Moisture Diffusion and its Effect on Performance of Thermoplastic Composite Sandwich Panels with Recycled PET Foam Cores

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Abstract

Moisture Diffusion and its Effect on Performance of Thermoplastic Composite Sandwich Panels with Recycled PET Foam Cores

Parinaz Nouraei Ashtiani

Thermoplastic composite sandwich structures represent an innovative solution in structural engineering, offering a lightweight yet durable alternative for various applications such as construction, aerospace, and automotive. These structures typically consist of two outer layers of thermoplastic composite sheets (facesheets) encapsulating a core material such as lightweight foams or honeycomb structures. Sandwich panels with recycled foam core offer a remarkable synergy between advanced engineering and sustainable practices. This study primarily focuses on the diffusion behavior of 100% recycled Polyethylene Terephthalate (rPET) foam cores with four different densities (70, 80, 100, and 150 Kg/m^3), Glass/ Polypropylene facesheets, and sandwich panels made of PET foam core with a density of 80 Kg/m^3. All the specimens were immersed in water at a temperature of 40 degrees Celsius for prolonged durations. It is observed that the diffusion behavior of the PET foams and facesheet is governed by the classical Fick's law. The experimental results indicated that the presence of facesheets in the sandwich structure acts as a moisture barrier and decreases the ingress of water into the composite sandwich panels by approximately 32%. The sandwich panels utilized in this investigation are manufactured using the double-belt lamination technique. To evaluate the influence of prolonged exposure to moisture on the mechanical characteristics of the structure, flatwise compression tests were conducted on the foam cores, revealing a significant decrease in compressive strength when exposed to moisture. Additionally, multiple flatwise tensile tests were conducted under both dry and wet conditions. The results revealed that wet samples demonstrate failure at the interface between the foam core and facesheet, while dry samples predominantly experience failure within the foam core. The study found that moisture exposure significantly reduced flatwise tensile strength, with bonding strength decreasing by approximately 55% after 730 hours of immersion. These findings highlight the significance of optimizing double-belt lamination parameters to have stronger and more uniform adhesion between facesheet and core under conditions of water exposure.

Keywords: Thermoplastic composite sandwich panels, Recycled PET foam, Moisture Diffusion, Flatwise Tensile testing, Mechanical Performance

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Nomenclature

Abbreviations

rPET	Recycled Polyethylene Terephthalate
PP	Polypropylene
GFRP	Glass Fiber-Reinforced Polymer
Tg	Glass Transition Temperature
SEM	Scanning Electron Microscope
ESEM	Environmental Scanning Electron Microscope
MTS	Material Testing System
FEA	Finite Element Analysis

List of Symbols

M_t	Moisture content at time t
W_t	Weight of the wet specimen at exposure time t
W_d	Mass of the dry specimen
M_{sat}	Saturation moisture absorption level

D	Diffusion Coefficient
h	Thickness of the specimen
l	Length of the specimen
w	Width of the specimen
C	Concentration of moisture
t	Time

Chapter 1: Introduction

1.1 An Overview of Composite Sandwich Panels

Composite sandwich panels have found wide engineering applications due to their exceptional strength-to-weight ratio and structural efficiency. These panels consist of two thin, stiff, and strong facesheets that are adhered to a thick, lightweight core. This strong and lightweight structure is ideal for various applications in the aerospace, automotive, marine, and construction sectors [1]. The facesheets, commonly composed of fiber-reinforced polymers (FRPs) such as carbon fiber-reinforced polymer (CFRP) or glass fiber-reinforced polymer (GFRP), offer the necessary strength and stiffness. The core material, which can be made from polymeric foams such as Polyethylene Terephthalate (PET), honeycomb structures, or natural materials such as balsa wood, provides thickness while lowering the composite's overall weight. The main function of the core is to transfer shear loads between the facesheets while increasing the panel's compression strength, bending stiffness and resistance to buckling [2–4]. Figure 1.1 depicts a schematic diagram of the foam-cored sandwich structure.

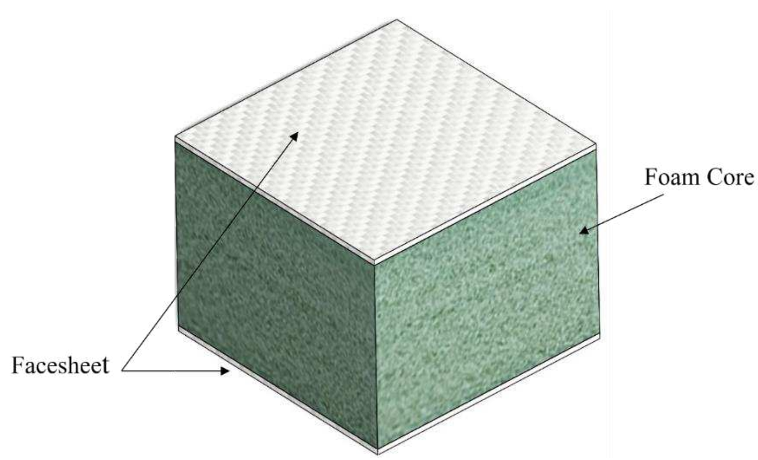


Figure 1.1. Schematic diagram of sandwich structure with foam core.

1.2 Thermoplastic-based Sandwich Panels

Thermoplastic-based sandwich panels are widely used in a range of applications from marine applications to prefabricated building constructions [5] due to their superior characteristics such as superior flexural properties, and effective thermal and acoustic insulation [6–8]. These panels also present considerable advantages over thermoset materials in terms of the fabrication process and sustainability. Thermoplastic-based sandwich panels offer a higher production rate, resulting in decreased manufacturing costs. Moreover, they possess a high potential to be recycled [9]. However, there are challenges, particularly in achieving strong adhesion between the facesheet and core material during production. Consequently, researchers [6,10–12] have investigated numerous manufacturing methods for thermoplastic composite sandwich panels. This study aims to assess the properties of PET Foam core sandwich panels fabricated via the continuous roll-forming process, a method that shows potential for improving efficiency and performance.

1.3 Moisture Absorption and Mechanical Degradation

Composite sandwich structures are often exposed to environments with high humidity, temperature variations, and other adverse environmental factors. Moisture ingress into the facesheets, the core material, and the interface between the facesheet and the core occurs through a diffusion process, following Fickian [13–15] or non-Fickian [16–18] diffusion behavior.

In addition to understanding the moisture diffusion mechanism of sandwich panels, it is crucial to consider the effect of moisture absorption on the mechanical properties of these panels. In many applications, such panels are exposed to high moisture conditions. Extended exposure to moisture can cause a decrease in the mechanical properties and affect the operational service life of composite sandwich panels [19–21]. The flatwise tensile test is an ideal method to determine the strength of interfacial debonding in sandwich panels. Additionally, the mechanical properties of the core can be assessed through various tests, including three-point bending, four-point bending, and flatwise compression tests.

1.4 Problem Statement and Research Objectives

1.4.1 Problem Statement

The increasing use of sandwich structures with rPET foam cores in various applications is driven by their lightweight properties and the sustainability benefits of using recycled and recyclable materials. However, in applications such as prefabricated constructions on farms and storage cabins that are exposed to high humidity, moisture ingress poses a significant threat to the structural integrity of these sandwich panels. Despite their advantages, the performance of rPET foam-cored sandwich panels under prolonged moisture exposure remains inadequately understood. This study aims to address this gap by investigating the moisture absorption behavior and its impact on the mechanical properties of these panels. The following section outlines the specific research objectives designed to achieve this goal.

1.4.2 Objectives

This study aims to investigate the moisture absorption behavior of each component of PET foam core sandwich panels and to understand how moisture affects the mechanical properties of the foam and the bonding strength of sandwich panels. This comprehensive investigation focuses on the moisture absorption behavior and diffusion coefficients of 100% recycled Polyethylene Terephthalate (rPET) foam cores with four different densities: 70, 80, 100, and 150 kg/m^3, and Glass/Polypropylene facesheets. Moreover, the diffusion coefficient and the maximum moisture uptake will be assessed for a sandwich panel with 80 Kg/m^3 PET foam, fabricated using a double-belt lamination technique. The study seeks to gain a comprehensive understanding of diffusion behavior and the effects of moisture exposure on these materials by utilizing experimental techniques such as moisture diffusion analysis and flatwise compressive and tensile tests and identify areas for future research to optimize the performance and durability of thermoplastic composite sandwich panels in moisture-prone environments.

