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ORIGINAL

Cork as a building material: a review

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Abstract This review focuses on cork as a natural, renewable and sustainable construction raw-material. Cork has an unusual combination of properties making it suitable for application in buildings and infrastructures, for example insulation, wear-resistance and durability. The material properties combined with a favourable ecological footprint allow designers, architects and engineers to meet some of the Green Building demands. A summary on cork production, structure, chemistry and properties was made. The processing into cork-based products, for example cork agglomerates and composites, is detailed as well as their properties and applications in construction. The aptitude of cork-based products for compliance with sustainability and energy efficiency criteria is also addressed.

1 Introduction

Cork is obtained from the outer bark of an oak species, the cork oak (*Quercus suber* L.). It is a "green" material with a very favourable ecological footprint since its production is carried out along tree's life time. Cork oak forests spread in the western Mediterranean areas of Southern Europe and North Africa, where they play a substantial ecological role, for example against desertification and in maintaining animal and plant biodiversity. Most cork oaks integrate multifunctional agro-forestry systems which combine cork production with cattle grazing, hunting and other non-wood productions (Pereira 2007).

The cork oak forests cover a total area of approximately 2.1 million hectares, of which about one-third is in Portugal. The annual production of cork totals about 201 thousand tons mostly from the cork oaks of Portugal and Spain which produce 49.6 and 30.5 % of the total raw-material, respectively. Cork is the raw-material for an integrated industrial chain of high economic importance: in Portugal, cork products represent about 1 % of GDP, and are directed towards global markets with annual exports of more than 1346 million euros, according to recent data from the Portuguese Cork Association (APCOR 2015).

Cork is known worldwide as a sealant in bottles (it coined the expression of wine corks!), but it is also a material suited for various demands of the construction sector: its combined characteristics of lightness, elasticity and resilience, impermeability, insulation, wear-resistance, fire retardant qualities, hypoallergenic properties and durability differentiate it from wood or stone (Pereira 2007; Fortes et al. 2004).

The increasing market pressure towards natural and sustainable materials contributes to the natural appealing of cork, also associated with an exotic character in some distant and valuable markets (e.g. Asia, USA and Australia). The use of cork in flooring, wall coverings and insulation has increased, and adopted innovative design approaches as well as product development and applications. The media exposure of some out-of-the-box cork applications as exterior cladding of buildings was also decisive to increase public awareness of cork: this was the case for Portuguese pavilions in the last two World Expos of Hannover 2000 and Shanghai 2010 (Fig. 1).

Different cork-based materials may be used in building, of which the main ones can be grouped as:

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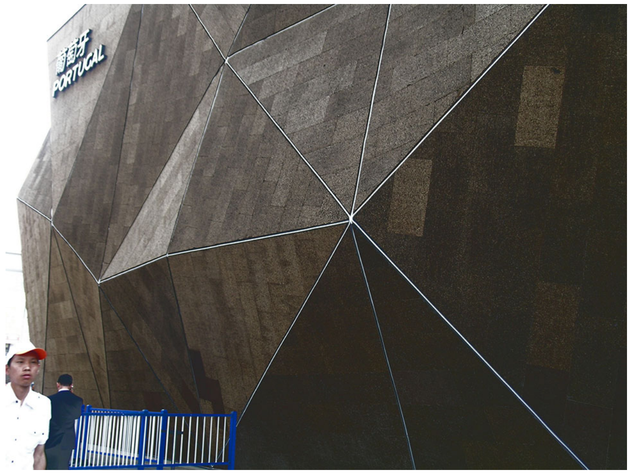


Fig. 1 The use of cork in the external cladding of the Portuguese pavilion in the World Exposition of Shanghai 2010; the project was from architect Carlos Couto, with a complete external cladding of the building by expanded cork agglomerated boards

1. Unprocessed cork planks obtained by removal from the tree stem;
2. Granulated cork;
3. Cork agglomerates as composites of cork granules and resin, namely rubber-cork composites;
4. Expanded cork agglomerates without resin;

Other cork products may also be used such as industrial by-products, cork-assembled materials and cork composites with other materials, which are usually applied to specially designed solutions.

Cork research is active and since the compilation made in the most recent reference book on cork (Pereira 2007) the number of scientific publications has increased steadily, covering different aspects of the material's characterization, processing and usage, including patenting of products and processes. Despite the information gathered, a focused and structured approach to cork properties and products as construction materials is missing.

This is the objective of the present review which focuses on cork as a sustainable construction raw-material, bridging from its production, structure and properties, to the different cork products and end-uses. The first part includes a description of how cork is produced, and a compilation of the fundamentals of cork structure, chemistry and properties. A review of processing and manufacturing of cork products of interest for the construction sector is made afterwards, including the properties of the most important products, followed by a synthesis of the applications of cork products in construction. At the end, an analysis of the aptitude of cork products for compliance with sustainability and energy efficiency criteria is presented.

2 Cork: a natural and sustainable material

Cork is a biological cellular material with a unique set of properties which result from the features of its structure and chemical composition, associated with the physiological process of its formation in the cork oak (*Quercus suber* L.) bark (Pereira 2007, 2015).

2.1 The production of cork

Cork is a protective tissue known in plant anatomy as phellem and is part of the periderm in the outer bark involving tree stem, branches and roots. Reference descriptions of tree barks are given in plant anatomy books (e.g. Evert 2006).

In short, the observation of a cross-section of a tree stem shows two distinctive parts: the wood or xylem at the inside, and the bark located to the outside. Both components accumulate during tree growth by the functioning of two cell layers with meristematic activity (i.e. capable of cell division): the cambium which forms the wood cells to the inside and bark phloem cells to the outside; and the phellogen which forms the periderm with pheloderm cells to the inside and phellem or cork cells to the outside (Fig. 2).

The periderm of the cork oak has special characteristics which are not common among tree species: the phellogen is a continuous and regular layer enveloping the stem, with a high longevity and a considerable production intensity of cork cells. In addition, if the phellogen is destroyed, for example by human action, a new traumatic phellogen develops in the underlying phloem region and resumes its meristematic activity with the same characteristics. These features are the basis for the sustainable exploitation of the tree as a cork producer.

The periderm is formed in the cork oak during the first year, encircling the stem and accumulating successive layers of cork (Graça and Pereira 2004). Due to the large tangential tensions resulting from the growth of the young tree, the cork fractures. The appearance of the external bark of the cork oak is therefore of a thick cork bark with

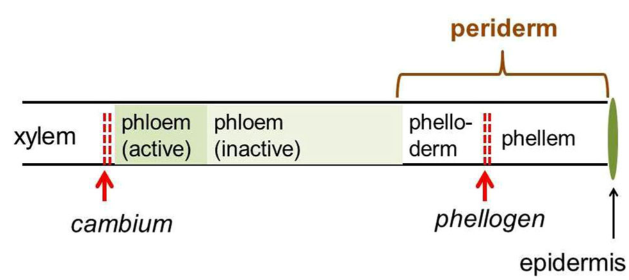


Fig. 2 Schematic representation of tissues in a cross-section of a young cork oak stem before cork exploitation

