DEVELOPMENT OF A LOW CARBON EMISSION COMPOSITE SANDWICH PANEL

A Thesis submitted by

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ABSTRACT

A low carbon emission construction material using waste streams and natural fibres is developed in this study. The mechanical behaviour of sandwich panels constructed with varying core and skin materials is investigated and optimised their performance for structural applications. The investigated sandwich panels involve the use of two different types of fabric (hemp and recycled PET) and three different types of waste-based core materials (composite wood, recycled plastic, and styrofoam). Skins for the sandwich panels were fabricated with bio-epoxy resin by vacuum infusion. The mechanical (tensile) and thermal (glass transition temperature) properties of skins were investigated under different environmental conditions (normal air, water, hygrothermal, saline water, and elevated temperatures). A theoretical model has been developed to calculate the bending capacity of the sandwich panels. The main findings of this study indicate that the proposed design of sandwich panels can reduce carbon dioxide emissions by 90% compared to traditional sandwich panels. Moreover, elevated temperatures have a greater detrimental effect on composite skin performance than any other environmental factor investigated in this study. Hemp skins are more susceptible to environmental effects than recycled PET skins. A higher core stiffness makes panels less likely to fail from indentation. Moreover, the core strength is the dominant factor for predicting failure loads for brittle core sandwich panels, while skin strength is the governing factor for flexible core sandwich panels. Through the optimisation of material selection and manufacturing processes, this study contributes to the advancement of eco-friendly composite technologies and the development of circular economies. It is recommended that further research should be conducted in order to determine the feasibility of large-scale production, long-term durability, and recyclability.

CERTIFICATION OF THESIS

I Md Ashiqul Islam declare that the Master of Research Thesis entitled *Development of a low carbon emission composite sandwich panel* is not more than 40,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes. The thesis contains no material that has been submitted previously, in whole or in part, for the award of any other academic degree. Except where otherwise indicated, this thesis is my own work.

Date: 19/02/2024

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CHAPTER 1: INTRODUCTION

1.1. Background and motivation

Low-emission composite sandwich panels have been emphasised as an alternative to high-carbon materials like steel and concrete due to the growing demand for sustainable materials in the construction, transportation, and infrastructure sectors. While conventional composites are lightweight and strong, their production typically involves energy-intensive processes and petroleum-based resins, resulting in significant carbon emissions (Karuppannan Gopalraj & Kärki, 2020; La Rosa et al., 2014; Norgate et al., 2007; Sorokin et al., 2021). The development of low-carbon composite sandwich panels is crucial for reducing environmental impact, improving material sustainability, and improving recyclability while ensuring structural integrity.

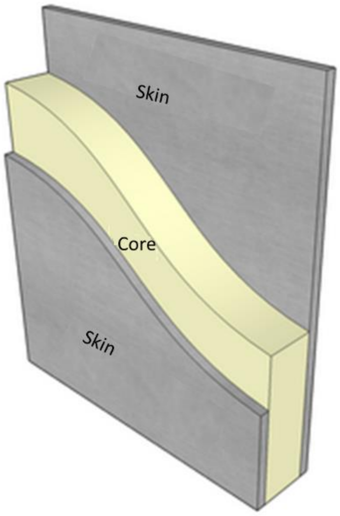


Figure 1.1: Typical sandwich panel (Dial4Trade, 2025)

A sandwich panel, which is composed of two thin, high-stiffness skins separated by a low-density, thick core, has significant advantages as a construction element because it is lightweight, strong, and provides thermally insulated characteristics. Aside from offering lightweight characteristics, composite sandwich panels should also contribute to the development of global carbon reduction goals and regulatory standards, including the European Green Deal, Net Zero and Circular Economy initiatives, by providing energy efficient transportation and reduced operational costs in buildings (Australian-Govt.; European-Commission, 2024). Aluminium, steel, plastics, and fibre composites are commonly used for the skins, while synthetic foam, wood, metal, concrete, and polymer are typically used for the core materials (Sorokin et al., 2021). The problem with the use of these commercially available materials for sandwich panels is that they emit high levels of greenhouse gases into the atmosphere as a result of their production process (Aholoukpè et al., 2023; Dietz et al., 2019; Kilgore, 2023c; Sustainable-Ships, 2023). Thus, the goal of this study is to develop a sandwich panel constructed from materials with low emissions.

Recycling wood dust (Coen, 2024), waste plastics (Replas, 2024), and styrofoam (Polystyrene, 2024) from landfills is crucial to tackle environmental issues like waste buildup, resource depletion, and carbon emissions. These materials cause landfill overflow, soil and water pollution, and greenhouse gas emissions if not properly handled. Wood dust can be reused in composite materials or bio-based fillers, reducing the need for new wood and lowering deforestation (Cherkasova, 2020; Owoyemi et al., 2016). Waste plastics and styrofoam, which are hard to degrade, can be recycled into lightweight composites, insulation, or construction materials, reducing reliance on fossil fuels and cutting plastic pollution (Kumar & Agrawal, 2021; Replas, 2024). Recycling these wastes promotes a circular economy, lowers production costs, conserves resources, and supports sustainable development while reducing the environmental impact of waste disposal. Additionally, bio-based, recycled, and low-energy processing techniques could improve their compliance with evolving sustainability regulations and market demands, thereby enabling them to be a commercially viable and environmentally responsible engineering solution in the future.

1.2. Objectives

This study aims to develop a low-carbon-emission sandwich panel made from landfill waste and bio-based materials. To achieve this aim, the specific research objectives are listed below:

Objective 1: Identifying low-emission, recycled and light-weight materials for manufacturing composite sandwich panels and understanding durability behaviour of the skins.

Objective 2: Understanding mechanical behaviour of the core and novel sandwich panels.

1.3. Scope of study

The study covers the mechanical and durability behaviour of proposed low-emission sandwich panels. It focuses on:

(a) A review of commercially available sandwich panels.

(b) Discussing the specific problems of commercially available sandwich panels.

(c) Discussing the suitability of recycled plastic, wood, styrofoam and hemp as materials for sandwich panels.

(d) A detailed procedure for the preparation of composite laminates from hemp and PET fabric.

(e) A detailed procedure of manufacturing sandwich panels by vacuum bagging process.

(f) The bending behaviour and failure mechanisms of the proposed cores and sandwich panels.

(g) The tensile and thermal behaviour of the proposed skin in different environments.

While a comprehensive strategy was adopted to define the principles of composite materials, specifically core and sandwich panels for subsequent research, the following areas were beyond the scope of this study.

(a) The lifetime cycle analysis of the composite sandwich panels.

(b) The full thermal performance of the composite sandwich panels.

(c) The fire rating of the composite sandwich panels.

(d) The connection or installation of the panels.

1.4. Organisation of thesis

This thesis comprises four chapters that explain the different investigations carried out in this study.

Chapter 1 provides a general introduction to sandwich panels, including issues, the objectives and scope, and the structure of the dissertation.

Chapter 2 assesses the currently available commercial and research-grade sandwich panels, their particular issues, and potential research opportunities.

Chapter 3 focuses on the proposed materials, the manufacturing of the composite laminates and sandwich panels, the bending, tensile, and thermal behaviour, and the analysis of the skin and sandwich panels.

Chapter 4 summarises the main findings of the research and offers recommendations for further investigations.

1.5. Summary

The introductory chapter outlines the rationale, aims, and scope of the study, highlighting the necessity for sustainable construction materials to address climate change. It emphasises the environmental consequences of traditional materials such as concrete, steel, and aluminium, which are carbon-intensive, and promotes low-carbon alternatives. Sandwich panels, valued for their lightweight nature, strength, and thermal insulation characteristics, are recognised as a potential construction component. This study aims to develop low-carbon-emission sandwich panels with recycled materials, including plastic, wood, styrofoam, natural hemp and recycled plastic fabric, and bio-epoxy resin. The research examines the mechanical and durability characteristics of these materials including tensile, flexural, and dynamic mechanical analysis (DMA), contrasting their performance and emissions with those of commercial panels. The chapter outlines the study's scope, encompassing material selection, manufacturing procedures, and testing. The thesis comprises four chapters, advancing from a topic overview to experimental investigations and closing with findings and recommendations.

CHAPTER 2: LITERATURE REVIEW

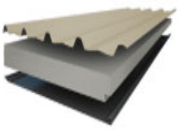
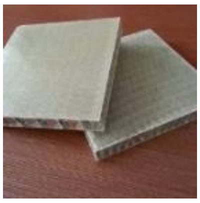
2.1. General

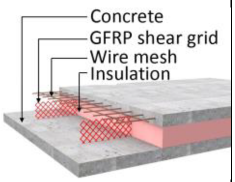
The rising demand for sustainable and high-performance materials has led to research on low-carbon composite sandwich panels, especially those using recycled and bio-based materials. This chapter examines existing studies on composite sandwich structures, focusing on material choice and environmental impact. It identifies key challenges like material durability and cost-effectiveness and aims to address these gaps. By summarising previous findings, this review lays the groundwork for understanding the potential of low-emission composite sandwich panels in promoting sustainability, resource efficiency, and circular economy principles in modern engineering.