Specifically, the objectives of this research are:

1. To evaluate and compare the moisture absorption behavior and diffusion coefficients of rPET foam cores with different densities.

2. To evaluate the role of Glass/Polypropylene facesheets in influencing moisture ingress and diffusion within the sandwich panels.
3. To determine the diffusion behavior and maximum moisture uptake of sandwich panels fabricated with an 80 kg/m^3 PET foam core.
4. To analyze the effects of prolonged moisture exposure on the mechanical properties, specifically the compressive properties of rPET foams and the flatwise tensile strength of the sandwich panels fabricated using the double-belt lamination technique.
5. To identify the failure mechanisms of the sandwich panels under dry and wet conditions, focusing on the adhesion strength between the foam core and the facesheet.

1.5 Structure of the Thesis

The rest of the thesis is structured into five comprehensive chapters, each addressing a specific aspect of the research, as outlined below:

Chapter 2: Literature Review

This chapter provides a comprehensive review of existing research on moisture absorption in polymeric foams and composite materials. It discusses the factors affecting moisture uptake, diffusion mechanisms, and the impact of prolonged moisture exposure on mechanical properties. Additionally, the chapter addresses the environmental sustainability of composite sandwich panels and the manufacturing processes.

Chapter 3: Materials and Methods

This chapter covers the materials used, including rPET foam and Glass/PP facesheets, and the double-belt lamination manufacturing process. It also provides a detailed description of the experimental procedures for testing water absorption, compressive properties of foam, bonding strength of sandwich panels, and microscopic observations. Moreover, this chapter explains the principles of moisture absorption based on Fick's second law and provides the assumptions made for Fickian diffusion for foam and facesheet samples.

Chapter 4: Results & Discussion

This chapter presents and analyzes the results of the experimental investigations, providing insights into the moisture diffusion characteristics and mechanical properties of the composite sandwich panels with rPET foam core.

Chapter 5: Conclusion and Contribution

This chapter summarizes the key findings of the research, highlighting the effects of moisture absorption on the performance of thermoplastic composite sandwich panels with rPET foam cores, and discussing the contributions to the field.

Chapter 6: Future Work

This chapter outlines the potential for improving the performance of the discussed sandwich panels and suggests areas for future investigations into moisture behavior and mechanical properties of composite sandwich panels with rPET foam cores manufactured using the double-belt lamination technique.

Chapter 2: Literature Review

This section presents a comprehensive literature review that focuses on the analysis of moisture absorption in polymeric foams used as core materials, Glass Fiber Reinforced Polymers (GFRPs), and thermoplastic-based sandwich panels. Additionally, it explores previous works on various diffusion mechanisms, such as Fickian and non-Fickian behavior, providing a thorough examination of the theories and models used to understand moisture diffusion in these materials. Research on the impact of prolonged moisture exposure on the mechanical properties of these materials is also investigated. This review provides the necessary background to support the experimental work and analysis in this thesis and highlights the gaps where our research contributes to advancing knowledge and practice.

The performance of polymeric materials can be significantly influenced by moisture absorption. Polymeric foams and composite materials are widely utilized in applications demanding lightweight and high-strength structures, including aerospace, marine, and structural applications. These applications often expose the materials to environments with fluctuating humidity and temperature, which can alter their properties. In our work, one application of PET foam core sandwich structures is in prefabricated buildings used in farms in humid environments. Figure 2.1 shows the structure of one of the prefabricated buildings being developed by Innovative Composite Product (ICP) Inc. This structure uses FRP face sheets and a recycled PET foam core. Additionally, ICP company sought to assess the feasibility of using these sandwich panels as water containers. Therefore, it was crucial to evaluate whether PET foam core sandwich panels produced via continuous roll forming are sufficiently resistant to moisture and to determine if the production line requires optimization.

Before describing our findings, it is necessary to understand the mechanism of moisture absorption in polymer foams and composite structures and to review previous studies in this domain. Also, a comprehensive review of the effect of moisture on the properties of foam-cored composite sandwich panels will be provided. This foundation allows for a better understanding of the challenges and potential solutions related to moisture absorption in these materials.

Figure 2.1. Structural design of a prefabricated building by ICP company.

2.1 Moisture Absorption in Polymeric Foams and Composite Materials

The moisture uptake in polymers is mainly governed by the process of diffusion of water molecules throughout the material. This process is the result of random molecular movements, by which penetrant molecules are moved freely into the polymer [22,23]. Moisture transport through polymer matrices is influenced not only by the polymer's characteristics such as the molecular chain arrangement, degree of crosslinking and swelling, and polymer polarity but also by the temperature and the humidity content of the exposure environment [24,25].

2.1.1 Factors Affecting Moisture Uptake in Polymeric Foams

Polymeric foams are lightweight materials with unique cellular structures. These materials are composed of a solid polymer matrix with numerous tiny, gas-filled cells distributed throughout. These properties make polymeric foams ideal for a wide range of applications due to their superior characteristics such as excellent strength-to-weight ratio, acoustic and thermal isolation properties along with cost-effectiveness, and ease of manufacturing [26]. However, when exposed to wet environments, their unique structure can become a disadvantage. Polymeric foams are highly susceptible to moisture absorption due to their porous structure, which allows moisture to diffuse more easily, resulting in reduced mechanical and thermal properties. The extent of water absorption in polymeric foams is mainly determined by the cell structure of the foam [27]. Polymeric foams are classified into two types based on their cell connectivity.

Open-cell foams have interconnected cells that allow moisture to flow freely within the material. This interconnected structure enables faster penetration and spread of moisture, but it can also result in accelerated deterioration of mechanical properties due to increased moisture ingress. Closed-cell foams consist of individual cells that are separated by solid cell struts. This configuration improves insulation and dimensional stability while also providing a more effective barrier to moisture penetration, significantly slowing the process of diffusion [26,28]. Although closed-cell foams provide better moisture resistance, they can accumulate moisture over time, potentially causing internal damage if not adequately controlled. When closed-cell foam materials, like PET foam, are immersed in water, there is usually a noticeable increase in weight during a short immersion time. This increase is attributed to the accumulation of moisture in the open cells on the cut surfaces of the material. The density and cell size of a foam also affect the moisture uptake. Foams with higher density tend to absorb less moisture due to smaller cell sizes and higher material content per unit volume which result in lower mobility of penetrant inside the foam structure [29]. In the following studies, the long-term behavior of moisture absorption in closed-cell polymeric foams will be analyzed.

In [17] the moisture behavior of closed-cell PVC foams was investigated at 40 °C and 95% relative humidity (RH) and water immersion at 40 °C for over 2,5 years. It was found that closed-cell PVC foam undergoes a multi-stage process of moisture absorption. In each stage, a linear increase in weight with the square root of time was observed, followed by a plateau. This multi-stage mechanism was attributed to the progressive diffusion into the polymer cell walls, accompanied by moisture ingress into cell cavities. It was concluded that moisture penetration reached only the third cell layer, based on the three observed plateaus, indicating an ingress depth of 1.2 mm. To validate this finding, the foams were sectioned and blotted with a paper towel to observe the dry bulk. The study indicated that the classical Fickian diffusion model properly described the first stage of absorption but failed to represent the complexity of long-term behavior.

In another work [30] an investigation was conducted to study the moisture absorption and the impact of hygrothermal exposure on closed-cell semicrystalline PET foam. The study discovered that moisture absorption in PET foam happens through two separate mechanisms: the permeation and absorption of moisture by the polymer matrix at rates comparable to those observed in PET films, and the gradual filling of cell cavities with liquid water during immersion. Notably, there was no long-lasting deterioration in the chemical composition or physical characteristics of the PET foam over six months of exposure to high temperature (40°C) and high humidity (80% relative humidity), as well as a one-year period of immersion in water at normal room temperature. The study determined that the degradation of PET foam due to moisture and heat is not primarily influenced by diffusion. This degradation has a negligible effect on the foam's ability to insulate, even when water is trapped in the cell cavities.