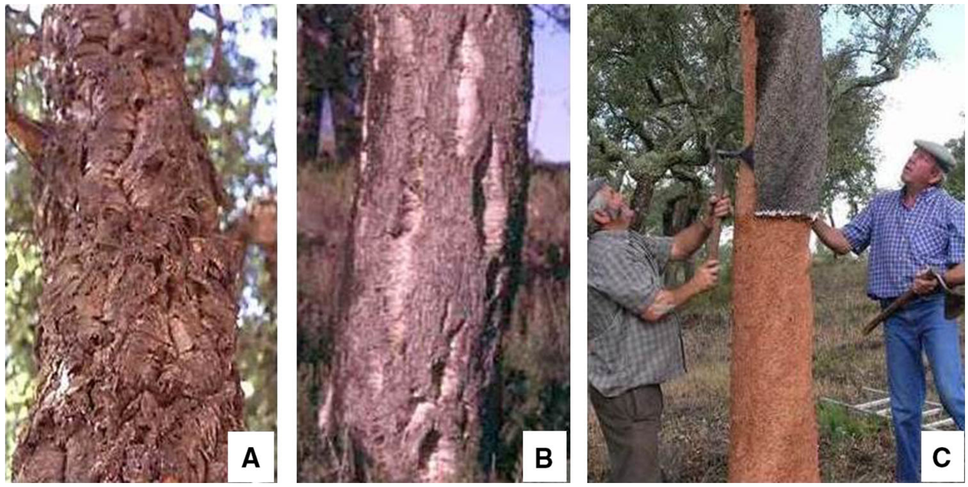


Fig. 3 External appearance of the stem of: a young cork oak with virgin cork (**a**), a tree with the second cork (**b**), and a mature cork oak under cork exploitation (**c**)

numerous fissures which gives it a striking appearance: it is called virgin cork (Fig. 3).

If virgin cork is deliberately removed (by the operation called cork stripping), a new phellogen is formed and rebuilds a new periderm, keeping the same characteristics of regularity and activity. The cork layer, now called reproduction cork, is subject to much less tangential growth stress (the tree has a larger diameter) to which it can largely resist. Therefore, less fractures are rarely to occur (Fig. 3). The reproduction cork is covered at the outside by a lignocellulosic layer of phloem which represents the part of the phloem that remained to the outside when the phellogen was regenerated inside the phloem; it is called the back of the cork planks.

These features are at the basis of cork's sustainable exploitation, i.e. during the tree's lifetime, by successive removals of the reproduction cork and the formation of successive periderms. In short, cork exploitation relies on its periodical removal from the stem and branches to an extent which is considered compatible with maintenance of the tree's good physiological vitality. Cork stripping is usually done manually by cutting large rectangular planks through the tree periderm and by pulling them out by separation at the phellogen (Fig. 3). This is done when the tree is physiologically active (late spring and early summer) and the phellogen and newly formed cells are fragile, therefore allowing easy tearing out.

Cork exploitation begins with the removal of virgin cork when the tree reaches 70 cm in perimeter at 1.3 m of height, which is around 20–25 years of age in most growing conditions. The trees are then debarked every 9 years (the legal minimum allowed in Portugal and Spain), which is called production cycle. The cork layers which are produced form a continuous envelope with an appreciable thickness around stem and branches: the cork layer which is accumulated each year has an average thickness of 4.1 mm but may vary between 1.7 and 6.0 mm (Costa et al. 2003; Ferreira et al. 2000; Pereira et al. 1992). The resulting cork planks after the 9-year-production cycle have therefore variable thickness and are grouped commercially by calliper: extra thin (<22 mm); thin (22–27 mm); half standard (27–32 mm); standard (32–40 mm); thick (40–54 mm) and extra thick (>54 mm).

2.2 Cork structure

Cork is a cellular material with a structure formed by closed cells with a shape of hexagonal prisms, stacked base-to-base in rows (Pereira et al. 1987; Gibson et al. 1981). These rows are assembled in parallel into a compact space-filling arrangement and in adjacent rows the prism bases lay in a staggered position. The rows are aligned in the tree radial direction, so that the individual cells have the prism height oriented in the radial direction and the prism base in a tangential plane. Therefore, the structure of cork shown by the sections differs: a hexagonal honeycomb in tangential section and a brick-layered structure in radial and transverse sections (Fig. 4).

The cork contains about 4×10^{-7} to 7×10^{-7} cells per cm^{-3} representing a solid fraction under 20 % of the total volume (Pereira 2007). The cells have on average 40 µm prism height, 20 µm base edge, and 1 µm wall thickness, hollow lumens and no inter-cellular communication (Table 1). The cellular dimensions are not uniform and vary within and between samples. An important feature of cork cells is the undulation of the cell walls, especially of the lateral prism faces which show in most cases a regular undulation with 2–3 per face (Fig. 4) but which can increase to intense corrugation or to irregular patterns if subjected to stresses during cork growth (Pereira 2007). There are no microscopic openings (i.e., at the µm level) in the walls but at the sub-microscopic level there are minute, stuffed channels

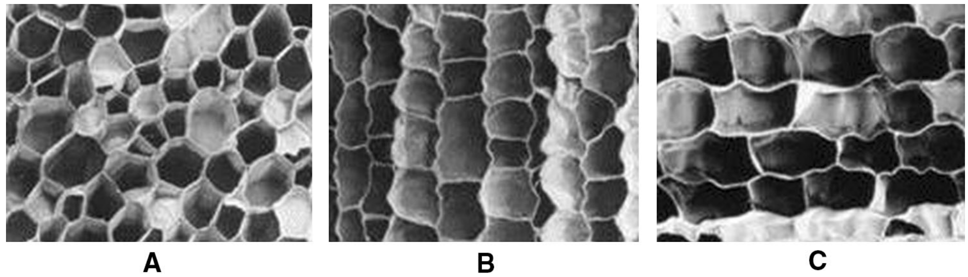


Fig. 4 Scanning electron microscopic images of the three sections of cork: tangential (**a**), transverse (**b**), and radial (**c**) (Pereira 2015)

Table 1 Main characteristics of cork structure (Pereira 2007)

Material	Natural suberised lignocellulosic composite
Density	120–170 kg m^{-3}
Type of cells	Closed
Mean edges/face	6
Mean faces/cell	14
Individual cell shape	Hexagonal prism
Symmetry of structure	Axisymmetric
Cell thickness	1–1.5 µm
Fraction of solid material	10 %
Largest principal cell dimension	40 µm
Smallest principal cell dimension	20 µm
Intermediate principal cell dimension	30 µm
Shape anisotropy ratios	$R_{13} = 1.5–1.7$, $R_{12} = 1–1.1$
Other specific features	Growth rings, lenticular channels

Table 2 Dimensional characteristics of earlycork and latecork cells (Pereira 2007)

	Earlycork	Latecork
Prism height (h)	30–40 µm	10–15 µm
Prism base edge (l)	13–15 µm	13–15 µm
Average base area	4×10^{-6} to 6×10^{-6} cm^{-2}	4×10^{-6} to 6×10^{-6} cm^{-2}
Cell face thickness	1–1.5 µm	2–3 µm
Number of cells per cm^3	4×10^{-7} to 7×10^{-7}	10×10^{-7} to 20×10^{-7}

which can be observed by transmission electron microscopy: the plasmodesmata have a sectional diameter of approximately 100 nm (Teixeira and Pereira 2009).

One factor of variation is related to the seasonal growth rhythm of the tree: cells formed in the first period of growth (called earlycork) are larger and have thinner walls while the cells formed at the end of the growing season (called latecork) show thicker walls and a much smaller prism height (Table 2). This difference allows for the delimitation of the annual cork rings, since the latecork cells are darker in colour. An annual growth ring comprises normally 50–150 cell layers in the earlycork and only a few cell layers in the latecork (Pereira et al. 1992).

