Chapter 4
Vibration Damping Applications with Cork Composites

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4.1 Introduction

4.1.1 Cork

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

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

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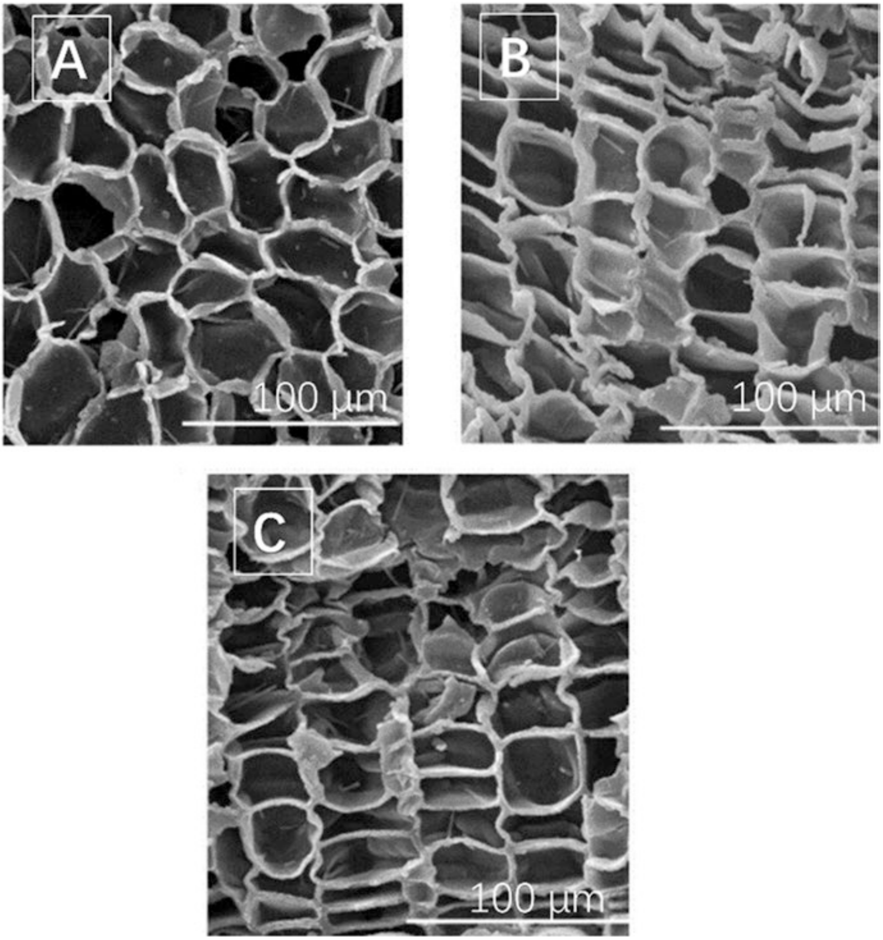

Fig. 4.1 SEM observations of cork from *Quercus cerris* var. *cerris* bark: (**a**) tangential section, (**b**) transverse section, and (**c**) radial section [1]