2.1.2 Factors Affecting Moisture Uptake in Polymeric Composites

Many researchers [31–34] observed the moisture absorption behavior of fiber-reinforced polymer (FRP) composite materials. It has been found that the majority of engineering fibers have minimal moisture absorption capacity and may not be significantly influenced by moisture, while the polymer matrix can absorb moisture. Water molecules can penetrate the polymer and fill the spaces between the polymer chains. The absorbed water in a composite affects the interface between the fibers and the matrix, which can result in a decline in the mechanical properties of the composite. The type of fiber can impact moisture absorption, for example, carbon fibers demonstrate superior resistance compared to glass fibers. Additionally, other factors influencing water diffusion in FRP composites include fiber volume fraction, polymer matrix type, temperature, additives, humidity levels, fiber orientation, fiber surface coating, fiber size, and void volume [35]. In the following paragraphs, research on the hygroscopic effects on FRP composites will be reviewed.

Authors in [36] investigated various hygroscopic effects for epoxy/ carbon fiber laminates. Glass transition temperature (Tg) was shown to decrease linearly with increasing moisture absorption. The study also revealed that moisture absorption behavior is influenced by previous hygrothermal exposure conditions. This implies that previous exposure conditions can have an impact on the future uptake of moisture. As expected, an increase in the matrix volume ratio and the void volume ratio resulted in a rise in the diffusion coefficient. Also, the laminate thickness and lay-up sequence were found to have minimal effect on the diffusion rate and equilibrium water uptake for water absorption in the through-thickness direction. However, the water absorption rate of 90°-z composite laminates was greater than that of 90°-y laminates due to the interlaminar resin-rich areas typically present in thick composite laminates. The curvature of [0/90] specimens decreased with increased water absorption, resulting from the release of internal stresses caused by the plasticization of water molecules.

The paper [37] evaluated the long-term durability and mechanical performance of glass fiber-reinforced polypropylene (Glass/PP) composites when exposed to various environmental conditions. The study revealed that the moisture saturation level in Glass/PP composites reached approximately 3.75%, which can be attributed to the high porosity resulting from the continuous molding process. The water uptake analysis demonstrated that elevated temperatures and extended immersion durations resulted in more moisture absorption. In addition, salt solutions demonstrated a reduced absorption rate in comparison to tap water because of the barrier effect caused by the presence of dissolved NaCl crystals. The results of Scanning electron microscopy (SEM) analysis showed significant damage to the fiber/matrix interface after 168 days of immersion at 70°C. Also, the mechanical tests revealed that the flexural strength and elastic modulus of the PP/Glass composites decreased significantly with prolonged exposure to moisture.

2.2 Moisture Absorption in Composite Sandwich Panels

Moisture absorption in composite sandwich panels is a big concern, particularly for marine, aerospace, construction, and water storage industries. Foam-cored composite sandwich structures, which are made up of fiber-reinforced polymer face sheets and foam cores, are extremely valuable due to the remarkable strength-to-weight ratios and structural efficiency that they possess. They are widely used in a variety of applications exposed to high humidity environments, including building panels and water reservoirs, where maintaining structural integrity and performance under moisture exposure is crucial.

The absorption of moisture can result in a variety of unfavorable effects, such as a decrease in mechanical strength, a change in thermal and acoustic characteristics, and the possibility of failure at the interface between the face sheet and the core [38–41]. Exposure to moisture and humidity for an extended period of time can drastically deteriorate the sandwich structures in building industry, which can have an effect on both performance and safety. Consequently, in order to improve the performance of these composite structures and ensure that they last for a longer period of time, it is essential to have a solid understanding of the factors that influence the amount and rate of moisture uptake and the mechanisms that govern the moisture absorption process.

2.2.1 Factors Affecting Moisture Uptake in Composite Sandwich Panels

The face sheet and the core have a major impact on the amount of absorbed water. In addition to these components, the interface between the face sheet and the core is especially susceptible to damage that is caused by moisture. The weakening of this interface due to moisture penetration can lead to significant reductions in interfacial bonding strength, especially under hygrothermal conditions where there is a combination of high temperature and humidity [42].

Several parameters influence the rate and extent of moisture absorption in sandwich panels:

- *Material Composition*

  The type of polymers and fibers used in the facesheets and the core material significantly affects moisture absorption. Researchers investigated the moisture absorption characteristics in various polymer materials. The difference in moisture absorption behavior of different polymers was mainly attributed to the free volume fraction of polymers and segmental mobility in the polymer. In addition, other variables such as the degree of saturation, crosslinking density, and degree of crystallinity might indirectly impact diffusion by changing the mobility of segments. Also, the glass transition temperature (T_g) has a notable influence on moisture diffusion. As the T_g drops, the mobility of segments and the diffusivity of moisture rise. On the other hand, when the size of the polymers' molecules increases, the movement of the molecular chains becomes significantly limited, resulting in slower rates of diffusion and reduced moisture content [43,44].

- *Environmental Conditions*

Foam-cored sandwich structures can experience a wide range of temperature and humidity conditions due to their diverse applications. In foam-cored composite sandwich panels, the polymer material of the core and the facesheet matrix can be affected by these conditions. Hygrothermal conditions, combining both temperature and humidity, can have notable negative effects on the performance of the entire structure by impacting the behavior of its components and the interface between the core and facesheet. High temperatures combined with high humidity accelerate the degradation process, while immersion in water exacerbates the absorption and subsequent damage [40,45].

- *Manufacturing Processes*

The moisture absorption of composite sandwich panels is significantly influenced by the manufacturing techniques, which directly affect the quality of the final product. A superior manufacturing process reduces defects and voids in the face sheets, therefore minimizing moisture ingress via capillary action. Additionally, it is necessary to obtain a strong and uniform adhesion between the facesheet and the core to decrease moisture uptake in the interface and minimize mechanical deterioration of the sandwich panel [46,47].

- *Core density and structure*

The density of foam plays a significant role in determining its moisture absorption characteristics. Higher-density foams generally have smaller cell sizes and thicker cell walls, resulting in less moisture absorption. This is because the increased density results in fewer and smaller pores, limiting the pathways for water ingress. Conversely, lower-density foams with larger cell sizes and thinner walls tend to absorb more moisture due to their higher porosity and greater free volume.

The number of studies investigating the effect of cell size and foam density on moisture absorption in polymeric foams is quite limited. However, valuable insights can be derived from previous research specifically the findings presented in [27]. In this study, it was observed that foams having a higher density, have superior resistance to the penetration of moisture. This is attributed to smaller cell sizes, thicker cell walls, and more uniformly distributed cells, which limit the pathways for water penetration.

The study also observed that increasing the amount of blowing agent leads to a reduction in foam density. This reduction results in larger cell sizes and a higher risk of cell surface breakage. The cracks formed on the cell walls create additional pathways for water penetration, thus increasing the rate of moisture absorption in lower-density foams. This illustrates the inverse relationship between foam density and moisture resistance, where lower-density foams with larger, less uniform cells are more prone to water ingress and subsequent absorption.

2.2.2 Moisture Absorption Mechanisms

The moisture absorption behavior in sandwich panels typically conforms to the classical Fickian diffusion model, where the absorption rate initially increases linearly with the square root of time and then gradually decreases until reaching a saturation point. However, due to the complex interactions within the polymeric materials, prolonged exposure can lead to non-Fickian diffusion behavior [48,49].

If we consider the moisture absorption in one direction from the skin to the core, the moisture absorbed by the sandwich panel can be distributed into five locations respectively [50]. Each part contributes to the final moisture saturation level. First, moisture penetrates the free volume between polymer matrix molecule chains and fills these spaces. The second region is the interface between fibers and polymer matrix. Absorbed water at the fiber-matrix interface can deteriorate the bond between the fibers and polymer, leading to mechanical degradation. The interface between the core and the skin is the third location where water diffuses in it. Water absorption in this area can significantly decrease the bonding strength, which can affect the structural integrity of the panel. In the next step, the moisture diffuses into the foam core pores and fills the free volume between the polymer chains. Over time, moisture enters the empty cells within the foam. If the absorbed water becomes trapped in the core, it can lead to weight gain and cause irreversible damage to the structure [51].

