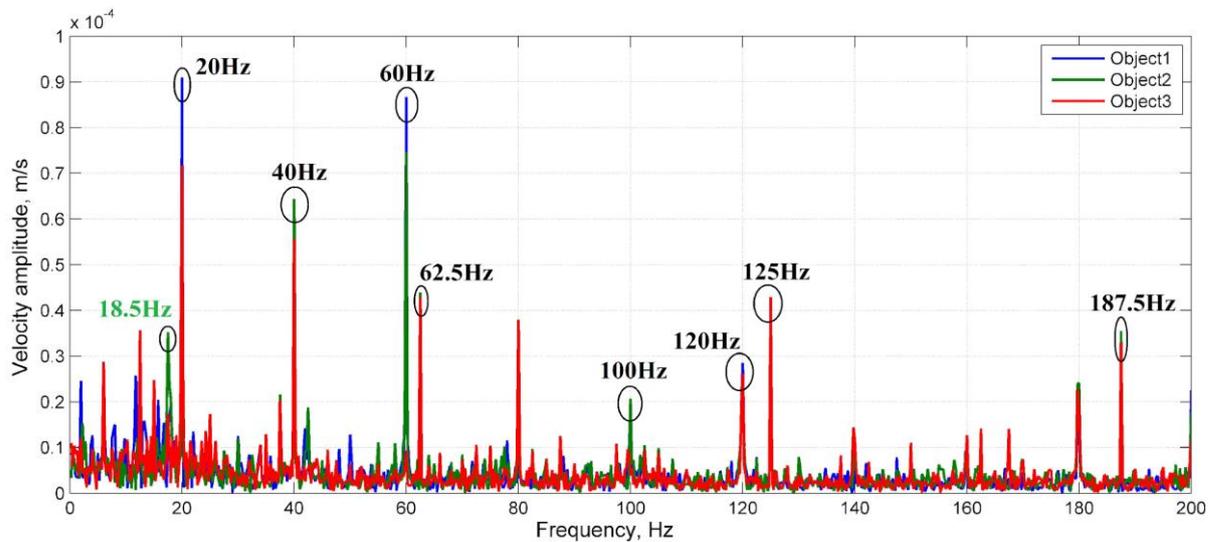


Figure 4.36 Comparing analysis: graphs of spectrum analyses – frequency's response of Cork material objects.

From frequency analysis comparing (Figure 4.36) seems that the central resonance frequency of laminated cork materials is in the low frequency (0 – 200 Hz) range and beginning of middle frequency (200 Hz – 500 Hz) range. It should be noted that in this frequency range can observe the main resonant modes. The comparison is presented up to 200Hz for better displaying of obtained results.

By frequency analysis, the main and first resonance frequency of investigated composite material equals 20 Hz with harmonic by each 20 Hz (20/40...80/100...etc. Hz). Also, it should be the pointed frequency in the low-frequency range of 62.5 Hz with the harmonic step that has continued going in the middle range frequency (125Hz...187Hz, etc.). The composite nature of laminated cork explains a second resonance frequency.

The comparison of damping properties of objects is provided in the example of the first resonance point 20 Hz:

In the current point, the 1st object vibrated with a velocity amplitude – $0.9 \cdot 10^{-4}$ m/s; 2nd object – $0.68 \cdot 10^{-5}$ m/s; 3rd object – $0.72 \cdot 10^{-5}$ m/s. That can lead to the first conclusion that object 2 has a better damping property than the two other objects of laminated cork.

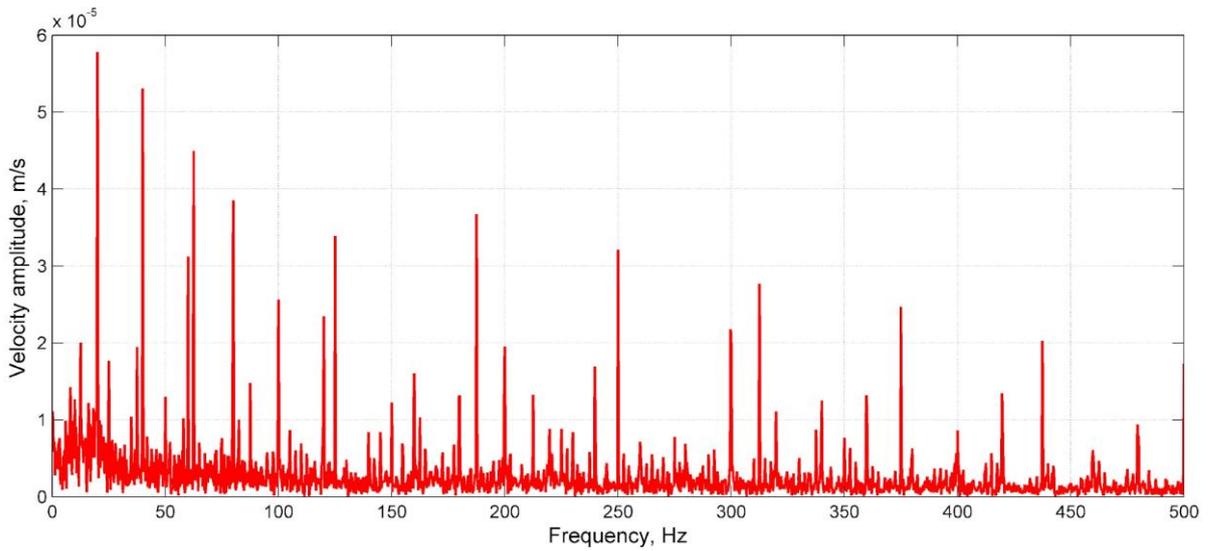


Figure 4.37 Graphs of spectrum analyses – frequency's response of the fourth object.

**Additionally, a video of shape mode on the first resonance point - 20Hz (+gif) is presented in a separate file.*

4.4.4 Second Analysis Conclusion

The second analysis includes a comparison of laminated cork (object 2) and polymethacrylimide (object 4) materials frequency response (object two was accepted for comparison since it shows the best damping property) (Figure 4.38):

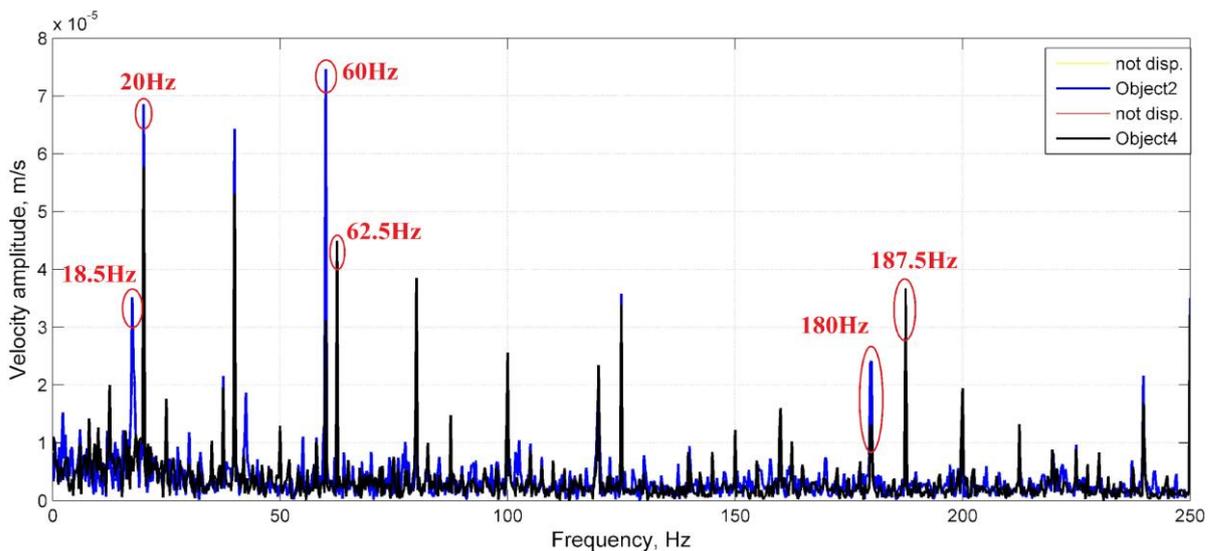


Figure 4.38 Comparing analysis: graphs of the spectrum – frequency's response of laminated cork and polymethacrylimide foam material.

From frequency analysis comparing (Figure 4.38) seem that the main resonance frequency of laminated cork and polymethacrylimide foam materials are almost the same and in the low frequency (0 – 200 Hz) range and beginning of middle frequency (200 Hz – 500 Hz) range. By frequency analysis, the main and first resonance frequency of investigated composite materials equals 20 Hz with harmonic by each 20 Hz (20/40...80/100...etc. Hz). Also, it should be the pointed frequency in the low-frequency range of 62.5 Hz with the harmonic step that has continued going in the middle range frequency (125Hz...187Hz, etc.). The lamination of cork and polymethacrylimide foam with the same material can explain the match of resonance points on the same frequency. The main difference, in this case, is that object 4 provides a better damping property on the main resonance points from ~16% to ~57%, depending on frequency.