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

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

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

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

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

4.1.2 Cork Composites

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

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

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

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

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

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

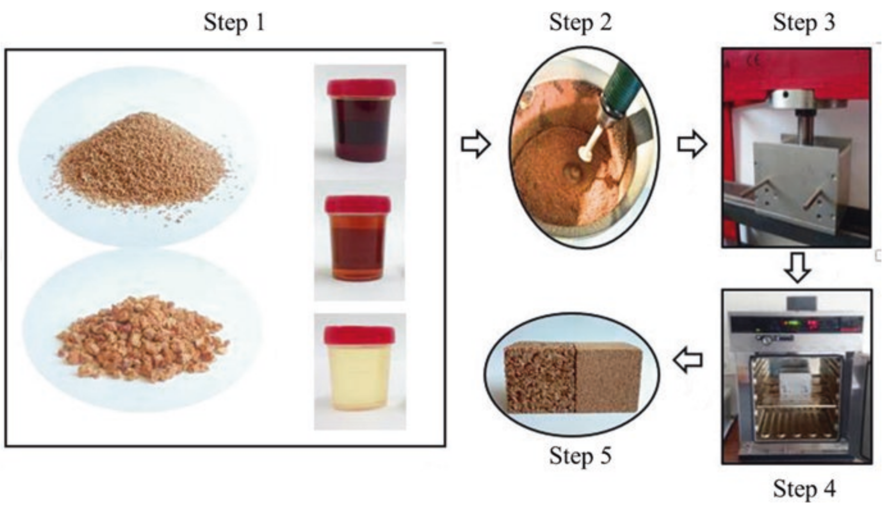

Fig. 4.2 General process of cork composite manufacturing [16]

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

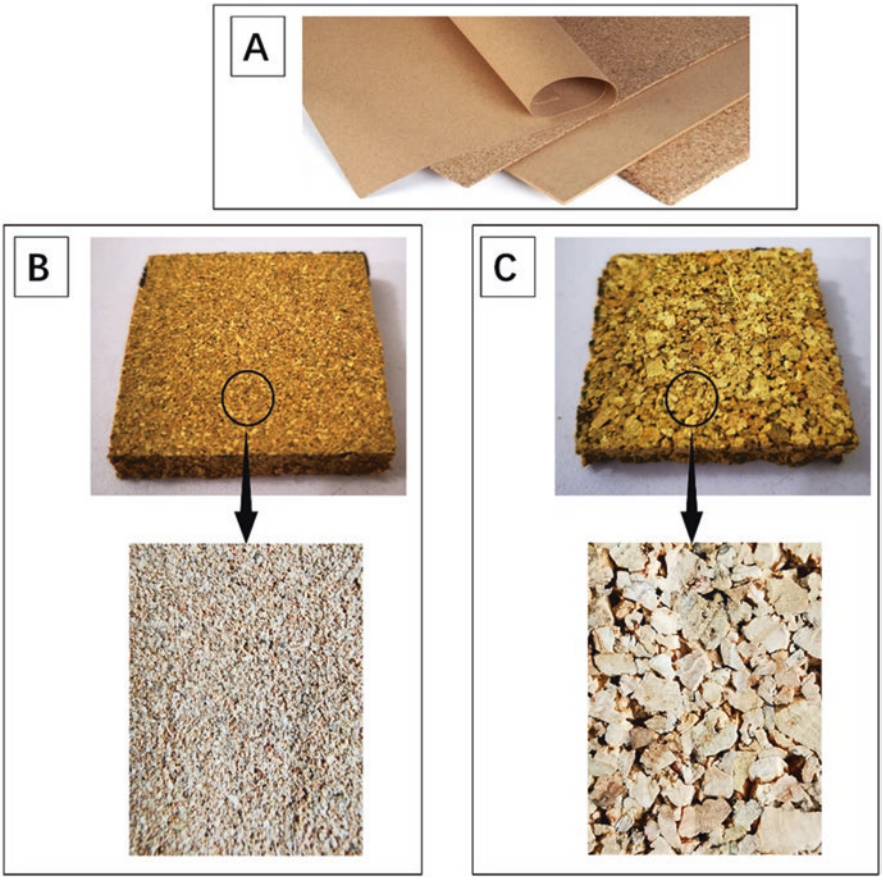

Fig. 4.3 (**a**) Coarse and fine-grained agglomerated cork sheets, (**b**) fine-grained agglomerated cork, and (**c**) coarse-grained agglomerated cork

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

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

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

Table 4.5 Application of cork composites [29]