2.3 Fickian and Non-Fickain Diffusion Behavior

The Fick's second law also known as the "diffusion equation" is the most widely employed model to predict absorption behavior and moisture content in polymers. Adolf Fick derived the diffusion equation from the first Fick's law (flux equation) and the conservation of particles. This model takes into account both time and spatial variations in concentration. This model is popular due to its simplicity and mathematical tractability. Fick's second law of diffusion states that the rate at which the concentration of a substance varies in a specific region is determined by the curvature of the concentration gradient in that region (Figure 2.2) and is generally expressed as Equation (1). [52,53].

$$\frac{\partial C}{\partial t} = \nabla.(D\nabla.C) \tag{1}$$

Where C is the penetrant concentration, t is the time and D is the diffusion coefficient.

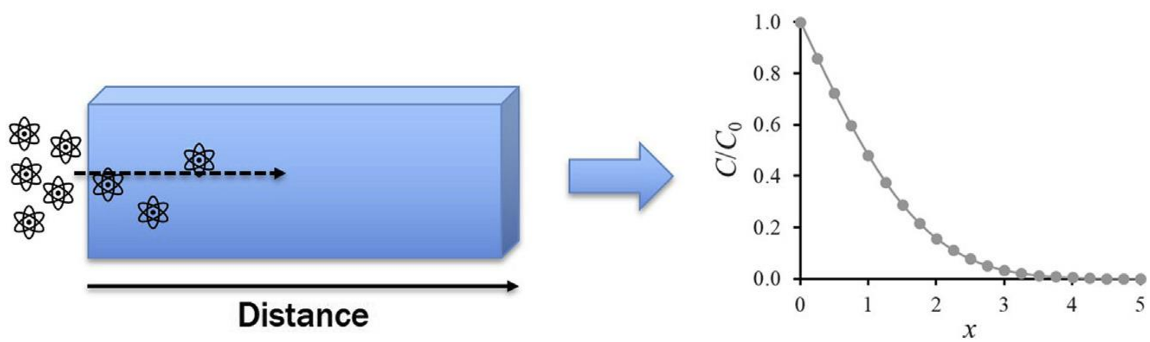


Figure 2.2. Schematic of non-steady state diffusion process [53].

Fickian diffusion is often observed during a short-time moisture uptake[13–15,54], while most polymeric materials exhibit non-Fickian absorption behavior in the long term [18,55,56]. In fickian behavior after the initial linear moisture uptake followed by a gradual absorption, the increase in mass stops immediately. This model assumes that the diffusion coefficient remains constant. In contrast, the non-fickian behavior which is also known as anomalous or hindered diffusion, is due to considering physical or molecular interactions at the microscale, the diffusion coefficient is not constant and is time dependent. Although non-Fickian diffusion is more complicated, there are some methodologies and models that can predict its behavior by incorporating additional parameters to account for the multi-stage nature of the diffusion process [18,48,49]. Figure 2.3 demonstrates the comparison of moisture absorption behavior in Fickian and Non-Fickian (two-stage) processes.

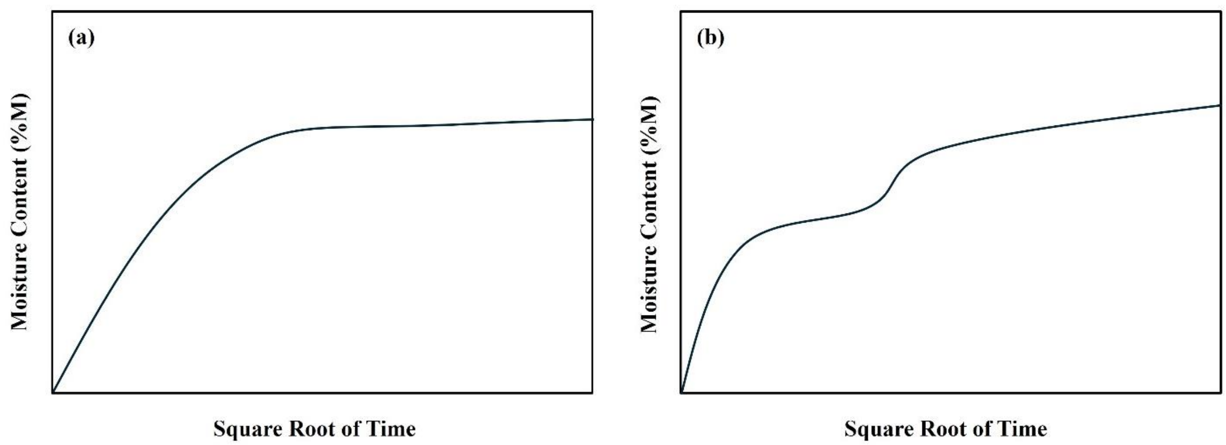


Figure 2.3. (a) Fickian versus (b) Non-fickian (two-stage) moisture absorption behavior.

2.4 Environmental Sustainability in Composite Sandwich Panels

Over the past few decades, there has been a significant increase in the usage of plastic products, leading to waste accumulation and excessive use of resources. As a result, there has been a growing focus on sustainable and recycled materials. This shift has prompted extensive research into using these materials and evaluating their performance across different applications. One area that has seen significant progress is the growing utilization of composite sandwich panels that contain recycled components. Recycled materials for these panels offer numerous environmental benefits. For example, when considering the global warming potential (GWP100) of different foam cores, which is assessed in kilograms of CO_2 equivalent emitted during the production (from cradle to gate) of 100 kg of material, there are notable variations between recycled PET, virgin PET, and PVC foams. Recycled PET foam yields 226 kg of CO_2 equivalents, virgin PET foam produces 337 kg, and PVC foam emits 472 kg for the same density [57]. Armacell's unique rPET technology produced from plastic bottles reduces CO_2 emissions by 37% compared to foam cores made from non-recycled PET [58]. Substituting traditional PET materials, which constitute a significant portion of global plastic waste, with recycled PET (rPET) not only offers relatively high mechanical properties but also addresses the need for waste reduction and promoting greener manufacturing processes [59,60]. Figure 2.4 highlights the steps of the recycling process of PET, from the initial collection and sorting to the production of 100% recycled ArmaPET Struct foams.

A comprehensive review [61] presented the latest advancements in developing environmentally friendly sandwich structures. In this review paper, two primary approaches were categorized for enhancing the environmental benefits of sandwich panels: 1) using thermoplastic-based skins and cores for future recycling and 2) incorporating recycled thermoplastics as the components. This paper also identified GFRP with PP matrix as the most common skin material and PP or PET foams as typical thermoplastic cores for fully recyclable panels. The results showed promising mechanical performance of sandwich panels using sustainable materials. In another work, authors in [62] manufactured a sustainable sandwich panel using recycled carbon fibers with PP matrix as facesheets and recycled PET as the core. The results of mechanical testing demonstrated excellent flexural strength and modulus, as well as superior bonding between the skin and core.

Despite the significant progress that has been achieved in the development of sustainable materials for sandwich panels, several challenges still need to be resolved. The optimization of production processes, the enhancement of the overall mechanical properties and durability of environmentally friendly sandwich panels, and ensuring consistent quality and performance are some of these challenges.

Figure 2.4. Stages of the ArmaPET Struct recycling process [58].

2.4.1 Thermoplastic Polymers and Their Recycling Potential in Sandwich Panels

Thermoplastic materials are increasingly recognized as excellent candidates for developing eco-friendly sandwich panels due to their recyclability, low cost, and ease of processing. They can be reshaped and reprocessed multiple times without significant degradation of properties [9]. The frequent use of thermoset resins as adhesives on the interface between the core and facesheets in thermoplastic sandwich panels restricts the recyclability of the panels. In this regard, direct fusion bonding between the core and skin is beneficial for thermoplastics, as it ensures strong adhesion without the need for additional adhesives. ICP company is applying the same approach by using continuous roll forming as a manufacturing method ensuring that the final products remain recyclable after production. The following section will discuss various manufacturing methods, with a particular focus on the technique utilized for the sandwich panels in this project.