2.2. Existing sandwich panels

There are various types of commercially available sandwich panels, and each panel is designed for specific applications. A common type of skin is a fiber-reinforced polymer (FRP), such as carbon fiber-reinforced polymer (CFRP), glass fiber-reinforced polymer (GFRP), or aramid fiber-reinforced polymer (AFRP) (Shi et al., 2019). These materials provide high strength-to-weight ratios and excellent fatigue resistance. A metal skin, particularly aluminium or stainless steel, can also withstand harsh environments due to its durability (Faidzi et al., 2021). In certain applications, thermoplastic skins like polypropylene and polyethylene are versatile and cost-effective (Joseph et al., 2022). Materials for the cores are equally diverse, with lightweight foam cores such as polyurethane, polystyrene, and polyvinyl chloride (PVC) providing good thermal insulation (Basher & Mahmood, 2023; Garay et al., 2016; Khan et al., 2020). Aluminium, Nomex (aramid), and paper honeycomb cores offer exceptional strength and rigidity while remaining lightweight (Liu et al., 2019; Okur M. Ziya, 2016). Cores made of wood, especially balsa wood, are valued for their stiffness and low density (Atas & Sevim, 2010; Chairi, 2024). Furthermore, corrugated cores, made of plastic or metal, provide structural support and are frequently used in the construction and packaging industries (Rejab & Cantwell, 2013; Tarlochan, 2021). In addition, in case of geometry and orientation of corrugated core, the Kirigami corrugated cores are good impact resistance, 3D printed bi-directional corrugated cores are better the conventional core, trapezoidal corrugated are good shocked absorber, axial/ circular corrugated cores have good impact resistance characteristics and trapezoidal, rectangular and triangular cores have higher energy absorption ability (Tarlochan, 2021). Through the combination of these skins and cores, sandwich panels can be customised to meet the performance, weight, durability, and cost requirements of various industries. While these materials provide good structural performance, their environmental sustainability in terms of carbon emissions remains an issue (Karuppannan Gopalraj & Kärki, 2020; La Rosa et al., 2014; Norgate et al., 2007; Oliveira et al., 2022; Sorokin et al., 2021). Materials that are routinely utilised in the production of sandwich panels are summarised in Table 2.1.

Table 2.1: Materials used in existing sandwich panels

Existing panels	Skins		Core		Reference
	Materials	Density (kg/m^3)	Materials	Density (kg/m^3)	
	Steel sheet	8050	Expended polystyrene	40-100	(Argalis et al., 2023; Asutkar et al., 2022; Panelmarkers, 2025)
	Aluminium sheet	2700	Polyethylene terephthalate (PET FOAM)	1400	(F.S.R.I, 2023; Topolo, 2025a; UK, 2023)
	Fiberglass Plastic	1800	Honeycomb Aluminium	190-2250	(Mehany et al., 2023; Popov et al., 2023; Topcomb, 2025)

	Plywood	714	Expended polystyrene	40-100	(Argalis et al., 2023; Topolo, 2025c; Wang et al., 2023)
	Fiberglass and Concrete	2224	Fiberglass and Expended polystyrene	480	(Argalis et al., 2023; Fiberwalls, 2025; Kushartomo & Ivan, 2017)
	FRP face sheet	1800	Balsa core	150	(Mehany et al., 2023; Topolo, 2025b; Yang et al., 2023)

In response to the challenges associated with carbon-intensive sandwich panels, researchers have investigated new sandwich panel materials that are less carbon-intensive. The researchers examined bio-based sandwich beams that were constructed from paper honeycomb cores filled with foam and flax fiber-reinforced composite coverings with varying orientations. Some structural requirements such as load carrying capacity, are satisfied by this sandwich panel (Fu & Sadeghian, 2023). In addition, the flax and epoxy face sheet, with agglomerated cork serving as the core and bonded by epoxy resin, was examined; however, the strength of the sandwich panels was inadequate (Sarasini et al., 2016). In another instance, flax fibers with reinforced polymer faces, bio-epoxy glue, and recycled corrugated cardboard cores were investigated, and the results showed that the strength of the sandwich panel was not reduced after an impact event (Betts et al., 2020) . Other thin sandwich panels were produced using flax mat and a balsa core, which were fully bio-sourced. The mechanical properties of these panels were under evaluated temperature conditions (Le Duigou et al., 2011). In a separate research study, the flax fibre reinforced polylactic composite with double cell walls and an interlocking core sandwich structure was subjected to compression testing only (Alsubari et al., 2020). Additionally, Certain researchers investigated the mechanical properties of sandwich panels made from recycled flax fiber and bio-based epoxy, and found them suitable for semi-structural applications. (Ravindran et al., 2023). However, The polylactide-flax fabric laminate skins and polylactide honeycomb cores with epoxy resin sandwich panels demonstrated structural integrity, as they satisfied the necessary structural requirements (Lascano et al., 2021). In another case, the jute fibre-based sandwich panels were manufactured using reinforced epoxy woven jute fabric as the skin and waste oil palm biomass composite foam as the core. The mechanical properties of these panels were not optimised (Cheng et al., 2017). A further investigation was performed on sandwich panels with cork as the core and woven jute fibre with epoxy as the skin; the sample size was limited to approximately 150mm in length, 100mm in width and 14mm in thickness, and the strength was withstanding a load of 2kN at a displacement ranging from 6 mm to 15 mm. (Hachemane et al., 2013). In a particular study, the bonding of the skins and core was achieved without the use of resin. The compression moulding press method was employed, utilising jute and polypropylene fractions for the skin and balsa wood for the core, resulting in panels with notable structural properties (Karaduman & Onal, 2016). In a study, the reinforced jute polyester was used as the skin, and the natural fibre reinforced honeycomb PVC foam was used as the core (Vitale et al., 2017). In terms of the basalt fibre skin, panels were manufactured using basalt fibre that was reinforced with bio epoxy as the skin and cork as the core (Andres-Esperanza et al., 2013). In a different instance, basalt fibre sandwich panels with epoxy resin structures offered an adequate level of mechanical performance (Chen et al., 2014). When kenaf and polypropylene fibres are used as the skin of sandwich panels and bagasse and polypropylene fibres are utilized as the core of the sandwich panels, the structural performance such as bending property is not exactly as expected (Chen et al., 2005). Despite the fact that another group of researchers employed conventional plywood for the skin and oil palm wood in a variety of orientations for the core, the performance of the construction was not perfect (Jantawee et al., 2023).

Researcher conducted study using bio-based polypropylene composite skins made from balsa wood cores and cellulose fabric. It is, however, necessary to further examine this form of sandwich panel before it can be commercialised as the analysis on the property of fabric is not done (Khalili et al., 2023). In addition, experimental research was conducted with the corrugated cardboard core sandwich beams with bio-based flax fibre composite skins for large-scale building applications. These beams had varying orientations of the core and the skins (Aidan m., 2018). A separate study was conducted by another researcher using an aluminium epidermis, a gapping bamboo ring core, and a castor oil biobased adhesive, and the outcome showed that the 40% increase of internal void by bamboo ring cores reduced the maximum load and flexural strength by 63% and 59% respectively, and, the team has recommended that future research be conducted with large dimensions and small gaps in the bamboo rings which will ensure the bending conditions (Napolitano Santos, 2022). In a different piece of study, the aluminium sheet was used as the skin, and recycled bottle caps with epoxy glue were used as the core. Mechanical testing was carried out, and the results showed that it is suitable for secondary structural purposes (Oliveira et al., 2017; Oliveira et al., 2018). On the other hand, another study was conducted using aluminium alloy skin, cork stopper core, and resin adhesive(Liu et al., 2023). It is interesting to note that sandwich panels with fibre-reinforced recycled aggregate concrete as the skin and an insulated layer of foam concrete blended with sand and fly ash core exhibited extremely good performance in terms of structural use (Alsubari et al., 2020). The low carbon emission sandwich panels that were mentioned earlier are currently in the research stage and some of them do not meet structural requirements.

2.3. Carbon emission challenges of existing sandwich panels

The manufacturing processes and materials used in the construction of existing sandwich panels contribute to carbon emissions. The production of materials like foam cores and synthetic fibre composite skins often involves energy-intensive procedures, resulting in significant emissions of greenhouse gases. The extraction, transportation, and processing of raw materials, such as metals and plastics, can further increase the carbon footprint of sandwich panels. In Table 2.2, some of the most commonly used materials of sandwich panels are shown with their carbon emissions. It is apparent that the carbon emission rate is relatively high for traditional materials, with an estimated range of 2 tonnes to 7 tonnes of CO2 equivalent per tonne of material production.

Table 2.2: Carbon emissions from existing sandwich panel materials

Materials	Carbon emission (tCO_2 e/t)	References
Steel	1.37 – 2.33 tonnes	(DeFilippo, 2025; S-Ships, 2023)
Aluminium	4.80 tonnes	(Dietz et al., 2019)
Concrete (cement)	0.732-0.941 tonnes	(Anderson & Moncaster, 2020; Konice Yèyimè Déo-Gratias Aholoukpè, 2023)
Expended polystyrene	6.9 tonnes	(Lokke, 2023)
Glass fibers	1.7 tonnes	(Barth et al., 2015)
Plastic	3 tonnes	(Kilgore, 2023d)
Petroleum based-epoxy resin	6.6 tonnes	(La Rosa et al., 2014)

In terms of end-of-life disposal, traditional composite sandwich panels (e.g., glass or carbon fiber matrices, thermoset resin matrices, and polymer or foam cores) pose significant challenges due to their non-biodegradable nature, complex material compositions, and limited recycling capabilities. Recycling techniques, such as mechanical or chemical, are often found to be inefficient, energy-intensive, or cost-prohibitive, which leads to landfilling or incineration being the primary disposal methods. However, landfilling contributes to long-term environmental pollution, while incineration emits toxic gases and greenhouse gases, further increasing their carbon footprint. Due to the lack of closed-loop recycling systems and viable reuse strategies for these materials, their sustainability is compromised, and resources are depleted. To address these challenges, eco-friendly composite alternatives must be developed, recycling technologies must be improved, and policies must be implemented to promote circular economy principles in composite material applications.

2.4. Research gap and novelty

Despite the aforementioned research attempts to develop low carbon emission sandwich panels, their resin selection is largely petroleum based (potential for high carbon emission), and their core material is composed of natural materials. It is possible to further reduce the carbon emissions of sandwich panels by replacing petroleum-based resin with bio-based resin and natural materials with landfill waste-based materials. The novelty of this study lies in the introduction of bio-based resin and landfill waste materials for the development of sandwich panels with low carbon emission which has not been investigated yet.