The comparison of damping properties of objects is provided in the example of the first resonance point 20 Hz:

At the current point, the laminated cork vibrated with a velocity amplitude – of $0.68 \cdot 10^{-5}$ m/s and laminated polymethacrylimide foam – $0.57 \cdot 10^{-5}$ m/s (the difference in damping ~ 16%). Additionally, on frequency 60 Hz: laminated cork velocity amplitude – $0.74 \cdot 10^{-5}$ m/s and laminated polymethacrylimide foam – $0.32 \cdot 10^{-5}$ m/s (the difference in damping ~ 57%). The deformation velocity amplitude on frequencies 62.5 Hz, 125 Hz, etc., almost does not damp by polymethacrylimide foam (*at some point even higher). *The difference in the amplitude of materials confirmed that polymethacrylimide foam is better used for damping an impact impulse than cork material since the stiffness and deformation of objects are different. At the same time, the second object shows close characteristics for damping in a few resonance points, which can hold to conclude that laminated cork in some tasks can be used apart from laminated polymethacrylimide foam.*

4.5. Bending Tests of Cork-Based Sandwich-Structured Composites

4.5.1 Samples

Four test panels were manufactured to compare different bending characteristics of the sandwich-structured panels. Three of them used different cork-based composite fillers. The main characteristics are presented in Table 4.3. One of them contains polymethacrylimide foam filler. Its characteristics are shown in Table 4.4. All panels were coated on both sides with a uniform glass-plastic laminate with a thickness of 0.135 mm. The fiberglass used in it is *Interglas 91110*, its weight is 110 g/m², and the weaving type is herringbone. It is noteworthy that the panels were coated with weaving at the same angle on both sides. The fiberglass fabric was impregnated with a two-component epoxy resin, „Epoxy Resin L + Hardener L“, and was compressed to the surface of the panels by placing them in a sealed vacuum bag, where a vacuum of 820 mbar was applied. After 14 hours, the pressure in the bag was

equalized to the atmospheric, but the panels were removed only after 24 h. An image of laminated panels is presented in Figure 4.39.

Table 4.3 Characteristics of the cork-based composites.

Cork material plane No.	1	2	3
Cork granule size	2-5 mm	0.5-1 mm	2-5 mm
Granule bonding material	Polyurethane	Specialized polyurethane	Polyurethane
Density	186.1kg/m ³	165.3 kg/m ³	357.7kg/m ³
Tensile strength	≥500 kPa	≥400 kPa	≥400 kPa
Compressibility	10-25 %	30-50 %	5-25 %
The return to the initial position	≥70 %	≥75 %	≥70 %

Table 4.4 Characteristics of polymethacrylimide foam.

Material name	CASCELL 30 RS
Density	30 kg/ m ³
Compressive Resistance	400 kPa
Tensile Strength	800 kPa
Elastic Modulus	38 MPa
Bending stiffness	800 kPa
Shear resistance	400 kPa
Shear modulus	15 Mpa
Thermal resistance	≥200 °C



Figure 4.39 a) Sandwich-structured panels with different cork-based composite filler, b) A sandwich-structured panel with polymethacrylimide foam filler.



Figure 4.40 Prepared panels for the bending test. The red arrow indicates 0°, green 90°.

The surfaces of the laminated sandwich-structured panel with a cork-based composite filler have a higher surface roughness than those with polymethacrylimide foam filling. It is worth mentioning that the smaller the granules of a cork-based composite, the smoother the surface is.

Samples with dimensions: 40x75x3mm are cut from each panel. 16 sample panels were manufactured, i.e., 4 samples were obtained from each sandwich-structured panel. They were subjected to bending tests. It should also be noted that samples were prepared by turning the glass fiber 0-90° along the direction of the longest side of the sample. Their image is shown in Figure 4.40.

4.5.2 Conducting Bending Tests

Tensile and bending tests were carried out using a Tira test 2300 universal testing machine with digital test data logging. Catman expresses three software were used for data recording. A Three-point Bend Stand was used. The distance between the fixed bearings was set to 50mm. The bending press speed was 2-0.4 mm/min. The image is presented in Figure 4.41. The thickness and width of all samples were measured with a caliper.

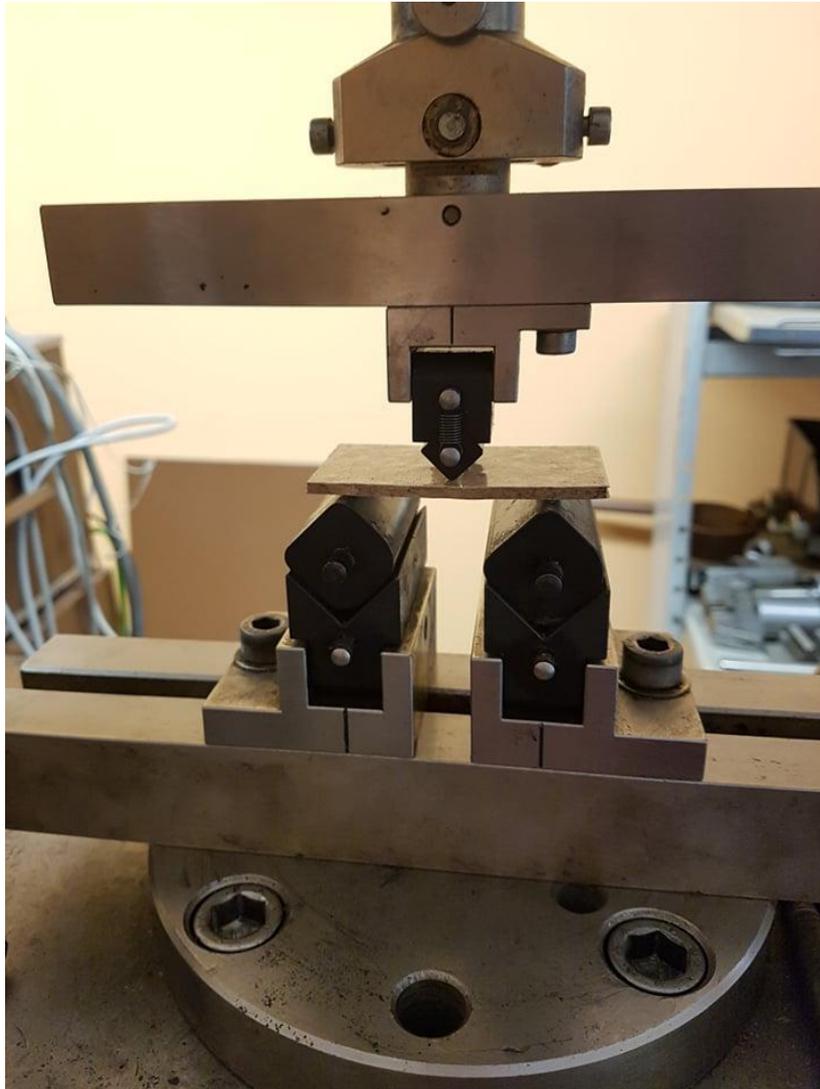


Figure 4.41. The bending test stand.

It is vital to prepare the system accordingly to obtain accurate results from the practice tests. Due to the uneven surface of the materials, it is necessary to indent the sample during the test. The samples are deformed by 0.3-0.4 mm until proportional* loading begins. The graph of the interdependence between the deflection and the tensile strength on sample 2_2 is presented in Figure 4.42.

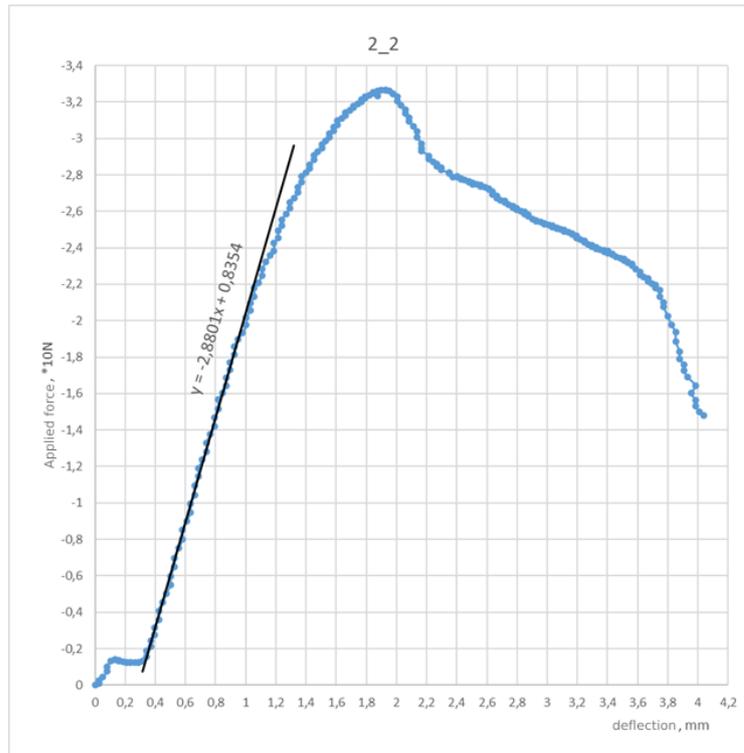


Figure 4.42 The interdependence between the deflection and the applied force on sample 2_2.

Within the limits of proportional loading, an approximating curve was drawn, and each sample's strength and modulus of elasticity were calculated.

The strength (σ) was calculated referring to the formula (Eq. 4.1):

$$\sigma = \frac{3FL}{2bh^2} \quad (4.1)$$

L - Bending force in Newtons; L - distance between fixed bearings in millimeters; b - sample width in millimeters; h - sample thickness in millimeters.

For elastic modulus calculations, deflections were calculated at the corresponding stress values $\varepsilon_{f1}=0.0005$ and $\varepsilon_{f2}=0.0025$ (Eq. 4.2).

$$s_i = \frac{\varepsilon_i L^2}{6h} \quad (i=1;2) \quad (4.2)$$

s_i - deflection in millimeters; ε_{fi} - corresponding stress values given above; L - the distance between fixed bearings in millimeters; h - sample thickness in millimeters.

Elastic modulus was calculated according to the formula (Eq. 4.3):

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - \varepsilon_1} \quad (4.3)$$

σ_1 - strength in MPa, at the bending point of s_1 ; σ_2 - strength in MPa, at the s_2 bending point.

4.5.3 Comparison of the Results and Analysis

Table 4.5 presents data collected during the testing. Also, it provides the calculated E_f of each sample (Figure 4.43).