2.5 Manufacturing Processes of Thermoplastic Composite Sandwich Panels

Thermoplastic composite sandwich panels can be manufactured using different manufacturing processes. The manufacturing method can directly influence the properties of the final product, and a lot of considerations need to be taken to achieve a final product with consistent properties and quality. Various manufacturing methods were reported by researchers for thermoplastic composite as follows:

- Vacuum molding [8]
- Compression molding [7,63]
- Double belt laminating [64,65]
- In-situ foaming [66–68]

Among these methods, double belt laminating is a superior choice for the industrial production of sandwich panels with not complicated shapes due to its time-efficient and economical process. Additionally, this technique allows the final product to be recyclable since no adhesive material is used. This process is an efficient method for continuously producing large-scale thermoplastic composite sandwich structures by using fusion bonding. At first, an automated system assembles the skins and core layer before they are transported to a sequence of heating elements by two belts. During this stage, the sandwich structure is subjected to heat and pressure to achieve fusion bonding. Subsequently, the sandwich is consolidated by a series of cooling elements while under pressure [11,69]. Figure 2.5 depicts the schematic of the double-belt lamination method.

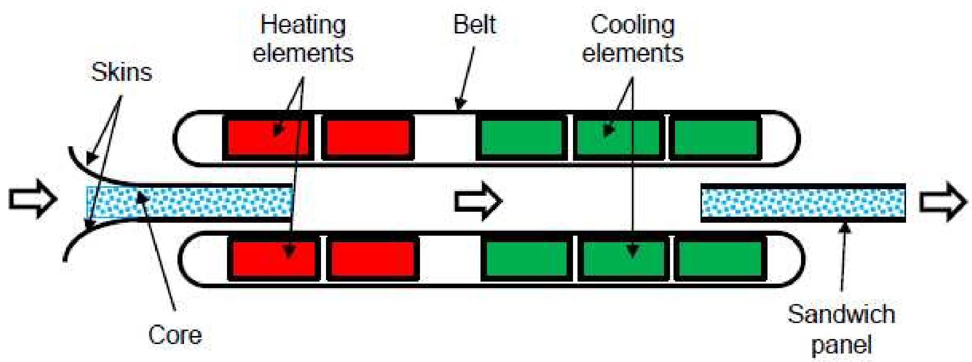


Figure 2.5. Illustration of double belt lamination technique [65].

The interfacial joint in the double belt lamination technique is provided by intermolecular diffusion of the polymer chains between the core and facesheet. When the molecules near the surface soften, the bond is formed through a process that includes surface rearrangement, wetting, diffusion, and the randomization of molecules [70], as illustrated in Figure 2.6. This contrasts with adhesive joining, which involves the creation of the bond through the mechanical interlocking of two substrates on the surface.

Figure 2.6. Illustration of the bonding fusion model [9].

Fusion bonding of two or more dissimilar polymers can be challenging due to differing melting points and the immiscibility of core and facesheet polymers [71]. To address these issues, careful control of process parameters such as temperature and compressive pressure is essential. To achieve the softening point on both surfaces, it is necessary to employ distinct chambers to heat the core and facesheet separately. Furthermore, it is essential to maintain adequate pressure to produce a strong bond between the skin and core, while also preserving the integrity of the core. Excessive pressure, used to make intimate contact, can lead to the collapse of the low-density core [72]. The detailed manufacturing process used to produce PET foam cored sandwich panels in this project is provided in Chapter 3.

2.6 Impact of Moisture on Mechanical Properties of Composite Sandwich Panels

Several researchers have studied the effect of hygrothermal conditions on various properties of composite sandwich panels. The authors of [73] specifically investigated the effect of seawater exposure on the interfacial strength of PVC foam-cored sandwich panels. In their study, pre-cracked sandwich samples were subjected to delamination tests in dry conditions and after being soaked in seawater under controlled laboratory conditions. The results revealed that seawater exposure led to a significant reduction in delamination fracture toughness, approximately 30%. Additionally, it was observed that conditioning the samples in seawater caused the delamination location to shift from within the foam to the interface between the foam and the facesheet.

In another work [35], the response of sandwich panels made of polyurethane foam core with E-glass-reinforced vinyl-ester composites was investigated under hygrothermal aging conditions. They exposed the specimens to salt fog conditions with 95% relative humidity and artificial seawater fogging for up to 180 days. The results of three-point bending, flatwise, and edgewise compression tests showed degradation in flexural and compressive strength. SEM images revealed the reason for this reduction in properties is moisture absorption causing plasticization of the matrix, which led to microcracks, fiber-matrix debonding, and core cracking. These damages significantly reduced the flexural and compressive strengths of the sandwich composites.

Since foam-cored composite sandwich panels are mainly used in structural applications due to their promising thermal insulation and acoustic properties, the integrity and strength of these structures under harsh environments are of great importance. Despite research on the moisture behavior of sandwich panels, more studies are needed to understand the mechanical performance of structures made to industry standards under high moisture conditions, especially regarding the impact of moisture on the quality of interfacial bonding. This research is crucial for ensuring the optimal design and durability of sandwich composites used in structural applications.

Chapter 3: Materials and Methods

3.1 Material Selection and Manufacturing Technique

In this research, the 100% recycled closed-cell PET foam panels with a thickness of 38.1 mm were sourced from Armacell with four different densities of 70, 80, 100, and 150 kg/m^3 (ArmaPET Struct GR70, GR80, GR100, and GR150). A single layer of 2/2 twill weave fabrics consisting of glass and polypropylene (commingled) has been chosen as the facesheets. These fabrics have a nominal thickness of 0.9 mm and a weight fraction of 40% glass fiber. The thermoplastic sandwich composite panels were made of Glass/PP facesheets that were adhered to a closed-cell PET foam core with a density of 80 kg/m^3.

The sandwich panels were manufactured using a double-belt sandwich lamination technique which is an automated continuous roll-forming process that produces panels with a width of 1.5 meters. Figure 3.1 illustrates the manufacturing process for thermoplastic composite sandwich panels utilizing the double belt lamination technique. As depicted in Figure 3.1, the machine is continuously fed with solid PET foam and commingled woven glass/PP rolled fabrics. To precisely control the feeding rate of the rolled raw sheets, set screws are meticulously adjusted at the bearing supports. This ensures consistent feed rates, which is essential for maintaining the quality of the final product. In this process the gripping force applied during feeding and the traction force exerted by the forming rollers of the machine. These forces are essential for maintaining the fibers in precise alignment during the production process. Such detailed control is crucial as it prevents manufacturing flaws such as wrinkles or overlaps in the facesheets, which can deteriorate the mechanical properties and final appearance of the panels. Furthermore, due to the inherently higher viscosity of thermoplastic resins, the manufacturing of PP-based composites requires precise control of both temperature and pressure. Control of these parameters guarantees that the laminate is fully impregnated, reducing the presence of voids and improving the mechanical properties of the composite. A series of experiments was carried out in partnership with Innovative Composite Products (ICP) Inc. to optimize these essential production parameters [74].

In the initial phase of production, the glass/PP commingled fabrics are exposed to temperatures ranging from 160 to 165 °C in the primary heating chambers. This controlled heating facilitates the preparation of the material for the next stages of the process. Following this, the heated sheets pass through a series of rollers designed to both shape and consolidate the facesheet laminates under consistent pressure, ensuring uniformity. During the next stage of the manufacturing process, the facesheet is subjected to additional heating in a separate chamber, with a temperature range of 160 to 165 °C. At the same time, the core material, PET foam panel, is exposed to a higher temperature bracket of 200 to 205 °C. It is important to note that during this stage, only the surfaces of the PET core are heated. Implementing this heating technique is important because it improves the adhesion between the skin and core components without causing the PET core to reach its melting temperature. The preheating of the core surfaces plays a key factor in improving adhesion, as the thermoplastic resin of the facesheet, which is in a molten state, cools rapidly upon contact with the core. If the core surfaces are not properly prepared, the temperature difference between the core and the facesheet can potentially weaken the bonding process. Hence, it is crucial to attain the optimal surface temperature on the PET core to guarantee strong adhesion between the facesheet and the core. As the parts move through the secondary heating chamber, two sets of rollers are employed to press the facesheets onto the PET core. However, to avoid crushing the core during the procedure, it is necessary to monitor the gap between the rollers. This ensures that the applied pressure is sufficient for bonding without damaging the core. After the heating and pressing steps, the panels are cooled using air-cooled rollers. This step allows the panels to gradually reduce in temperature, which helps to stabilize the material properties and ensure dimensional accuracy. After the panels have been cooled, they are precisely cut to desired lengths using an automated saw.

Setting the processing time and controlling temperature and pressure are essential for high product quality and cost-effective manufacturing. These characteristics must be precisely managed to maintain production efficiency and sustainability. It has been seen that a reduction in production speed may lead to unforeseen challenges, such as sticking melted PP resins to the rollers. This occurrence has an adverse effect on the quality of the panels and the continuous flow of production.