One natural feature of cork is the presence of lenticular channels which cross the cork planks radially, linking the outside to the internal living tissues and allowing gas exchange. The lenticular channels, which vary in frequency and dimension, are a cause of cork's variability in structure and properties. They are also a conspicuous macroscopic characteristic of the material, with different 2D appearance in the tangential and in the non-tangential sections of cork, as shown in Fig. 5 (Pereira 2007; Pereira et al. 1996; Oliveira et al. 2012).

2.3 Chemical composition

Cork properties also depend on the chemical characteristics of its components, their relative amount and distribution in the solid. The chemical components are located in the cell faces and edges, making up a three-dimensional network of a solid matrix which encircles the hollow air-filled cells. Cork properties like chemical and biological inertness, and durability are in direct relation with its chemical composition.

Fig. 5 Images of a cork plank showing the lenticular channels: transverse section (**a**) and tangential section (**b**)

Table 3 Chemical composition of cork

	Mean	Std.
% o.d. cork		
Extractives, total	16.2	3.9
Dichloromethane	5.8	0.8
Ethanol	5.9	3.0
Water	4.5	1.6
Suberin, total	42.8	6.2
Long chain lipids	41.0	5.2
Glycerol	3.8	0.6
Lignin, total	22.0	3.3
Klason lignin	21.1	3.3
Acid soluble lignin	0.9	0.2
Monosaccharide composition, % of neutral sugars		
Glucose	46.1	3.6
Xylose	25.1	3.7
Arabinose	18.0	3.0
Mannose	3.0	2.8
Galactose	7.3	1.2
Rhamnose	0.5	0.5

Mean of 58 samples and standard deviation (Pereira 2013)

Table 3 summarises the results of a recent study on the natural variation of cork chemical composition (Pereira 2013).

Cork is mainly composed of suberin, representing on average 43 % of the total dry mass, which is responsible for many of the cork's properties. Suberin is a glyceridic polyester of linear long chain fatty acids and alcohols which are assembled forming ribbon-like structures, therefore being the component responsible for the elastic properties of cork and allowing the bending and collapse of cell walls (Pereira 2007, 2015). The monomers obtained by depolymerisation of suberin are long chain fatty acids and alcohols (the major monomers are α,ω-diacids and ω-hydroxyacids), and glycerol which are inter-esterified in the polymer (Graça and Pereira 2004).

Lignin is the second most important structural component, representing on average 22 % of the cork dry mass, and it is also determinant for the behaviour of the material (Pereira 2013). Lignin is an aromatic cross-linked polymer which is responsible for the structural rigidity of the cells and their resistance to compression. Lignin is formed by the polymerisation of three phenylpropane monomers with different methoxyl substitution in C3 and C5: p-coumaryl alcohol, coniferyl alcohol and sinapyl alcohol. The aromatic rings of these alcohols are named respectively p-hydroxyphenyl (H), guaiacyl (G) and syringyl (S) on which the designation of the different chemical types of lignin is based. The lignin in cork is mostly made of G units with minor contents of S and H units, with 96.4, 2.5 and 1.1 %, respectively (Marques and Pereira 2013).

Cellulose plays a lesser role in the construction of the cork cell wall, only representing about 10 %, as well as hemicelluloses which are mostly made up of xylans with an appreciable content of arabinose monomers (Table 3), and amount to approximately 10 % (Pereira 2013).

Cork also contains extractives, i.e. components that can be solubilised without impairing the materials properties. The extractives include non-polar compounds (e.g. lipids and terpenes) and polar compounds, mostly of phenolic and polyphenolic nature. Extractives represent on average 16.2 % of cork, including 5.8 % of non-polar compounds and 10.4 % of polar compounds (Table 3).

2.4 Cork properties

Cork has an unusual combination of properties: low density, very low permeability to liquids and gases, low conductivity, chemical stability and durability, and high compressibility with dimensional recovery (Tables 4 and 5).

Cork is anisotropic due to the orientation of the cells (Fig. 4): the properties measured along the direction coincident to the prism axis (usually referred to as the radial direction of cork) differ from those measured in the perpendicular plane (non-radial directions). However, the shape anisotropy ratios are small (Table 1) and the differences in properties are much less than, for instance, those of wood.

Cork is a light material, with density values ranging from below 120 to over 200 kg m^{-3} due to its cellular

Table 4 Cork properties

Property	Value	References
Density, kg m^{-3}	120–180 (reproduction)	Rosa and Fortes (1988)
	160–240 (virgin)	
Surface energy, dispersive component, mJ m^{-2}	24–38 (40 °C)	Cordeiro et al. (1995)
	41 (25 °C)	Gomes et al. (1993)
		Godinho et al. (2001)
Electrical conductivity, S m^{-1}	1.2×10^{-10} (25 °C)	Fortes and Nogueira (1989)
	1.67×10^{-13} (50 °C)	
Acoustic resistivity, kg m^{-2} s^{-1}	1.2×10^{5}	Medeiros (1945)
Specific heat, J kg^{-1} K^{-1}	350	Gil (1998)
Thermal conductivity, W m^{-1} K^{-1}	0.045	Gil (1998)
Thermal diffusivity, m^{2} s^{-1}	1×10^{-6}	Gil (1998)
Water diffusion coefficient, m^{2} s^{-1}	4×10^{-10} (NR)	Gil (1998)
	1×10^{-11} (R)	

Table 5 Mechanical properties of cork

Property	Value	References
Young's modulus, natural cork, unboiled, MPa	4.2–21.5 (R)	Oliveira et al. (2014)
	3.5–22.5 (NR)	
Young's modulus, boiled, Mpa	6 (R)	Rosa et al. (1990)
	8–9 (NR)	
Young's modulus, heat treated at 100 °C, Mpa	11 (R)	Rosa and Pereira (1994)
	11 (NR)	
Young's modulus, heat treated at 150 °C, MPa	15 (R)	Rosa and Pereira (1994)
	14 (NR)	
Tensile modulus, boiled, MPa	38 (R)	Rosa and Fortes (1991)
	24–26 (NR)	
Collapse (buckling) stress, boiled, MPa	0.75–0.8 (R)	Gibson et al. (1981), Vaz and Fortes 1998
	0.6–0.7 (NR)	
Collapse (buckling) strain, %	4 (R)	Gibson et al. (1981)
	6 (NR)	
Fracture stress under tension, MPa	1.0 (R)	Gibson et al. (1981)
	1.1 (NR)	
Fracture strain under tension, %	5 (R)	Gibson et al. (1981)
	9 (NR)	
Fracture toughness, boiled, MPa $m^{1/2}$	60–130	Rosa and Fortes (1991)
Poisson's ratio, boiled	0–0.097 ($\nu_{R/NR}$)	Gibson et al. (1981), Fortes and Nogueira (1989)
	0–0.064 ($\nu_{NR/R}$)	
	0.26–0.5 ($\nu_{NR/NR}$)	

structure of hollow and closed cells with a small solid fraction (Fig. 4).

