TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Materials and Environmental Technology

NOISE REDUCTION AND MECHANICAL PROPERTIES OF BIRCH PLYWOOD SANDWICH PANELS WITH CORK COMPOSITE CORE

KORKKOMPOSIIDIST SÜDAMIKUGA KASEVINEERIST SÄNDVITŠPANEELIDE MÜRASUMMUTUS JA MEHAANILISED OMADUSED

MASTER THESIS

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Tallinn 2023

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THESIS TASK

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Thesis topic:

(in English) "Noise reduction and mechanical properties of birch plywood sandwich panels with cork composite core "

(in Estonian) "Korkkomposiidist südamikuga kasevineerist sändvitšpaneelide mürasummutus ja mehaanilised omadused"

Thesis main objectives:

1. To develop an optimized design approach for birch plywood sandwich panels that incorporate cork composite core materials of various thicknesses,

2. To achieve superior noise reduction and mechanical properties suitable for architectural applications.

Thesis tasks and time schedule:

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PREFACE

This master thesis entitled " Noise reduction and mechanical properties of birch plywood sandwich panels with cork composite core" was initiated by the Department of Materials and Environmental Technology at Tallinn University of Technology. The major work for this thesis was carried out at the laboratory of Wood Technology in wood building and at the Department of Mechanical and Industrial Engineering where acoustic, where various mechanical and acoustic tests were conducted on the cork composite core birch plywood sandwich panels. The sandwich panels are prepared with varying core materials (cork, amorim cork, and rubber cork) with the thicknesses of 3 and 6 mm.

I am grateful to my supervisor, professor Jaan Kers for their guidance and support throughout the research process. I would also like to thank early stage researcher, Tolgay Akkurt for his assistance in data collection and analysis; their insights and suggestions were invaluable in shaping the direction of the research and improving the quality of the results. The experimental part of this thesis would not have been possible without the invaluable assistance of Margus Kangur, who provided his technical expertise as a technician at the laboratory of wood technology. Therefore, I extend our sincere appreciation to him for his contribution to this study.

This thesis aims to evaluate the effect of different types of core materials and their thicknesses on the noise reduction and mechanical properties of birch plywood sandwich panels. The mechanical tests conducted include bending strength and modulus of elasticity tests, tensile strength perpendicular to the plane of the board, and shear strength tests. The noise reduction index test, according to ISO 10140, was also conducted to assess the acoustic properties of the panels.

The results of this research demonstrate that the type and thickness of core materials have a significant impact on the noise reduction and mechanical properties of the panels. The use of cork and cork composite as core materials shows promising results in improving the noise reduction index property of the birch plywood panel.

In conclusion, this thesis provides valuable insights into the noise reduction and mechanical properties of birch plywood sandwich panels with different core materials and thicknesses, which could be useful for the development of sustainable building materials.

Keywords: acoustic properties, noise reduction, mechanical properties, birch plywood sandwich panels, cork, cork composite.

List of abbreviations and symbols

BPSP - Birch Plywood Sandwich Panel

C - Cork

AC - Amorim Cork

PVA - Polyvinyl Acetate

PU - Polyurethane

RC - Rubber Cork

Note: Abbreviations will be explained where they first appear in the thesis text.

Symbols:

E - Modulus of Elasticity

S - Shear Strength

T - Tensile Strength

Δ - Change

ΔE - Change in Modulus of Elasticity

ΔS - Change in Shear Strength

ΔT - Change in Tensile Strength

1. INTRODUCTION

In recent years, there has been a growing interest in developing effective sound insulation materials. Although some panels are already available in the market (see Table 1), the mechanical and noise reduction properties of different materials and the production process still require further investigation. Therefore, this study aims to address this gap in research by examining the impact of different thicknesses of cork, rubber cork, and amorim cork on the acoustic properties of birch plywood.

Wood panels with core materials, including natural wood and cork-based composites, have been the subject of a number of research for their sound insulation and acoustic properties in various applications [1] [2] [3] [4] [5]. As noise pollution and acoustic privacy concerns continue to grow, there is an increasing demand for sustainable and effective soundproofing solutions. This has led to the development of innovative wood-based materials and designs aimed at improving acoustic performance [6] [5]. To ensure the comprehensiveness of our study, different studies were reviewed regarding sound insulation materials and their properties on sandwich panels with core materials [7] [8] [9] [10] [11]. It was found that the efficiency of sound insulation is strongly influenced by the thickness and density of the core material, as well as the overall design of the panel [12] [13]. However, it was also discovered that there are very few studies that have examined the specific combination of materials that we are focusing on in this study.

The findings suggested that the choice of core material, thickness, and design can significantly affect the acoustic and mechanical performance of the panels.
Based on these findings, this thesis aims to develop an optimized design approach for birch plywood sandwich panels that incorporate cork materials of various thicknesses, to achieve enhanced noise reduction and mechanical properties suitable for architectural and transportation applications. The research will assess the sound reduction index, bending strength, modulus of elasticity, tensile strength perpendicular to the plane of the board, and bonding quality of the composite sandwich panels to identify the effective combination of design parameters. Incorporating the findings from the literature review and the results of the research, this thesis will contribute to the development of sustainable and effective soundproofing solutions for architectural and transportation applications.
Therefore, it is important to understand how cork-based composites materials can be used to improve the noise reduction properties of birch plywood.

Previous studies have explored the use of cork materials in composite panels to improve acoustic performance. However, further research is needed to investigate the noise reduction and mechanical properties of Birch plywood sandwich panels with cork materials of varying thicknesses and compositions. This study is addressed to fill in the research gap is that there is no comprehensive dataset available where noise reduction properties of various core material types (cork, Amorim cork and rubber cork core materials) and thicknesses are compared on the same basis in birch plywood sandwich panels made with same adhesive. Noise reduction is important characteristic of plywood sandwich panels, but the core material thickness has effect to the mechanical properties (MOR, MOE, crosswise tensile strength and shear strength in bonding) of the panels that needs to be studied thus the optimal balance between the properties should be defined.

The study aims to answer the following research questions:

1. Are the noise reduction properties of birch plywood sandwich panels linearly correlated with the core materials thickness?
2. How do the noise reduction properties of the sandwich panels vary with different core material types (cork, Amorim cork, and rubber cork)?
3. What are the mechanical properties of the sandwich panels with different core materials and thicknesses?

Objectives

The main objectives of this study are:

1. To develop an optimized design approach for birch plywood sandwich panels (BPSP) that incorporate cork composite core materials of various thicknesses.
2. To study the noise reduction effect of the sandwich panels with various core material types (cork, Amorim cork, and rubber cork)?
3. To study the relation of improving noise reduction properties to the mechanical properties of birch plywood sandwich panels.

To achieve these objectives, the following tasks needs to be completed:

1. To evaluate potential of cork and cork composite sandwich panels as sustainable materials for improving sound quality in transportation means and public rooms alike, dining rooms, open space offices, and manufacturing facilities.
2. Assessing the sound reduction index of the plywood sandwich panels,

3. Testing the mechanical properties of the plywood sandwich panels with different core materials like bending strength, modulus of elasticity, tensile strength perpendicular to the plane of the board.
4. Evaluation of the bonding quality of the composite sandwich panels
5. Relation between noise reduction and mechanical properties will be studied.

2. LITERATURE REVIEW

2.1. Methods for Measuring Sound Transmission

The measurement of sound transmission is an essential aspect of acoustic engineering design, and various methods have been developed to quantify this parameter. Two commonly used techniques are the impedance tube system and the reverberation room. The impedance tube system involves the use of a long, narrow tube with microphones at each end [14]. A loudspeaker emits sound waves into the tube, and the microphones measure the sound pressure at each end. The difference in pressure is used to calculate the acoustic impedance of the material or product being tested, providing information on sound absorption coefficient, sound transmission loss, and sound reflection properties. This method has been used extensively in the evaluation of materials such as insulation, carpets, and acoustic tiles [15] [16].
The reverberation room is a large, enclosed space with highly reflective surfaces that allow sound waves to bounce around and create a diffuse field of sound. Equipped with multiple speakers and microphones, the sound field is measured to determine the room's acoustic properties, such as its reverberation time, sound absorption coefficient, and sound transmission loss. This method has been widely used in the evaluation of acoustic products such as loudspeakers, headphones, and musical instruments [17] [16].

The choice of method depends on the specific application and the type of information required. The impedance tube system is useful for measuring the acoustic properties of materials, whereas the reverberation room is better suited for evaluating the performance of acoustic products in a realistic environment. the impedance tube system and the reverberation room provide valuable information for measuring sound transmission. These methods have been widely used in various fields, such as construction, industrial, and acoustic engineering, to develop and evaluate sound insulation and acoustic products [18] [19].

2.2. Sound reduction index (SRI)

Sound insulation refers to the ability of a structure to block the transmission of sound waves through it. It is determined by the ratio of incident sound power to the radiated sound power from the structure. The standardized measure of sound insulation is known as the Sound Reduction Index (SRI), which is defined as the ratio of the incident sound power to the radiated sound power on a logarithmic scale [20] [21].

The formula for sound reduction index (R) calculation is:

$$R = 10\log\left(\frac{W_1}{W_2}\right) \quad (2.1)$$

where W_1 is the incident sound power on the element, and W_2 is the radiated sound power from the element.

The SRI is presented in decibels (dB) and captures the relative changes in sound pressure levels as perceived by human beings. A 10 dB increase in sound level is perceived as being twice as loud, while a 10 dB decrease is perceived as being half as loud. In building acoustics, the SRI is typically presented in one-third octave bands between 50 and 5000 Hz, with some applications capturing levels down to 20 Hz [22] [23] [20].

The measurement procedure for SRI is defined in ISO 10140 series, where the structure or specimen under investigation is placed between two rooms that ideally have diffuse acoustical fields [24]. The SRI is calculated on the basis of the sound pressure levels in the source and receiving rooms, the area of the specimen, and the equivalent absorption area that defines the losses present in the receiving room during the measurement [25].

2.3. Sound insulation materials

Sound insulation materials are designed to reduce the transmission of sound waves from one area to another. These materials are typically used in building construction to reduce the amount of noise that can travel through walls, floors, and ceilings, and they are also used in other applications such as in automobiles, airplanes, and industrial settings [26]. Common sound insulation materials include fiberglass batts or blankets, mineral wool, foam panels, mass-loaded vinyl, and acoustic tiles. These materials work by absorbing or blocking sound waves, thereby reducing the amount of noise that can pass through a particular surface [27] [28]. The selection of sound insulation material depends on the application and the desired level of sound reduction. Factors such as thickness, density, and the type of material used can all affect the performance of the sound insulation.

2.3.1 The impact of material physical properties on sound insulation performance

The effectiveness of sound insulation materials is determined by several factors, including their physical and acoustical properties. Among these factors, the physical properties of sound insulation materials play a significant role in their performance.

Density, thickness, and surface area are the critical physical properties that affect sound insulation performance. Higher density materials provide better sound insulation due to their increased mass, which reduces sound transmission. Similarly, thicker materials offer improved sound insulation due to increased mass and reduced sound transmission. Furthermore, a larger surface area can enhance sound insulation performance by increasing the number of sound wave reflections [29] [26] [7] [30] [13].However, the micro-structure of the material also plays an important role in sound insulation. The micro-structure of a material refers to its internal composition, such as the arrangement of its fibers or particles. A material with a complex micro-structure can scatter sound waves and prevent them from passing through the material, providing better sound insulation [1] [26].

2.3.2 Wood sandwich panels, acoustic and mechanical properties

Wood is a widely used construction material with anisotropic, viscoelastic, polymeric and porous structures. It is known for its low heat conductivity, low bulk density, easy machinability, high strength, good acoustic properties, material sustainability, low energy consumption, and low carbon footprint. With the developing technology, wood has also found its use in building systems such as cross-laminated timber and glulam [31]. Additionally, it is preferred for making musical instruments as a structural and semi-structural material. Selection of wood species is made according to usage and purpose, and thus, their properties must be determined accurately. Using wood materials in the decoration environment has a direct impact on the acoustic behavior of the space, particularly in terms of sound transmission or sound absorption [32].