On the other hand, an increase in production speed can weaken the bonding to the core or the impregnation of facesheet laminates. The insufficient bonding time between the PET core and the facesheets at higher speeds prevents the adequate fusion of materials, leading to weak spots and potential delamination under stress. Therefore, after conducting thorough experimentation and analysis, it has been found that a production speed of 0.64 m/min is the most effective for laminating PET core sandwich panels with a final thickness of 40.5 mm. This chosen speed maintains a balance between efficient production and maintaining impregnation processes and adequate bonding. At this rate, the materials have sufficient time to bond and consolidate under the controlled temperature and pressure conditions, resulting in panels that exhibit the desired mechanical properties and surface quality.

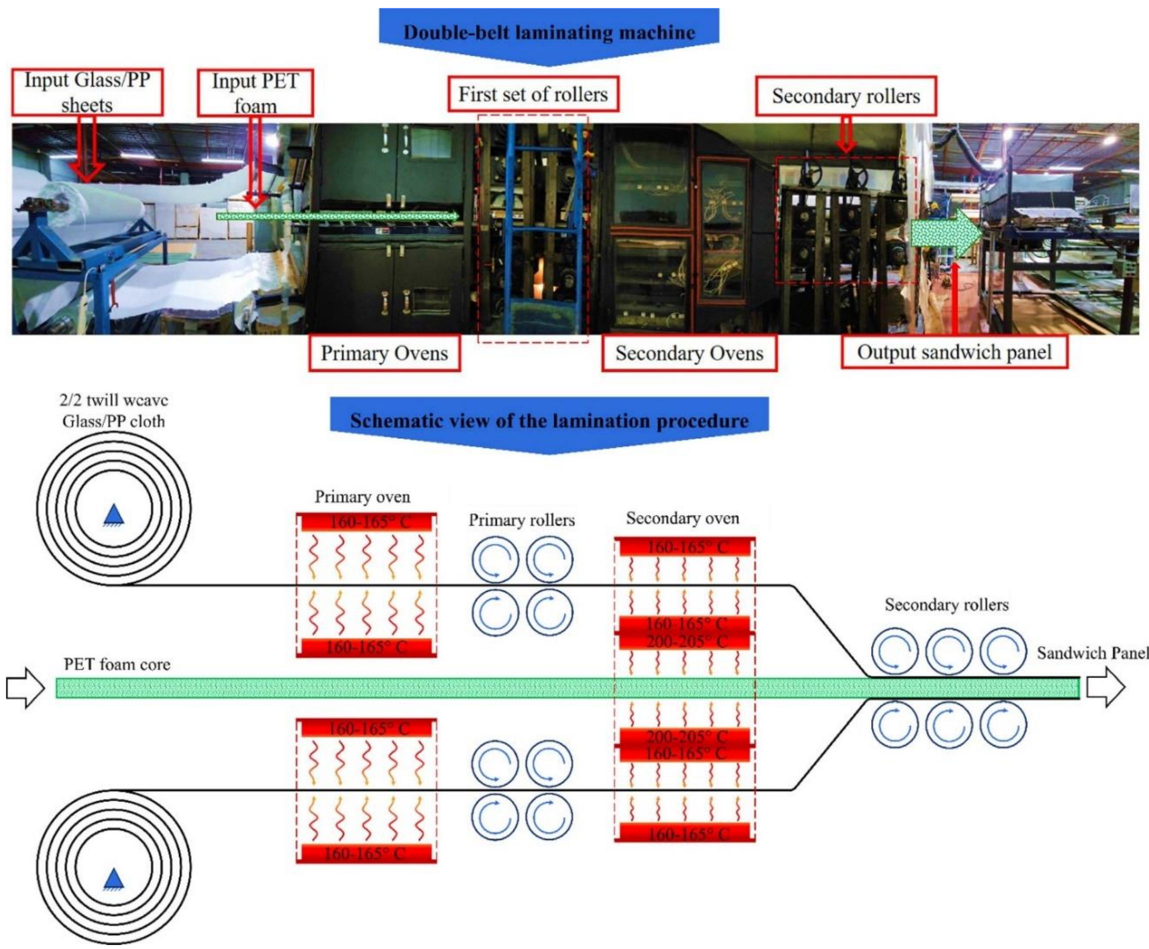


Figure 3.1. The manufacturing process of thermoplastic composite sandwich panels via double-belt lamination technique [74].

3.2 Experimental Test Procedure

3.2.1 Water Absorption Test

The water diffusion process in polymeric materials is intrinsically slow [75]. To speed up the moisture diffusion in an experimental environment, PET foam, glass/PP composite facesheets, and PET foam core sandwich panel samples were placed in a water bath, maintained at a temperature of 40 °C. The water absorption test is conducted to determine the amount of absorbed water by the foam, glass/PP composite, and sandwich panel. In the first step, these materials were precisely sectioned into smaller specimens using a diamond saw, as detailed in Table 3.1. Sectioning with accuracy guarantees uniformity and consistency among all test specimens. For each type of sample, three identical specimens were prepared and tested under the same conditions to ensure the reliability of the data.

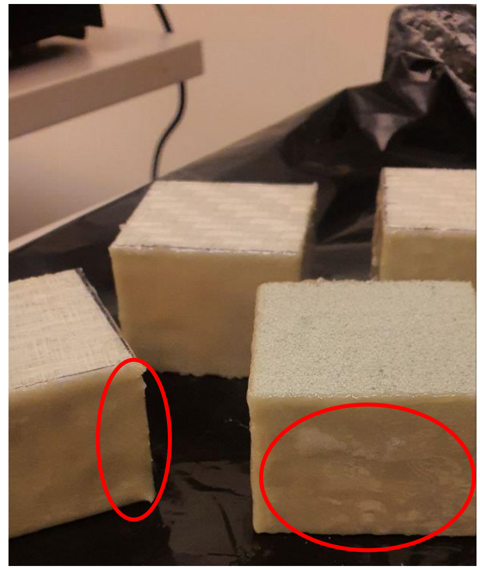
To observe the diffusion in one direction, efforts were made to block the four sides of the foam and sandwich samples. Initially, the sides of the samples were covered with moisture-resistant aluminum tape (3M 3340). After two weeks, stains appeared on the aluminum foil. After contacting the supplier, it was revealed that the tape consisted of acrylic compounds which can dissolve in water under harsh environments. This deterioration in adhesion might result in the peeling off the tape and subsequent penetration of water from the sides. Figure 3.2 shows the sample covered with aluminum tape before and after two weeks of conditioning in water. Due to the inadequate performance of the aluminum tape, an alternative coating was chosen to prevent water penetration from the sides. It was crucial to find an effective way to guarantee that moisture diffusion occurred mostly through the exposed surfaces and not from the covered sides, to accurately simulate one-directional diffusion.

(a) (b)

Figure 3.2. A sandwich specimen covered with aluminum tape a) Before and b) After two weeks of conditioning.

In the second attempt, an epoxy-based structural plastic bonder from J-B Weld was applied to the side surfaces of the foam and sandwich samples. A uniform layer of this two-part adhesive was carefully applied to the side surfaces and allowed to dry for 24 hours, ensuring a solid seal. After one month of immersion, however, signs of swelling appeared on the plastic coat. Figure 3.3 depicts the samples coated with the adhesive before and after one month of conditioning in water. This swelling indicated that the adhesive layer, which initially acted as a barrier, was compromised over time, allowing water to penetrate. As a result, this strategy was also considered ineffective. Given the challenges in creating a perfect moisture barrier for the samples, it was decided to allow diffusion to occur through the sample from all directions in subsequent tests. This approach not only simplifies the setup but also accelerates moisture uptake, providing a thorough understanding of the effect of moisture exposure on the service life of these panels. By enabling multi-directional diffusion, we can better assess the long-term performance and durability of the panels in applications where moisture is a critical factor, particularly in environments characterized by high humidity and significant precipitation.

(a)



(b)

Figure 3.3. Samples coated with the adhesive before and after one month of conditioning in water.