2.5. Opportunities with new materials for sandwich panels

A comprehensive approach is required to address the carbon emission challenges, such as using low-carbon manufacturing techniques, recycled materials, and designing buildings that optimise energy efficiency and minimise operational carbon emissions. Combining different materials effectively is important to fully utilize the benefits of these versatile construction elements. To support future green construction, it is important to explore alternative sources such as waste-derived or naturally processed materials. When it comes to waste-based materials, the manufacturer does not have to construct the product from scratch. For example, if landfill plastics are used in the panel, the manufacturer does not have to produce new plastics that contribute to environmental sustainability. On the other side, natural plant-based materials can take and store carbon dioxide from the atmosphere throughout their life, and they can store carbon in their bodies until they are burned.

Furthermore, several studies have confirmed that these green construction materials are able to meet the similar or superior performance criteria as traditional construction materials (Agarwal & Gupta, 2017; Lu et al., 2019; Mansour & Ali, 2015; Raj et al., 2014; Sassoni et al., 2014). Table 2.3 identified some of the potential materials for low carbon emission sandwich panels.

It is shown in Table 2.3 that a range of materials are available for manufacturing sandwich panels that emit between 0.5 tonnes to 2 tonnes of carbon dioxide for every tonne of panel manufactured. Based on Table 2.2, it is interesting to note that the carbon emissions from concrete production with cement seem lower than many of the other materials in Table 2.3, however, the heavy weight of concrete renders sandwich panels unsuitable for developing high strength-to-weight ratios. The use of this technology is therefore restricted to a specific field of application.

Table 2.3: Potential materials for sustainable sandwich panels

Potential materials	Components	Carbon emissions (tCO_2 e/t)	References
Hemp	Skin	2.6	(Jacobsson & Elin, 2018)
Flax	Skin	2.0	(Jacobsson & Elin, 2018)
Jute	Skin	1.2	(Boyce, 1995)
Kenaf	Skin	1.5	(Mahdi Khalatbari et al., 2014)
Bamboo	Core	0.5	(Chen et al., 2021)
Balsa wood	Core	1.8	(Kilgore, 2023c)
Recycled Wood	Core	0.45	(Kim & Song, 2014)
Recycled Plastic	Skin and core	0.9	(Neste, 2023)
Recycled Expanded Polystyrene	Core	1.8	(EPSbranchen, 2020)
Recycled Nylon	Skin and core	0.2	(Kilgore, 2023a)
Recycled Polyethylene	Core	1.48	(Alsabri et al., 2021)
Recycled steel	Skin	0.88	(Kilgore, 2023b)
Landfill ashes	Core and skin	1.04	(G.S.S., 2022)

2.7 Summary

An extensive review of existing literature indicates that although traditional composite sandwich panels offer high strength-to-weight ratios, durability, and structural efficiency, they contribute significantly to carbon emissions due to their petroleum-based resins, energy-intensive manufacturing processes, and limited recycling capabilities. It has been shown that the production of synthetic fiber reinforcements and thermoset resins involves high energy consumption and a significant amount of greenhouse gas emissions. Additionally, the end-of-life disposal challenges associated with these panels, such as incineration and landfill accumulation, further exacerbate their environmental impact. Research efforts have explored recycled fillers and natural fiber reinforcements as potential alternatives for mitigating emissions. However, challenges remain regarding mechanical performance, cost, and widespread application. There is an urgent need for low-carbon composite solutions that balance environmental sustainability with structural efficiency, leading to the development of next-generation composite sandwich panels with reduced carbon footprints.

CHAPTER 3: EXPERIMENTAL AND THEORETICAL STUDY OF NOVEL COMPOSITE SANDWICH PANELS

3.1 Introduction

Composite sandwich panels require a combination of experimental testing and theoretical modelling to evaluate their performance in terms of mechanical behaviour, failure mechanisms, and structural efficiency. This chapter provides an analysis of the carbon footprint and a detailed experimental and theoretical investigation of the load-bearing capacity, bending stiffness, and durability of composite sandwich panels under various loading conditions. Several tests are conducted to analyse the strength, stiffness, and failure modes of the panels, including tensile and glass transition temperature tests of the skins and bending tests of the core and sandwich panels. These characteristics have been selected for the study to assess the structural compatibility of the proposed materials. In addition, analytical modelling is used to predict load carrying capacity, allowing results to be validated against experimental data. By integrating both approaches, this chapter aims to provide a comprehensive understanding of the performance characteristics of composite sandwich panels, providing valuable insights for optimising, improving, and applying composite sandwich panels for sustainable engineering applications.

3.2 Carbon emission analysis from potential sandwich panels

This section examines the potential carbon emissions resulting from different combinations of sustainable materials for sandwich panels. The weighted average analysis is based on the assumption that a sandwich panel consists of 10% volume of skins and 90% volume of cores. An environmental impact analysis of sandwich panels involves assessing the carbon emissions associated with raw materials, manufacturing process, transportation, energy sources, adhesives and binders, panel design, service life, maintenance, and durability. This chapter focuses primarily on a carbon emissions analysis of raw materials used in sandwich panels. A summary of the analysis is provided in Table 3.1. The estimation of carbon emissions for the sandwich panels was conducted using data from Table 2.3. For example, the carbon emissions for the hemp skin are 2.6 tCO_2e/t (10% by volume), and for the recycled wood core, 0.45 tCO_2e/t (90% by volume), accordingly, the total carbon emission is calculated to be 0.665 tCO_2e/t. It is important to note that this analysis is based on the carbon emission from the manufacturing of materials. However, the detail carbon emission analysis including transportation and disposal can be determined through a comprehensive life-cycle analysis which requires a significant volume of work and is currently outside of the scope of this study.

The selection of material combinations in Table 3.1 is prepared to address the challenges in developing a lightweight and low carbon emission sandwich panel. This table provides guidelines how the proper selection of low emission materials could help minimising the carbon emission problem. It is advised that the researchers and end users should be able to utilise the approach used in calculating carbon emissions. If an evaluation of traditional sandwich panels composed of petroleum-based resin (epoxy), synthetic fibre (glass fibre), and a polystyrene core, the estimated carbon emissions are approximately 6.35 tonnes per tonne of production. This analysis suggests that the proposed sandwich panels have the potential to achieve a 90% reduction in carbon emissions.

Table 3.1: Potential sandwich panels and their carbon emissions

Proposed sandwich panels	Carbon emission (tCO_2 e/t)
Hemp fibres skin (10%) + Recycled wood core (90%)	0.665
Hemp Fibres skin (10%) + Recycled plastic core (90%)	1.07
Hemp Fibres skin (10%) + Recycled styrofoam core (90%)	1.88
Recycled plastic skin (10%) + Recycled wood core (90%)	0.495
Recycled Plastic skin (10%) + Recycled plastic core (90%)	0.90
Recycled Plastic skin (10%) + Recycled styrofoam core (90%)	1.71

According to the results of this study, sandwich panels can be manufactured within two tonne of carbon emissions per tonne of panel produced. Although the recycled styrofoam core-based sandwich panel shows greater carbon emission, their lightweight nature is attractive to many applications. It is possible to reduce the carbon emissions generated by sandwich panels through a collaborative approach aimed at minimising their environmental impact during production, use, and end-of-life. To reduce energy consumption and associated emissions during panel fabrication, it is crucial to adopt low-carbon manufacturing techniques that utilise renewable energy sources. It is also possible to significantly reduce the carbon footprint by using sustainable and recycled materials for the core and skin layers. Moreover, optimising transportation logistics to reduce distances and dependence on fossil fuels during material distribution further reduces emissions. A structure designed to maximise the thermal performance of sandwich panels will reduce operational carbon emissions over its lifetime. The use of circular economy principles, such as designing panels that can be disassembled and recycled easily, prolongs their useful life and reduces the amount of waste produced. It is essential to take a holistic approach to reducing carbon emissions throughout sandwich panel lifecycles that integrates sustainable sourcing, efficient manufacturing, smart design, and responsible end-of-life management.

The study examines all six combinations of skin and core materials (Table 3.1), as well as a bio-based resin system, to develop low carbon emission sandwich panels.

3.3 Materials

3.3.1. Bio-epoxy resin

In this study, a bio-based epoxy resin was utilised to manufacture the laminates and binder of sandwich panels. Bio epoxy resin is a non-toxic, recyclable resin created from a by-product of biodiesel (Change-climate, 2024). The pH of bio-resin was 6-8 and the thermal decomposition temperature was 180°C. This bio-epoxy can be used for structural adhesives. Bio-epoxy resin consists of two components, part A and part B, with densities of 1.24 kg/L and 0.93 kg/L, respectively, as well as a mixing ratio of 75% to 25% (by weight). The viscosity of part A resins was 750cP and part B resin was 15cp at 25°C with a mixed viscosity of 150cP at 25°C.

3.3.2. Fabric

The two types of skin materials used were hemp fabric and PET fabric. A hemp fabric was made from natural hemp fibres grown in Australia, which is primarily used in composite reinforcement applications. The hemp fabric had a simple woven pattern and was uniform in its strength. The density of lightweight, strong and eco-friendly hemp fabric was about 135 g/m2 (Colan, 2024). Similarly, PET fabric made from recycled PET polyester had a woven pattern and was uniform in strength with a density of about 105 g/m2 (Colan, 2024).