Wood sandwich panels have been gaining attention as effective materials for acoustic applications. Sandwich structures, which consist of two face-sheets and a core layer, were first developed in the aerospace industry for their high performance and stiffness-to-weight ratio [33]. Researchers have explored various core geometries, such as metallic foam, honeycomb, and corrugated cores, to enhance the mechanical and acoustic properties of sandwich structures. Hollow cores with discrete geometry have higher stiffness-to-weight ratio and provide additional thermal and acoustic benefits. Sandwich structures are not limited to the aerospace industry, as they are also used in the automotive, marine, and civil industries [34] [35]. In fact, the building industry has borrowed this concept to develop construction materials such as the structural insulated panel (SIP), which comprises an insulated foam core between OSB face-sheets. Various materials can be used in the panels to improve their sound reduction properties, making

wood sandwich panels a promising option for acoustic applications in building construction [36] [3] [4].
Sandwich panels used for acoustic applications can be made from a variety of materials. The face sheets of the sandwich panel are usually made from materials with high stiffness and low density, such as plywood, medium density fiberboard (MDF), or high-density particleboard (HDPB). The core material, which is the layer between the face sheets, is often made from materials with low density and good sound absorption properties, such as acoustic foam or mineral wool. Additionally, there are other materials [12] [8] [2] [9] [37] that can be used in the skin and core layer to improve the sound insulation properties of sandwich panels. Several materials have been found effective in improving the sound insulation properties of wood sandwich panels [38] [39] [40] [5] [37]. Studies have shown that materials such as cork, textile and fibrous materials, rubber, and plywood made from beech, alder, birch, and spruce have a positive impact on the sound insulation performance of the panels. These materials can be used as the core layer of the sandwich panel or applied as an additional layer to enhance sound insulation. Additionally, the combination of different materials can further improve the acoustic properties of the panels [41] [40] [5] [37] [42] [43] [8] [2].

Moreover, materials like gypsum, plasterboard, and cement board are commonly used as face sheets for sandwich panels in construction applications. These materials are known for their excellent sound insulation properties due to their high mass, density, and stiffness. However, they are not ideal for acoustic panels used in musical applications, as they do not provide good sound absorption properties. Overall, the selection of materials for acoustic sandwich panels depends on the specific application and desired acoustic properties [44].

2.3.3 Cork and cork composite materials

Cork is a versatile and sustainable material that has been used for centuries in a wide range of applications. Its unique properties, such as low density, high compressive strength, and excellent thermal insulation, make it an attractive choice for many industries. In recent years, cork composites, such as Amorim cork and rubber cork, have emerged as popular materials due to their unique mechanical properties [45].

Cork

Cork is a natural material harvested from the bark of cork oak trees found mainly in Portugal, Spain, Algeria, Morocco, Tunisia, Italy, and France [46]. cork oak (Quercus suber L.) is composed of an aggregate of cells with a closed-cell structure. This unique material possesses many exceptional properties that make it highly versatile and valuable for a wide range of industrial and consumer applications. For example, cork's lightweight and elastic nature, combined with its impermeability, thermal and acoustic insulation properties, and natural texture and color, make it a popular choice for flooring, wall tiles, insulation, gaskets, seals, and other applications. Cork is sustainable harvesting practices further enhance its appeal as an environmentally friendly choice for various applications. Harvesting the bark of the cork oak trees is done without harming the tree, and the bark regenerates naturally over time. This makes cork a sustainable and renewable resource that benefits both the environment and the economy.

Cork has some limitations due to its low tensile strength and susceptibility to tearing. However, it has excellent compressive strength and resilience, which make it ideal for certain applications. Its unique cellular structure also makes it elastic and flexible, although relatively soft and susceptible to scratches and dents. Cork's density of approximately 220 kg/m^3 makes it a lightweight material that is highly porous, with approximately 50% of its volume consisting of air [47]. Its ability to dampen sound vibrations also makes it an excellent sound insulator, making it a popular choice for acoustic applications such as flooring, wall tiles, and soundproofing. Additionally, cork is resistant to water due to its natural waxy substance, suberin, and is resistant to many chemicals, including acids and bases. It is naturally fire-resistant and does not emit toxic gases when burned [48] [49] [50] [51] [52].

Rubber cork

Rubber cork is a composite material that is made from a blend of cork granules and synthetic rubber. The combination of cork and rubber creates a material with unique properties that make it suitable for a wide range of industrial and commercial applications. rubber cork is a highly durable and long-lasting material that can withstand high temperatures and extreme weather conditions [53]. The natural texture and color of cork give rubber cork a pleasant aesthetic appearance, making it ideal for use in decorative applications. Rubber cork can be easily cut, molded, and shaped to fit specific needs, making it highly versatile and adaptable to different applications. In terms of physical properties, rubber cork has a moderate density and is relatively lightweight compared to other sealing sheets. It has excellent compressive strength and resilience, which allows it to withstand pressure and return to its original shape after compression. Rubber cork also has good shock absorption properties, which make it ideal for use in vibration-dampening applications [54] [55].

Amorim cork

Amorim Cork is one of the cork products that are utilized in several industries, including marine, transportation, construction, and other industrial applications. The combination of cork with polymers enables manufacturers to increase the acoustic and thermal performance of their products significantly. One of the notable features of cork is its exceptional insulation properties, which make it an ideal material for use in various applications. Its low thermal conductivity and high thermal resistance make it an excellent thermal insulator, while its ability to dampen sound vibrations makes it an effective sound insulator. The Amorim Cork Composites team is dedicated to the development of materials that can cater to the specific requirements of various industries, such as marine, transportation, construction, and others. By incorporating cork with recycled materials, Amorim Cork Composites has been able to enhance the acoustic performance and environmental sustainability of its products in many different applications. [56] [57] [58].

2.3.4 Birch plywood

Birch plywood is an engineered wood product (EWP) that has been used for decades in a wide range of applications. It is composed of an odd number of thin wood veneers or plies, typically ranging 1.5 millimeters in thickness, which are bonded together with adhesive. Adjacent veneers have their grain direction oriented perpendicular to one another, resulting in a strong and stable material [59].

Birch, a hardwood species widely distributed in northern Europe and across the Eurasian continent has superior physical and mechanical properties. Birch wood's tensile strength parallel to the grain of individual plies has been reported to exceed 100 MPa, comparable to other hardwoods such as oak and beech [60] [61] [62]. Nordic and Baltic countries, have significant standing crop of birch [63].

Despite its desirable properties, birch plywood is rarely used in structural engineering applications, and only partial information on its mechanical properties parallel and perpendicular to the face grain is available in the literature [64] [65]. One area where birch plywood has shown room for improvement is in its acoustic properties, which can limit its use in applications requiring effective sound insulation. As a result, recent research has focused on developing composite panels that incorporate sound-absorbing materials to improve the acoustic performance of birch plywood. One approach involves using cork and cork composites materials, which are known for their excellent sound absorption properties, as the core material in the composite panel.

2.3.5 Current acoustic plywood sandwich panels with cork and cork composite in the market

Birch acoustic plywood panels that incorporate cork and cork-based materials as the core layer are becoming increasingly popular due to their superior acoustic performance. These panels have found widespread use in the transportation industry and building sector for their sound insulation capabilities. Several manufacturers, including UPM Plywood and KoskiSound F, produce acoustic birch plywood panels with cork core material in various thicknesses. Similarly, PlyGuard Phone utilizes birch acoustic plywood panels that incorporate cork and rubber cork core materials. Metsä Wood produces birch Ply sonix light panels with amorim cork core material and birch ply phonix panels with rubber cork core material, both available in different thicknesses. The sound reduction index of these panels varies between 30 and 35 dB. Additionally, WISA-PHON N/A offers birch plywood panels with rubber cork core material in varying thicknesses. The properties of acoustic birch plywood panels that feature cork and cork-based materials from various companies are summarized in the table below [66] [67] [68] [69].

Table 1. Properties of birch plywood sandwich panels with cork and cork composite in the market [66] [67] [68] [69] .

No	Panel's name	Company	Plywood	Core material	Panel's thickness, (mm)	Applications	Index Rw, (dB)
1	UPM Plywood	UPM	Birch	Cork	16, 21	Transport industry	35
2	KoskiSound F	KoskiSound F	Birch	Cork	16, 18, 22	Transport industry	31-32
3	PlyGuard phone	PlyGuard phone	Birch	Cork, Rubber cork	15, 18	Transport industry	32-35
4	Birch Ply sonix light	Metsä Wood	Birch	Amorim cork	16, 19	Transport industry & Buildings	30-31
5	Birch ply phonix	Metsä Wood	Birch	Rubber cork	15, 18	Transport industry	30-31
6	WISA-PHON N/A	WISA-PHON N/A	Birch	Rubber cork	16, 21	Transport industry	32, 34

3. MATERIALS AND METHODS

3.1. Materials

In this study, a total of 12 plywood sandwich panels were produced, consisting of birch plywood as the upper and bottom layers with cork, rubber cork, and Amorim cork as the core materials. Birch plywood (3000 × 1500 mm) was obtained from Estonian Plywood company and cut into size of 2420 × 1150 mm with a thickness of 6.5 mm with a density of 640-700 kg/m^3. Cork and rubber cork of 3 and 6 mm thicknesses were provided by Korkowy Company in Poland with the densities of 220 kg/m^3 and 600 kg/m^3, respectively. Amorim cork of 3 and 6 mm thicknesses were obtained from ACM18, with a density ranging from 900 to 1030 kg/m^3.

Polyurethane, Kestopur 200/90, was used as the adhesive to bond the core materials to the Birch plywood. The resin had a density of approximately 1.60 kg/m^3, and the hardener had a density of approximately 1.20 kg/m^3. The table below displays the properties of materials utilized in panel production, with data sourced from the official website of the materials company.

Table 2. Materials used in plywood sandwich panels

No	Materia	Thickness (mm)	Density (kg/m^3)	Supplier/Source
1	Birch plywood	6.5	640-700	Estonian Plywood company
2	Cork	3, 6	220	Korkowy Company, Poland
3	Rubber cork	3, 6	>600	Korkowy Company, Poland
4	Amorim cork	3, 6	900-1030	ACM18
5	Polyurethane adhesive	N/A	Resin approx. 1.60 kg/dm^3, Hardener approx1.20 kg/dm^3.	K-Rauta company

3.2. Methods

For the sandwich panel design, the following test standards of acoustic and mechanical properties with their requirements for test specimens number and sizes and conditioning were used (see Table 3**Error! Reference source not found.Error! Reference source not found.**).

Table 3. Testing Procedures and Sample Dimensions

No	Test	Sample Size	Quantity	Test Standards	Conditioning	Equipment
1	Sound Insulation	2100 mm x 1000 mm	12 (one samples from each panel)	ISO 10140 and TalTech acoustic laboratory' standardized test methods and equipment.	Room temperature (23°C)	Reverberation room
2	Tensile Strength	50 mm x 50 mm	144 (12 samples from 12 panels)	EN 319	65% RH and 20°C for 24 hours	ZwickRoell Z050 testing machine
3	Bending and Modulus of Elasticity	430 mm x 50 mm (6 mm core material) and 370 mm x 50 mm (3 mm core material)	144 (12 samples from 12 panels)	EN 310	65% RH and 20°C for 24 hours	ZwickRoell Z050 testing machine
4	Bonding Quality	170 mm x 50 mm	144 (12 samples from 12 panels)	EN 314-1	Immersed in water at 23°C for 24 hours or conditioned in a climate chamber with a relative humidity of 65% and a temperature of 20°C	ZwickRoell Z050 testing machine

3.3. Sample Preparation

Layouts for preparing samples for testing are shown in Figures 1 and 2. Sampling and cutting of test pieces were carried out according to EN 326-1. The dimensions of the samples' group were marked on the panels according to the corresponding standard (ISO 10140, EN 310, EN 314, EN 319) [24] [70] [71] [72].