Table 4.5 Table of the test data.

	h - total thickness	Laminate thickness	Filler thickness	b- width	l - distance	Fm	σ	E_f
	mm	mm	mm	mm	mm	N	MPa	MPa
01 01	2,96	0,135	2,69	40,3	50	60,88	12,93146	10,32732
01 02	2,9	0,135	2,63	40,1	50	59,52	13,23682	11,70209
01 03	2,91	0,135	2,64	40,3	50	57,95	12,73573	11,34853
01 04	2,91	0,135	2,64	40,2	50	56,99	12,5559	11,20888
02 01	2,91	0,135	2,64	40,3	50	31,65	6,95575	6,153586
02 02	2,87	0,135	2,6	40,1	50	32,65	7,413722	6,539743
02 03	2,97	0,135	2,7	40,6	50	33,01	6,913021	6,104861
02 04	2,9	0,135	2,63	40,4	50	31,57	6,968808	6,295767
03 01	3,28	0,135	3,01	40,4	50	91,65	15,81484	9,001601
03 03	3,22	0,135	2,95	40,2	50	76,95	13,84625	10,24622
03 04	3,37	0,135	3,1	40,9	50	82,25	13,28049	8,753336
03 05	3,2	0,135	2,93	40,8	50	83,13	14,9231	9,717874
04 01	2,82	0,135	2,55	40,2	50	27,43	6,435211	11,04473
04 02	2,89	0,135	2,62	40,2	50	27,47	6,136181	9,911932
04 03	2,65	0,135	2,38	40,1	50	26,18	6,972601	10,8347
04 04	2,73	0,135	2,46	40,1	50	26,06	6,539823	10,39721

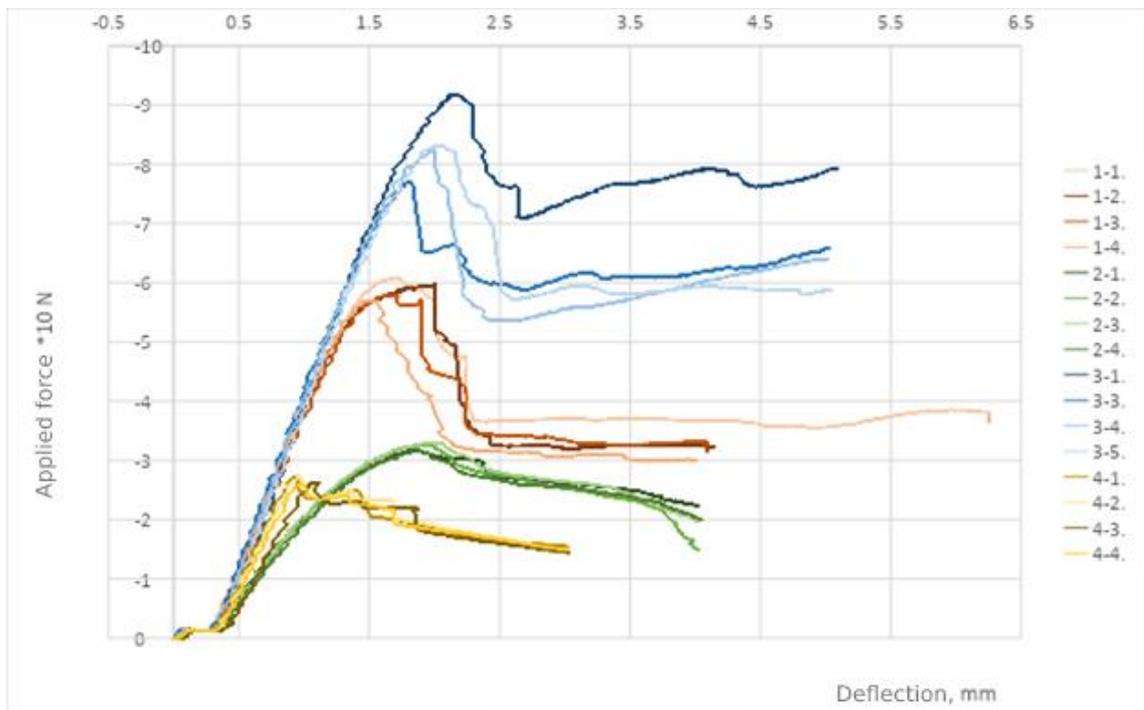


Figure 4.43. The calculated E_f of each sample.

As could be seen from the obtained results, the material with the highest strength rate was composed of the largest cork-based granules. The withstand force was three times higher than the composite material with polymethacrylimide foam filler. It is noteworthy that as the size of the cork-based granules decreased, the bending force withstood decreased too. The bending strength of the samples with the smallest granules was three times lower than that of the composites with the largest granules.

4.5.4 Tensile Tests

For the practical testing, the sample panels were cut off the laminated panels. The dimensions were selected according to the recommendations of the testing personnel (Figure 4.44). Sample shapes were cut from laminated panels using a milling machine (CNC).

The test was carried out using the tension stand. The main problem during the tests was sliding the plates in the grippers. Due to it, satisfactory results were not obtained. For the second test, in order to prevent the plates from slipping, a rubber plate was bonded with adhesive to the mounting points to increase adhesion.



Figure 4.44 Sample milling and dimensions.

4.5.5 Tensile Testing Results

As observed from the results given in the Table 4, the material with the highest tension rate was fabricated from granulated cork material. The tension rate was approx. 5 percent higher than the composite material with polymethacrylimide foam filler. The tension rate of the samples with the smallest granules was 20N lower compared to the ones with the largest ones. However, the bearing strength of the sample with medium-sized granules was about 10% lower than that of the sample with the largest granules.

Table 4.6 Table of the test data.

	a	b	S ₀	F _m	R _m
	mm	mm	mm ²	N	MPa
1_1	2.95	10.07	29,7	738,9	2,95
1_2	2.96	10.03	29.7	734.9	2.96
2_1	2.88	10.08	29.0	634.5	2.88
2_2	2.91	10.03	29.2	622.5	2.91
3_1	2.85	10.02	28.6	706.8	2.85
3_2	2.83	10.03	28.4	714.8	2.93
4_1	2.80	10.01	28.0	690.8	2.80
4_2	2.80	10.03	28.1	694.8	2.80

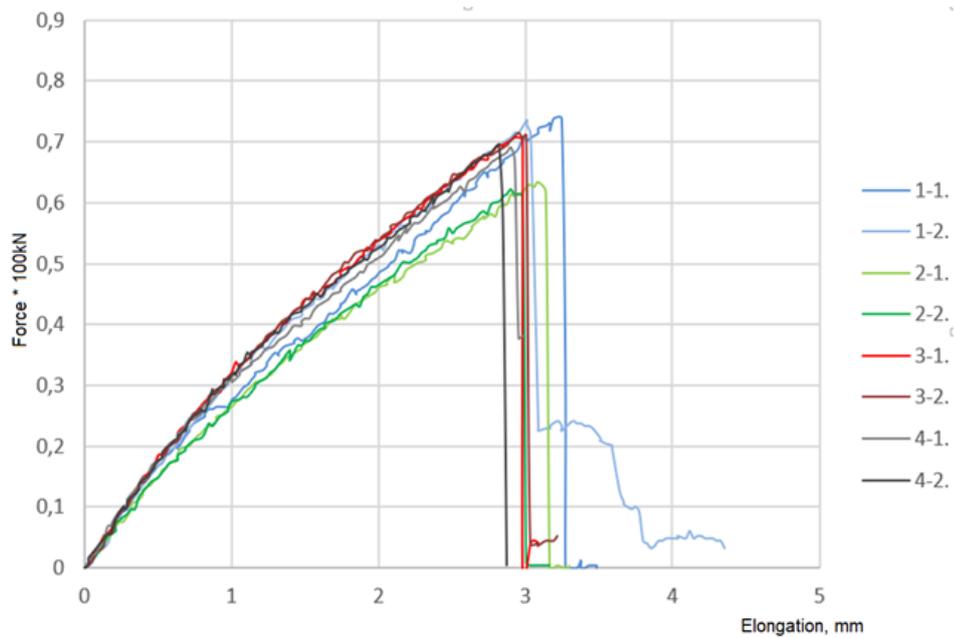


Figure 4.45 The interdependence between the elongation and the applied force on each sample.

Following the obtained tension results, the graphs showing the correlation between the elongation of the samples and the tensile force were drawn (Figure 4.45). It could be observed from the graphs that the tensile strength of different samples is similar (the results fluctuate within 10 percent boundaries) as it depends little on the filler material of a sandwich structure.

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CHAPTER 5

Aeronautical/Space Applications of Cork Composites

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Abstract

Cork is a naturally occurring, renewable, and long-lasting raw material that has been utilized for ages. The scholarly literature on cork is substantial due to this protracted interest. Most studies concentrate on cork's chemical structure, mechanical and physical capabilities, and products and sub-products. Starting with its growth, histology, and structure, the extensive attempts to thoroughly characterize cork and fresh advances and developing research are covered (at micro and macro scales). Next, cork's distinctive qualities are examined and compared to other materials used in similar industries. It has been attempted to describe why cork is better than other materials in various respects. The tensile strength, Young's modulus, and Poisson's ratios are addressed in various settings that are real-life applications while addressing their mechanical characteristics in this research. The mechanical and thermal characteristics of cork composites and their present utilization in aerospace applications are the topics of this review. Finally, a portion of the future use of these eco-friendly composites is discussed.

Keywords: Cork composites, eco-friendly, aerospace applications.