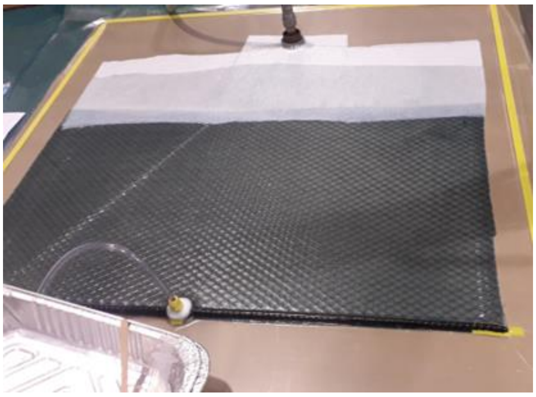
3.3.3. Waste based core materials

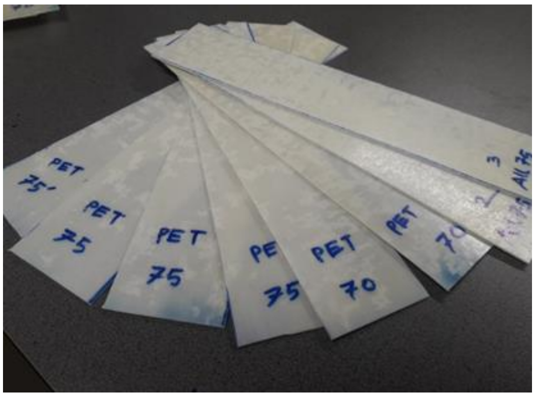
The three types of core materials used were composite wood, recycled plastic panel, and recycled styrofoam. The composite wood core material was made up of 60% recycled wood flour, 30% recycled HDPE plastic, and 10% binding agent. The composite wood was engineered for use in structural applications such as decking, cladding, and fencing (Coen, 2024). The recycled plastic cores were made from waste plastics and primarily used for decking bollards and fencing. Recycled plastic products have numerous benefits, including being environmentally friendly, low maintenance, termite resistant, and long lasting (Replas, 2024). The recycled styrofoam cores were made from waste styrofoam, are eco-friendly and can be customised in density and size (Polystyrene, 2024). The densities of composite wood, recycled plastic and recycled styrofoam were approximately 1300 kg/m^3, 900 kg/m^3, 15 kg/m^3 respectively.

3.4. Methods

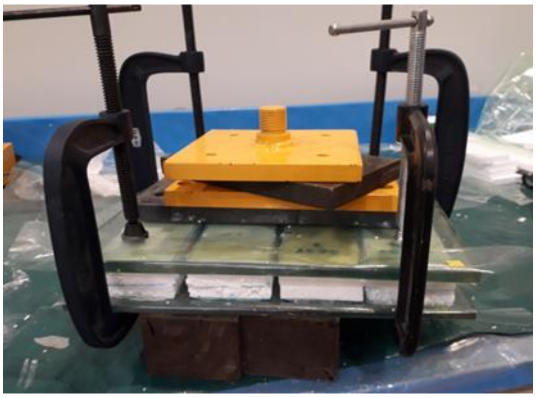
3.4.1. Manufacturing of skins

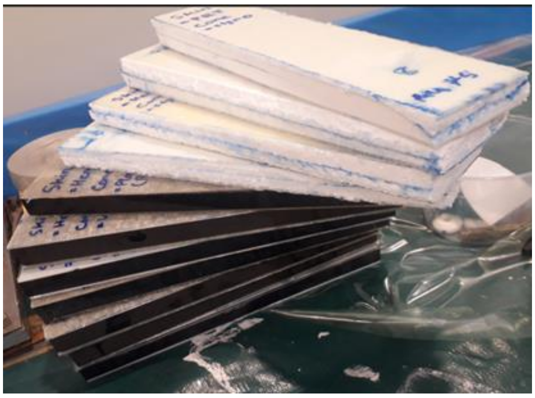
The vacuum bagging process were used to manufacture the skins of sandwich panels. The vacuum bagging process has the capability to produce superior performance and high-quality composite materials. Five layers of fabric with 0° orientation were placed in a vacuum bag to achieve the desired skin thickness, as shown in Figures 3.1(a) and 3.1(b). Resin was then infused into the vacuum bag under a pressure of approximately 100 kPa, converting the soft fabric layers into high-quality laminates in room temperature (Spasojevic, 2019). Laminates are cured in an oven at 100°C for one day. In general, hemp and PET composite laminates are approximately 900 mm long and 400 mm wide, with a 2 mm thickness and a 35% fibre and 65% bio-epoxy resin content (after trial mixing process). The full laminates were cut to the desired sizes using water jet cutter. Skins were exposed to normal air and four extreme environmental conditions, including water, hygrothermal (60°C temperature and 98% humidity), 10% concentrated saline water, and 80°C elevated temperature. In this research, only the skins were chosen for environmental testing as the outer surface of sandwich panels is typically the one that faces severe environmental impact. A period of seven months was considered for weathering sandwich skins.





(a) vacuum bagging process (b) typical PET skin laminates





(c) manufacture of sandwich panels (d) Typical sandwich panels

Figure 3.1. Composite laminates preparation

3.4.2. Manufacturing of sandwich panels

Two skins including hemp (375mm long x 75mm wide) and PET (375mm long x 68mm wide) were cut to specific dimensions along with three core types including composite wood (350mm long, 75mm wide, 25mm thick), recycled plastic panel (350mm long, 68mm wide, 24mm thick), and recycled styrofoam (350mm long, 75mm wide, 25mm thick). Bio epoxy resin was used to adhere the desired size cores and skins. The resin was first injected onto the rough skin surface, film applicators were used to ensure even coverage, and then placed onto the bottom glass, and the core was then gently placed on the skin. Secondly, the rough side of the other skin was chosen for spreading resin and placed on the core. Finally, the top glass was set and clamps and weights were placed in a systematic manner. As the base and top plates, two 25mm thick glass plates were used, and four clamps and a 20kg steel weight (set after initial specimen manufacturing trials) were used to apply uniform load to all four specimen and adequate pressure to the paneling system so that consistent bonding can be ensured across the skin and core interface. The panels were subjected to pressure for approximately one day. A total of six different types of panels were prepared.

3.5. Experimental investigation

3.5.1. Tensile test of skins

The ASTM D3039 (ASTM-D3039) testing standard was followed to test 10 different types of tensile samples (2 skins and 5 environments). Over the course of seven months, the skins were exposed to four different environmental conditions (normal air, water, hygrothermal (60ºC temperature and 98% humidity), 10% concentrated saline water, and elevated temperatures (80ºC hot weather) to simulate normal ambient environment, rainwater, high warm-humid en-vironment, coastal area or marine environment, and high heat environment from sun respectively). For each type of laminate, five replicate samples were tested. The tensile test result of skin was obtained using the MTS 10kN capacity testing machine. All samples were tested at a speed of 2mm/min. The MTS 10kN data acquisition system was used to collect the required data.

3.5.2. Dynamic mechanical analysis (DMA) of skins

The glass transition temperature of composite laminate was measured according to ASTM D4065 (ASTM-D4065, 2012). Eight different types of samples were prepared from hemp and PET laminates (i.e., two skins with four environments). There were two replicate samples of each type in four different environmental conditions (i.e., normal air, water, hygrothermal, 10% concentrated saline water). The dimensions of the samples were 45mm long by 10mm wide by 2mm thick, cut by water jet. The laminates were placed in a configuration and loaded at a frequency ranging from room temperature to 150°C with a ramp rate of 5°C/min. Storage modulus, loss modulus, and tan delta data were recorded and plotted against temperature.

3.5.3. Bending test of cores

The three different core samples, each with three replications, were tested in accordance with ISO 14125 (ISO-14125). Three-point bending tests were conducted to verify the bending capacity of cores. The testing was conducted on an MTS 100 kN testing device with a 2 mm/min test rate to test the core sample with a span length of

300 mm. The sample dimensions for the composite wood cores, recycled plastic panel cores, and recycled Styrofoam cores are 350 mm in length, 75 mm in width, and 25 mm in thickness; 350 mm in length, 68 mm in width, and 24 mm in thickness; and 350 mm in length, 75 mm in width, and 25 mm in thickness, respectively.

3.5.4. Bending test of sandwich panels

The dimensions of test samples were approximately 350mm long, 75mm wide, and 27.5mm thick. Tests were conducted on all sandwich panels under three-point bending on an MTS testing machine with a capacity of 100 kN, with a support span of 300mm and a test speed of 2 mm/min. The strain gauges were installed at the bottom of the mid span to measure the maximum bending strain of the panels.

3.6. Results and observation

3.6.1. Failure mode of skins

Under uniaxial loading, the tensile test revealed the failure mechanisms for the sample composite skins. An example of a typical skin failure following tensile testing on five-layered composite skins can be seen in Figure 3.2. The observed failure of the specimens primarily occurred within the tensile span, the central region between the grips, indicating that the specimens were subjected to pure uniaxial tensile forces during testing. This mode of failure confirms that the test setup successfully minimised the influence of other stress components, thereby allowing for an accurate assessment of the material's intrinsic tensile properties. The fact that failure did not initiate at or near the gripping areas further reinforces the validity of the test, as it implies that the gripping tabs effectively transferred the applied load without introducing stress concentrations or mechanical interference that could lead to premature failure. The integrity of the tabbed regions also suggests that proper tabbing techniques and materials were used, which is crucial in tensile testing to ensure reliable and reproducible results.