Cork absorbs water very slowly and floats on water with large buoyancy. The diffusion of water in cork is a considerably slow process, with diffusion coefficients of 1×10^{-11} and 4×10^{-10} m^{2} s^{-1} in the non-radial and radial directions, respectively (Rosa and Fortes 1993). A recent study reported a permeability of cork to liquid water of 280.5×10^{-13} mol/(m s Pa) and of 110.1×10^{-13} mol/(m s Pa) to water vapor (Fonseca et al. 2013). Such permeation properties are the result of the cellular structure of cork without intercellular communication channels as well as of the chemical composition of the cell walls namely the presence of the hydrophobic suberin and of the lipophilic extractives (Gil et al. 2000).

The permeability of cork to non-condensable gases, for example helium, oxygen, nitrogen, carbon dioxide is low (Faria et al. 2011; Lequin et al. 2012), and the transport mechanism through the cork cells was proposed to be a molecular flow regime mainly through the plasmodesmata (Brazinha et al. 2013).

Cork has very low heat transfer properties due to both its large air content and small cell size. Heat can be transmitted by conduction through the solid fraction and gas, and by convection and radiation. In cork, the small and closed cells eliminate gas convection, and radiation is reduced by absorption in the numerous cells; only conduction has importance but is reduced considering the small solid fraction of cork and the low thermal conductivity of air (Pereira 2007; Silva et al. 2005). Likewise, sound transmission is very low with an acoustic resistivity of 1.2×10^5 kg m^{-2} s^{-1} (Table 4).

Regarding surface properties, cork is a hydrophobic material with low wettability towards polar liquids (e.g. water), and high affinity for non-polar liquids (e.g. non polar resins), with a surface energy of 18 mN m^{-1} (Abenojar et al. 2014). The contact angle of water on cork is between 84° and 100° (Gomes et al. 1993; Abenojar et al. 2014).

Cork is a viscoelastic material which allows large deformations under compression without fracture, and with substantial dimensional recovery when stress is relieved (Mano 2002). Figure 6 shows a typical stress–strain curve for cork under compression: an elastic region up to about 5 % strain, followed by a broad plateau where the collapse of cells allows strong dimensional reductions for small stress increases. The difference in the compressive behaviour of cork in the different directions is not very large although the mechanical resistance is lower in the non-radial directions when compared with the radial direction (Anjos et al. 2014). Cork does not fracture under compression both across cells or cell walls and for the highest stresses, for example over 60 % strain, it undergoes a process of densification. When compressed, cork dimensions do not vary (or only very little) in the perpendicular directions (i.e. very small Poisson ratios). The compression properties of cork are significantly influenced by density. The Young's moduli averaged 10.4 and 9.2 MPa for the radial and non-radial directions, respectively, with individual values covering a large range, with coefficient of variation of the mean of 28–29 % (Oliveira et al. 2014).

The general stress and strain curves for tension of cork are also shown in Fig. 6. They show a linear elastic region approximately until 2 % strain (stress at 0.4 MPa), followed by a region of decreasing slope up to the fracture at an average stress of 0.6 MPa (strain of 5 %). The tensile properties, namely Young's modulus, fracture stress and fracture strain are influenced by cork density and porosity; under tension, cork pores play an important role and fractures initiate in the vicinity of a pore (Anjos et al. 2010).

In bending, cork fractures at the side under tension when the tensile strength is overcome. Therefore, cork's density and porosity affect its bending behaviour. Cork is also anisotropic regarding bending: for a load in the radial direction, the stress for a given strain is lower when the compression and tensile stresses are in the tangential direction than when they are in the axial direction, for example Young's modulus is 17.6 and 22.5 MPa, the maximum stress 1.1 and 1.6 MPa for a strain of 12.6 and 18.4 %, respectively (Anjos et al. 2011).

At a first glance, one could conclude that natural cork has poor mechanical behaviour when compared with other types of core materials, such as synthetic foams. However, for some specific applications, cork can compete with these materials. In fact, when comparing the specific compressive strength (σ_c/ρ) against the specific modulus (E/ρ), cork has a better mechanical behaviour than flexible polymer foams and comparable to some rigid polymer foams. Further, its low thermal conductivity combined with a reasonable compressive strength make it an excellent material for thermal insulation purposes as well as for applications where compressive loads are present (Castro et al. 2010).

As regards the reaction to fire, the classification of natural cork according to the euroclass classification (EN 13501-1) is not well established and data are missing.

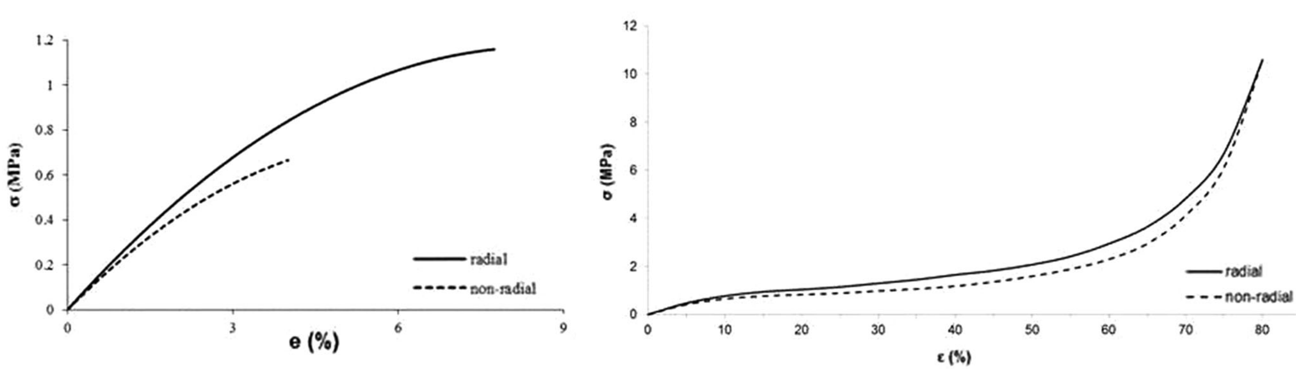


Fig. 6 General stress and strain curves for tension (*left*) and compression of cork (*right*)

The available information shows that expanded corkboards (insulation corkboards) and cork-polymer composites qualify as a class E (EN 13501-1) for reaction to fire according to the single flame fire test (EN ISO 11925-2) (Fernandes et al. 2011a; Roseta 2013). Impregnation with boric acid (1.25 %) and sodium borate (1 %) allowed improvement in the ignitability tests (EN ISO 11925-2) but the final result was still class E (Roseta 2013). A cork agglomerate using polyurethane resin for impact sound insulation of floors showed a class E_{fl} reaction to fire (European Technical approval ETA 11/0004 2011). When subjected to heating, cork has no emissions of furfural or acetic acid (Salthammer and Fuhrmann 2000).

3 Cork processing and materials

The use of cork for construction is mostly based on the production of cork agglomerates since the use of raw cork (cork planks) or of natural cork components is rare and limited to special designs.

Cork agglomerates are produced using the large amount of residual by-products from the manufacture of cork stoppers and discs, and also from the refuse raw-cork planks and other types of cork raw materials such as virgin cork (Pereira 2007), as schematically shown in Fig. 7. The cork materials have different compositions in terms of purity and characteristics of the cork tissue and, therefore, are directed to the different production lines according to their technical demands.