The samples were named on the cutting layout as follows: (B) for bending strength and modulus of elasticity test (EN 310), (I) for tensile strength perpendicular to the plane

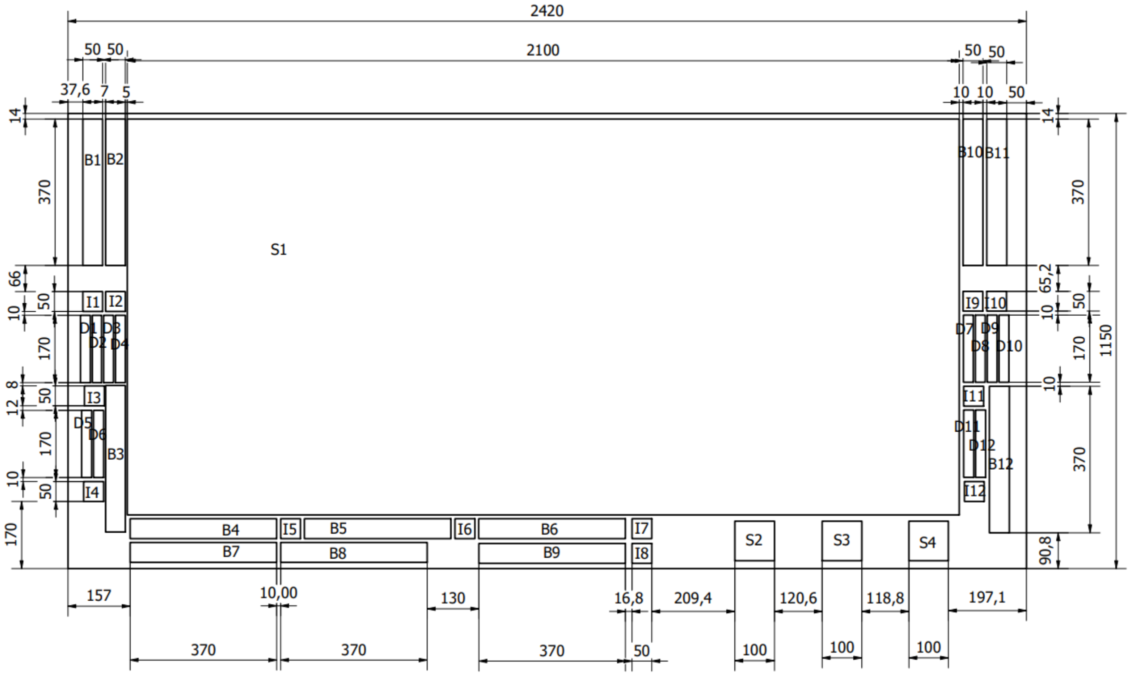

Figure 1. cutting plan for sampling test specimens for core materials with 3 mm thickness

of the board (EN 319), and (D) for the bonding quality test (EN 314-2). However, in the test results, samples are named according to the core materials’ type.

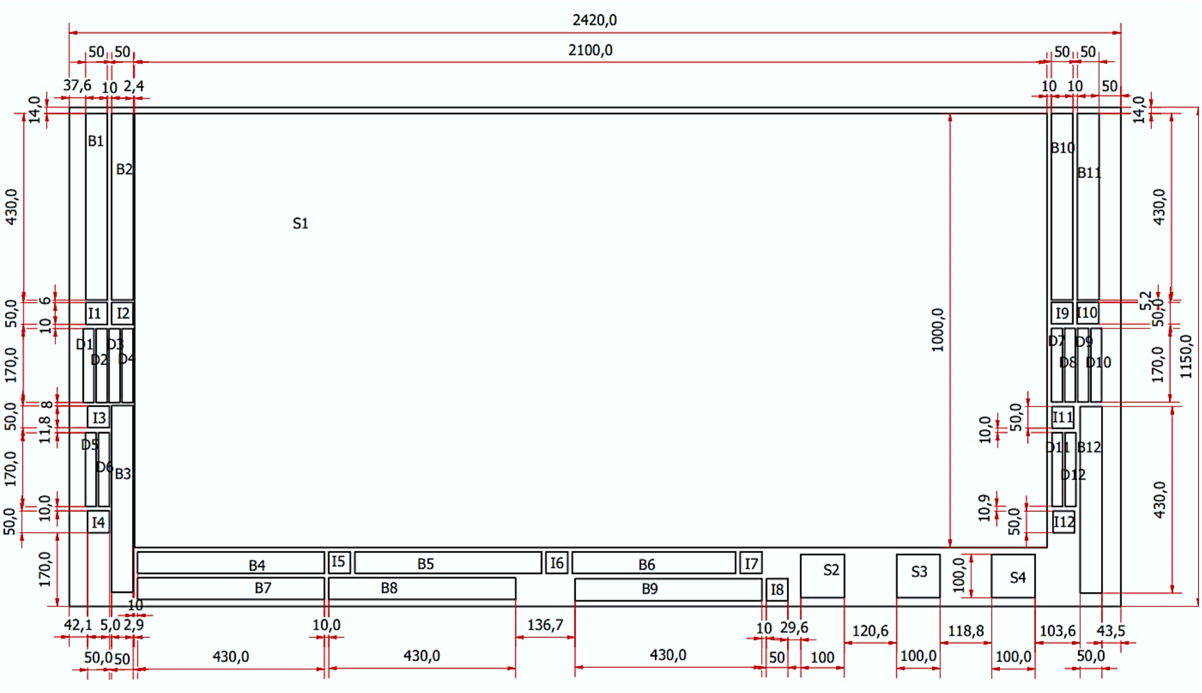

Figure 2. Cutting plan for sampling test specimens for core materials with 3 mm thickness

The insulation samples were marked as S1 according to the required size (2100 mm* 1000 mm) of the sound insulation test equipment in the acoustic department of Tallinn university of technology.

3.4. . Samples and Coding System for Test Results

The study utilizes a naming convention to identify samples based on the type and thickness of their core materials. The resulting coding system is presented in the table below, which details the samples associated with amorim cork of 3 mm thickness (AC3), amorim cork of 6 mm thickness (AC6), rubber cork of 3 mm thickness (RC3), rubber cork of 6 mm thickness (RC6), cork of 3 mm thickness (C3), and cork of 6 mm thickness (C6).

Table 4. Samples and Coding System for Test Results based on Core Material Type and Thickness

Sample Name	Core Material Type	Core Material Thickness
AC3	Amorim Cork	3 mm
AC6	Amorim Cork	6 mm
RC3	Rubber Cork	3 mm
RC6	Rubber Cork	6 mm
C3	Cork	3 mm
C6	Cork	6 mm

3.5. Panel Production

This study investigated the production of sandwich panels by combining cork and cork composite materials with Birch plywood. The materials were cut using a table saw into a size of 2420 × 1150 mm and were conditioned at room temperature (23 °C) for at least 24 hours prior to the pressing process. The process of applying the glue involved using a wooden trowel to apply a quantity of 1.670 kg of the polyurethane glue to each surface of the materials (in each panel, two surfaced were glued including the surface of button plywood and one surface of core materials for gluing the upper plywood), while adhering to a 5:1 mix ratio of Kestopur 200/90 resin and Kestopur 200/S hardener. Adherence to the glue standard required that the maximum amount of glue applied per unit area did not exceed 600 g/m². Once the glue was applied on the bottom side of plywood, the core material was placed on its glued surface, followed by the second plywood onto the glued side of the core material. The production of plywood sandwich panels was carried out in a vacuum press (TF-300HV) that had a size of 2900 × 1400 mm. The pressing process was conducted at a temperature of 20 °C and a pressure of 0.8 MPa for 360 minutes. Through adherence to the aforementioned methodology, 12 composite panels were successfully produced. All the process of production was conducted at the laboratory of wood technology of Tallinn university of technology.

Figure 4. Left: Application of glue on the surface of the plywood. Middle - Spreading of glue on the side of the plywood. Right - Application of glue on the surface of the core material.

Figure 3. left: the top plywood is glued and ready for pressing. middle: panel under the press. right: pressed panel.

Figure 5. Left: samples are cut. Right: samples are conditioned in the climate chamber.

3.6. Testing and Measurements

3.6.1. Sound Insulation Testing

A total of 12 samples (one sample from each Birch plywood sandwich panel) with a size of 2100 ×1000 mm were prepared (cut and conditioned at room temperature (23 °C) for sound insulation testing. A birch plywood with 18 mm thickness was tested as the control sample for this test. The outside dimensions of samples were determined by the acoustic laboratory, according to the test open area of the reverberation test room for the door requirement. The following is a test method for determining the sound reduction index Rw of a door using the reverberation method according to ISO 10140 [24].

The tests were conducted in the acoustic laboratory at Tallinn University of Technology under the condition of temperature 20.1°C, humidity 60%, and barometric pressure 1010 hPa. The sandwich panel with the size 2420 × 1150 mm. The sandwich panels were cut into the final size 2100×1000 mm to test acoustic properties in the door size opening. From each test series were two panels prepared with the same composition. The test facilities fulfilled the requirements of the standards ISO 10140-5 and ISO 10140-4 for the measurement of sound insulation of building elements.There were 12 sandwich test panels prepared of birch plywood top and bottom layers with various core materials like cork, amorim cork, and rubber cork of 3mm and 6mm thickness. Equipment used in the test included a 2-channel noise level meter Bruel & Kjaer 2270, measurement microphones Bruel & Kjaer 4189, an omnidirectional loudspeaker Bruel & Kjaer 4292-l, a scanning boom Bruel & Kajaer 3923, a sound amplifier Bruel & Kajaer 2734, and an acoustic calibrator Bruel & Kajaer.

The test method involved the following steps:

The test object (door) was installed in the test facility, and the test environment was set to a temperature of 20.1°C, humidity of 60%, and barometric pressure of 1010hPa.

The background noise level in the test facility was measured using the 2-channel noise level meter and the measurement microphones. The background noise level was recorded for each measurement point and used to correct the test results.

The loudspeaker was placed on one side of the door, and the measurement microphones were placed on the other side of the door. The scanning boom was used to position the measurement microphones at different heights and distances from the door. The loudspeaker was then activated, and a steady-state noise signal was generated at a sound pressure level of 100dB. The noise level was measured using the

2-channel noise level meter and the measurement microphones at each measurement point. The loudspeaker was then turned off, and the reverberation time in the test facility was measured using the 2-channel noise level meter and the measurement microphones.

Steps 3 to 5 were repeated for each panel of the door.

The sound reduction index R_w was calculated for each panel of the door using the following equation:

$$R_w = R_m + 10\log\left(\frac{A}{A_0}\right) \quad (3.1)$$

where R_w is the sound reduction index, R_m is the reference sound reduction index for the partition determined in accordance with ISO 717-1 [20], A is the average sound absorption coefficient of the receiving room, and A_0 is the reference sound absorption coefficient determined in accordance with ISO 10140 [24].

The results were recorded and analyzed to determine the acoustic performance of each panel of the door.

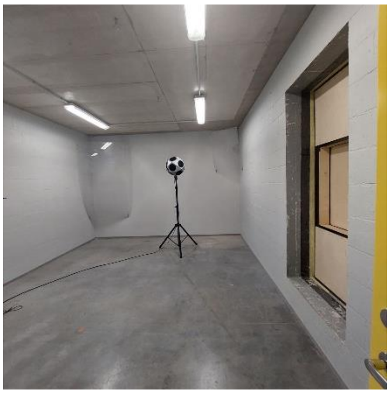

Figure 6. Left: noise source room, sound source. Middle: opening is of laboratory (test sample presented is not belonging to this test. Right: receiver room with microphone.