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

4.2 Vibration Damping of Cork Composites

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

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

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

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

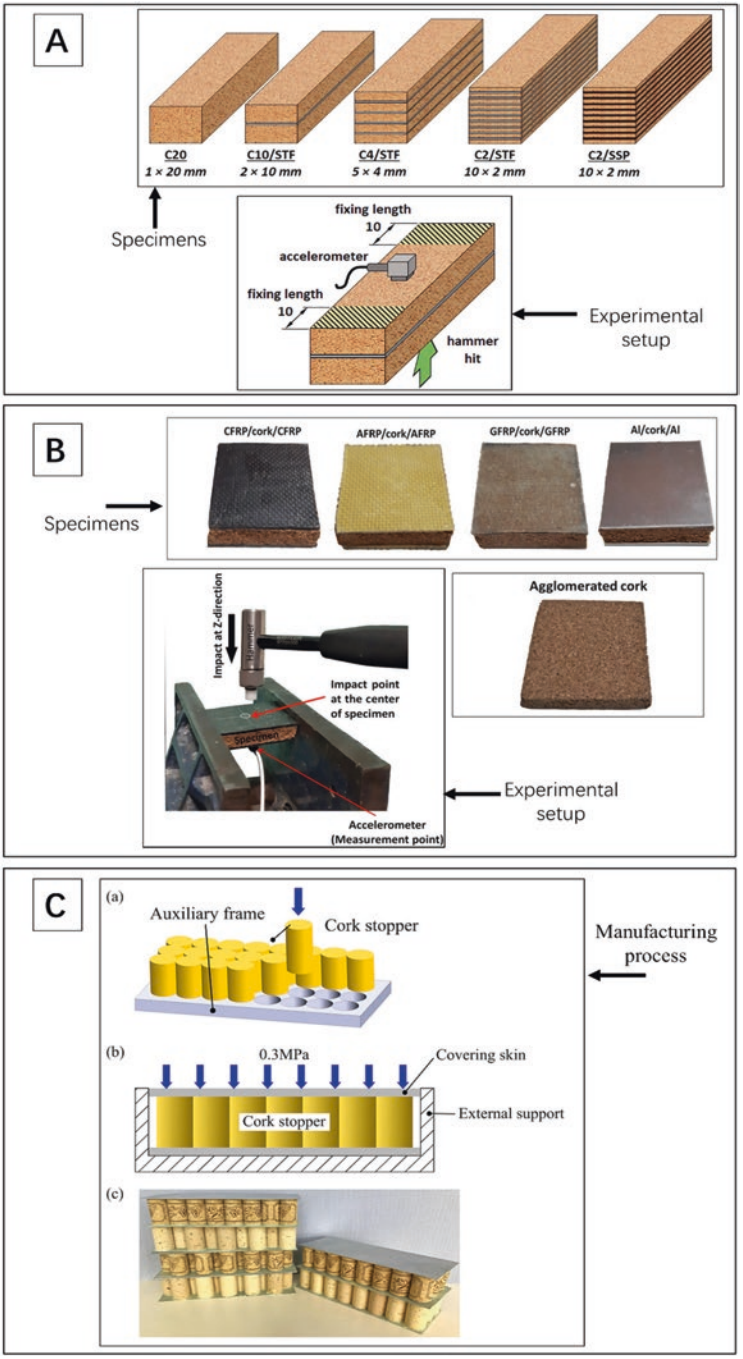

Fig. 4.4 (**a**) Smart polymer integrated cork composites, (**b**) cork-based sandwich structures, and (**c**) sandwich structure with cork stopper cores [34–36]