5.1 Introduction

Pursuing better natural materials with specific properties in engineering is vital for researchers. In different lines of engineering and design applications, one of the most well-known natural materials is cork, demonstrating the incredible potential to alter synthetic cellular materials. Moreover, the modern world has witnessed purchasers' awareness, governmental policies, and "eco-friendly" trends that require manufacturers to ensure recyclable variants to market solutions. In the 16th century, cork was one of the first materials discovered and investigated by Robert Hooke. He drew the slices of cork thanks to the microscope. The results of the research were published in 1665. As mentioned in the research, tiny structures in the cork material are named cells. The cell comes from Latin, and its meaning is a small

room. In Figure 5.1, Hooke's drawing can be seen. For that period of time, this drawing can provide us with information about lots of topological characteristics of cork cells. Cork has been used by humans for over 5000 years as a natural, renewable, and sustainable raw resource. Humanity uses cork materials for their daily-based needs throughout the world, such as sealing containers, fishing tools, and sandals. Modern usage as a cork-stopper shows up to life thanks to the Benedictine monk Dom Perignon in the first part of the 17th century. Up-to-date enhancement in cork research has been altered from the form of cork-wine relation to high-capacity, nature thinking, enforcing of cork industry remnants, and composites. In the 21st century, it is used for various implementations, not only as a cork-stopper but also as aerospace materials, thanks to composites used for floor, wall coverings, and various industrial applications, carving out a significant part of cork materials. Also, it is a versatile building material with properties such as lightness, elasticity, and resilience, as well as impermeability, insulation, wear resistance, fire retardant qualities, hypoallergenic properties, and durability that set it apart from wood and stone [1].

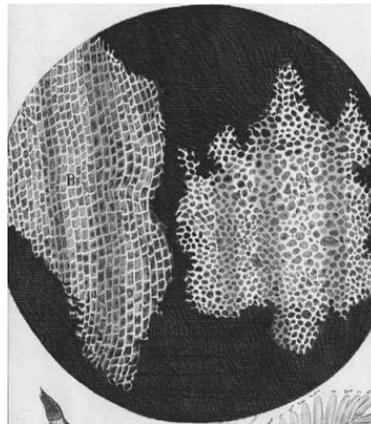


Figure 5.1 Drawing of a cork cell from a microscopic perspective [2].

The rigid part which provides crucial abilities to the cork is contained in the faces of every prismatic stage. These prismatic stages are called a cell, and the biosynthetic displacement of a polymer combines them. Besides, the form of the cell's solid materials is not homogenous. This type of ultrastructure manifests itself at the below-microscopic level due to the composition of chemical components and the arrangement of those components in space, in addition to the biological development process involved. The cell structure of the cork is unique. Foamed plastics have smaller and thinner cells than cork. An ideal average cell would have the following dimensions: 40 μm of prism height, 20 μm of base edge, 1 μm of cell wall thickness, two to three corrugations per prism lateral face, a wavelength of 15 meters, and an amplitude of 5–6 μm . Cork's cell walls are flexible to a large degree and will corrugate or undulate under compression to a variable degree. In addition, compared to the early cork cells, the thick-walled, short late cork cells are far more solid and strengthful. In Figure 5.2, the structure of virgin cork is demonstrated.

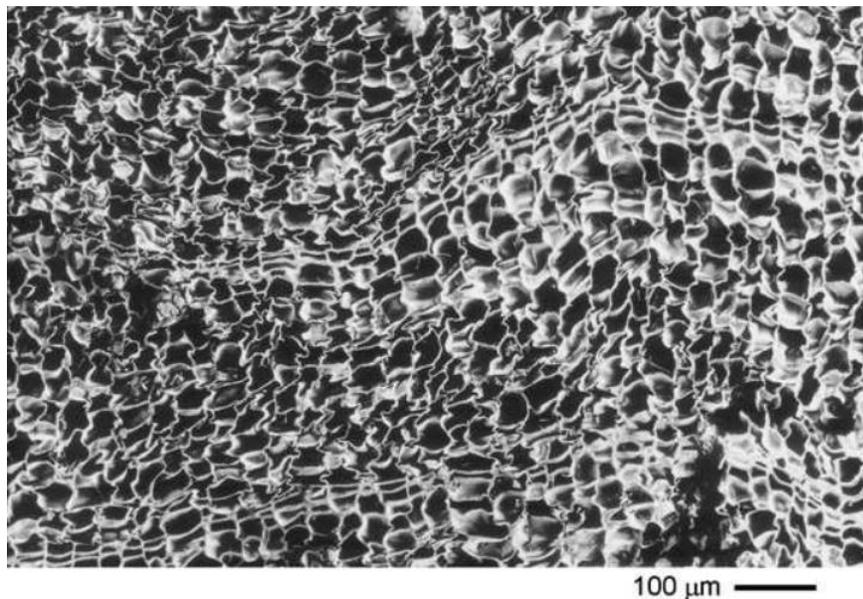


Figure 5.2 The structure of virgin cork [1].

The various implementations of cork materials are investigated by different researchers. The mechanical response of agglomerated cork in diverse situations was the topic of Jardin et al. [3] and Santos et al. [4]. In addition, they researched dependence characterization, such as density, binder type, and grain size of expanded cork material. Costas et al. [5] analyzed the cork composite as a frontal car hybrid impact absorber component. As well as absorber production, agglomerated cork was used for shaping side-impact reducers on-road vehicles to ensure safety. The research was led by Tay et al. [6]. Sanchez-Saez et al. [7] studied the ballistic impacts of the core structures made by cork.

The bark of an oak tree is used to produce cork, which is a tree-based substance. It has been harvested from the outermost layer of the bole of the trees, from which it is removed in an undamaged way from trees, and this happens every 9-12 years when the producer is sure that the layer reaches the required width. The bark is collected by qualified personnel, allowing the tree to grow another layer of outer bark that can be collected in the future. Therefore, cork may be collected 17 times during a cork oak tree's life, lasting 200 years. Cork is not just a natural resource but also a recyclable and renewable material. In other words, it is a totally "green" material with a negative carbon footprint because of its production period, which is carried during the tree's life cycle. 2.1 million hectares are covered with cork oak trees in Portugal, the home of one-third of all oak tree capacities worldwide. The sessional production of cork oaks in Spain and Portugal is approximately 30.5% and 49.6% of the total raw materials for the former and latter, respectively. For this reason, cork is the raw material for the integrated industrial chains that are of great economic significance to these countries.

The proportion of the solid volume of cork is approximately 15% of its volume in total in terms of its closed-cell property. In addition, the solid volume ratio is smaller than the gas volume. Another pivotal facet is the production of agglomerated cork. Cork grains are mixed with polyurethane thermosetting resins to form agglomerated cork. Pressure, heat, and the binder play a significant role in determining the material's properties. Once the granules have agglutinated, the mixture is squeezed and heated to temperatures between 110°C and 150°C. Extreme changes in the mechanical reaction under compressive loads arise depending on the type and quantity of the composite [4]. It is widely known that agglomerate has been tested for mechanical, thermal, and acoustic properties in cork-stopper production.

The application of cork material to other sectors continues to expand. In order to utilize cork-based composites in the aerospace sector, particular properties must be considered regarding their performance under extreme temperatures [8]. Cork's poor heat conductivity and high compressive strength make it an ideal material for thermal insulators in rockets, recording studios, acoustic insulation in submarines, combustion engines, and energy-absorbing floor plates.

This paper is split into four sections. The general characteristics of cork composites are examined in the second section of this study. The mechanical and thermal characteristics of cork material are explained. Following that, the third section explains the current uses of cork composites in the aerospace industry with examples. Finally, potential applications of cork materials are discussed in terms of aerospace applications. The conclusion is given at the end of the section.

5.2 General Properties of Cork Composites

Cork composites are obtained by processing the cork product with various methods. In general, they are structurally similar to composites already used in engineering. The properties of the composite structure depend on the way the composite material comes together and the properties and concentrations of the layers and materials that make up the composite. In this context, cork composites have properties such as lightness, heat and sound insulation, and impact-damping that cork materials have.

For utilization in different sectors, cork composites are manufactured thanks to various methods to obtain different physical and mechanical properties. These methods differ depending on how the cork material is processed and how the composite structure is put together. Composite materials can be roughly diversified for their product types and joining methods according to general usage. In terms of the production process, cork materials could be diversified as grounded, broken, and pressed. Furthermore, materials are named based on their joining methods, such as a sandwich, multi-layered, or agglutinative.

Since cork composites are similar to the physical and mechanical properties of cork in terms of general properties, the advantages of using cork composites are directly related to the properties of cork material.

Therefore, the advantages offered by cork composites are evaluated according to the application area. In this section, the mechanical and thermal characteristics of the cork composites will be evaluated and investigated from different sides [9].

5.2.1 Mechanical/Physical Properties

Cork possesses extraordinary properties, such as low conductivity, extreme compressibility, low density, relatively low permeability to liquids and gases, chemical stability, and durability. In addition, cork is anisotropic in terms of the orientation of its cells, so the properties show differences between measurements along with radial directions (R, coincident to the prism radial axis) and non-radial directions (N.R., perpendicular plane). Nevertheless, the anisotropy ratios of the shape are small, and the properties related to that are much less than other materials. Several mechanical properties have been observed in cork material. In Table 5.1, some of the crucial properties of the cork material are presented.

The compression curve is represented on a graph in three portions (Figure 5.3). Each portion is linked to one of three mechanisms that control the properties of flexible cellular materials [10],[11]. The first area, which demonstrates elastic bending of the cell walls, is up to 7% strain. Secondly, a horizontal plateau covers about 70% of the strain. Finally, due to the gradual buckling of cell walls, the crushing of cell walls, and the complete decadence of the cells, the curve begins to climb vertically [10],[11].