The weighted sound reduction index (R'_w) is a measure of the sound insulation performance of a building element, such as a wall or a ceiling. It is calculating using a combination of sound absorption and transmission measurements, with different weightings applied to various frequency bands. The formula for calculating R'_w is as follows by equation 3.2:

$$R'_w = R + C - 10\log\left(\frac{A}{T}\right) \quad (3.2)$$

where R is the weighted sound reduction index of the building element without correction for low-frequency noise, C is the correction factor for low-frequency noise, A is the measured sound absorption coefficient of the receiving room, and T is the total transmission loss of the building element.

In this formula, R and C are measured in decibels (dB), and A and T are dimensionless coefficients. The correction factor C is only used for low-frequency noise, typically in the range of 50 Hz to 100 Hz, and it is added to the weighted sound reduction index R to account for the additional difficulty in attenuating low-frequency sounds.

Sound Reduction Index Formula is calculated by equation 3.3:

$$R = L_1 - L_2 + 10\log\left(\frac{S}{A}\right) \tag{3.3}$$

where R is the Sound Reduction Index

L_1 is the average sound pressure level in the source room.

L_2 is the average sound pressure level in the receiving room.

S is the area of the test specimen (m^2)

A is the equivalent sound absorption area of the receiving room (m^2)

3.6.2. Tensile strength perpendicular to the plane of the board test

In accordance with established protocols, 12 samples were extracted from each panel, each with dimensions of 50 mm × 50 mm; in this way, a total 24 samples with the same properties and core material (12 samples × 2 panels) were prepared. Subsequently, the samples were affixed to test blocks (plywood bricks), in dimensions of 65 mm × 50 mm using PVA adhesive. The samples were then cold pressed with a 1 kg metal weight for a period of 24 hours. Following the gluing and pressurization procedures, the samples were conditioned in a climate chamber (with the condition of 65% RH and 20°C) for an additional 24-hour period. Finally, the samples were tested for tensile strength perpendicular to the plane of the board utilizing a ZwickRoell Z050 testing machine. The methodology employed during testing was conducted in accordance with the guidelines established by EN 319 [72].

The tensile strength perpendicular to the plane of the board of each test piece, F, expressed in N/mm^2, to two decimals, is calculated according to the following equation 3.4:

$$\text{Tensile strength perpendicular to the plane (MPa)} = \frac{F}{A} \tag{3.4}$$

Where:

F = maximum load at failure (N)

A = cross-sectional area of the specimen (mm^2)

Figure 7. The sample with rubber cork 6 mm thicknesses is tested according to EN 319.

3.6.3. Bending and modulus of elasticity test

The sample preparation procedure was conducted following the European standard EN 326-1, with the sample dimensions determined based on EN 310. Specifically, 12 samples were extracted from each panel, with dimensions of 430 × 50 mm for panels containing a 6 mm core material and 370 × 50 mm for those with a 3 mm core material. From the 12 samples obtained, 6 were designated for testing in the longitudinal grain direction and 6 in the transverse grain direction. In total, 24 samples were prepared with the same properties and core material (12 samples from two panels) for this test.

Before conducting the tests, all samples were conditioned in a climate chamber for 24 hours at a condition of 65% relative humidity and 20°C. The three-point bending and modulus of elasticity tests were performed on the conditioned samples using a ZwickRoell Z050 testing machine. The procedures and methodologies for testing were conducted in accordance with EN 310 guidelines.

Formula 1*: The formula for modulus of elasticity (E) according to EN 310 for a rectangular plywood specimen under a bending test is described in equation 3.5:

$$E = \frac{FL^3}{4bd^3\Delta} \tag{3.5}$$

where F is the maximum load applied to the specimen, L is the span between supports, b is the width of the specimen, d is the thickness of the specimen, and Δ is the deflection at the midspan. The modulus of elasticity is expressed in N/mm^2.

Formula 2*: The formula for bending strength (MOR) according to EN 310 is expressed in equation 3.6:

$$MOR = \frac{3PL}{2bw^2} \tag{3.6}$$

where MOR is the modulus of rupture in N/mm^2, P is the maximum load in N, L is the span in mm, b is the width of the specimen in mm, and w is the thickness of the specimen in mm.

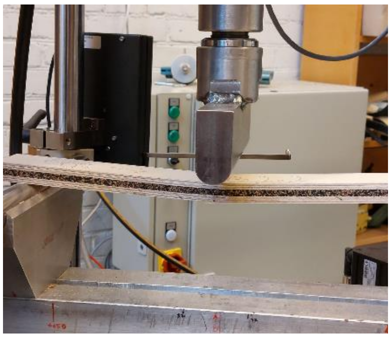

Figure 8. The sample with rubber cork 6 mm thicknesses
is tested according to EN 314.

3.6.4. Bonding quality test

The sample preparation protocol was executed in compliance with the European standard EN 326-1, whereas the dimensions of the samples were ascertained in agreement with EN 314. The shape and dimensions of the samples were determined based on EN 314-1. Prior to testing, the samples underwent pre-treatment (according to 5.1.1 pre-treatment EN 314-1 for dry condition) as follows: 12 samples (from each panel) were prepared with the dimension of 170 mm × 50 mm, and 6 samples from each panel were immersed in water at 23°C for 24 hours, while the remaining 6 samples were conditioned in a climate chamber with a relative humidity of 65% and a temperature of 20°C. In total, 24 samples (with the same property) were prepared for this test (12 samples for dry and 12 samples for wet condition).

Figure 9. Samples are immersed in water.

The testing methodology adhered to EN 314-1. The bonding quality test was conducted on the conditioned samples, using a ZwickRoell Z050 testing machine.

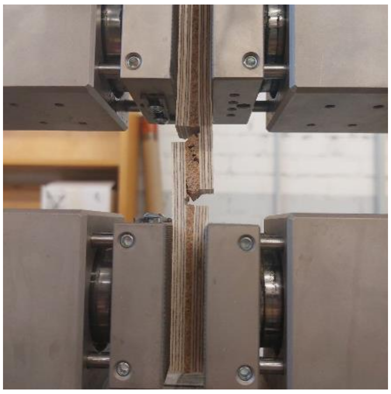

Figure 10. The sample with cork 6 mm thicknesses is tested according to EN 310.

Formula 3*: The shear strength (f_v) test formula according to EN 314 for plywood is:

$$f_v = \frac{F}{bd} \tag{3.7}$$

where:

f_v is the shear strength in N/mm^2

F is the maximum force required to shear the specimen in N

b is the width of the specimen in mm

d is the thickness of the specimen in mm

4. RESULTS AND DISCUSSION

4.1. Modulus of elasticity and bending strength

4.1.1. Modulus of elasticity

The test results showed that the modulus of elasticity (MOE) of birch plywood sandwich panels with cork, amorim cork and rubber cork materials varied depending on the thickness of the core material, the direction of the grain, and the type of material used for core.

In the 6 mm core materials, the MOE ranged from 2154.9 N/mm² for AC6 to 4100.9 N/mm² for C6 in the longitudinal direction, and from 1857.9 N/mm² for AC6 to 3723.6 N/mm² for C6 in the transverse direction. The standard deviation of the MOE values was generally higher for the transverse direction. In contrast, the MOE values for the 3 mm core materials ranged from 3579.4 N/mm² to 6139.8 N/mm² in the longitudinal direction, and from 2954.8 N/mm² to 4898.5 N/mm² in the transverse direction. The standard deviation values were also generally higher in the transverse direction for the 3 mm core materials.

In terms of the type of core material used, the cork-based samples generally had higher MOE values than the rubber cork and amorim cork materials. This trend was observed in both the longitudinal and transverse directions and for both 3 mm and 6 mm core materials. Additionally, there was a general trend of higher MOE values in the longitudinal direction compared to the transverse direction, regardless of the type or thickness of the core material.

Table 5. Mean modulus of elasticity test results for each group of samples

Core Material	Mean MOE Longitudinal (N/mm²)	Standard Deviation Longitudinal (N/mm²)	MOE Transverse (N/mm²)	Standard Deviation Transverse (N/mm²)
AC6	2154.9	99.1	1857.9	153.6
AC3	3579.4	407.3	2954.8	505.8
RC6	3581.5	610.7	3234.3	917.8
RC3	4278.3	656	4157.4	664
C6	4100.9	225	3723.6	745.8
C3	6139.8	633.2	4898.5	381

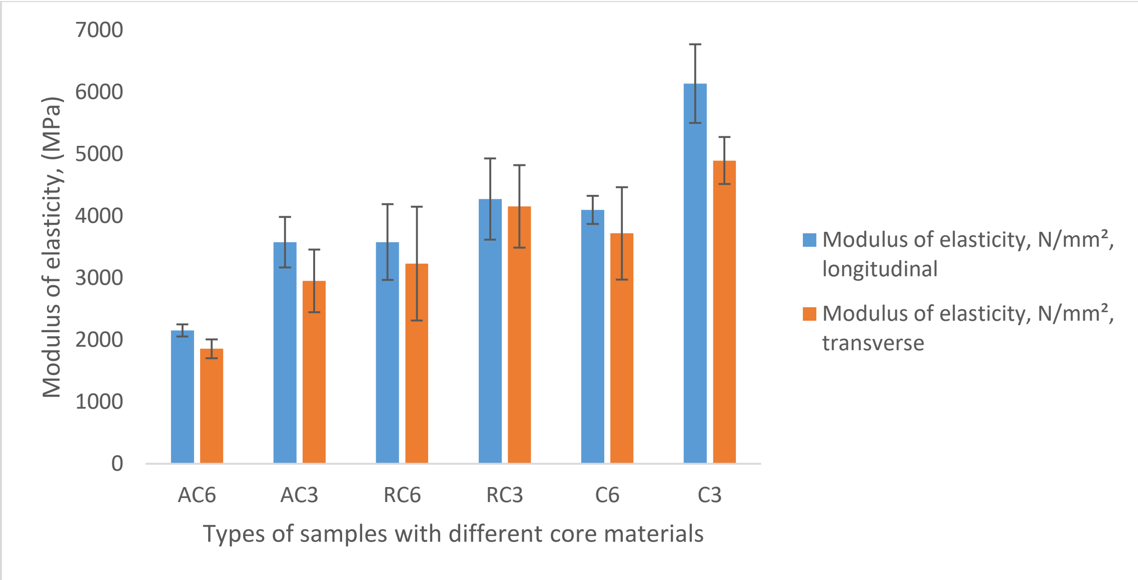

Figure 11. Mean values of elastic modulus test results test results for samples with different core materials.

Discussion

The MOE values for the longitudinal direction of the sandwich panel are higher than those for the transverse direction for all core materials; this result was expected due to the fact that if the wood fibers in the plywood top layer are oriented in the longitudinal direction, resulting in a stronger mechanical property in this direction.

Comparing the various core materials, it is observed that the amorim cork and rubber cork cores have lower MOE values than the cork cores. Increasing the core thickness from 3 mm to 6 mm results in a decrease in MOE values for all core materials. This is because thicker cores are subjected to higher total stress at the interfaces between the core and the plywood tops, resulting in a lower effective MOE for the sandwich panel since the core materials are weaker than the covering plywoods.

Finally, the standard deviation values presented in Table 5 indicated that there is some degree of variability in the MOE values obtained for each group of samples. This could be due to variations in the manufacturing process, as well as to natural variations in the properties of the wood.