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

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

4.3 A Case Study of Vibration Damping Capability of Cork Composites

4.3.1 Experimental Details

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

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

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

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

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

Fig. 4.5 Details of the components

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

4.3.2 Results and Discussion

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

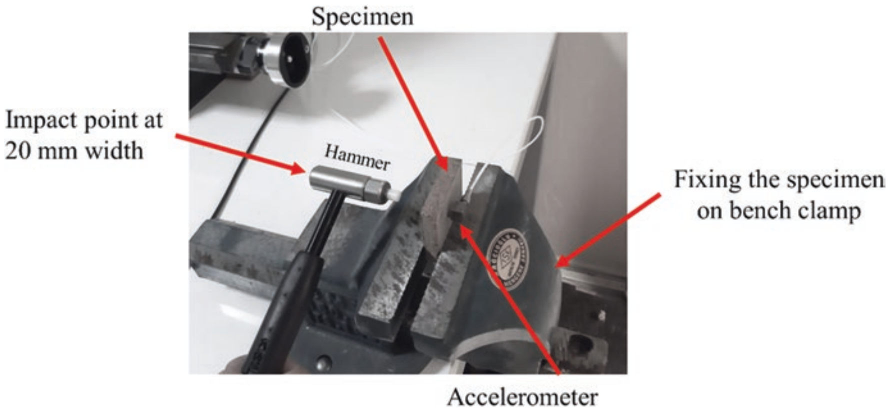

Fig. 4.6 Experimental setup in the vibration tests

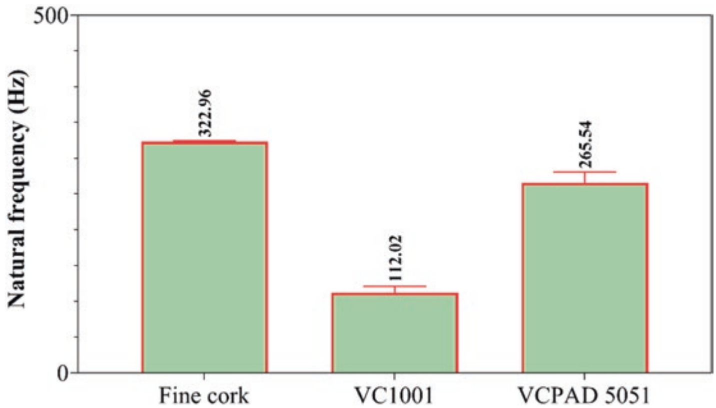

Fig. 4.7 Natural frequency of cork composites

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

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

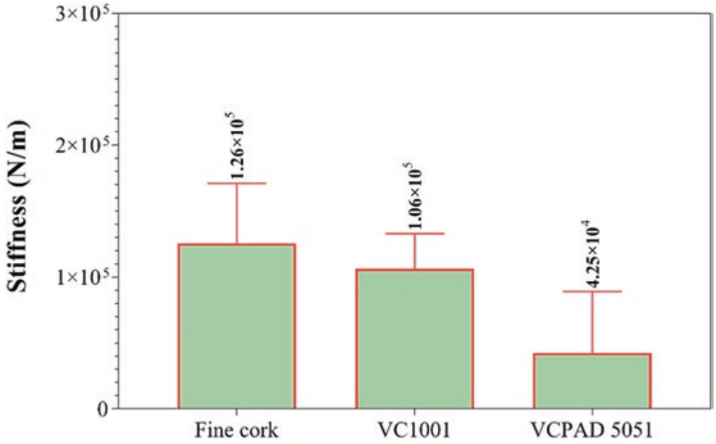

Fig. 4.8 Stiffness coefficient of cork composites

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

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

4.3.3 Discussion

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

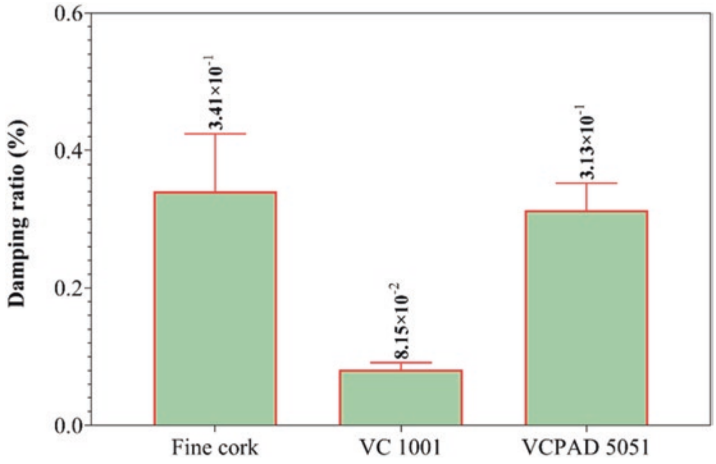

Fig. 4.9 Damping ratio of cork composites

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

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

4.4 Conclusions

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

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