Three sets of facesheet samples with different dimensions were utilized to characterize the diffusivity of the facesheet along three principal axes. This approach allows for a comprehensive understanding of the moisture diffusion behavior in different directions, which is essential for predicting the performance of the 2/2 twill weave glass/PP boards in a controlled moisture exposure setup. For the foam samples, a single set of test specimens was selected for evaluation, based on the assumption of global homogeneity within the foam for this study. This assumption simplifies the testing process and focuses on the inherent diffusion properties of the PET foam material without considering potential variations within the material. At the same time, the moisture absorption behavior of one set of sandwich specimens was examined, following the assessment of diffusion parameters for both the face sheet and foam core. The test specimens were prepared as per the ASTM D5229 standard [76]. To ensure comprehensive testing, three specimens of each type and size are subjected to the water absorption test.

Table 3.1. Dimensions of test specimens.

Specimen	Label	Density (kg/m^3)	Dimensions (mm)
PET Foam	PET 70	70	38.1×50.8×50.8
	PET 80	80	
	PET 100	100	
	PET 150	150	
GFRP	GFRP A	1400	1.2×50.8×50.8
	GFRP B		1.2 ×25.4×25.4
	GFRP C		1.2 ×25.4 ×12.7
PET Foam Sandwich	PET foam sandwich	-	40.5×50.8×50.8

The absorption test was performed in an insulated container with tap water to simulate rain, maintained at a pH level of 7.8. This setup was equipped with a thermal sensor to ensure the water temperature was consistently kept at 40 °C, providing a controlled environment for the experiment. To achieve homogeneous water absorption from all directions, a perforated stainless-steel sheet was utilized to submerge the samples while exerting minimal additional stresses and strains on the samples, as seen in Figure 3.4.

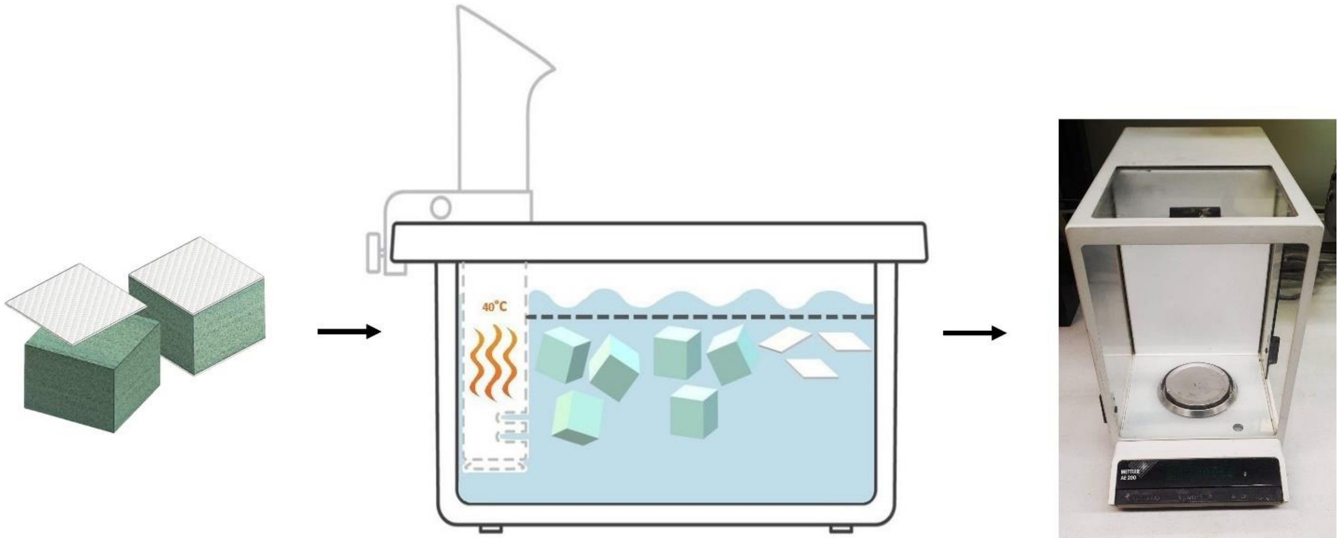


Figure 3.4. Schematic illustration of the experimental setup for the absorption test.

According to ASTM D5229, the specimens were uniformly dried before the test to ensure that all moisture absorbed in the material during the cutting process using a wet saw was removed. This was achieved by placing the specimens in a desiccator for 24 hours to reach a constant weight. Following that, the weight of samples was recorded using an Ohaus analytical balance as their initial dry weight. After initial weighing, the specimens were submerged in a water bath at a temperature of 40 °C. At predetermined intervals, each specimen was taken out from the water bath to remove the excess water on its surfaces using absorbent lint-free paper. Subsequently, the specimen was immediately re-weighed using the analytical balance. The periodic weighing process was repeated multiple times throughout the test until each material reached its moisture saturation level. This approach allowed for continuous monitoring of the water absorption rate and the overall moisture content of the specimens over time.

The moisture absorption of each specimen was determined by calculating the weight difference between the dry and wet specimens, employing the following Equation (2) to quantify the water absorption percentage of each specimen.

$$M(t)\% = \frac{Wt - Wd}{Wd} * 100 \tag{2}$$

Where $M(t)$ is moisture absorption content, W_t is the weight of the wet specimen at exposure time t and W_d is the mass of the dry specimen.

The data obtained from the periodic weighing were plotted to show the moisture content as a function of time, allowing for a thorough analysis of the absorption kinetics. The “Moisture absorption theory” section provides a more detailed explanation of the fundamental principles and mechanisms of moisture absorption.

3.2.2 Flatwise Compressive Test of PET Foam

To evaluate the compressive properties of the PET foams, in the thickness direction, a flatwise compressive test was conducted per ASTM C365 [77]. PET foam samples with dimensions of 38.1 mm × 50.8 mm × 50.8 mm were prepared for the test.

The testing was performed using an MTS universal testing machine equipped with a 5 kN load cell. The head displacement rate was set at 0.5 mm/min. Each specimen was carefully centered under the upper fixture in the test area. The MTS machine recorded the compressive force and deformation of the specimens. These data were then used to generate stress-strain curves. To ensure the accuracy and reliability of the results, three replicates of each sample were tested. Figure 3.5 illustrates the compressive testing setup.

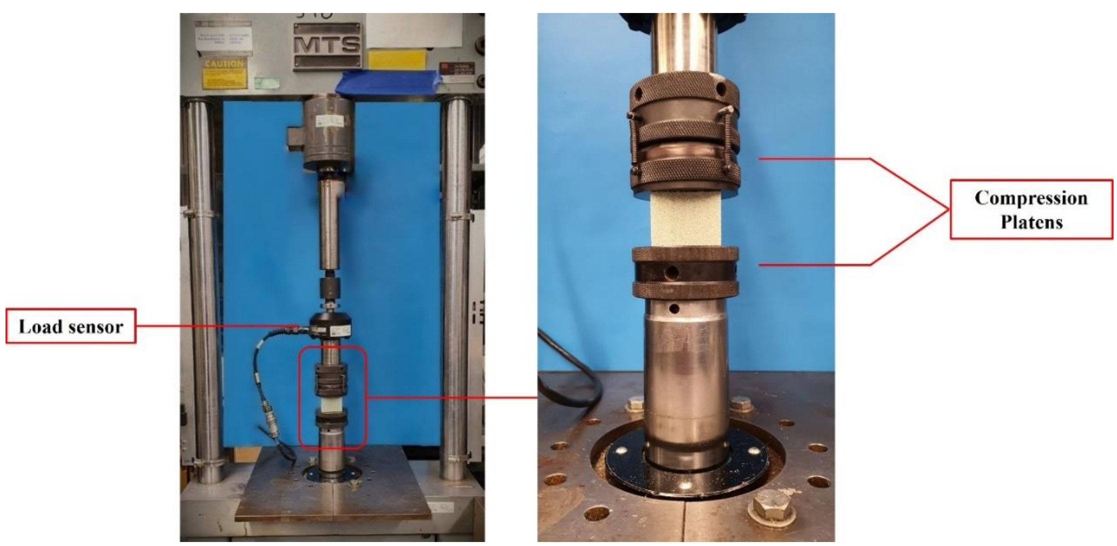


Figure 3.5. Flatwise compressive testing setup.