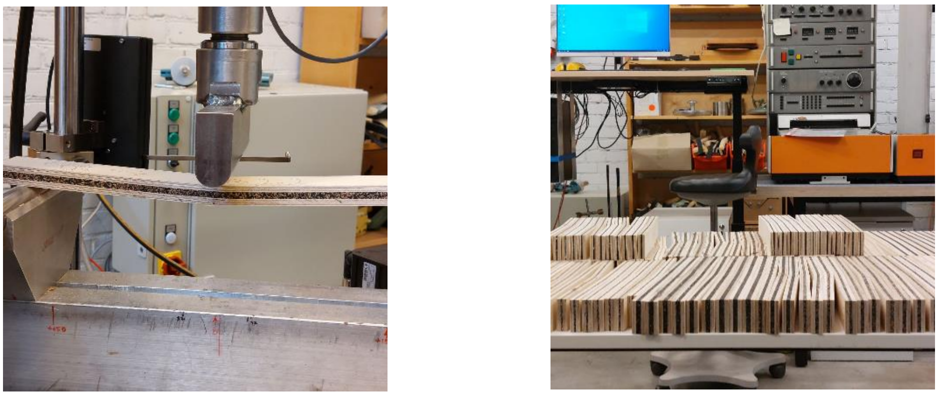

Figure 12. Left: 3-point bending test of the samples with rubber cork 6 mm is tested. right: the tested samples.

4.2. Bending strength

The bending test results for birch plywood sandwich panels with cork, amorim cork and rubber cork materials are presented in Table 6. The samples are categorized based on their thickness and type of core material used (AC for amorim cork, RC for rubber cork, and C for cork and the numbers represent the thickness of the core material). The bending test was conducted in both longitudinal and transverse grain directions.

Table 6. Mean bending strength test results for samples with each core materials

No	Core Materials	Mean Bending Strength, N/mm² (Longitudinal)	Standard Deviation, N/mm²	Mean Bending Strength, N/mm² (Transverse)	Standard Deviation, N/mm²
1	AC6	36.4	3.9	36.3	2.5
2	AC3	51.4	3.9	45.2	5.6
3	RC6	42.1	3.2	34.5	11.9
4	RC3	57.5	5.7	52.1	3.8
5	C6	37.9	4.7	30.6	10.5
6	C3	55.6	8	49.4	8.1

For the 6 mm thick samples, the mean bending strength values ranged from 36.4 N/mm² for AC6 to 42.1 N/mm² for RC6 in longitudinal direction, and from 30.6 N/mm² for C6 to 36.3 N/mm² for AC6 in transverse direction. Among the 6 mm samples, the highest bending strength was observed in RC6 (42.1 N/mm²) in the longitudinal direction, while the lowest bending strength was observed in C6 (30.6 N/mm²) in the transverse direction.

For the 3 mm thick samples, the mean bending strength values ranged from 51.4 N/mm² for AC3 to 57.5 N/mm² for RC3 in longitudinal direction and from 45.2 N/mm² for AC3 to 52.1 N/mm² for RC3 in transverse direction. Among the 3 mm samples, the highest bending strength was observed in RC3 (57.5 N/mm²) in the longitudinal direction, while the lowest bending strength was observed in AC3 (45.2 N/mm²) in the transverse direction.

The standard deviations for each group of samples varied from 2.5 N/mm² to 11.9 N/mm², with the highest standard deviation observed in RC6 in the transverse direction.

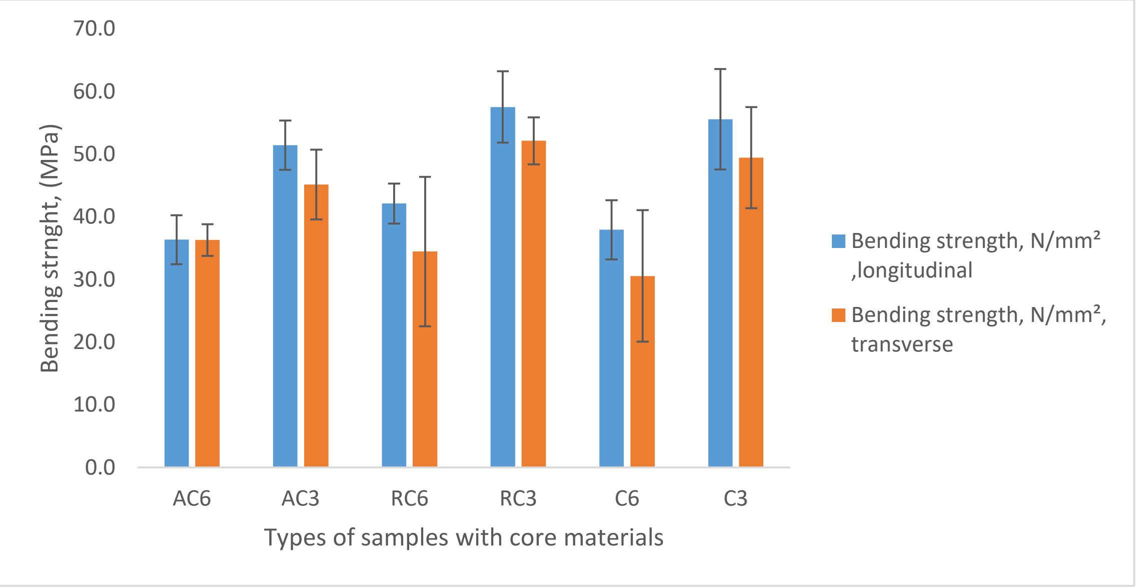

Figure 13. Mean values of bending strength test results for samples with different core materials.

Discussion

The results of the three-point bending strength tests showed that the choice of core material and its thickness significantly affect the mechanical properties of sandwich panels. The rubber cork-based sandwich panels generally demonstrated higher bending strength in the longitudinal direction compared to the other panels with cork and amorim cork cores. On the other hand, the panels with cork cores generally showed lower bending strength in the transverse direction.

As in the case of MOE, the bending strength of panels with 3mm core materials showed higher strengths comparing to 6 mm cores. Between the core materials rubber cork core panels showed higher strength values comparing to other two core materials.Also, longitudinal strength of panels was higher than transverse strength of panels as expected.

Among the samples tested, RC3 had the highest bending strength in the longitudinal direction, indicating that a rubber cork-based sandwich panel with a thickness of 3 mm can provide good mechanical properties in specific loading conditions. However, the manufacturing process of these panels should be optimized to reduce the variability of the material properties and ensure consistent quality.

Overall, the study highlights the potential of rubber cork-based sandwich panels as lightweight and resilient materials in specific applications. Further research is necessary to investigate the durability and environmental sustainability of these materials and optimize their design for specific engineering applications.

4.3. Tensile strength perpendicular to the plane of the board

The test was conducted according to EN 319 on birch plywood sandwich panels with cork, Amorim cork, and rubber cork materials. The samples were tested for mean tensile strength and standard deviation at thicknesses of 3 and 6mm for each of the core materials. The total number of samples tested was 144, with 8 samples failing from the plywood blocks.

Table 7. Tensile strength perpendicular to the plan test results.

No	Core Material	Number of total samples per each group	Number of samples were failed from the core materials	Number of samples were failed from the plywood holders	Mean Tensile Strength (MPa)	Standard Deviation (MPa)
1	C3	24	16	8	0.99	0.38
2	RC3	24	13	11	1.32	0.23
3	AC3	24	19	5	1.25	0.20
4	C6	24	22	2	0.67	0.31
5	RC6	24	14	10	1.28	0.23
6	AC6	24	22	2	0.64	0.19
7	Total samples	144	106	38		

For the 3mm thickness, the mean tensile strength ranged from 0.99 MPa for C3 to 1.32 MPa for RC3 core materials. Rubber cork had the highest mean tensile strength (1.32 MPa), followed by Amorim Cork (1.25 MPa) and Cork (0.99 MPa). The standard deviation for each core material, ranged from 0.20 MPa to 0.38 MPa.

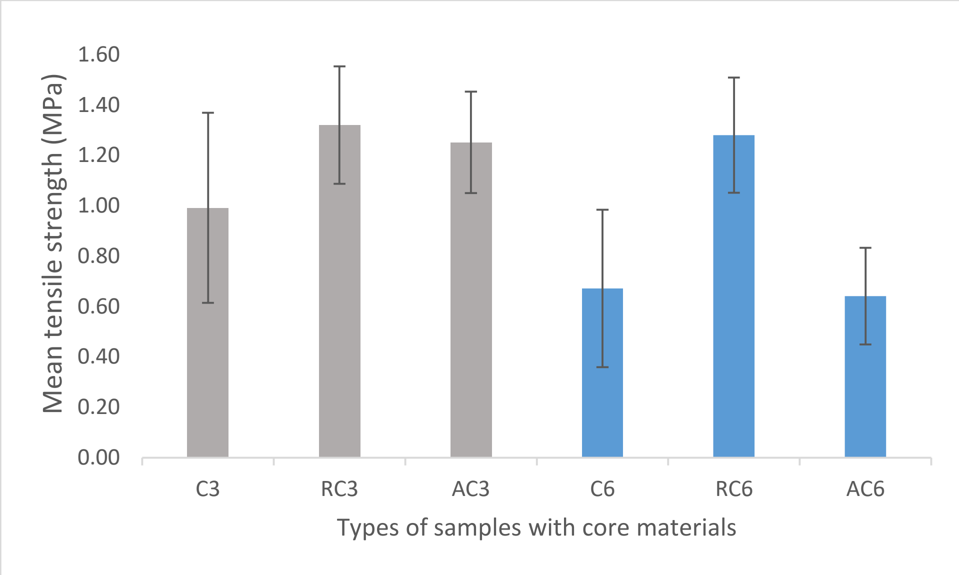

Figure 14. Mean values of tensile strength perpendicular to the plane test results for samples with different core materials.

For the 6mm thickness, the mean tensile strength ranged from 0.64 MPa to 1.30 MPa for the different core materials. Rubber Cork had the highest mean tensile strength (1.28 MPa), followed by Cork (0.67 MPa), and Amorim Cork (0.64 MPa). The standard deviation for each core material, ranged from 0.19 MPa to 0.31 MPa.

For 3 mm thickness, the number of accepted samples (those that did not fail from the plywood holder) also varied between the different core materials, with 19 accepted samples from Amorim cork, 16 from Cork, and 13 from Rubber Cork. For 6 mm thickness, on the other hand, the number of accepted samples was the same for Cork and Amorim Cork at 22 each, while Rubber Cork had the lowest number of accepted samples at 14. This indicates that the type of core material used in the birch plywood sandwich panels can significantly affect the failure mechanism and therefore the overall reliability of the test results, even at thicker core material thicknesses.

In terms of the effectiveness of the core material and thickness on the results, it can be seen that the type of core material and thickness had a significant effect on both the number of accepted samples and the mean tensile strength. Rubber Cork had the highest mean tensile strength for both thicknesses but also the lowest number of accepted samples. Amorim Cork had the highest number of accepted samples for both thicknesses but a slightly lower mean tensile strength than Rubber Cork. Cork had intermediate values for both number of accepted samples and mean tensile strength.

The thickness of the core material also had an effect on the results, with thinner core materials generally having higher mean tensile strength and a higher number of accepted samples.

In terms of the number of failed samples from the plywood holder, it is important to note that this can affect the overall reliability of the test results. In this case, 8 samples (5.5% of the total samples) failed from the plywood holder, which may indicate issues with the sample preparation or testing conditions. Further investigation may be required to identify the cause of the failure and ensure that the testing conditions are optimized for future tests.

Overall, the test results suggest that the choice of core material and thickness can significantly affect the mechanical properties of birch plywood sandwich panels, and the selection should be carefully considered based on the specific application requirements.