(a) Tensile test setup

(b) All skin samples tested after 7 months (Hemp skin-left side, PET skin-right side with five different environments)

Figure 3.2. Tensile sample failure patterns of composite skin

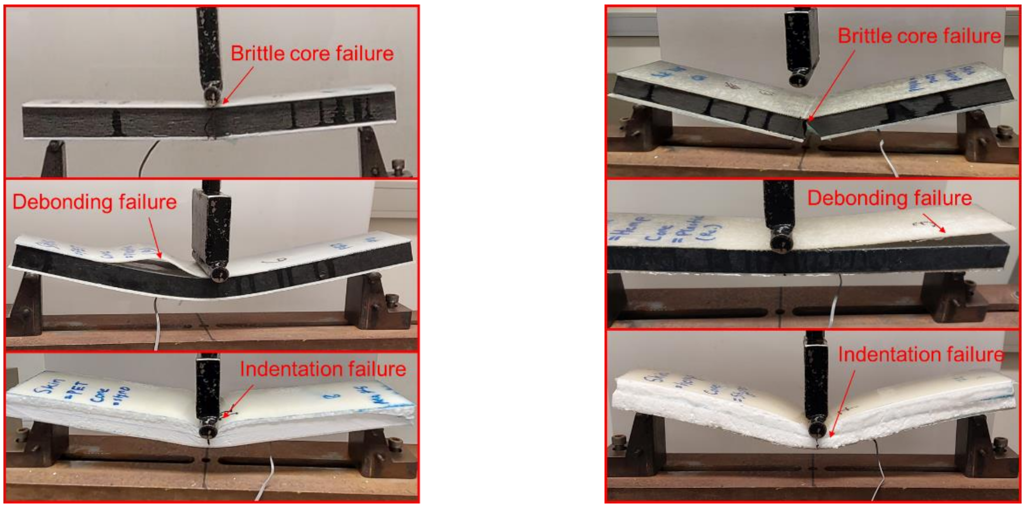
3.6.2. Failure modes of cores

Different failure modes were observed as a result of the use of different cores, as depicted in Figure 3.3. An abrupt failure of the wood core samples occurred at the mid-span representing a brittle nature of failure. The plastic core deflected much higher than the wood core before failure occurred at mid span. This is due to the composition of the material, which is a combination of different plastics, resulting in shorter polymer chains, thereby causing greater deformation under stress. The Styrofoam cores were able to deflect rapidly at low loads due to their easily compressible cellular structure and relatively low density.

Figure 3.3. Failure pattern of cores (Wood, Plastic, and styrofoam respectively)

3.6.3. Failure modes of sandwich panels

Different failure modes were observed among sandwich panels based on the variations in cores and skins (Figure 3.4). The brittle composite wood core panel failed at mid-span, which caused the bottom skins to fail prematurely. Therefore, it is essential to design the skin properly in order to be able to effectively utilize its strength for brittle cores. Sandwich panels with a plastic core failed due to debonding between the skins and the core. Due to the high deflection of the plastic core, there is a high horizontal shear stress between the skin and the core during bending, causing the skin to debond from the core. This indicates that in the case of flexible cores, it is essential to consider the bond strength between the skin and the core. Sandwich panels with a styrofoam core failed due to indentation. It is due to the variations in load resisting capacity between the compressible cellular structure of the core and the skin. Therefore, lightweight styrofoam cores may not be appropriate for sandwich panels with high stress concentrations.



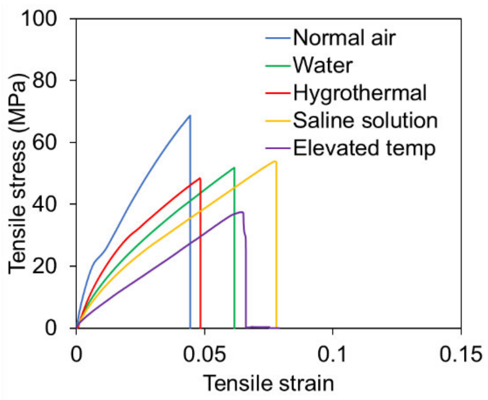
(a) PET skin with wood composite core, PET skin with plastic core, and PET skin with styrofoam core sandwich panel (top to bottom respectively)

(b) Hemp skin with wood composite core, Hemp skin with plastic composite core, and Hemp skin with styrofoam core sandwich panel (top to bottom respectively)

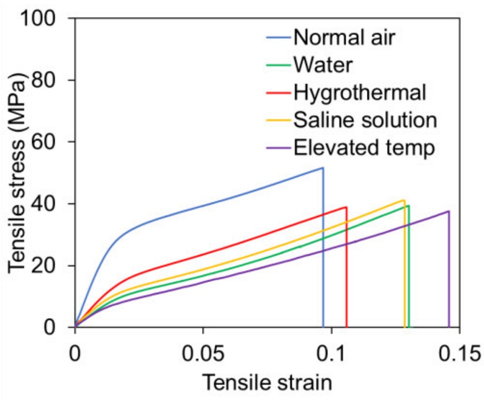
Figure 3.4. Failure pattern of sandwich panels (a) PET skin sandwich panels (b) Hemp skin sandwich panels

3.6.5. Tensile stress-strain behaviour of skins

All tensile samples of skins were loaded uniaxially until failure. Figures 3.5(a) and 3.5(b) show that the tensile strength decreased under different environmental conditions. The average ultimate tensile strength of hemp skins was 60 MPa in normal air, 52 MPa in water, 48 MPa in hygrothermal conditions, 48 MPa in saline solution, and 35 MPa in 80°C elevated temperature, as illustrated in Figure 3.5. The stress-strain curve of hemp skins was linear, and sudden failure occurred as shown in Figure 3.5(a). For PET skin, the average ultimate tensile strength for normal air, water, hygrothermal conditions, saline solution, and elevated temperature were 50 MPa, 40 MPa, 40 MPa, 45 MPa, and 39 MPa, respectively. According to Figure 3.5(b), the tensile stress-strain plot showed linear behaviour until a certain stress and strain level, then showed non-linear behaviour with gradually increasing stress and strain values, resulting in sudden failure.



(a) Hemp skin (one represented sample)

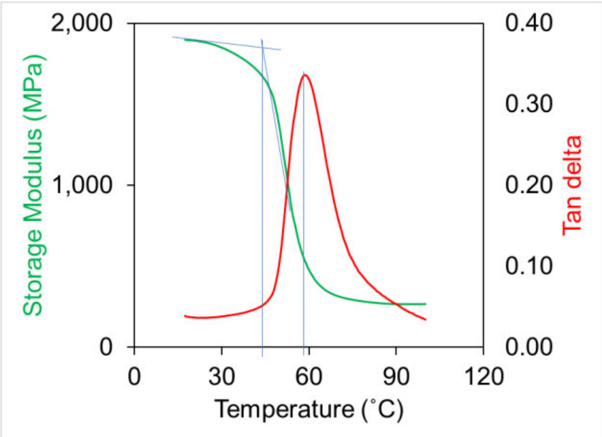


(b) PET skin (one represented sample)

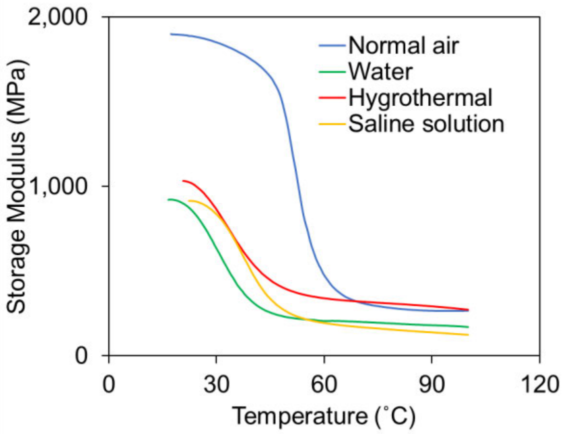
Figure 3.5. Variation of tensile stress-strain relationship of skin of sandwich panels in different environment

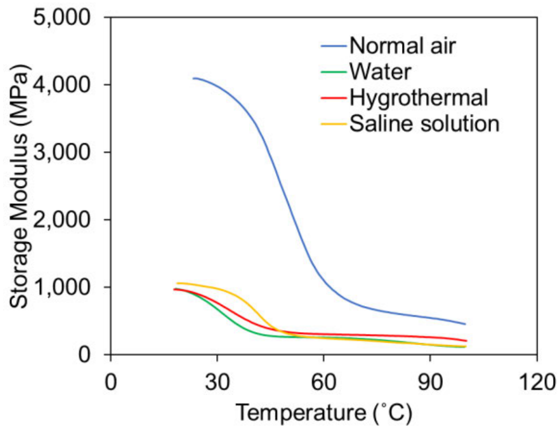
3.6.6. Dynamic mechanical analysis (DMA) of skins

The graph in Figure 3.6 illustrates a typical DMA graph, with each sample displaying three glass transition temperatures that can be estimated from tan delta, storage modulus, and loss modulus. There is a clear difference in the glass transition temperature (Tg) between the tan delta, storage modulus, and loss modulus curves. Determining the glass transition temperature of the storage modulus involves drawing two tangents. The first curve starts from the beginning point of the DMA curve, while the next one begins between the inflection point and the middle-point of the drop of the storage modulus curve. The tan delta Tg value was determined from the peak of the bend, where the value was a little higher Tg, while other researchers (Goertzen & Kessler, 2007; Li et al., 2000; Shamsuddoha et al., 2013) suggest evaluating the glass transition temperature (Tg), determined from the peak of the tan delta curve. Conversely, the ASTM D4065 (ASTM-D4065, 2012) standard suggests obtaining the Tg from the tip of the loss modulus curve.