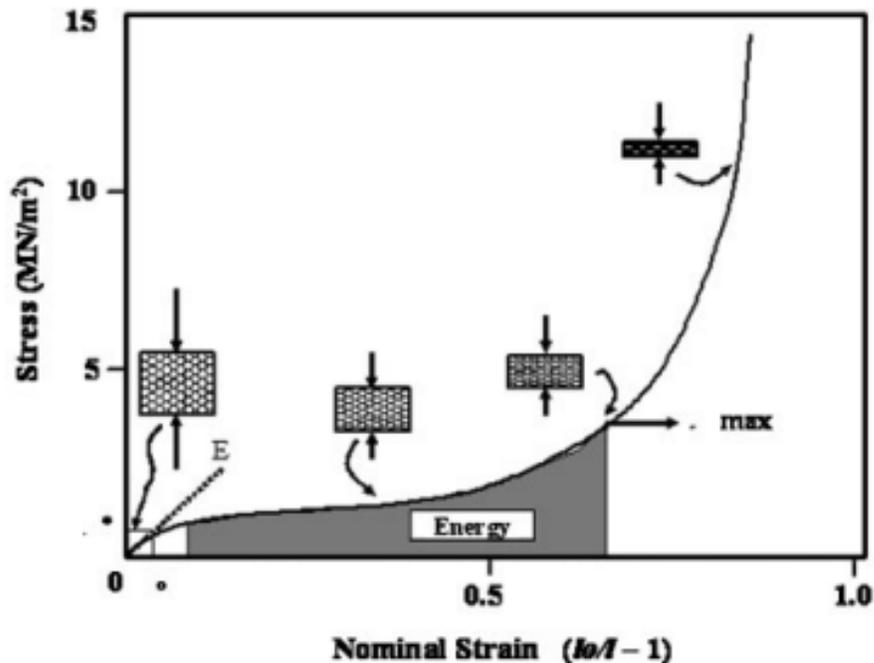


Figure 5.3 Compression curve of cork composite [16].

Table 5.1 Mechanical characteristics of cork.

Reference	Mechanical Property	Value
Gibson et al. [10]	Fracture strain under tension, %	5 (R) 9 (N.R.)
Gibson et al. [10]	Fracture stress under tension, MPa	1.0 (R) 1.1 (N.R.)
Rosa and Fortes [11]	Fracture toughness, boiled, MPa $m^{3/2}$	60–130
Gibson et al. [10], Fortes and Nogueira [12]	Poisson's ratio, boiled	0–0.097 ($v_{R/N \cdot R}$) 0–0.064 ($v_{NR/R}$) 0.26–0.5 ($v_{NR/N \cdot R}$)
Rosa et al. [13]	Young's modulus, boiled, MPa	6 (R) 8–9 (N.R.)
Rosa and Pereira [14]	Young's modulus, heat-treated at 150 °C, MPa	15 (R) 14 (N.R.)
Rosa and Fortes [11]	Tensile modulus, boiled, MPa	38 (R) 24–26
Gibson et al. [10]	Collapse (buckling) strain, %	4 (R) 6 (N.R.)
Gibson et al. [10], Vaz and Fortes [15]	Collapse (buckling) stress, boiled, MPa	0.75–0.8 (R) 0.6–0.7 (N.R.)

When a high compression level occurs with large deformations in the material, after relieving stress, recovery starts substantially. It is known that density impacts the compression properties of cork in a significant way. The compressive strength of cork in various directions is not very high. However, the mechanical strength is higher in the radial direction [16], [17], [18].

As was mentioned before, the staggered and random arrangement of cells, as well as the corrugation that occurs in lateral cell walls, have impacted the Poisson's coefficient, which can alter the variable properties of cork in diverse applications of it [12], [18]. When the material is crushed in a radial direction,

corrugations force cell walls to fold and pack, increasing corrugation amplitude and aligning cell bases in the radial direction. When compression aligns in the N.R. direction, the lateral cells bend, straighten, and reverse the undulation pattern at high strains, resulting in change withdrawals in the R direction and a negative Poisson's ratio at high strains [12]. It is known that cork plates have different thicknesses due to their growing environment. The thickness significantly impacts mechanical properties [19],[20]. For example, larger diameters reduce compressive strength and modulus in the pressing process.

Cork's alveolar cellular form is similar to that of a honeycomb. Therefore, the cells of cork consist of suberin, cellulose, and lignin. Because of their cellular structure, cork-based materials have excellent mechanical properties [21]. Pereira et al. [22] conducted experiments and provided data about the mechanical properties of natural cork. The compressive strength and specific modulus of natural cork are higher than flexible polymer foams and other rigid foams. In addition, when the compressive strength and low heat conductivity are combined, the material turns into excellent forms. This eco-friendly material shows perfect capability against thermal waves and compressive loads.

The permeability of cork material to non-condensable gasses like helium is not high [23],[24]. The cork has a low heat transfer rate because of the enormous air occurrence and small cell dimensions. Several ways provide heat transfer through material, such as gas convection, radiation, or conduction through the solid fraction. In cork composites, the barrier for the gas convention is formed by small and closed cells, and radiation is depleted by absorption in the numerous cells. For sound transmission, absorption is high since the acoustic resistivity is $1.2 \times 10^5 \text{ kg m}^{-2} \text{ s}^{-1}$ (Table 5.2) [1],[16].

It is related to surface characteristics, although cork is a hydrophobic material with low wettability toward polar liquids like water. Namely, for non-polar liquids, it demonstrates a high affinity with a surface energy of 18 mN m^{-1} [25].

Over the last decade, to determine the properties and characterization of cork, several projects have been carried out by researchers. There are some models to understand the mechanical properties of cork in terms of data mining and machine learning techniques when the material is under compressive loading [26]. The first and foremost experiments were carried out in the last century by various studies [27]-[31].

When comparing cork with other materials, on the one hand, natural cork has poorer mechanical properties than various core materials like synthetic foams. On the other hand, due to some specific characteristics and applications, cork can overcome other materials. While comparing the specific compressive strength (σ_c/ρ) and the specific modulus (E/ρ), cork has better mechanical behavior than flexible polymer foams. In addition, its low thermal conductivity merges with its compressive strength. As a result, the ingredient for thermal protection is obtained. This material could also be appropriate for places with compressive loads [32]. In Table 2, the general characterization of cork is demonstrated.

Table 5.2 General properties of cork materials.

Reference	General properties	Value
Medeiros [33]	Acoustic resistivity ($\text{kg}/\text{m}^2.\text{s}$)	1.2×10^5
Fortes and Nogueira [12]	Electrical conductivity (S/m)	1.2×10^{-10} (25 °C) 1.6×10^{-13} (50 °C)
Vaz and Fortes [15]	Friction coefficient (cork/cork), boiled	0.97 (R) 0.77 (N.R.)

Castro et al. [32] researched the possible way of producing a new agglomerated cork composite with different granule sizes and compared it with commercially available materials. Three different varieties of cork composited from varying sizes of granules and epoxy resin were manufactured to improve the strength. Granule sizes are as follows; small granule size (2/3), blended (mixture of small and big granules), and large granule size (3/4). The main issue is the method's difficulty in terms of agglomeration amount and epoxy resin ratio. However, when the desired ingredients are combined, ideal results can be achieved. Consequently, after several tries depending on the number of granules, the accurate resin rate was determined to be between 24% to 30%. The provisioning process begins with a cork granulate combination, and the resin rates are listed in Table 5.3. Next, various materials were molded and covered with steel sheets before being pressed. The last stage is placing the molded mix in an oven at a constant temperature of 80°C for roughly 2 hours and then waiting for the curing level to reach the desired value.

According to Castro et al. [32], a three-point bending test demonstrated that the granule size does not impact the face bending and shear stress. According to the test result, cork-epoxy composites show crucially better core shear stress, decreasing the spreading fracture area. As a result of this feature, cork agglomerates could be placed on top of various sandwich constructions. Impact test results revealed that cork sandwich composites could withstand high loads. Furthermore, the recovery capacity of cork-based sandwiches is unaffected by granule size or fabrication method. When comparing cork-based composites to ultra-performance foams, modified cork agglomerates-based sandwich composites have a higher absorption capacity and a lower damage threshold.

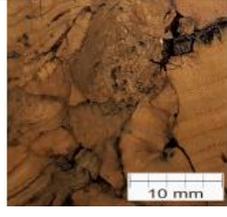
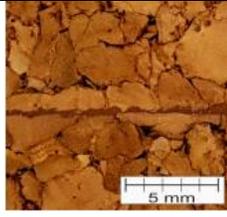
Table 5.3 Cork agglomerates preparation factors.

Cork agglomerate type	Resin percentage by weight	Agglomeration pressure [bar]	Cork granule mass [g]	Cure process
Small (2/3)	24%	50	270	2 hours (at 80°C)
Large (3/4)	24%	60	270	2 hours (at 80°C)
Blended (mixed)	30%	15	150	2 hours (at 80°C)

5.2.1.1 Temperature-Related Changes in Mechanical Properties

Kaczynski et al. [33] studied the alteration of mechanical properties according to temperature changes. Several cork composites were used to examine mechanical properties in different conditions in these tests (Table 5.4). Also, the dependence of material on the temperature of adjusting, the furnace, and a nitrogen cooling connector was analyzed experimentally. The cork pieces were heated up to 100°C, and with the help of nitrogen, the temperature was reduced to -30°C. The initial impact velocity was 9.2 m/s, and Instron Dynatup 9250HV was used for the drop tests. The tests were carried out using three samples from each cork type. The diameter of the impactor is 50 mm, and the total weight is equal to 11.2 kg. All the samples have a 50 mm × 50 mm cross-sectional area and 60 mm height. Drop tests were recorded with a Phantom V12 camera which possesses a 10 000 fps frame rate of 40 μs for minus-zero temperatures and 50 μs according to high temperatures.

Table 5.4 Material characterization and impact energy values of cork materials with respect to different temperatures [33].