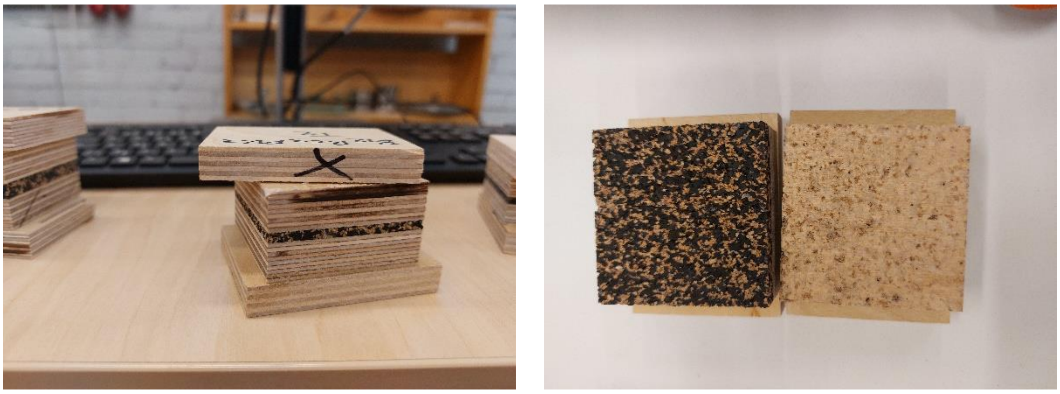

Figure 15. Left: plywood holder failure. right: adhesive failure.

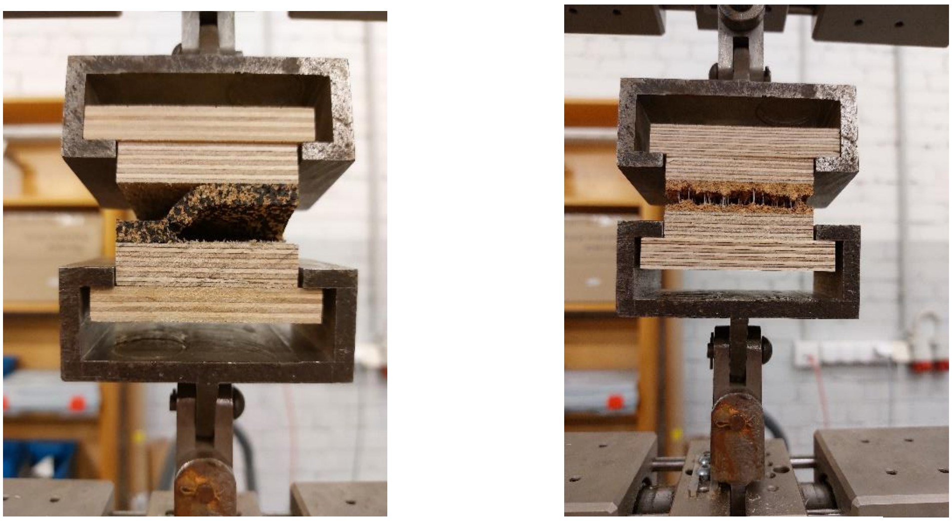

Figure 16. Left: Mixed failure. right: core failure.

Figure 17. Left: plywood failure right: core failure.

4.4. Shear strength

The present study aimed to evaluate the bonding quality of birch plywood sandwich panels with different core materials including cork, amorim cork, and rubber cork, using PU (Polyurethane adhesives). The study followed the requirements stated in EN 314-2 which include the mean shear strength and the mean apparent cohesive wood failure criteria. The bonding quality was evaluated through dry and wet shear strength tests, and the results were analyzed to determine the core failure percentage.

The results of the dry and wet shear strength tests are presented in Table 8. The mean shear strength of the samples ranged from 0.68 N/mm² to 1.57 N/mm² for dry samples and from 0.44 N/mm² to 1.49 N/mm² for wet samples. The standard deviation of the dry samples ranged from 0.08 N/mm² to 0.48 N/mm², while that of the wet samples ranged from 0.10 N/mm² to 0.26 N/mm². The core failure percentage ranged from 9% to 80.00% for dry samples and from 4% to 67.00% for wet samples.

Table 8. Mean values of shear strength test results for samples with different core materials.

No	Core Material	Mean Shear Strength, N/mm² (Dry)	Standard deviation, N/mm²	Mean Cohesive Core Failure, % (Dry)	Mean Shear Strength, N/mm² (Wet)	Standard deviation, N/mm²	Mean Cohesive Core Failure, % (Wet)
1	AC6	0.86	0.08	10	0.78	0.10	5
2	AC3	1.48	0.19	9	1.43	0.21	4
3	RC6	1.29	0.12	10	1.08	0.19	9
4	RC3	1.57	0.21	22	1.49	0.20	22
5	C6	0.68	0.25	80	0.44	0.20	67
6	C3	1.14	0.48	60	0.98	0.26	56

The results of the shear strength test showed that the bonding quality of the samples varied depending on the core material and thickness. In dry conditions, the samples with RC3 and AC3 as the core material had the highest shear strength, with values of 1.57 N/mm² and 1.48 N/mm², respectively. On the other hand, the samples with C6 as the core material had the lowest shear strength, with a value of 0.68 N/mm². In wet conditions, the samples with RC3 and AC3 as the core material had the highest shear strength, with values of 1.49 N/mm² and 1.43 N/mm², respectively. The samples with C6 as the core material had the lowest shear strength, with a value of 0.44 N/mm².

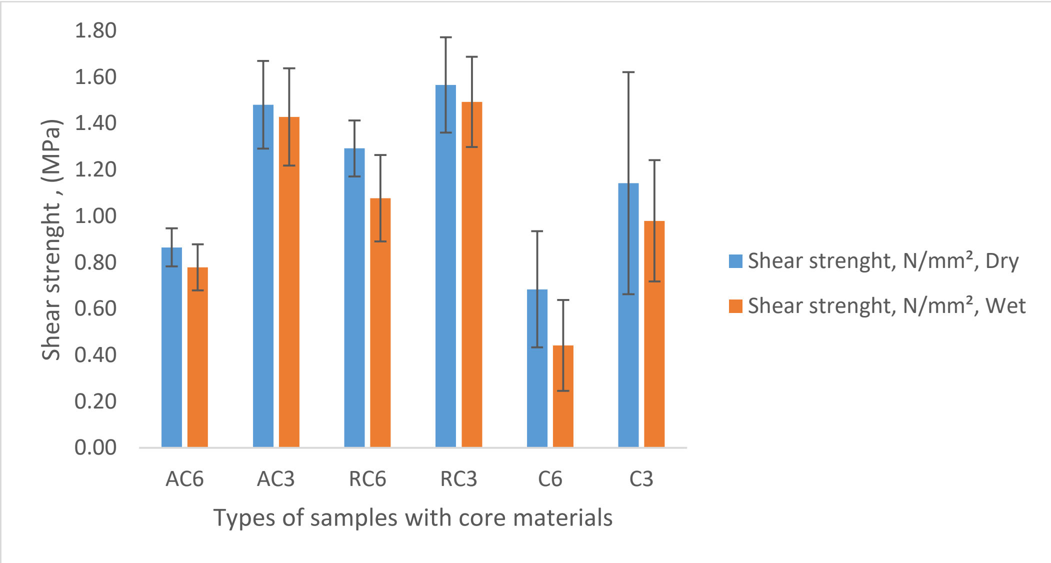

Figure 18. the mean of shear strength test result for samples with different core materials.

Discussion

Based on the results of this study, it can be concluded that the core material and thickness are important factors that affect the bonding quality of birch plywood sandwich panels. In particular, the results show that the use of AC3 and RC3 as the core material can lead to high shear strength, both in dry and wet conditions. This is likely due to the good mechanical properties of these materials.

Figure 19. left: the dry sample with cork core material is tested. right: the wet sample with Amorim cork core material is tested.

On the other hand, the samples with C6 and C3 as the core material showed the lowest shear strength. This could be attributed to their low density and poor mechanical properties, which can negatively affect the bonding quality. However, it is worth noting that the results of this study only apply to the specific types of core materials and adhesive used, and may not be generalizable to other materials or applications.

Furthermore, the results also suggest that thinner core materials (3 mm) can lead to higher shear strength compared to thicker core materials (6 mm). This could be due to the fact that thinner core materials are more flexible and can conform better to the surfaces of the facesheets, resulting in better bonding between the core and facesheets. Additionally, thinner core materials may allow for better adhesive penetration and distribution, which can also improve the bonding quality.

Finally, the results also showed that the wet samples had lower shear strength compared to the dry samples, which is expected due to the effect of water on the adhesive properties. Overall, these findings highlight the importance of carefully selecting core materials and evaluating the bonding quality through appropriate tests and standards in order to ensure optimal performance of sandwich panels in various applications.

The cohesive failure

In accordance with the EN 314-2 standard, the mean shear strength and mean apparent cohesive core failure were evaluated for each core material. Table 8 summarizes the results of the analysis.

According to EN 314-2, each glue line should satisfy two criteria: the requirements the relationship between the mean apparent cohesive wood failure and the mean shear strength as combined in following:

Table 9. the mean apparent cohesive wood failure and the mean shear strength

Mean shear strength, f_v in N/mm2	**Mean apparent cohesive core failure, in %**
$0.2 \le f_v < 0.4$	≥80
$0.4 \le f_v < 0.6$	≥60
$0.6 \le f_v < 1.0$	≥40
$1.0 \le f_v$	no requirement

Figure 20. Left: wet samples tested. right: dry samples tested.

Based on the analysis of the results, it can be concluded that the AC6, AC3, RC6, and RC3 core materials fail to meet the minimum mean apparent cohesive core failure requirements of the EN 314-2 standard, regardless of whether the samples were dry or wet. On the other hand, C6 meets the minimum requirement of ≥80% mean apparent cohesive core failure for dry samples but fails to meet the minimum requirement for wet samples. C3 meets the minimum requirement of ≥40% mean apparent cohesive core failure for both dry and wet samples. Therefore, C3 may be considered as a suitable core material for meeting the EN 314-2 standard, especially for mean shear strengths in the range of $0.6 \le \mathbf{f_v} < 1.0$ N/mm².

4.5. Noise reduction test

In this study birch plywood sandwich panels with different core materials, including cork, rubber cork, and Amorim cork were evaluated to investigate their sound insulation performance. The weighted sound reduction index ($\mathbf{R'_w}$) was used to assess the sound insulation properties of the panels, with additional corrections for low-frequency noise ($R'_w + C$ and $R'_w + C_{tr}$). The objective of this analysis is to compare the effectiveness of different core materials and their thicknesses in terms of sound insulation performance, particularly in low-frequency and high-frequency ranges. The results of the sound insulation tests are presented in table 1 in appendix A.

The R'_{w} values for all panels were greater than 26 dB**,** which indicates that core materials improved of sound insulation performance birch plywood. The R'_{w} values for panels with cork core materials (C3PU and C6PU) were slightly lower compared to panels with rubber cork and Amorim cork core material. The *R*'w values for panels with Amorim cork core materials (AC3PU and AC6PU) were the highest among all panels, which suggests that Amorim cork has better sound insulation properties than cork and rubber cork.

In the low-frequency range, the $R'_w + C$ and $R'_w + C_{tr}$ values, which represent the corrected values, were lower than the R'_{w} values, indicating the necessity of applying correction factors for low-frequency noise. The panels with thicker core materials generally showed better low-frequency sound insulation performance than the panels with thinner core materials. The $R'_w + C$ and $R'_w + C_{tr}$ values for the 6 mm thick panels were higher than those for the 3 mm thick panels. This trend was observed for all core materials, which indicates that increasing the thickness of the core material can improve the low-frequency sound insulation performance of the panels. However, the improvement with thickness is not linear with the sound insulation performance. While for all types increasing thickness from 3 mm to 6 mm means double the amount of material usage; the increase in sound insulation properties is just 75%, 40%, and 67% for rubber cork, amorim cork, and cork materials, respectively.