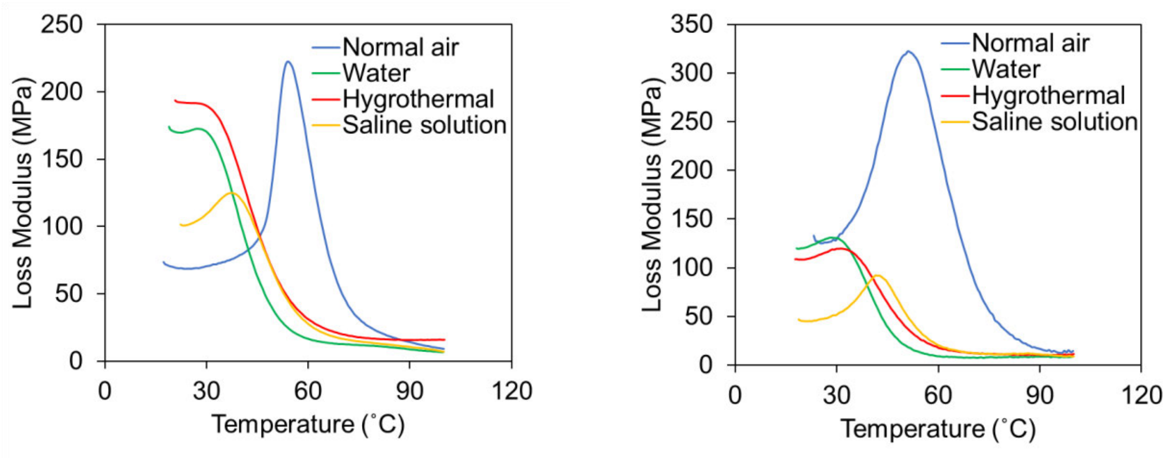
(a) Typical DMA plot (ASTM D7028)





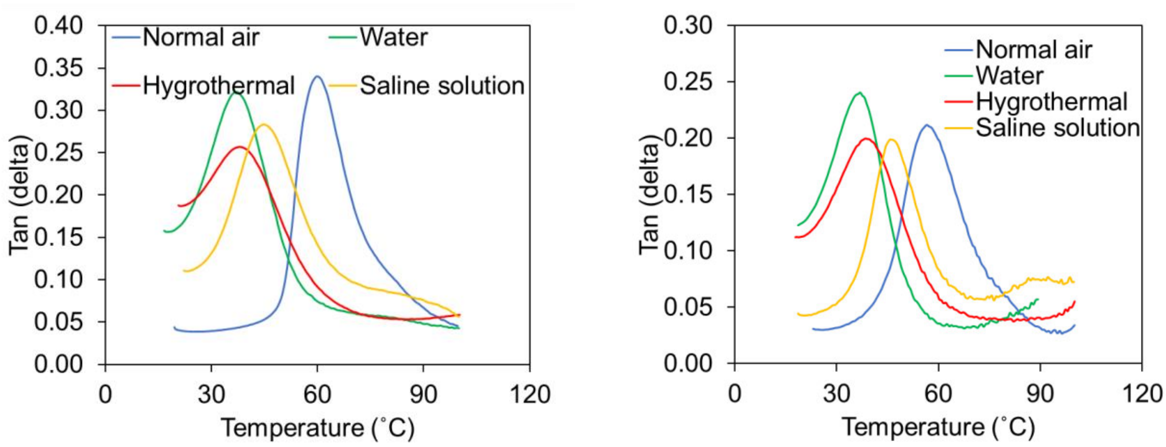
Hemp skin PET skin

(b) storage modulus vs temperature (Hemp left side & PET right side)



Hemp skin PET skin

(c) Loss modulus vs temperature



Hemp skin PET skin

(d) Tan delta vs temperature

Figure 3.6. Variation of Dynamic Mechanical Properties

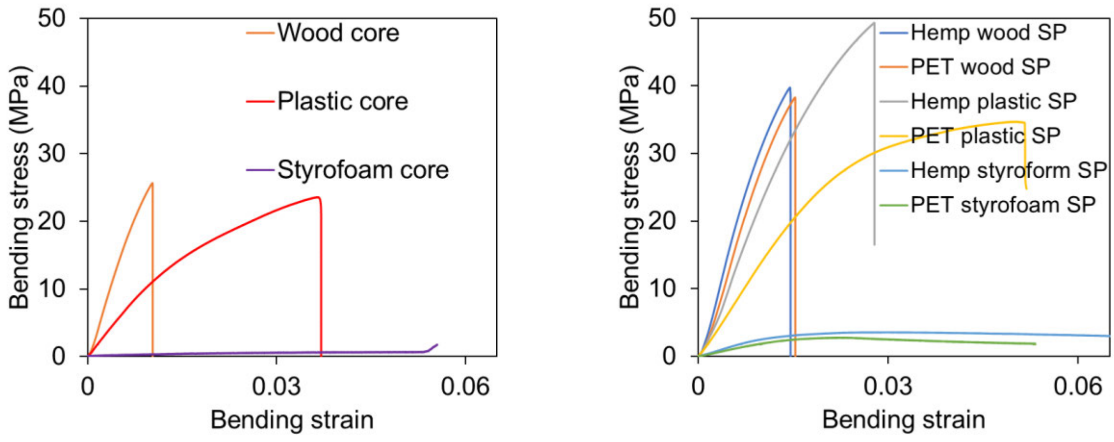
The Tg of hemp skin for storage modulus and loss modulus ranged from 45°C to 55°C in normal air. When hemp skin was placed in various environments, the Tg values for storage modulus and loss modulus ranged from 25°C to 40°C. The Tg value for hemp skin in normal air was found 60°C in the case of tan delta and ranged from 35°C to 45°C under varying environmental conditions. The Tg values of PET skin ranged from 38°C to 50°C for both storage modulus and loss modulus cases, and in various environmental types, the Tg values ranged from 25°C to 45°C. The Tan Delta curve of PET skins provided a Tg value of 57°C, and in varied environmental conditions, the Tg value varied from 35°C to 45°C. Table 3.2 provides a summary of the skin results.

Table 3.2: Summary of skin results

Environmental condition	Tensile strength (MPa)		Tensile modulus (MPa)		Tg from tan delta (ºC)	
	Hemp	PET	Hemp	PET	Hemp	PET
Normal Air	60	50	1099	1772	60	57
Water	52	40	690	662	35	35
Hygrothermal	48	40	852	880	38	38
Saline solution	48	45	611	909	45	45
Elevated temp.	35	39	681	462	-	-

3.6.7. Bending properties of core materials

The flexural stress strain behaviour of sandwich core materials is shown in Figure 3.7(a). In the case of brittle wood core material, the stress strain behaviour was linear, while for plastics, it was slightly nonlinear, and for soft-lightweight styrofoam, it was linear but highly flexible. As a result of this study, the average bending stress of the wood core, the highly flexible plastic core, and the soft-lightweight styrofoam core were found to be about 28 MPa, 28 MPa, and 1 MPa respectively. The stiffness of materials appears to play a significant role in determining their bending strength. The atomic structure of wood composites and plastics is usually more compact and has stronger intermolecular forces, resulting in a higher degree of bending resistance compared with styrofoam, which is less dense and has weaker intermolecular forces.



(a) Behaviour of core (b) Behaviour of sandwich panels

Figure 3.7. Bending behaviour of cores and sandwich panels (SP: Sandwich panels)

3.6.8. Bending properties of sandwich panels

The stress-strain behaviour of the sandwich panels is presented in Figure 3.7(b). The bending stress-strain curves for the sandwich panels were plotted using the wood, plastic, and styrofoam cores with specific additions of hemp and PET skins. The maximum bending stress of wood core hemp skin sandwich panel, plastic core hemp skin sandwich panels, and styrofoam cores hemp skin sandwich panels were 39 MPa at strain 0.014, 49 MPa at strain 0.027, and 3 MPa at strain 0.025 respectively. On the other hand, the bending stress of wood core PET skin sandwich panel, plastic core PET skin sandwich panel, and styrofoam cores PET skin sandwich panels were 38 MPa at strain 0.015, 36 MPa at strain 0.053, and 3 MPa at strain 0.025 respectively. A full summary of the average bending results of cores and sandwich panels is shown in Table 3.3.

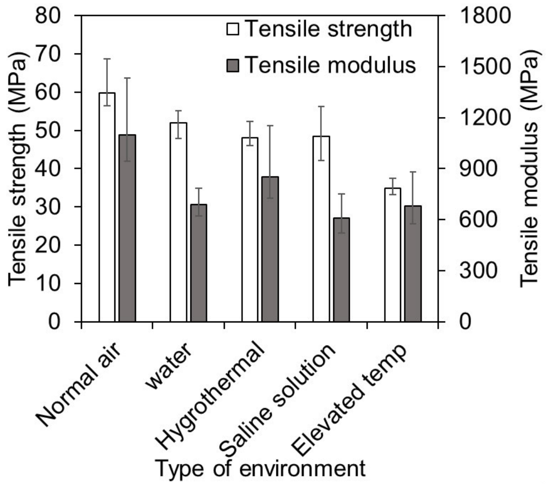
Table 3.3: Summary of bending strength and bending modulus of cores and sandwich panels

Core types	Core average results		Sandwich panel average results			
			Hemp skin		PET skin	
	Strength (MPa)	Modulus (MPa)	Strength (MPa)	Modulus (MPa)	Strength (MPa)	Modulus (MPa)
Wood	28	2753	37	3103	34	3042
Plastic	28	990	47	2000	33	1352
Styrofoam	1	16	3	203	3	159

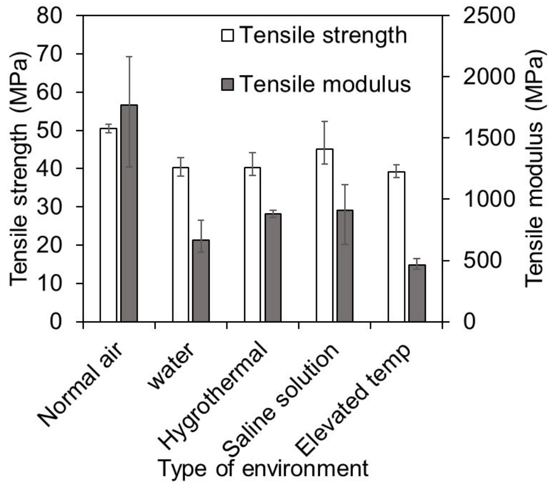
3.7. Discussion

3.7.1. Effect of environmental conditions

The skins were tested for tensile strength and glass transition temperature after conditioning for seven months in five different environments. In normal air, hemp skin samples have a tensile strength of 60MPa which decreased by 13%, 20%, 20%, and 42% when exposed to normal water, hygrothermal, saline water, and elevated temperatures respectively. Moreover, the tensile modulus of hemp skin in normal air is 1099 MPa, whereas the tensile modulus of hemp skin samples under different environmental conditions are decreased, such as 37% under water, 22% in hygrothermal condition (60°C temperature and 98% humidity), 44% under saline solution environment, and 38% in elevated temperature condition (Figure 3.8).