Cork Name Grain size [mm] Density [kg/m ³]	Impact Energy [J]	Temperature [°C]	Section
AC199A 199 0.5–2	100	24	
AC216 216 2-4	100 500	For 100 J: 24 For 500 J: -30; -15; 0; 24; 100	
EC159_AC199A n.a. n.a.	100	24	
EC159 159 4-10	100 500	For 100 J: 24 For 500 J: -30; -15; 0; 24; 100	
EC159_AC216 n.a. n.a.	100	24	
EC159_AC216 n.a. n.a.	100	24	

Furthermore, Kaczynski et al. [33] conducted a study to understand the interaction between temperature, compression, and cork cell characteristics. All movement of samples linked to the influence of compression was captured and analyzed using the high-speed camera. It was predicted that cork cell walls would bow and potentially collapse during the compression stage. The samples were crushed at temperatures ranging from -30°C to 100°C . During the testing process, cracks were visible at all compression degrees except -30°C . According to the test findings, the crashworthiness of the cork is directly dependent on temperature. Consequently, they claimed that increasing the temperature from -30°C to 100°C reduced energy absorption by less than 25%. Therefore, cork materials in safe places or in the aerospace sector need to be adjusted to the environmental conditions. Cork composites' energy-absorbing and temperature-altering properties are linearly related, allowing producers to ensure safety through suitable data computations. Another important aspect is the impact of grain size on energy in different cork materials. The findings show that grain size has a substantial effect on cork crashworthiness. The reason is polyurethane glue, which is a binding technique. According to the authors, the number of glue changes with grain size. As the temperature is raised to 100°C , the viscosity of the cork increases, causing the substance to lose its adhesive properties. Furthermore, grain separation occurs at the microstructural level because of this. Therefore, if the grain size is large, the dangers are worth noting as the temperature rises. Temperature is the most influential variable that significantly impacts the mechanical characteristics of cork under dynamic stress. As a result, these findings demonstrate that evaluating cork material in various compression and temperature conditions before using it in manufacturing is a critical step. Regarding its mechanical behavior, there is a study about the impacts of temperature alteration upon agglomerate's energy intervals between 120 J and 850 J at $21- 50^{\circ}\text{C}$ [31], [34], [35].

5.3 Current Cork Utilizations in Aeronautical/Space Applications

The material properties of cork and the fact that cork composites can be produced with the desired methods make this product group suitable for use in aviation and especially the aerospace industry. Cork composites are used primarily in applications that are exposed to relatively low loads and where properties such as heat or vibration insulation, impact damping, lightness, and impermeability are sought. The utilization of cork material in the automotive and industrial sectors is well known. The use of cork composites in the aerospace industry has diversified over the years and will evolve into more different areas with ongoing studies. The most intensive engineering use of the cork material group is the coating of the body and various parts of spacecraft for thermal insulation purposes. Multiple projects have been made and are being carried out to use cork materials in aircraft bodies and other areas of aviation. For

instance, the protective heat shields of some missiles and space shuttles are made of cork. Furthermore, in terms of the fire-retardant ability of cork, it is used in warships and the internal lining of submarines [36].

Components of aerospace systems are typically designed for low weight, high strength, and increased damage tolerance. It is possible to achieve these characteristics by choosing materials correctly. Recent advances have put sandwich-based materials at the top of the list of candidate materials for aeronautical applications. Furthermore, sandwich components, such as flexural, compression, and impact components, have higher stiffness and perform better under the specified loading conditions. Polymer-based fiber-reinforced composites are common materials used to make sandwich components, and they are coupled with different types of low-density core materials, typically balsa wood, honeycombs, and polymeric foams. As expected, core materials are primarily chosen for their low density, high modulus of elasticity, massive strength perpendicular to the faces, and good thermal and acoustic insulation ability. In this case, as a natural material, cork fulfills these requirements due to its intrinsic cellular morphology, suggesting that cork-based agglomerates can be considered an alternative material option. Clearly, a cork cell's strength is comparable to some synthetic foams, and the cork's specific strength is much higher. Furthermore, it has low thermal conductivity as well as a reasonable compressive strength, making it an excellent choice for thermal insulation and for applications with compression loads. Also, cork has been used for a long time in components that are subjected to dynamic loads since its exceptional damping properties make it ideal for vibration suppression. To sum up, regarding many properties, cork sandwich materials are highly convenient for use in the production of the fields of aerospace and aeronautical sectors [8].

Cork-based material is an appropriate sandwich component and core material for lightweight structures. This material is used in aerospace applications [37]. When comparing sandwich composites with high-performance foams, composites certainly have a larger energy absorption capacity and superior crashworthiness features when loading occurs. In addition, cork agglomerates show better thermal properties, which is a significant way of designing structures.

The utilization of cork material in the automotive and industrial sectors is well known. Also, the aeronautic and military industries are significant users of it. For instance, the protective heat shields of some missiles and space shuttles are made of cork. Furthermore, in terms of the fire-retardant ability of cork, it is used in warships and the internal lining of submarines [36].

At first glance, when compared to alternative core materials, such as synthetic foams, it can be demonstrated that natural cork has weak mechanical behavior. However, its thermal conductivity and compressive strength make it an ideal material for heat retention. Composite sandwich panels gained prominence in aeronautical design because of their resistance to buckling, just like aluminum alloy sheets.

A sandwich wall patent by von Karman and Stock in 1924 is a prime example of sandwich construction being applied to aeronautical construction. In 1934, at the Schneider-Creusot factory in Le Creusot, France, S. E. Mautner applied sandwich structures to an existing airplane for the first time. In 1938, the same engineer made a low-cost mono-wing plane that featured a sandwich wing with a ply-cork sandwich structure. There has been extensive use of cork composites in the space industry since weight reduction plays an even more crucial role within the space context, which yields significant cost savings. Additionally, ablative materials are one of the most common uses for cork agglomerates. Material that produces ablation dissipates energy via vaporization instead of heat absorption. As a result, it protects structures from high thermal energy sources.

Sandwich composites in different designs are utilized for the construction of constituent materials, such as face sheets, cores, and adhesives, for quasi-static and dynamic loading scenarios. When the priority usage of sandwich composites is considered, their susceptibility to foreign object damage is first for preferability. In several instances, the performance of structural sandwich sections under impact loads has been observed. Local interactions with tiny but potentially heavy things, such as tool drops, bird hits, stones, or ice, can cause aircraft or planes to be damaged during the loading and unloading of goods. In addition, horizontal surfaces, such as airplane floors, can be damaged easily [38],[39].

There are two types of cork agglomerates: insulation and composition corks. The former is produced without any additional binding tools or materials; therefore, it could not be named a composite material. The latter is made from granules that have been combined with various synthetic or natural binders, such as urethane, phenolic resins, etc.

When doing a brief investigation into the use of cork composites in the aerospace sector, Amorim Cork Composites (ACC) Company has several products. The company has produced two cork composites (P45 and P50) that may be used as protective shields in various sectors. Different characterizations of these types are provided in Table 5.5.

5.3.1 Structural Components with Cork in Space Applications

The aerospace sector makes the most extensive use of cork materials and composites in the bodies and components of spacecraft (Figure 5.4). Cork materials have been used extensively in spacecraft from the early days of space exploration. Cork composites are being used in high-temperature propulsion systems of spacecraft, as well as sections such as fuel tanks that require thermal insulation. Apart from providing thermal insulation, cork is also used as a protective layer in the case of a sudden temperature change because it is less expensive than high-tech materials. Because cork burns without flame or ignition, it will be the first layer to burn at high temperatures, protecting the spacecraft's main body and parts from fire.

Table 5.5 Some characteristics of P45 and P50 cork composites.

Properties	P45	P50	Units
Elongation	>30	>13	(%)
Specific heat	2.5	2.1	($\frac{KJ \times K}{Kg}$)
Tensile Strength	>0,86	>1,70	(MPa)
Cork particle size	1/2	0.5/1	(mm)
Sheet dimension	1270 x 760	1270 x 760	(mm)
Thermal Conductivity	0.06	0.07	($\frac{W}{m K}$)
Density at 20°C	300-350	448-512	($\frac{kg}{m^3}$)

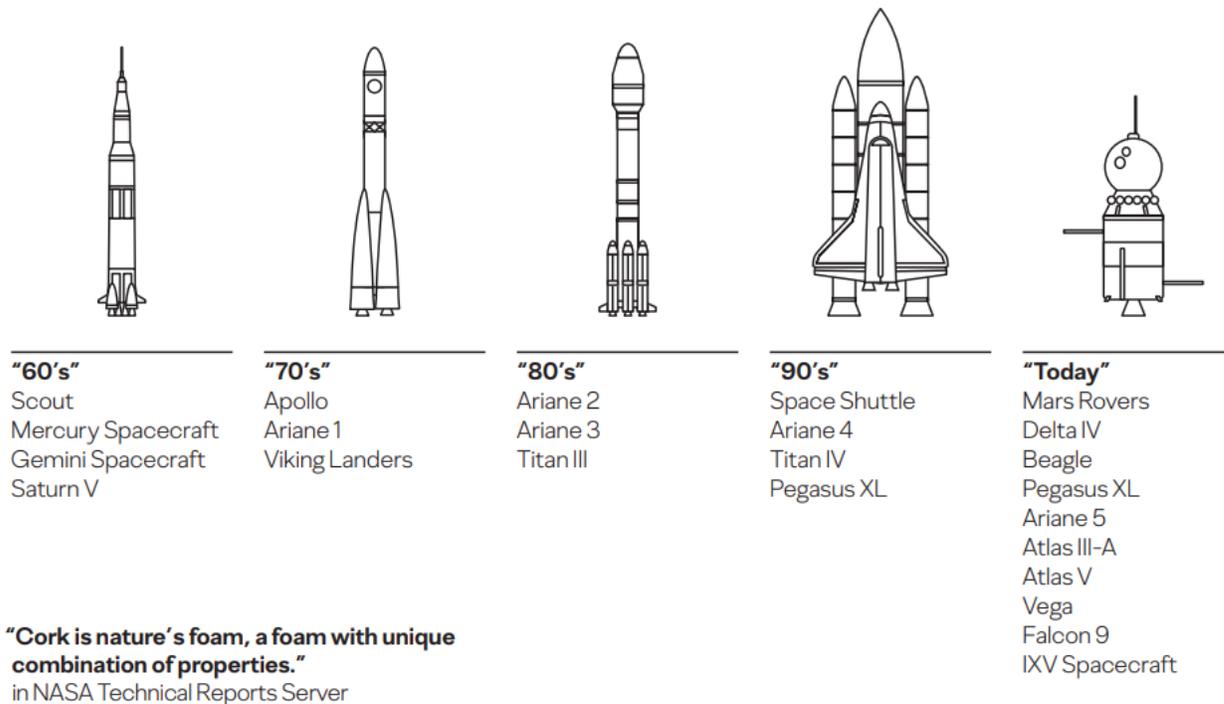


Figure 5.4 Spacecraft using cork materials and cork composites [40].