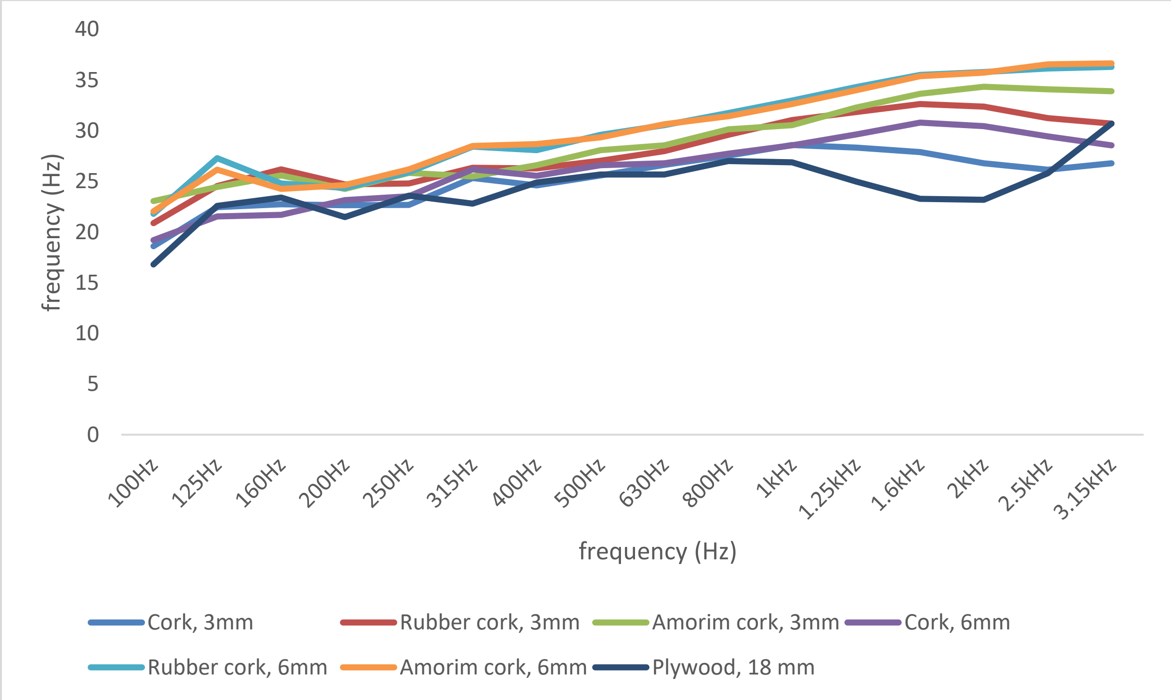

Figure 21. Sound reduction index (SRI) ranged from 100Hz to 3.15Hz of birch plywood sandwich panels with different core materials and thicknesses

In the high-frequency range, the R'_w, $R'_w + C$ and $R'_w + C_{tr}$ values for all panels were similar, regardless of the core material or its thickness. This suggests that the sound insulation performance of the panels in the high-frequency range is not affected by the core material or its thickness. The high-frequency sound insulation performance of the panels is mainly determined by the surface density and stiffness of the panel.

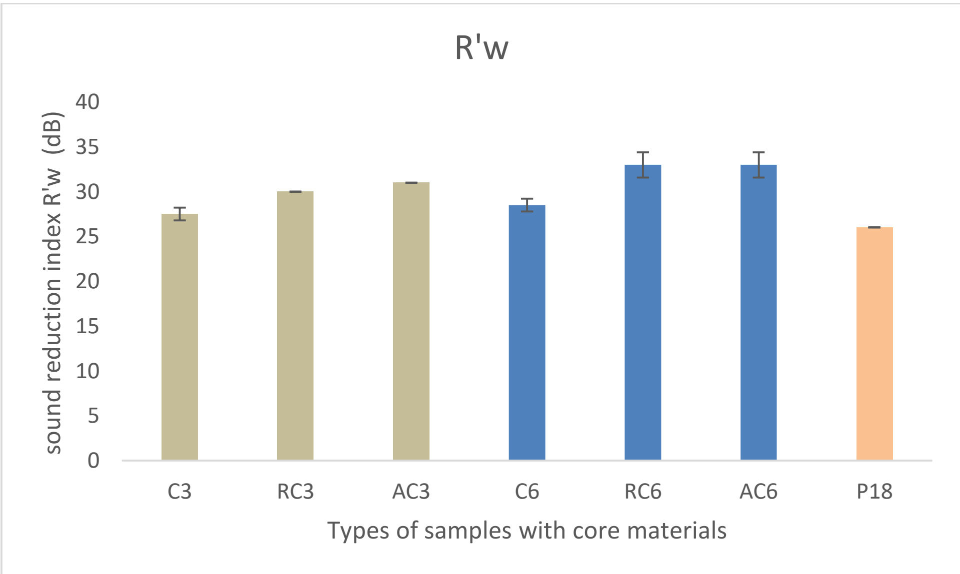

Figure 22. Mean weighted sound reduction index (R_w) for birch plywood sandwich panels, expressed in (dB).

The samples with amorim cork and rubber cork core material had the highest weighted sound reduction index (R'_w) values, with AC6PU and RC6PU having the highest R'_w values of 33. The samples with cork core material had the lowest R'_w values, with C3PU and C6PU having R'_wvalues of 27.5 and 28.5, respectively.

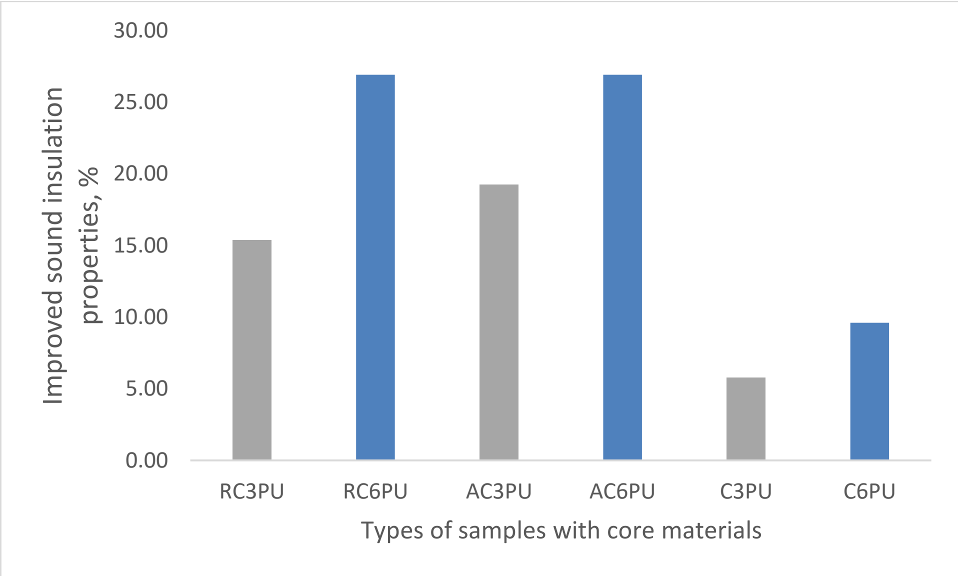

Figure 23. Improved sound insulation property for each core materials.

Based on the results (see Figure 23. Improved sound insulation property for each core materials), it appears that the addition of core materials to the plywood samples has generally improved their sound insulation properties.

Comparing the plywood sample control (P18) with the other samples, we can see that all the samples with core materials (RC3PU, RC6PU, AC3PU, AC6PU, C3PU, C6PU) have higher R'_w values and therefore better sound insulation properties than the plywood sample control. In particular, the samples with rubber cork and Amorim cork as core materials (RC3PU, RC6PU, AC3PU, AC6PU) show the greatest improvement in sound insulation properties, with R'_w values ranging from 30 to 33 and percentage improvements ranging from 15.38% to 26.92%.The samples with cork as the core material (C3PU, C6PU) show more modest improvements in sound insulation properties, with R'w values ranging from 27.5 to 28.5 and percentage improvements ranging from 5.77% to 9.62%.

Discussion

The experiment conducted on the sound insulation performance of birch plywood sandwich panels with cork, rubber cork, and Amorim cork core materials provides important insights for optimizing the acoustic properties of composite materials. The results show that the choice of core material and its thickness greatly affect the sound insulation performance of the panels, particularly in low-frequency noise.

Furthermore, the thickness of the core material also plays a crucial role in sound insulation performance. Thicker core materials provide better sound insulation, particularly in low-frequency noise. This is evident in the results where panels with thicker core materials (AC6PU, RC6PU, C6PU) had higher R'w values than panels with thinner core materials (AC3PU, RC3PU, C3PU). However, this role is not linear with the thickness.

In terms of frequency, the results show that the sound insulation performance of the panels varied across different frequency ranges. The Amorim cork panels (AC3PU and AC6PU) provided the highest sound insulation performance in the low-frequency range (100-315 Hz), while the rubber cork panels (RC3PU and RC6PU) provided the highest sound insulation performance in the mid-frequency range (400-1250 Hz). The cork panels (C3PU and C6PU) provided the lowest sound insulation performance across all frequency ranges.

Overall, the results of this experiment suggest that the selection of core material and its thickness is critical in optimizing the acoustic properties of composite materials. The use of Amorim cork as a core material with a thickness of 6mm provides the best sound insulation performance, particularly in low-frequency noise. The use of rubber cork as a core material with a thickness of 6mm is recommended for mid-frequency noise. However, further research is needed to investigate the effect of other factors such as panel size, shape, and boundary conditions on the sound insulation performance of composite materials. This study evaluated the sound insulation performance of birch plywood sandwich panels with different core materials and thicknesses. The results showed that Amorim cork has better sound insulation properties than cork and rubber cork. Thicker core materials generally provided better low-frequency sound insulation performance, while the high-frequency sound insulation performance was not significantly affected by the core material or its thickness. The findings of this study can be used to optimize the acoustic properties of composite materials for sound insulation applications.

4.6. Comparing acoustic properties of birch plywood sandwich panels: market vs. novel design with variable cores and thickness

In comparison to the sandwich panels available in the market (see Table 1), our 'project's sandwich panels (see Table) utilize a diverse range of core materials and thickness options. The market primarily offers sandwich panels consisting of birch plywood and cork or rubber cork as the core material, with thickness varying from 15 mm to 21mm and specifically targeted towards the transport industry. The sound insulation properties of the market panels are measured using the R'_w index, and the values range from 30 to 35 dB.

our 'project's sandwich panels consist of rubber cork, Amorim cork, and cork as the core material, with thicknesses of either 3mm or 6mm. The sandwich panels also contain birch plywood, with PU glue used as the bonding agent. The R'_w value of our samples ranges from 27.5 to 33 dB. However, direct comparison of the acoustic properties of our 'project's sandwich panels and those available in the market is challenging due to differences in the specific materials used, their thickness, and the application contexts targeted by each product. Nevertheless, the available information suggests that our 'project's panels exhibit sound insulation properties comparable to some of the market offerings while providing a broader range of core materials and thickness options.
In conclusion, our novel sandwich panel design has the potential to offer a competitive advantage over the market offerings, particularly in applications that require specific sound insulation properties or necessitate a wider range of core materials and thickness options.

5. CONCLUSION

Based on the experimental findings, it can be inferred that the incorporation of cork and cork composite materials into birch plywood sandwich panels can significantly enhance their acoustic properties.

The best noise reduction results were observed in plywood sandwich panels with core material made of amorim cork and rubber cork with a thickness of 6 mm. Furthermore, the thicker core materials displayed better acoustic performance, while the thinner materials demonstrated higher mechanical performance within each group of core materials. On the other hand, it should be kept in mind doubling the sound insulation core does not double insulation properties.

Regarding mechanical properties test results among all the samples, rubber cork with a thickness of 3 mm showed the highest bending strength, tensile strength, and shear strength. The sandwich panels with 3mm cork core had the highest MOE test results.

The study findings indicate that the plywood sandwich panel design used in this thesis has a competitive advantage in comparing the sound reduction effects of different core materials and thicknesses. This design offers a broader range of core materials and thickness options, which is particularly beneficial for construction and transportation applications that require specific sound insulation and mechanical properties. In conclusion, our novel sandwich panel design has the potential to outperform existing market offerings, especially in applications that demand specific sound insulation properties or a wider range of core materials and thickness options. So, considering the environmental impact and total material usage, using thinner material in the core can make a lighter, more economical, and environment-friendly solution for sound insulation panel production. These findings underscore the potential of cork and cork composite materials as promising components for the development of high-performance birch plywood sandwich panels.