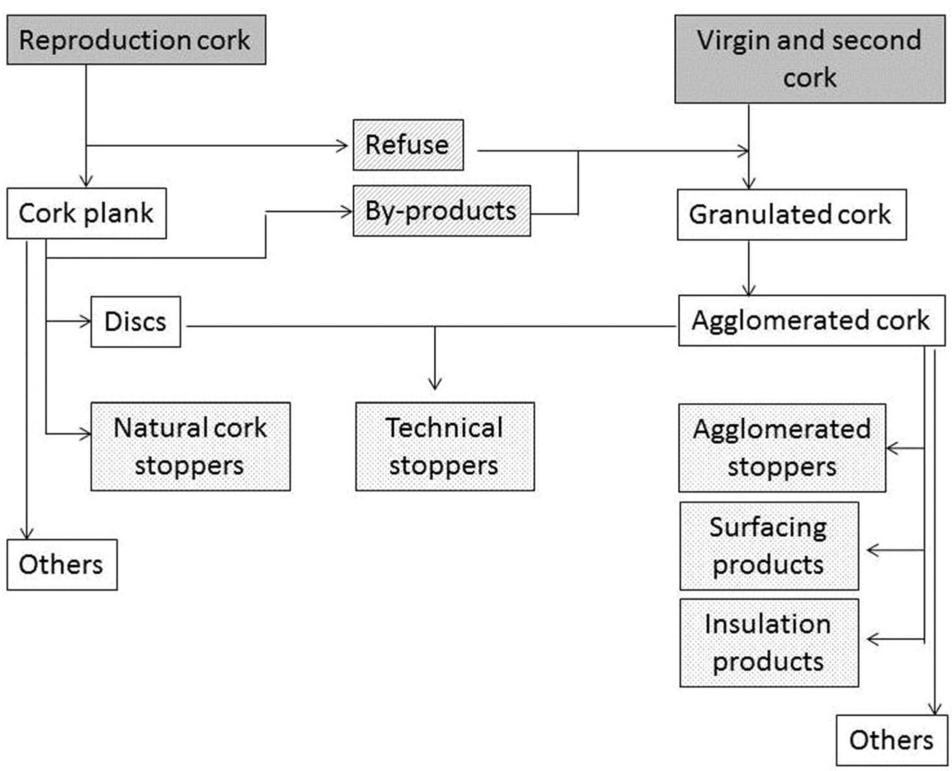
Trituration is necessary to produce cork granules of different dimensions and density whicht constitute the basis for the production of agglomerates. Usual dimensions of granulate are in the range 1–10, 2–5, 1–2, 0.5–1 and 0.2–0.5 mm, but the product specifications dictate the particle distribution and density.

The cork granules may be directed to three processing lines (Fig. 7): the production of cork composites with a resin binding the cork granules; the production of expanded cork agglomerates under superheated steaming and without external binding agent; and the copolymerisation with rubber to make rubber-cork composites.

3.1 Agglomerated cork composites

The production of cork agglomerates requires a mixture of cork granules and resin. The process is carried out under a moderate pressure and heating as adequate for the specific polymer curing and bonding. The adhesives include thermosetting polymers, such as urea–formaldehyde, melamine or phenolic adhesives (e.g. for flooring agglomerates), or thermoplastic polymers such as polyurethanes (e.g. for softer surfacing materials).

Fig. 7 Schematic flowsheet for industrial cork products



The flooring and surfacing agglomerates are produced from rectangular prismatic blocks which are laminated into boards. Cylindrical blocks are also produced for rotary lamination originating a continuous cork sheet. The cork agglomerates may be produced with different densities: 200–300 kg m^{-3} for surfacing, partitioning and insulation applications and higher densities up to 500 kg m^{-3} for flooring (Pereira 2007).

The compression of the cork particles during the agglomeration process causes partial densification of the cells with collapse and corrugation originating higher density values of the materials in comparison to the natural cork (Fig. 8). The cork agglomerate can be described by a reference Young's modulus of 7.4 MPa in compression and 17.4 MPa in tension (Moreira et al. 2010). The thermal conductivity coefficient of flooring cork tiles with thickness between 3.2 and 8 mm is 0.06–0.10 W m^{-1} K^{-1} (Gil 2007).

3.2 Expanded cork agglomerates

In the expanded cork agglomerates, the granules are bound together without any extraneous adhesives, leading to 100 % natural product (Fig. 9). The adhesion is obtained due to the chemical compounds resulting from the thermal degradation of the extractives and structural components of cork. These agglomerates are also called black agglomerates due to their dark colour induced by the high temperatures associated with this process. Their properties are summarized in Table 6.

Agglomeration is carried out by autoclaving with superheated steam at around 300–350 °C and 40 kPa for approximately 20 min. During the heating the cork cells expand, the cell walls stretch and decrease in thickness, and the cell volume increases over 100 %. The cells acquire rounded forms and the material becomes more isotropic (Ferreira and Pereira 1986). A significant mass loss of

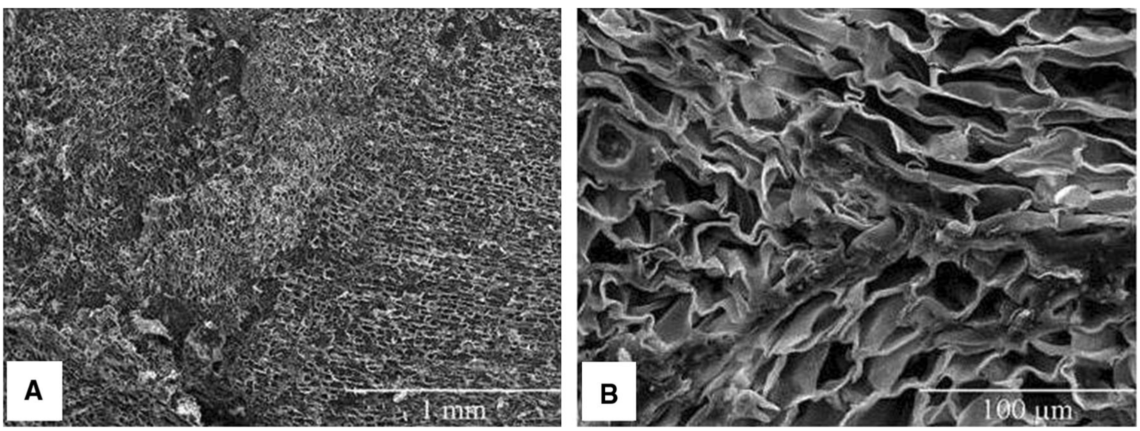


Fig. 8 Macroscopic appearance and cellular structure shown by SEM of: cork agglomerate with fine granulometry (**a**); cork agglomerate with large granulometry (**b**)

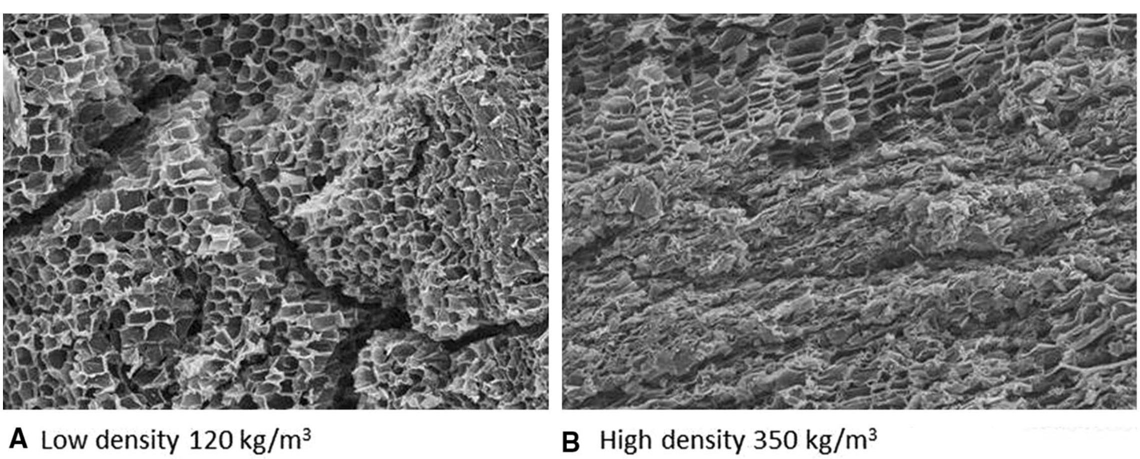


Fig. 9 Macroscopic appearance and cellular structure shown by SEM of: Expanded cork agglomerate, low density (**a**); Expanded cork agglomerate high density (**b**)