(a) Hemp skins



(b) PET skins

Figure 3.8: Effect of environmental conditions on skin material

Glass transition temperature (Tg) of hemp skin is higher in normal air than the samples under different types of environmental conditions, as shown by the storage modulus, loss modulus, and ten delta plots. The Tg of tan delta of hemp skin samples in normal air is 60°C whereas the Tg value under different environmental condition are decreased, such as 42% under water samples, 37% in hygrothermal samples, and 25% under saline solution samples as shown in Table 3.2.

Tensile properties and glass transition temperature analysis reveals that the skins can be affected by the weather conditions. Water absorption typically reduces overall skin strength, which leads to the degradation of mechanical and thermodynamic properties of laminates. A hygrothermal environment was created in which the skins were placed in a chamber with a temperature of 60°C and a relative humidity of 98%. Before characterising the environmental impact of the specimens, the specimens were visually inspected. When the resin is exposed to hygrothermal conditions, it swells, softens, or undergoes hydrolytic degradation, weakening its bond with the fibres. As a result, stiffness, strength, and dimensional stability can be reduced. Moisture absorption increases at elevated temperatures, which speeds up degradation. Moisture can also cause plasticization of the resin, resulting in a lower glass transition temperature (Tg), which causes the resin to soften sooner. High moisture can also weaken fibres themselves and lead to debonding of fibres and matrixes. This combination of elevated temperature and moisture substantially diminishes the durability and mechanical performance of the skin materials (i.e., 22% of tensile strength and 37% of glass transition temperature were reduced for hemp skin). When exposed to saline environments (10% salinity), the polymer matrix can swell, plasticize, and degrade. Moisture absorption deteriorates for fibres, reducing tensile strength, stiffness, and structural integrity. Moreover, prolonged exposure to saline conditions can accelerate chemical degradation processes, such as hydrolysis, further compromising the composite's durability. Tensile tests of skin were conducted at an elevated temperature of 80°C. When the resin is heated, it becomes softer, and degradation mechanisms become more active. Moreover, the tensile strength of hemp skin is reduced by 42% at elevated temperatures because the Tg of the tan delta is 60°C, which is lower than the 80°C elevated temperature.

3.7.2. Effect of skin materials

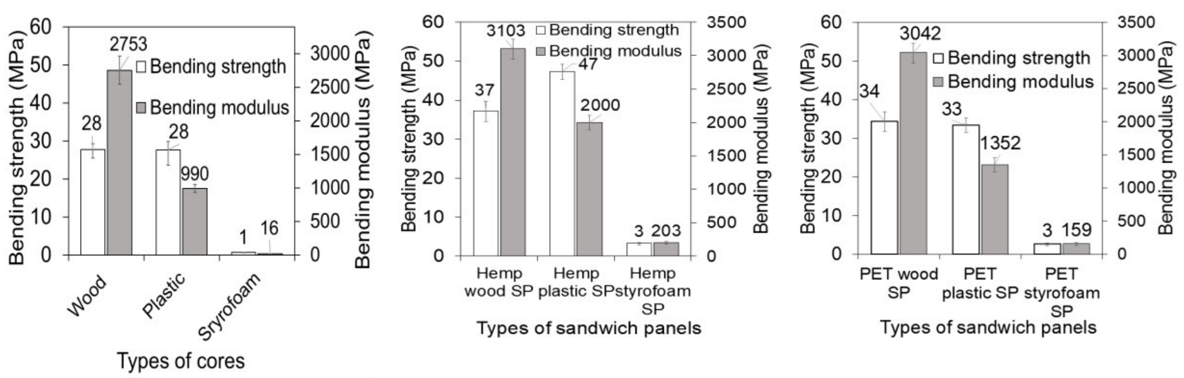
The hemp and PET skins were utilised in the study and the skin behaviour is revealed by conducting the tensile tests, and dynamic mechanical analysis. Overall, the tensile strengths of natural fabric hemp skins under different environments are affected more than the PET skins. In normal air, hemp skin has tensile strength of 60MPa and PET skin has tensile strength of 50MPa, while their tensile modulus is 1.1GPa and 1.77GPa, respectively. Despite this, both hemp and PET skins exhibit similar glass transition temperatures (Tg), as shown in Table 3.2. The performance of natural laminate hemp skin compared to PET skin in sandwich panels can be affected by several factors. Biodegradable hemp skins possess a lower mechanical performance than synthetic PET skins. The Tg of PET is determined by the mobility of the polyester backbone, whereas hemp fibres have a Tg determined by the relaxation of the amorphous regions within the cellulose matrix. Aside from this, recycling PET fibres may contain structural changes as a result of processing and degradation, which lead to chain scission and cross-linking, leading to a Tg similar to that of natural hemp laminates.

3.7.3. Effect of core materials

The core materials have a significant impact on the behaviour of the sandwich panel as results shown in Figure 3.9. After manufacturing the sandwich panels, the bending load capacity of wood cores with hemp and PET skins rose by 32% and 21%

respectively. Similarly, in case of the bending load capacity of composite plastic cores with hemp and PET skins increased by 68% and 18% respectively. In terms to styrofoam cores, the bending strength is improved 200% for both hemp and PET skins. The hemp skin-composite wood core sandwich panels failed in less bending strain compared to the hemp skin-plastic core sandwich panels due to the stiff nature of wood core. The hemp skin-wood core sandwich panels bending strength and strain are 18% and 40% less respectively than the hemp skin-plastic core sandwich panels as illustrated in Figure 3.7. The reason for this is that the breakdown appeared in the core for a skin-wood core sandwich panel, whereas the plastic core was able to withstand significant deformation before failing.

There is a general observation that panels with a high core density are generally stiffer. Wood composites, plastic, and styrofoam cores have densities of 1300 kg/m^3, 900 kg/m^3, and 15 kg/m^3, respectively. Increasing the density of the core improves the material's ability to transfer shear forces between the face sheets, thereby reducing core deflection. When a low-density styrofoam core is used in a design, greater shear deformation occurs, adversely affecting the face sheet's ability to distribute the load over the core. Due to excessive compression at the loading point, the core's yield strength is exceeded, which leads to the indentation failure of the sandwich panels made from styrofoam. The use of recycled styrofoam core sandwich panels can meet a variety of structural requirements, regardless of these challenges, especially in non-load-bearing or low-impact environments. Due to the lightweight insulation and buoyancy provided by the styrofoam core, these panels are ideal for applications that require a low weight and high thermal efficiency.



(a) Cores only (b) hemp skin sandwich panels (c) PET skin sandwich panels

Figure 3.9. Bending test results

3.8. Theoretical analysis for the prediction of failure loads

The theoretical estimation of failure load for the sandwich panels was the subject of this section. Load capacity of the sandwich beams was determined based on experimentally observed failure modes. These are core bending failures for composite wood core panels, skin debonding failures for recycled plastic core panels, and indentation failures for styrofoam core panels.

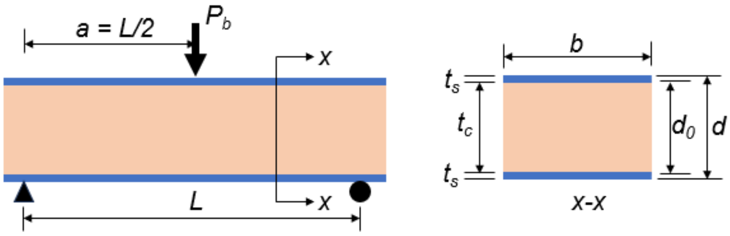


Figure 3.10. Sectional dimensions and test setup

3.8.1. Brittle wood core panel failure load

It is anticipated that the sandwich panels will fail in bending when the core's bending stress (σ_c) approaches its maximum value. In order to determine the ultimate failure load (P_b) resulting from bending failure of a flatwise oriented sandwich panel, the equation (1) (Ferdous et al., 2017) should be used.

$$P_b = \frac{4(EI)\sigma_c}{a\,dE_s} \quad (1)$$

Equation (2) (Ferdous et al., 2017) can be used to calculate the theoretical bending stiffness EI in flatwise orientation.

$$EI = \frac{bt_c^3}{12}E_c + \frac{bt_s}{2}\left(\frac{t_s^2}{3} + d_0^2\right)E_s \quad (2)$$

where E_s, $E_c$are the facing and core moduli respectively. In some cases, the contribution of core to the bending stiffness can be ignored to make the theoretical estimation more conservative.

3.8.2. Flexible plastic core panel failure load

In flatwise orientation, the sandwich panels are expected to fail in skin due to high deflection of the core. The ultimate failure load resulting from bending loads

(Pb) of flatwise sandwich panels can be ascertained using the equation (3) (Ferdous et al., 2017).

$$P_b = \frac{4(EI)\sigma_s}{a\, dE_s} \quad (3)$$

where, σ_s is the strength of the skins.