The study successfully answered the research questions posed at the outset, indicating that the noise reduction and mechanical properties of the sandwich panels vary significantly with different core materials and thicknesses. Based on test results there was no obvious relation between the noise reduction and mechanical properties of birch plywood sandwich panels.

Further research is needed to explore the required properties for potential applications of these panels, including the impact of different manufacturing processes, variations in core material composition, and bigger-size wall testing methods to gain a more comprehensive understanding of the performance characteristics of these panels.

SUMMARY

he present study investigated the effect of different core materials and thicknesses to the noise reduction and mechanical properties.

In the introduction, the motivation and context of the study was presented, highlighting the need for improved noise reduction and mechanical properties of building materials. Thorough literature review was provided of relevant studies on cork and cork composite materials in sandwich panels.

This study aimed to fill the research gap that the commercial data of the various plywood producer´s products published on websites does not contain any information of the core material thickness and noise reduction relationship. There is a need for the comprehensive dataset of noise reduction properties of various core material types (cork, Amorim cork and rubber cork core materials) and thicknesses that are compared on the same basis in birch plywood sandwich panels made with same adhesive.

Noise reduction is important characteristic of plywood sandwich panels, but the core material thickness has also effect to the mechanical properties (MOR, MOE, cross-wise tensile strength and shear strength in bonding) of the panels that was under study.

The materials and methods for this thesis involved the production of Birch plywood sandwich panels with cork and cork composite materials using a vacuum press. Birch plywood and cork composite materials of various thicknesses were used to make the sandwich panels. The cork materials used in the study include cork, amorim cork, and rubber cork. The production process involved cutting the materials to size, gluing them together, and subjecting them to a vacuum press to ensure proper bonding. The produced sandwich panels were then cut into size by panel saw subjected to the mechanical and sound insulation tests in accordance with the applicable standards.

The mechanical tests were carried out according to the EN 310, 314, and 319 standards to evaluate the bending strength, modulus of elasticity, tensile strength perpendicular to the plane of the board, and bonding quality of the composite sandwich panels.
The sound insulation tests were performed in accordance with the ISO 10140 standard to assess the sound reduction index of the panels. MS Excel was used to analyze the data obtained from the mechanical and sound insulation tests.

The acoustic test results showed that thicker core materials had better sound reduction index particularly in low-frequency noise, while thinner cork cores had better mechanical strength. Rubber cork materials exhibited the best results in both acoustic and mechanical tests. Additionally, the type and thickness of core material were found to have a significant impact on the noise reduction and mechanical properties of the panels, with the addition of cork core materials improving the acoustic performance of the panels.

The increasing of the core material thickness from 3 mm to 6 mm does not actually increase the sound insulation properties of the birch plywood sandwich panels two times. The sound insulation properties of birch plywood sandwich-panels with thicker 6 mm core material increased for 75%, 40%, and 67% for rubber cork, amorim cork, and cork materials, respectively.

Based on test results there was no obvious relation between the noise reduction and mechanical properties of birch plywood sandwich panels.

In mechanical tests the plywood sandwich-panel samples with thinner core materials with a thickness of 3 mm showed the higher performance in terms of bending strength, tensile strength, and shear strength compared thicker 6 mm cores.
However, further research is needed to explore the full range of properties and potential applications of these panels. Future studies could investigate the impact of different manufacturing processes, variations in core material composition, and alternative testing methods to gain a more comprehensive understanding of the performance characteristics of these panels.

The findings of this study could contribute to the development of innovative sustainable plywood sandwich materials for use in transportation and architectural applications. The study could also provide insights into the acoustic and mechanical properties of BPSP with cork and cork composites as sound absorption materials, which could lead to the production of more effective and sustainable plywood sandwich-panels for noise-reduction. The study's results could be of interest to architects, technical specialists, and manufacturers of wood composite sandwich materials for transportation and building applications.

KOKKUVÕTE

Käesolevas magistritöös uuriti erinevate südamikumaterjalide tüübi ja paksuste mõju korkkomposiidist südamikuga kasevineerist sändvitš-paneelide mürasummutus- ja mehaanilistele omadustele.

Sissejuhatuses toodi välja probleemi kirjeldus, kontekst ning motivatsioon, milleks on vajadus parandada ehitusmaterjalide mürasummutus ja mehaanilisis omadusi. Esitati kirjanduse ülevaade asjakohastest uuringutest korgi ja korkkomposiitmaterjalide kohta sändvitš-paneelides.

Kirjandusandmete analüüsi ja avaliku info kogumise tulemusena, selgus, et vineeritootjate veebilehtedel esitatud tooteandmed ei võimalda hinnata südamikmaterjali kihi paksuse mõju kasevineerist sändvitš-paneeli mürasummutavatele omadustele. Selle uurimistööga soovitigi täita senistes uurimistöödes esinev tühimik, mis seisneb kasevineerist sändvitš-paneelide südamikumaterjali kihipaksuse mõjuanalüüsil selle mürasummutus omadustele. Selleks, et luua terviklik tehniline andmestik erinevate südamikumaterjalide tüüpide (kork, Amorim kork ja kummikork-südamiku materjalid) ja kihi paksuste mürasummutus omaduste kohta, tuleks välja töötada, metoodika, et valmistada kõik kasevineerist sändvitšpaneelid sama liimiga ja samadel tehnoloogiliste parameetritega ja tingimustel.

Mürasummutus on oluline vineerist sändvitš-paneelide omadus, kuid südamikumaterjali paksus mõjutab ka uuritavate paneelide mehaanilisi omadusi (MOR, MOE, risttõmbetugevus ja nihketugevus liimimisel) ja seetõttu tuleb leida optimaalne tasakaal nende omaduste vahel.

Materjalid ja meetodite osas kirjeldati kasevineerist sandwich-paneelide valmistamise metoodikat vaakumpressi abil. Sandwich-paneelide valmistamiseks kasutati erineva paksusega kasevineeri kork, amorimkork ja kummikork ja komposiitmaterjale. Tootmisprotsess hõlmas materjalide mõõtu lõikamist, kokku liimimist ja vaakumpressi st, et tagada õige nakkumine ja ühtlane paksus. Seejärel lõigati toodetud sandwich-paneelidest katsekehad vastavalt katsestandardites et teostada mehaanilised ja mürasummutus katsed.

Mehaanilised katsed viidi läbi vastavalt standarditele EN 310, 314 ja 319, et hinnata paneelide paindetugevust, elastsusmoodulit, plaadi tasapinnaga risti asetseva tõmbetugevust ja sändvitš-paneelide liimliite tugevust ja kvaliteeti.

Heliisolatsiooni testid viidi läbi vastavalt ISO 10140 standardile, et hinnata paneelide helisummutusindeksit. Mehaanika- ja heliisolatsioonikatsetest saadud andmete analüüsimiseks kasutati programmi MS Excel.

Selle uuringu tulemused näitasid, et korgi- ja korkkomposiitmaterjalidest mürasummutava täidise lisamine võib oluliselt parandada kasevineerist sändvitš-paneelide mürasummutus- ja mehaanilisi omadusi. Paksemad südamikumaterjalid tagavad parema heliisolatsiooni, eriti madala sagedusega müra korral.

Tulemused näitasid, et paksematel 6 mm paksustel südamikumaterjalidel oli parem mürasummutusindeks, samas kui õhemate 3 mm korgisüdamikuga sändvitš-paneelidel oli parem mehaaniline tugevus. Kummi ja korgi komposiitsegust südamikumaterjaliga kasevineerist sändvitšpaneelid näitasid parimaid tulemusi nii mürasummutusel kui ka mehaanilistes katsetes. Lisaks leiti, et südamiku materjali tüübil ja paksusel on märkimisväärne mõju paneelide müra vähendamisele ja mehaanilistele omadustele.

Erinevat tüüpi täidisega kasevineerist sändvitš-paneelide puhul ei suurenda südamiku materjali paksuse suurendamine 3 mm-lt 6 mm-le nende mürasummutusomadusi tegelikkuses kaks korda. Paksema 6 mm südamikumaterjaliga kasevineerist sandwich-paneelide heliisolatsiooniomadused kasvasid võrreldes 3mm südamikmaterjaliga paneelidega vastavalt 75%, 40% ja 67% kummikorgil, amorimkorgil ja 67%.

Katsetulemuste põhjal ei ilmnenud selget seost kasevineerist sandwich-paneelide müra vähendamise ja mehaaniliste omaduste vahel.

Mehaaniliste katsete tulemused näitasid 3 mm paksuste õhemate südamikumaterjalidega vineerist sändvitš-paneelide paindetugevuse, tõmbetugevuse ja nihketugevuse osas paremaid tugevusnäitajaid võrreldes paksemate 6 mm südamikuga panellidega.

Siiski on vaja teha täiendavaid uuringuid, et uurida nende paneelide kõiki omadusi ja potentsiaalseid rakendusvõimalusi. Tulevased uuringud võiksid analüüsida erinevate tootmisprotsesside, täidismaterjali koostise erinevuste ja alternatiivsete katsemeetodite mõju, et saada põhjalikum ülevaade nende paneelide tugevusnäitajatest.

Selle uuringu tulemused võivad aidata kaasa uuenduslike jätkusuutlike kasevineerist sändvitšpaneelide väljatöötamisele transpordi- ja arhitektuurirakendustes. Uuring andis ülevaate kasevineerist sändvitšpaneelide akustilistest ja mehaanilistest omadustest kui nende sisekihis kasutada korgist ja korkkomposiitidest kui heli neeldumismaterjalidega, siis võib see viia tõhusamate ja säästvamate mürasummutuspaneelide tootmiseni. Uuringu tulemused võiksid huvi pakkuda arhitektidele, tehnilistele spetsialistidele ja transpordiks ja ehituseks mõeldud kasevineerist sändvitšpaneelide tootjatele.

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APPENDICES,

Appendix A:

Table 1. Mean value of sound insulation test result.

Samples' name	Core material	R'w	R'w+C	R'w+Ctr	100Hz	125Hz	160Hz	200Hz	250Hz	315Hz	400Hz	500Hz	630Hz	800Hz	1kHz	1.25kHz	1.6kHz	2kHz	2.5kHz	3.15kHz
C3	**Cork, 3mm**	27.5	26.5	26.5	18.6	22.45	22.75	22.65	22.7	25.35	24.6	25.6	26.65	27.55	28.6	28.35	27.9	26.8	26.15	26.8
RC3	**Rubber cork, 3mm**	30	30	29	20.9	24.55	26.2	24.7	24.8	26.35	26.3	27.05	28	29.6	31.05	31.85	32.65	32.4	31.25	30.7
AC3	**Amorim cork, 3mm**	31	31	29.5	23.05	24.45	25.6	24.25	25.85	25.5	26.6	28.1	28.55	30.15	30.55	32.3	33.65	34.35	34.1	33.9
C6	**Cork, 6mm**	28.5	28	27	19.2	21.55	21.7	23.15	23.55	26.2	25.55	26.6	26.8	27.75	28.55	29.65	30.8	30.45	29.45	28.55
RC6	**Rubber cork, 6mm**	33	32.5	30.5	21.8	27.3	24.8	24.35	25.9	28.45	28.1	29.6	30.55	31.75	33	34.3	35.5	35.8	36.15	36.3
AC6	**Amorim cork, 6mm**	33	32.5	30.5	22.05	26.15	24.25	24.65	26.2	28.5	28.7	29.35	30.65	31.45	32.65	34	35.4	35.75	36.55	36.65
P18	**Plywood, 18 mm sample control**	26	25	25	16.8	22.6	23.4	21.5	23.6	22.8	24.9	25.7	25.7	27	26.9	25	23.3	23.2	25.8	30.7