Table 6 Properties of expanded cork agglomerate

Property	Value
Density	105 to 130 kg m^{-3}
Thermal conductivity coefficient	0.040 W m^{-1} k^{-1}
Acoustical absorption coefficient (for 500 Hz)	0.33
Tension to stress (MOR)	0.14 to 0.20 MPa
Temperatures of usage	−180 to +140 °C
Fire class	Euroclass E

Source: isocor (http://www.isocor.pt)

about 30 % occurs and the cork chemical composition is altered: extractives and hemicelluloses are degraded, while suberin and lignin have higher thermal stability (Pereira et al. 1992; Sen et al. 2014).

The pre-compression of the granules prior to the heating controls the final product density which is set depending on the final use, for example 80–100, 100–150 and 175–320 kg m^{-3}, for acoustic, thermal and vibration type agglomerates, respectively. The manufactured blocks are cut into boards of varying thicknesses or machined to other forms, for example, for pipe insulation. Rejected blocks, defective boards or those obtained from demolitions are triturated to produce regranulated expanded cork.

Due to the irregular shape of cork granules, some intergranular spaces remain in the agglomerate: for instance, a 130 kg m^{-3} board has 16 % of voids (Pereira 2007). This is one of the reasons why these agglomerates have low bending and tensile strength and are not resistant to friction and wear, due to the weak inter-granular adhesion. The tension to stress of expanded cork agglomerates is in the range of 0.14–0.19 MPa (Table 6). They have an average bending strength of 0.250 MPa, a value well above the 140 kPa limit specified by the normative in force (UNE 56-907-74, Díaz-Parralejo et al. 2003).

Expanded cork agglomerates have high durability under use conditions as a result of their chemical and biological inertia, a low water absorption and comparatively high mechanical resistance under a wide range of temperatures (Pereira 2007). They present excellent dimensional stability (even when subjected to wide thermal variation) with a thermal conductivity coefficient of 0.040 W m^{-1} K^{-1} (Table 6).

Cork expansion may also be achieved by microwave radiation and used in the production process of expanded agglomerates (Pereira et al. 2009).

Regranulated cork has on average a density of 70–80 kg m^{-3} and a thermal conductivity coefficient of 0.048 W m^{-1} $°C^{-1}$ (Gil 2007).

3.3 Cork-polymer composites

The best known and commercially important cork-polymer composite is the so-called rubber-cork. Rubber-cork is made by mixing and cross-binding of cork granules with natural or synthetic rubber (Fig. 10).

The process seeks a combination of the best properties of both materials. For instance, the cork compressibility and recovery characteristics, and the very small lateral flow under compression, compensate for the relatively large positive Poisson coefficient of rubber and its small recovery after deformation. The chemical and thermal stability of cork also overcomes the fact that rubber is easily oxidised, thermally degraded and suffers aging effects. On the other hand, the comparatively smaller resistance of cork and its dimensional variations are compensated by the rubber.

Cork and rubber particles usually with fine granulometries are mixed with cross-linking agents and catalysts, and additives such as antioxidant or colouring materials. The mixture is homogenised and repeatedly roll pressed to obtain a homogeneous paste that is injected or compression moulded before inducing the cross-linking polymerisation (Pereira 2007).

The density of rubber-cork composites varies from 250 to 950 kg m^{-3} (Cork Information Bureau 2014). The product properties depend on the proportion of cork and rubber, allowing tailor-made solutions. Rubber-cork can withstand a wide range of fluids and has chemical resistance over long periods, allowing surface sealing; under compression it has negligible lateral flow, and resistance over long periods, with vibration and shock absorption, high friction and resistance to abrasion (Pereira 2007).

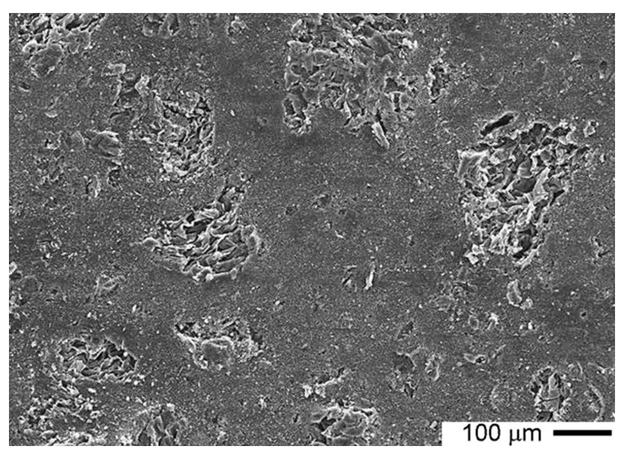


Fig. 10 Macroscopic appearance and cellular structure shown by SEM of: rubber-cork

Table 7 Properties of rubber-cork composites

Property	Waterproof	Acoustic
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
Tensile strength, MPa	>1.3	>0.6

Source: Amorim cork composites (http://www.amorimcorkcomposites.com)

Table 7 presents one example of some properties of commercial rubber-cork materials for waterproof and acoustic insulation applications. The waterproof material has a very low thermal conductivity of 0.018 W m^{-1} K^{-1} and a tensile strength superior to 1.3 MPa.

Cork composites with other polymers have also been studied, for example with polypropylene or polyethylene, as well as in combination with natural fibres (Fernandes et al. 2010, 2011a, 2013a, b, 2014). Although the results show application potential of such cork-polymer composites, they are yet at a research and development stage.

4 Use of cork solutions in construction

Most of the uses of cork products in construction are related to the thermal insulation and energy absorption properties in combination with its physical, chemical and biological stability.

When using cork in buildings, it is possible to have a range of applications drawing on its anti-vibrational, thermal and acoustic absorbing properties, for example in several applications like flooring, wall and ceiling tiles or underlay, gaskets, expansion joints, and external cladding, as well as in concrete and road pavement. Table 8 shows examples of cork products used in construction. Other applications, as is the case in automobile industry or clothing, are not addressed in this revision.

The agglomerated cork composites are used mostly for surface coverings such as wall panels and flooring applications, as well as a core material in sandwich-type structures.

Cork tiles of different types, dimension and design are used for floor coverings and also for wall panelling with multiple cover treatments (polish, wax, varnish, urethane or vinyl coatings). Because of abrasion resistance they are used in all sorts of public buildings such as schools and hospitals, libraries, airports, etc. Notoriety has been given to applications in well-known monuments, for example the flooring of the Sagrada Familia cathedral in Barcelona is made of agglomerated cork tiles. In home applications, in addition to living and bedroom floors, they can also be used in kitchens and bathrooms due to their resistance to moisture and a non-slippery surface.