A few key features put these composites ahead of the pack compared to other varieties. Firstly, cork composites are more process-friendly than others. Cork-based composites are easily attached to most substrate materials using standard adhesive techniques. Trimming and machining may be performed using

common facilities and machines without special protective gear. Sandwiches may be easily included; no complicated fitting processes are required. Furthermore, these materials have already shown themselves as adjectival heat shields in rocket applications and interior thermal insulation in heated constructions on several missions. In Figure 5.5, the demonstration belongs to the ogive shell of Vulcan Rocket which the United Launch Alliance developed.



Figure 5.5 Fairing shell with Amorim P50 ablative thermal solution [41].

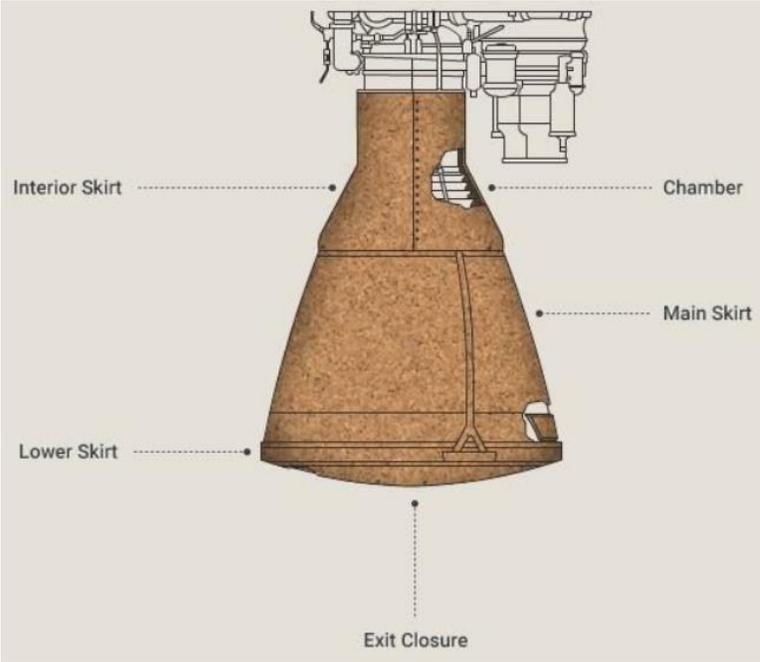


Figure 5.6 Typical usage of cork composites in rockets [42].

A layer of cork covered the outer skin of the cylindrical shell. The cork, attached to the outer skin of the fairing's composite sandwich, shields it from the heat created by aerodynamic friction on the covering's exterior. In addition, since the 1970s, cork composites have been used to ensure thermal protection systems for aircraft sectors. Figure 5.6 shows how cork composites are commonly used as heat absorbers in space. In addition, cork composites might be easily molded.

In addition to orbital flight and re-entry vehicles, aerospace thermal protection systems (TPS) also form an integral part of the primary structure of sounding rockets. Over the past several decades, the German Aerospace Center (DLR)'s Mobile Rocket Base (MORABA) has used epoxy-based, two-component thermoset coatings to provide thermal protection on a wide range of launch vehicle structures, including fins, nose cones, conical adapters, and heat shields. It is relatively simple to manufacture and can be sprayed on almost any geometry. The key drivers for developing a new thermal protection system using special cork materials are its noxious fumes, limited shelf life, extensive storage requirements, and the residues it leaves close to payload components. A sounding rocket's primary structure - including the fin, nose cone, conical adapter, and heat shield assembly - is designed to protect the rocket from thermal radiation. It can be seen obviously in Figure 5.7. The thermal protection system material used to be an ablative, epoxy-based, two-component thermoset coating of the Mobile Rocket Base (MORABA) of the German Aerospace Center (DLR). neighboring payload elements during ablation have contributed to the rising demand for a new thermal protection system.



Figure 5.7 Improved Malemute (IM) vehicle enhanced with cork-based TPS on fin [43].

In terms of TPS material selection, there are some preferences, such as low weight, formability, eco-friendliness, low costs, low maintenance fees, and no export restrictions. Therefore, infiltrated cork has been chosen as the most usable TPS material according to these requirements. In other parts of our research, the NORCOAT LIEGE will be explained.

Hereby, NORCOAT LIEGE is the primary preference of the EU market as a semi-finished product. The manufacturing process of TPS components from cork materials has several essential steps: surface preparation, structural bonding implementation, TPS covering application, vacuum bagging, and curing. In Figure 5.8, the preparation process of the VSB-30 FNC structure with NORCOAT LIEGE is demonstrated.

Following the successful production process development on a VSB-30 FNC superstructure, it has been applied to additional TPS-related structures such as heat shield assemblies, motor adapters, and fins (Figure 5.9).

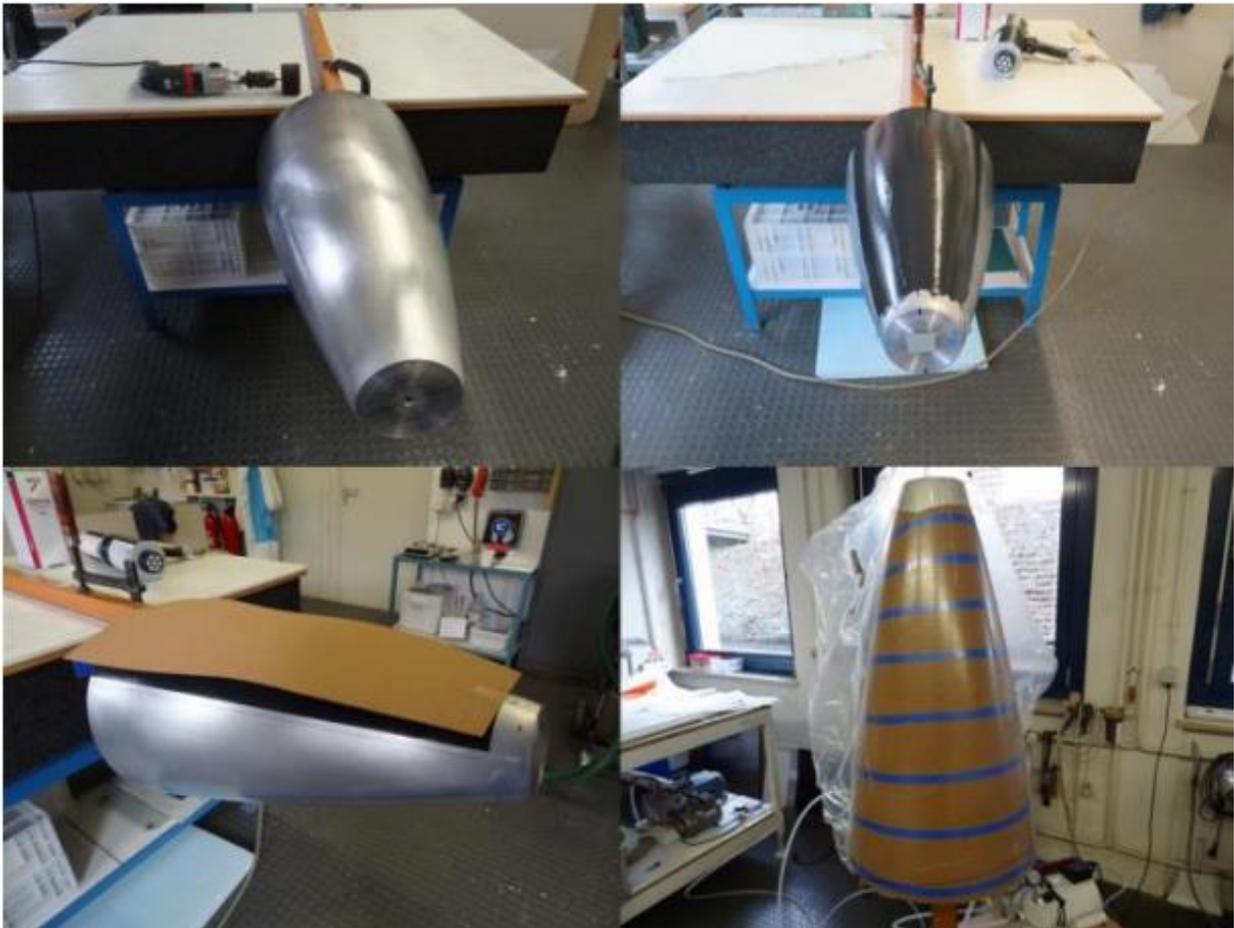


Figure 5.8 VSB-30 FNC structure with NORCOAT LIEGE [43].