3.8.3. Soft-lightweight styrofoam core panel failure load

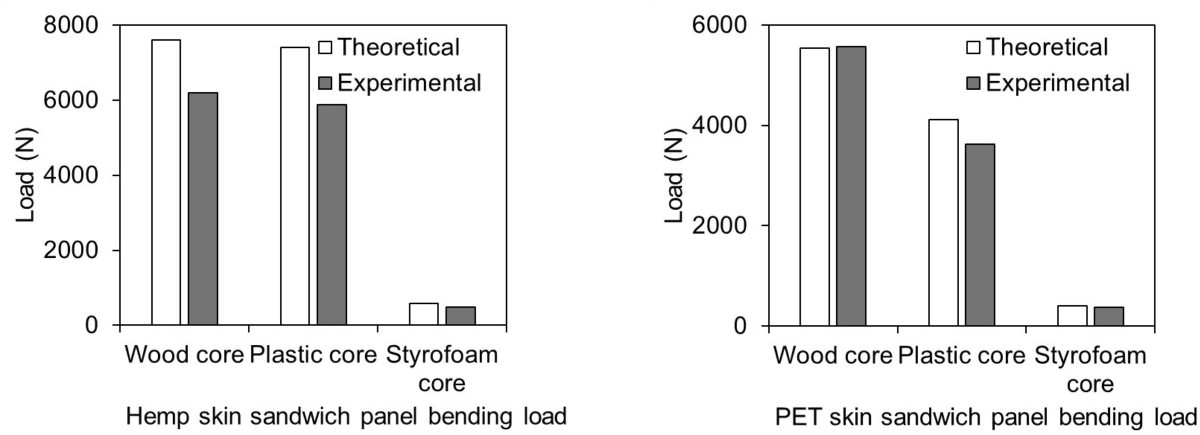
It is expected that soft-lightweight styrofoam core sandwich panels will fail in indentation when oriented flatwise. The ultimate failure load of flatwise sandwich panels resulting from bending loads (Pb) can be determined by the equation (4).

$$P_b = \frac{4}{3} k b t_s \sqrt{\sigma_c \sigma_s} \quad (4)$$

In this equation, k represents the support coefficient. In many cases, the load-carrying capacity can be reduced by as much as 60% when switching from an elastic foundation to simply supported conditions due to the loss of continuous support. Therefore, the value of k is 1 if the beam is supported on an elastic foundation, while it is taken 1/3 if it is simply supported (Gdoutos et al., 2002). The key contribution in this study is to identify the right equation for each sandwich panel.

3.8.4. Experimental and theoretical failure load

The load-displacement relationship is used to evaluate the bending stress and bending modulus experimentally, as shown in Table 3.2 and Table 3.3. The experimental failure stresses are determined from the laboratory data. Theoretically, the bending failure load of sandwich panels in flatwise orientation can be estimated using Equations (1-4).



(a) Hemp skin panels failure load (b) PET skin panels failure load

Figure 3.11. Comparison between experimental and theoretical failure load of the sandwich panels.

Figure 3.11 illustrates a comparison between the experimental and theoretical failure loads. The theoretical estimation of failure load is slightly higher than the corresponding experimental loads. This is perhaps due to the consideration of core stiffness in Eq. (2) where the bending loads of the beam are usually carried by skins. The results indicate that the analytical equations are capable of reasonably estimating the actual failure load of the sandwich panels. The load-displacement curve derived from laboratory data for sandwich panels is presented in Appendix B.

3.9. Summary

A comprehensive experimental and theoretical investigation of composite sandwich panels was presented in this chapter in order to evaluate their mechanical performance. An analysis of the carbon footprint of panels and a number of experimental studies, including tensile tests of the skins and glass transition temperature tests of the core and sandwich panels, provided insight into the panels' load bearing capacity, failure modes, and durability characteristics. The results demonstrated that material selection and core structure had a significant impact on the performance of the panels.

CHAPTER 4: CONCLUSION AND RECOMMENDATION

An overview of the key results from the experimental and theoretical investigation of composite sandwich panels is presented in this chapter, with emphasis on their mechanical properties. This research has provided valuable insights into the strength, stiffness, and failure mechanism characteristics of these panels under a variety of loading conditions. This chapter discusses the scientific contributions, practical implications, and limitations of the study while outlining recommendations for future research and advancements in composite sandwich panels.

4.1. Investigation of composite sandwich *panels*

This study investigates carbon footprint as well as the mechanical and durability characteristics of two types of skins (hemp and recycled PET), and three different types of waste-based cores (wood composites, recycled plastics, and styrofoam), incorporating six types of sandwich panels. The tensile behaviour and glass transition temperatures of the skins are studied under normal air, water, hygrothermal, saline solution, and elevated temperature conditions. The bending behaviour of the cores and sandwich panels are investigated, and the capacity of the panels is predicted using theoretical modelling. Based on the results, the following conclusions are drawn:

- Bio-based resin, natural fibres and waste-based core materials can reduce carbon footprint by up to 90% compared to traditional panels made of petroleum-based resin, synthetic fibres and synthetic foam core, demonstrating the potential for sustainable building materials.

- Temperature is found to be more detrimental to fibre composite laminates than other environmental conditions (water, hygrothermal, saline solution and normal air). The reason for this is that elevated temperatures soften the polymers of the skins, which results in a faster loss of mechanical properties than other environments.

- Hemp skins are more sensitive to different environmental conditions than recycled PET skins. While hemp skins lost up to 40% of their tensile strength, PET skins lost around 20% due to aggressive environments. However, both hemp and recycled PET skins drop their glass transition temperatures quite similarly by 35%. The higher mechanical degradation of hemp skins than recycled PET skins is a result of the fact that hemp is a natural fibre that is prone to absorbing more water than synthetic polymer PET skins, facilitating faster degradation.

- Stiffness of core plays an important role in the bending behaviour of sandwich panels. The stiffer core improves the material's ability to transfer shear forces between the face sheets, thereby reducing core deflection. Higher core stiffness makes panels less likely to fail from indentation.

- The type of core has a significant impact on the theoretical prediction of the failure load of sandwich panels. The strength of the core dominates the load capacity in brittle core sandwich panels, while the strength of the skin dominates the load capacity in flexible core sandwich panels. In low stiffness core, the load capacity is dependent upon the resistance to core indentation.

4.2. Possible areas for future research

The findings of this study suggest several future directions for composite sandwich panels to improve performance, sustainability, and real-world applicability. Future research should focus on the following aspects:

4.2.1. Optimal manufacturing and scalability

To enhance the feasibility of mass production for industrial applications, the bond performance between the skin and the core can study, which is a crucial aspect of sandwich panels. Additionally, the limitations related to the carbon footprint study can address and research should focus on scalable production methods, such as automated fabrication and additive manufacturing, as well as energy-efficient curing techniques. Moreover, the detail carbon emission analysis including transportation and disposal can be determined through a comprehensive life-cycle analysis. It is also possible to improve quality control and consistency through the integration of smart manufacturing processes.

4.2.2. End-of-life and sustainability strategies

Minimising environmental impact requires a study of circular economy approaches, including recycling, reusability, and waste recovery. In the future, work should examine closed-loop recycling processes for composite materials, as well as assess life cycle impacts from the extraction of raw materials to their disposal.

4.2.3. Real world applications

The practical application of composite sandwich panels would be validated through full-scale prototype development and field trials in sectors such as transportation, aerospace, and civil infrastructure. Standards and regulations could be established through collaboration with industry partners and policymakers.

The development of composite sandwich panels can contribute to sustainable engineering solutions by addressing these research areas, ensuring their widespread adoption in structurally demanding and environmentally conscious applications. At the end of the service life, the panels should be crushed into smaller pieces to produce core for new sandwich panels, thereby promoting circular economy.

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APPENDIX [A] LIST OF PUBLICATIONS

Journal article publication

Ashiqul Islam, Wahid Ferdous, Paulomi (Polly) Burey, Kamrun Nahar, Libo Yan and Allan Manalo "Polymer composite sandwich panels composed of hemp and plastic skins and composite wood, recycled plastic, and styrofoam cores", ***Polymers*** 2025, 17(10), 1359; https://doi.org/10.3390/polym17101359

Conference papers publications

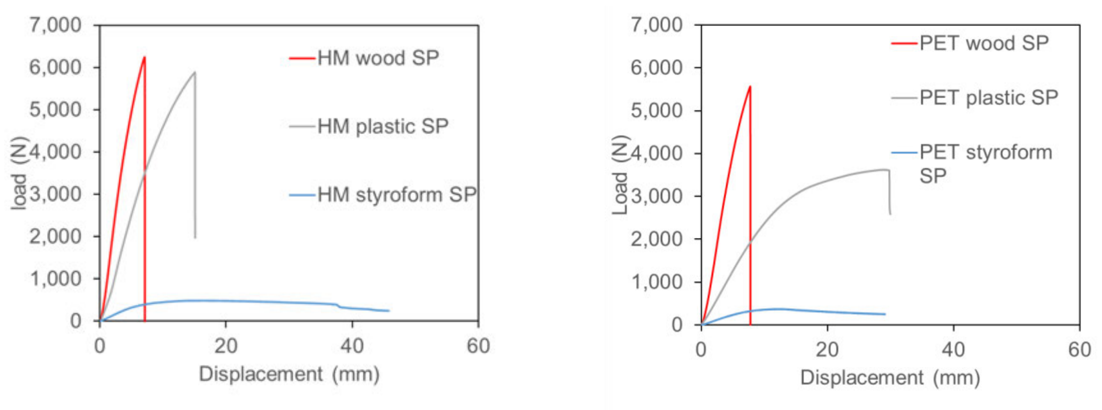
Ashiqul Islam, Wahid Ferdous, Paulomi (Polly) Burey, Kamrun Nahar and Allan Manalo "Towards the development of a low-carbon emission Sandwich panel – a state-of-the-art review", 26th Australasian Conference on Mechanics of Structures and Materials (***ACMSM26***), 3–6 December 2023, Auckland, New Zealand

Ashiqul Islam, Wahid Ferdous, Paulomi (Polly) Burey, Kamrun Nahar and Allan Manalo "Effect of core materials on the flexural behaviour of composite sandwich panels", Ninth Asia-Pacific Conference on FRP in Structures (***APFIS 2024***), 8-11 December 2024, Adelaide, Australia

APPENDIX [B] LOAD-DISPLACEMENT GRAPH

B.1. Load -displacement behaviour

The load-displacement graph for the bending test of sandwich panels is shown in Figure A1. It illustrates the stiffness, strength, and failure behaviour of the material under applied loads. The peak load point indicates the maximum load-carrying capacity before failure. This is then followed by a sudden reduction in load-carrying capacity (brittle failure) for wood core and plastic core panels. With small loads, however, styrofoam panels exhibit high deflection. In order to determine the flexural strength and stiffness of composite sandwich panels, slope, peak load, and failure characteristics are analysed.



(a) Hemp skin sandwich panels (b) PET skin sandwich panels

Figure B1: Load vs displacement curve