Most of the cork floors are made up of agglomerated cork, but other options are possible, for example glued together cork pieces which are subsequently laminated into sheets showing either tangential or transverse sections (Gil 2007).

Cork mechanical behaviour precludes this material from playing a structural role by itself, although there is a future ahead for agglomerated cork composites as a core material in sandwich structures (Soares et al. 2011). A recent study on the evaluation of light-weight alternatives to particle boards, cork layered composite plywood boards were prepared and characterized showing bending strength and modulus of elasticity higher than those of commercial plywood and particleboards (Král et al. 2014). Multilayered sandwich panels of wood veneer and a core of cork agglomerates were also produced and found suitable for indoor applications (Lakreb et al. 2015a).

Cork-epoxy agglomerates a core material in lightweight structures has good thermal insulating properties similar to other types of core materials (Castro et al. 2010).

A study comparing the performance of cork-polymer composites (cork powder mixed with polypropylene or polyethylene) with medium-density fibreboard and high-density fibreboard considered that the cork composites present some promising properties (Fernandes et al. 2011a, 2014). The inclusion in cork-polymer composites of natural fibers, for example sisal fibres or short coconut fibres improves the mechanical performance (Fernandes et al. 2013a, b). Other composites with cork residues and biopolymers were suitable for several applications such as flooring and structural applications (Vilela et al. 2013).

The expanded cork agglomerates are mostly used for thermal and acoustic insulation, and for vibration absorption. They are used for insulation in roofs, walls, floors, and ceilings in private and public buildings. The expanded corkboards are also used for sound-absorption in noisy environments or to insulate from external sounds and reduce reverberation (Gil 2007). Sandwich panels using wood veneer and a core of expanded cork agglomerate were found suitable for partioning and other interior applications (Lakreb et al. 2015b). A recent patent addresses the use of expanded cork agglomerate to make flexible panels with embedded optical fibres to solve the lack of translucency of cork-based products (Machado Pinto Germano 2014).

The granules or regranulated expanded cork (with granulometry from 0.25 to 22.4 mm) can be used as a final product for thermal insulation, filling empty spaces between double walls, floors or as a ceiling application to the last floor of a building. Recent studies on the acoustical performance of cork granulates show that this material has

Table 8 Cork products used in different applications in construction and their underlying properties

Uses	Products	Examples	Required properties
Coverings (floors, walls and ceilings)	Agglomerated cork composites	Cork tiles for flooring	Wear resistance
			Resilience
	Expanded cork agglomerates	Underlay for ceilings	Shock absorption
	Rubber-cork composites	Underlay for flooring	
Thermal and acoustic insulation	Agglomerated cork composites	Cork-epoxy agglomerates	Low thermal conductivity coefficient
	Expanded cork agglomerates	Interior wall and roof panels	Non-moisture absorption
			Adequate mechanical resistance
	Granulated cork	Filling material for empty spaces between double walls and floors	Fire resistance
			Durability
			Low density
Vibration insulation	Agglomerated cork composites	Sandwich-type structures	Vibration shock absorption
	Expanded agglomerated cork	Expanded corkboards with high density	
	Rubbercork	Structural joints	
Expansion joints	Agglomerated cork composites	Expanded corkboards	High compressibility and recovery
	Rubbercork		

high sound absorption performance varying with particle size (Maderuelo-Sanz et al. 2014a) and may be mixed with polyurethane and epoxy resins (Maderuelo-Sanz et al. 2014b).

The cork-rubber composites are used for more technologically demanding applications such as gaskets and sealing systems in the automobile industry, vibration and acoustic insulation for industrial machinery, civil engineering and railways, gaskets for electrical transformers, heaters and gas meters or heavy-duty flooring and footwear (Pereira 2007; Gil 2007). A patent addressing a cork-rubber composite was developed to improve water resistance and the strength of the floor (Zheng et al. 2008).

The insulation properties and the low density of cork granules suggest their inclusion in a number of composite materials for building applications, i.e. cork-gypsum (Hernandéz-Olivares et al. 1999), lightened plaster (Río Merino et al. 2005), lightweight polymer mortar (Nóvoa et al. 2004) and concrete (Aziz et al. 1979; Branco et al. 2008; Pereira 2007).

Cork-gypsum composites have potential to be used as partition walls owing to their thermal insulation properties and sound reflecting and absorption ability (Panesar and Shindman 2012).

A composite material with incorporation of cork granules in traditional cemented mortars (de-Carvalho et al. 2013), showed a lower relative density, in the range of 1900–2300 kg m^{-3} when compared with concrete density (around 2400 kg m^{-3}) and a reduction in the production costs.

The initial motivation for including cork in concrete was to develop lightweight concrete (Aziz et al. 1979), but more recent reports revealed improvement of concrete thermal resistance although with some reduction in mechanical properties (Branco et al. 2007, 2008; Silva et al. 2005). The presence of cork improves the thermal behaviour of concrete block walls and makes them lighter and easier to handle, also emphasizing the ecological benefits of using cork in concrete blocks (Castro et al. 2011).

Research on road pavement materials is currently considering the production of economic and friendly asphalt mixtures using small amounts of new materials such as cork (Pereira et al. 2012).

There are several patents assigned to different cork-based materials, namely referring to the production of panels for use in the construction industry (Coelho and Sousa Lamas 2011; David 2012), fibre-reinforced cork-based composites (Fernandes et al. 2011b), concrete applications (Machado Pinto Germano 2014), fibre composite (Kalbe 2011), roof solutions (Lee and Shim 2009), interior construction panels (Chagas 2009), heat insulating solutions (Yamazaki et al. 2011) and flooring applications (Gang and Kang 2011).

5 Cork contribution to green building

Nowadays, and eventually more in the future, the objective is to "build green", giving priority to processes and materials with favourable environmental factors, aiming at reducing the impact of the built environment on human health and on nature throughout the entire building life-cycle. All the steps along the full process have to be taken into account, from raw-material selection, and application to use, to recycling and waste management. Improving energy efficiency, implementing renewable energy resources and using materials and processes which comply with environmental sustainability criteria are key issues in building construction and research, often under societal and market-driven pressures (Kibert 2008).

The aim is to be efficient in using energy, water, and other resources together with a reduction of waste, pollution and environmental degradation. For example, green buildings may incorporate sustainable materials in their construction (e.g. reused, recycled, or based on renewable resources), healthy indoor-environment may be created with minimal pollutants (e.g. reduced product emissions) and landscaping featured to reduce water usage (e.g. adequate native plants).

In this perspective, life cycle assessment (LCA) is a standardized framework (ISO 14040) to evaluate the environmental burdens associated with a product, process or activity throughout its life cycle, from extraction of raw materials, through production, use and end-of-life, i.e. from-cradle-to-grave approach (Blengini and Di Carlo 2010). According to ISO 14040/44:2006, LCA is divided into four phases: (1) goal definition, which defines the aim and scope of the study as well as the functional unit; (2) inventory analysis, which lists emissions of pollutants into air, water and soil, solid wastes and consumption of resources per functional unit; (3) impact assessment, which assesses the environmental impact of the pollutants emitted throughout the life cycle; (4) interpretation of results.

LCA was initially developed for industrial products in the 70′s, and its first application in the building sector concerned only energy aspects (Peuportier et al. 2013). Although LCA is recognized as the best way to evaluate the environmental impacts of buildings, it is not yet a consistent requirement of green building rating systems and codes. For instance, in North America, LCA is included to some extent in the Green Globes® rating system, and is part of the new American National Standard based on Green Globes (ANSI/GBI 01-2010: Green Building Protocol for Commercial Buildings) and is also included in the LEED (Leadership in Energy & Environmental Design) system.