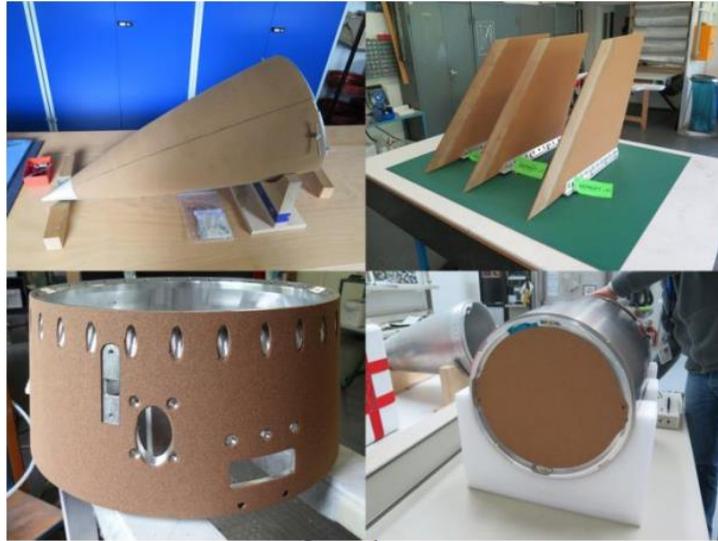


Figure 5.9 Implementation of NORCOAT LIEGE to various parts of rocket structures [43].

5.3.2 Projects about Cork Usage in Aerospace Structures: Aerocork Project

With the starting of the 21st century, wine industries tend to use plastic and metal stoppers with the technological boost. Therefore, the utilization of cork materials drops gradually. For this reason, cork producers have started research and studies so that cork materials and products can be used in alternative areas. In 2008, Dyn'Aero Industrie (DAI), a Portuguese lightweight aircraft manufacturer, requested assistance from industry and academia to replace oil-derived components with cork composites in its aircraft models. As a result, a collaboration was created, and a QREN R&D grant was authorized and granted to the consortium in late 2008. The project aims to phase out as many components made of oil-derived substances as feasible. PVC-based materials and spheres are examples of oil-delivered components. The elimination of these materials would result in significant cost savings throughout the manufacturing process. Oil-derived components are at risk of becoming more expensive as oil prices rise with global demand.

There were two types of materials in the DAI's aircraft, PVC core (sandwich) and Sphere (micro-sandwich). These materials are oil-derived, and their topologies are carbon face sheets. ACC declared that replacing these materials with cork-based sandwiches could be possible, so they initiated experiments to achieve sustainability.

During the research, it was hoped that cork materials and composites would be used to create airplane sections subjected to relatively modest loads and deemed acceptable for lightning. Units such as the pilot seat, wing leading edges, and wing rib structures were tested. The parts produced in the AEROCORK Project are depicted in the figures below (Figs. 5.10-5.11).



Figure 5.10 The AEROCORK cork composite material [44].



Figure 5.11 Dyn'Aero's MCR UL aircraft [44].

5.4 Potential Applications of Cork Composites in Aeronautical/Space Structures

Cork powder, composites, and other derived products can be utilized in different forms for protection, thermal resistance, and anti-impact in aerospace. Throughout this section, several possible applications of cork material will be analyzed.

5.4.1 Cork and Ceramic Matrix Composite in Aeronautical/Space Applications

Firstly, the combination of cork and ceramic matrix materials is one of the leading research topics. Cork is preferable for applications thanks to its nonlinear elasticity, strength to the fracture, and unique dimensional recovery capabilities. Currently, several studies are performed on bonded laminar structures occurring from C/C-SiC ceramic matrix composite and a cork-based ablative material. It is widely known that adhesive bonding is the most used method for combining two different types of materials. For resisting cyclic stress, shear stress, and fatigue resistance, adhesive bonding shows more lifetime,

durability, and comfort than mechanical joining techniques [45]. The ablative material for this combination is utilized for re-entry programs during the launch process. NORCOAT LIEGE was applied in 2003 to the Beagle 2 probe, which stepped into Mars's atmosphere, and in 1998, the Atmospheric Re-Entry Demonstrator re-entered Earth [46]. It's an ablator cork material that's been tested in space. Furthermore, the C/C-SiC was improved by the German Aerospace Centre (DLR). To obtain SiC in this matrix, we need to take the product from the reaction of residual carbon and liquid silicon. In terms of ensuring an adhesive combination of C/C-SiC with the NORCOAT LIEGE, three commercial inorganic glutinous can be used to provide resistance until the temperature of 1650°C. The selection criteria for this adhesive are based on the temperature requirements of bonding surfaces. In other words, this cork ceramic matrix material can be utilized in prospective aerospace applications to ensure heat resistance and impact absorption. Before common industrial use of it, several kinds of tests can be carried out to check the adaptability of conditions.

In other words, this cork ceramic matrix material can be utilized in prospective aerospace applications to ensure heat resistance and impact absorption. Before common industrial use of it, several kinds of tests can be carried out to check the adaptability of conditions. A schematic configuration of cork and ceramic matrix composites is given in Figure 5.12.



Figure 5.12. A schematic configuration of cork and ceramic matrix composites [47].

5.4.2 Space Launch System Insulations

The Space Launch System, NASA's new heavy-lift rocket, faces tremendous temperature changes during space travel, ranging from -423 degrees Fahrenheit to more than 200 degrees Fahrenheit. According to NASA, new models have been designed by scientists with cutting-edge technology for providing thermal protection. The parts of these new models consisted of environmentally friendly materials like cork and smaller parts made by a 3D printer. These parts can be combined for NASA's ORION spacecraft, which is required to be robust for transporting astronauts to the Moon and Mars.

Spray-on foam insulation and other classic insulation materials like cork will offer thermal protection for all rocket components. The Space Launch System speeds from 0 to 17,400 miles per hour and flies to more than 100 miles above Earth in under 8 minutes, and the insulation is flexible enough to move with the rocket yet hard enough to withstand aerodynamic stresses. The cryogenic fuel that drives the rocket is made up of liquid hydrogen, and liquid oxygen must remain extremely cold to remain liquid. The temperature of hydrogen must stay at minus 423 degrees Fahrenheit, while the oxygen temperature must remain at minus 298 degrees Fahrenheit. The fuel becomes a gas if temperatures increase too much [48].

The team leader of the thermal protection system for the Space Launch System core stage of NASA, Michael Alldredge, described that "As the Space Launch System flies, it builds up tremendous heat. Without insulation, heat from the launch would affect the stability of the cryogenic propellants, and the rocket's structural integrity would be compromised. NASA is asking this unique foam material to do an incredible job of protecting critical rocket systems, which vary from large structures to electronics and fuel lines, in an unforgiving launch environment with extreme temperatures and pressures."

NASA decided to use foam instead of cork for this covering. Since the foam is more easily applied by hand and easy to find everywhere, they used 3-D printed molds for avionics positioning. Although cork is denser than foam, it ensures more retentive preservation for several implementations. Cork sheets could be used in the core stage engine section (Figure 5.13).



Figure 5.13 Spray-on foam thermal insulation on the Launch Vehicle Stage Adapter [48].

5.4.3 Cork on Mission to Mars

Cork was combined with innovative engineering to create a new Earth re-entry capsule for the European Space Agency (ESA) to carry samples from Mars to Earth. The consortium created by Critical Materials, ISQ, PIEP, and Amorim Cork Composites created the capsule for NASA. A re-entry capsule concept for Earth, with optimal thermomechanical properties to ensure passive re-entry into Earth's atmosphere, was the challenge. There will be no parachute or other auxiliary impact-attenuation system when the container, with soil samples from Mars, makes contact with the earth's surface.

Coatings used to protect capsules carried into space are another critical application of cork materials. When space capsules enter the planet's atmosphere, they will land; and swiftly heat up. Temperatures can reach 1600°C, especially on the capsule's surface. Materials that can survive high temperatures, such as metal or ceramic, will be significantly heavier than cork. Furthermore, these materials do not exhibit the requisite heat conduction capability. Cork materials are suitable for distributing high temperatures across a surface and preventing heat from reaching the body.

A unique solution for integrating various materials in the design and construction of the capsule, along with a defined geometric configuration, is used here, fulfilling all of the ESA's specifications for its Mars exploration program. The solution offers a multifunctional system that can withstand the high thermal and dynamic loads associated with re-entry into the Earth's atmosphere while complying with all predefined requirements. Besides the weight reduction compared to the European Space Agency's initial conditions, this new solution eliminates auxiliary systems and reduces production costs. A re-entry capsule is expected to arrive on Earth in 2026 to transport samples. Cork composite coated Mars landing pod is given in Figure 5.14 [49].



Figure 5.14 Cork composite coated Mars landing pod [49].

5.5 Conclusions

This study reviews cork composites' mechanical and thermal characteristics and their existing and prospective applications in aerospace, military, and other fields. Research has shown that cork composites have been used for space shuttles and rockets as heat insulators for their shells. Furthermore, the paper discusses the distinctions between foam materials, various forms of composites, and cork composites. Although priority is given to aerospace applications of cork sandwiches, the findings may have a bearing on the vehicle industries. The study's lack of information on potential applications of this material in aviation and knowledge of the current usage of cork as a thermal insulator is likely due to privacy policies. Despite its limitations, the study contributes to our understanding of cork's environmentally favorable and sustainable properties in aviation manufacturing. If further research could be investigated to harden this side by mixing cork agglomerates with additional materials and the production of composites, a better experience of force absorption must be developed. These pieces of knowledge can be used to develop targeted interventions aimed at renewability in industries and set an environmental mindset among manufacturers thanks to cork composites for a better future.

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