A renewed interest is therefore given to natural and renewable materials, for example stone, wood or cork, and over the years their use in the construction sector has been expanding both using traditional approaches as well as by a renewal of applications or product reengineering. The advantages given by the specific materials' properties are combined with durability, aesthetics and recyclability.

The environmental impact of building materials is related to energy consumption (choosing energy efficient materials), consumption of natural resources (selecting renewable materials), impact on ecosystems (selecting materials which do not endanger sensitive ecosystems), emissions generated (selecting materials and insulation systems which ensure indoor air quality) and behaviour as "waste" (choosing materials with great lifetime and possible recycling) (Gil 2011). A recent study addresses the environmental impacts and the consumption of renewable and non-renewable primary energy on the production of conventional thermal insulation material (Pargana et al. 2014).

To reduce CO_2 emissions by 20 % and increase 20 % energy efficiency is a global European goal for 2020. Moreover, according to the 2010/31/EU directive, a requirement for new buildings in 2018 is the so-called "*Nearly Zero Energy Buildings*". Globally, 30–40 % of all primary energy is used for buildings, largely related to their insulation, and they are responsible for 40–50 % of greenhouse gas emissions (Ramesh et al. 2010). Therefore, lowering energy intensity and environmental impacts of buildings has become a priority in energy and environmental policies in European countries.

In this context, the use of cork products as building materials can be a valuable contribution. Cork is a renewable material for which an enhanced interest has developed during the last years. In parallel with its advantageous properties as a material, cork is associated with a particularly sustainable and environmentally rich production system which adds to its value and is highly prized by environment-related organizations (WWWF 2006). Building green with cork means to have a natural recyclable material upon the demolishment of a building. Along with their economic and social value, cork oak stands and consequently cork play an important role in the ecological protection, water retention and soil conservation being essential reservoirs of fauna and flora biodiversity (Pereira 2007). For instance, the new cork oak plantations in Portugal can provide a significant contribution to the Portuguese commitments to the Kyoto Protocol (Coelho et al. 2012).

A recent study on life cycle assessment of building materials compares the most commonly used building materials with some eco-materials (Table 9). EPS or polyurethane are responsible for the emission of, on average, 7 kg CO_2-eq kg^{-1} with high consumptions of gas and

Table 9 LCA results for several insulation materials

Building product	Density ($kg\ m^{-3}$)	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)	Primary energy demand ($MJ\text{-}Eq\ kg^{-1}$)	Global Warming Potential ($kg\ CO_2\text{-}Eq\ kg^{-1}$)	Water demand ($l\ kg^{-1}$)
EPS foam slab	30	0.0375	105.486	7.336	192.729
Rock wool	60	0.04	26.393	1.511	32.384
Polyurethane rigid foam	30	0.032	103.782	6.788	350.982
Cork slab	150	0.049	51.517	0.807	30.337
Cellulose fibre	50	0.04	10.487	1.831	20.789
Wood wool	180	0.07	20.267	0.124	2.763

Primary energy demand—refers to the direct use at the source, or supply to users without transformation; Global Warming Potential—is a relative measure of how much heat a greenhouse gas traps in the atmosphere

Source: Zabalza Bribián et al. (2011)

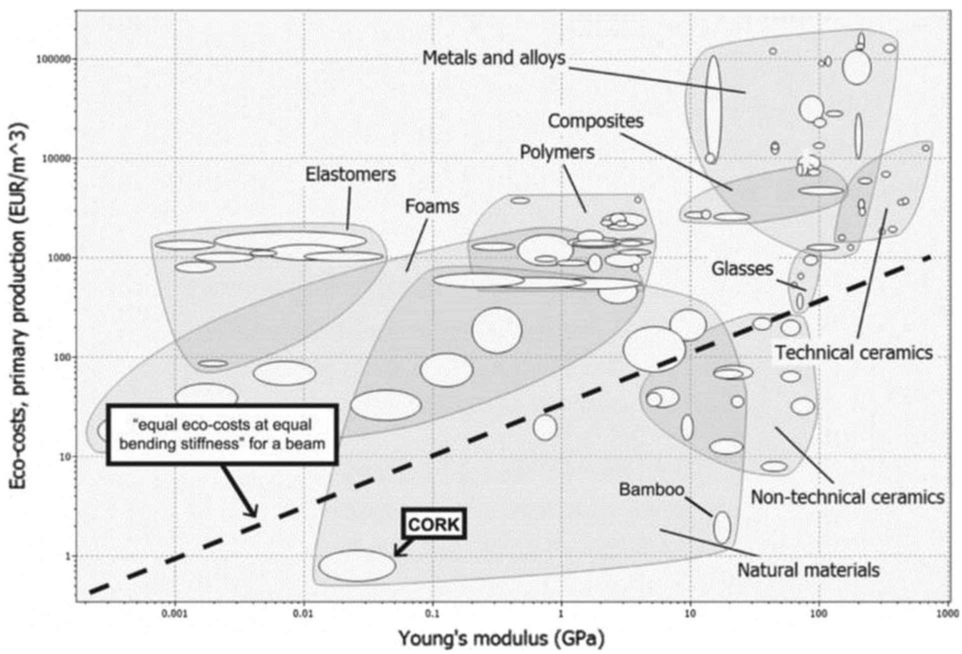


Fig. 11 Eco-costs of primary materials as a function of Young's modulus to select stiff materials with low eco-costs (Mestre and Vogtlander 2013)

petroleum, while insulation materials of natural origin, such as cork, emit only 0.8 kg CO_2-eq kg^{-1} (Zabalza Bribián et al. 2011). La Rosa et al. (2014) analysed the environmental impacts and the thermal insulation performance of an innovative eco-sandwich using cork as core. Rives et al. (2012) present an environmental analysis of the production of cork granulates (black and white cork granulates) following LCA methodology.

The environmental impacts associated with the manufacturing process of a cork floating floor were evaluated aiming at identifying the most significant stages and processes to improve the process and the sustainability of the product (Demertzi et al. 2015).

Hoang et al. (2009) studied the ozone removal by green building materials and found that natural cork wall-covering have high ozone reaction probability, hence being a major contributor to ozone removal in buildings. A recent study on eco-efficient value creation of cork products developed an LCA-based method for design intervention (Mestre and Vogtlander 2013), concluding that cork itself has a very good eco-cost compared to many other materials such as wood, metals and polymers (Fig. 11).

Cork is a green product, allowing designers and architects to meet some of the Green Building demands. In fact, the expanded insulation cork is even mentioned in the BuildingGreen's annual "Top-10 Green Building Products" list (http://www2.buildinggreen.com/buildinggreens-top-10-products-2013). The recycling of cork products extends the lifetime of the products, thus increasing the emissions delay of the carbon fixed by the cork oak tree and incorporated in cork. Therefore, building with cork will allow a more efficient building reuse and construction waste management.

6 Concluding remarks

Cork as a material combines physical, chemical and biological stability with enhanced thermal insulation and energy absorption properties. Cork is also a natural and renewable material with a sustainable production, and therefore cork-based products such as agglomerates and composites have very favourable environmental footprint. This combination of features makes cork an appealing building material which may be a valuable contribution to make greener and more sustainable buildings.

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