3.2.3 Flatwise Tensile Test of Sandwich Panel

To evaluate the impact of water aging on the bonding strength between the core and the skins of sandwich composite samples, flatwise tensile tests were performed at different immersion time points. The test was carried out on specimens of sandwich samples with a square cross-section of 50.8 mm × 50.8 mm, in three conditions: dry, after being conditioned in water for 7 days, and after being conditioned in water for one month.

The flatwise tensile tests were conducted using an MTS universal testing machine, as illustrated in Figure 3.6. The testing setup was according to the procedures described in ASTM C297 [78], so ensuring the accuracy and reliability of the results. The testing procedure adopted a 5 kN load cell to measure the applied forces accurately. The testing procedure involved several key steps. To adhere the specimen to the end tabs, the specimen was mounted using a toughened epoxy adhesive (3M DP460). The adhesive was allowed to harden for 24 hours, ensuring proper alignment and secure attachment between the gripping fixtures and the sample surfaces. To maintain moisture within the wet samples during the adhesive hardening process, the conditioned specimens were wrapped with a watertight Parafilm M Lab film (see Figure 3.7). After 24 hours, the specimen sandwiched between two end tabs was installed into the testing machine fixtures.

A displacement rate of 0.5 mm/min was set for the tests according to ASTM C297, ensuring that the load was applied steadily and uniformly across the specimens. The MTS universal testing machine recorded the force and displacement data continuously throughout the test, which was crucial for calculating the bonding strength of the sandwich composites. To demonstrate the accuracy of the test results, three identical specimens were tested for each condition.

The data collected from the flatwise tensile tests were analyzed to determine the force at failure and bonding strength between the core and the skins of the sandwich composite samples. The peak tensile load recorded during the test was used to calculate the bonding strength using Equation (3).

$$Bonding\ Strength\ (MPa) = \frac{Load\ at\ failure\ (N)}{Cross\ Sectional\ Area\ (mm^2)} \tag{3}$$

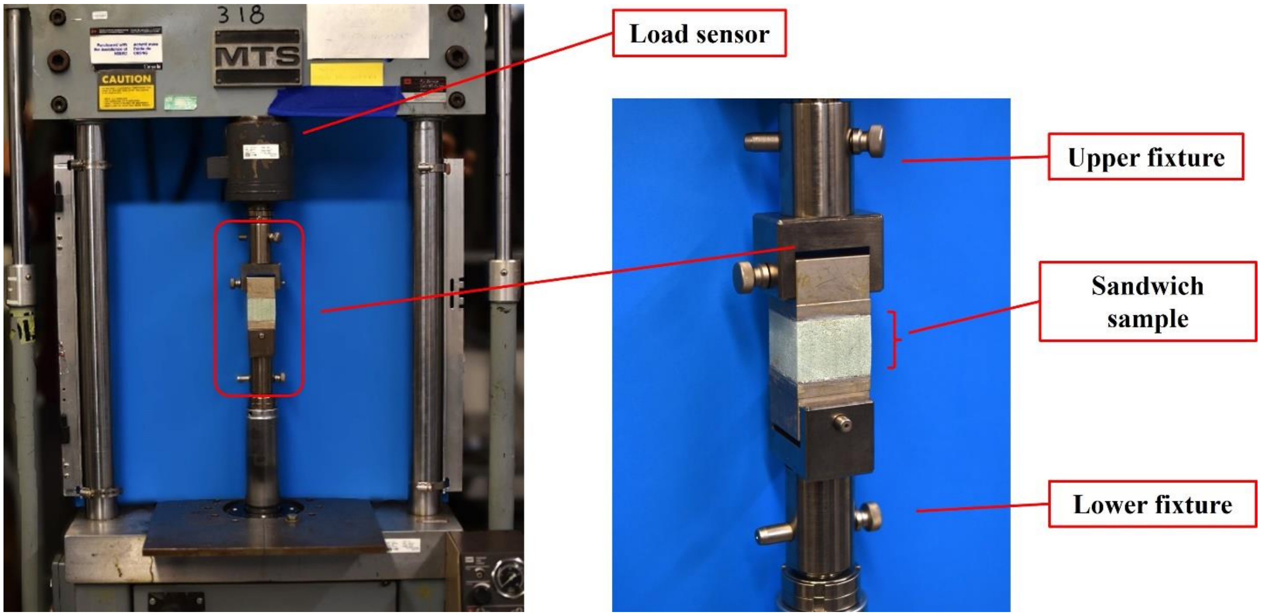
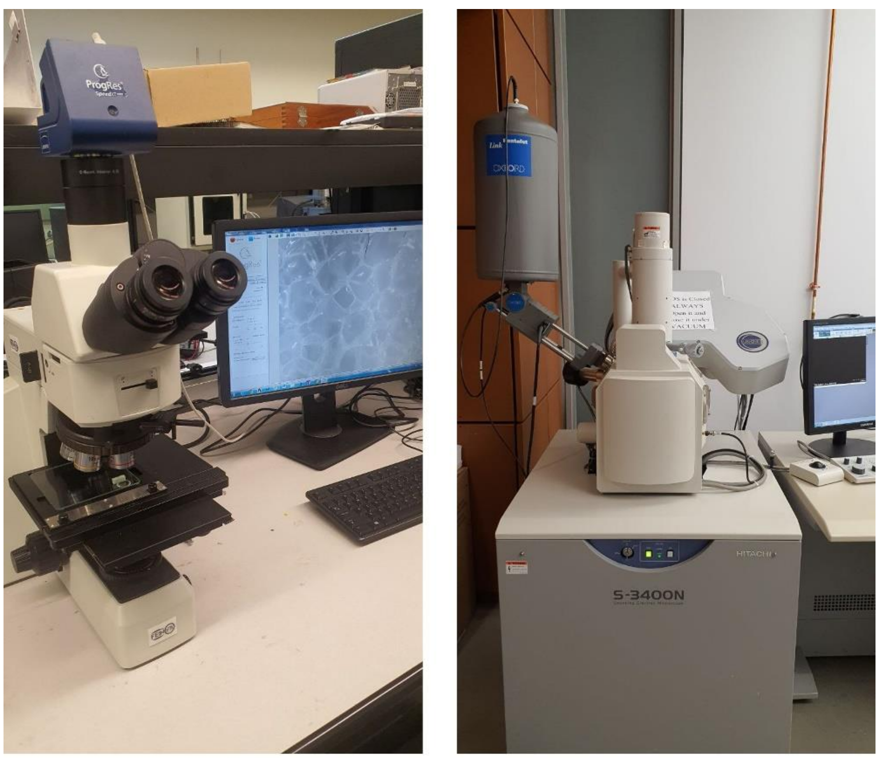


Figure 3.6. MTS machine and the flatwise test setup.

Figure 3.7. Wet samples wrapped with Parafilm M Lab film during the adhesive curing process.

3.2.4 Microscopic Tests

In this study, the detailed analysis of specimen microstructures was conducted using imaging techniques to better understand the effects of moisture exposure on the materials. Figure 3.8 shows the testing machines used in this study, including the optical microscope and Environmental Scanning Electron Microscope (ESEM). To examine the morphology of the foam cells in different densities and observe the moisture captured within the cells, an optical microscope from Fein Optic was used. This allowed for the visualization of the foam microstructure, identifying changes in cell size and shape at different foam densities. Furthermore, the analysis of sandwich specimen microstructures was carried out with a HITACHI S-3400N ESEM. This investigation involved observing the interface between the core and facesheets. it was possible to evaluate changes in the microstructure and detect areas where moisture might have compromised the bond between the core and facesheets.



(a) **(b)**

Figure 3.8. (a) Optical Microscope, and (b) Environmental Scanning Electron Microscope.

3.3 Moisture Absorption Theory

Moisture absorption behaviors of PET foam and glass/PP composite boards are characterized by Fick's second law. Fick's second law relates the change in moisture concentration (*C*) over time (*t*) to the spatial concentration gradients in each dimension (*x, y, z*), modulated by their respective diffusion coefficients (D_x, D_y, and D_z) [79].

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x}\left(D_x \frac{\partial c}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial c}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial c}{\partial z}\right) \tag{4}$$

3.3.1 Assumptions for Fickian Diffusion in Foam Samples

To simplify the analysis for foam samples and define the bulk diffusion, the following assumptions were made.

- The material is assumed to be homogenous and isotropic with the same properties all over the sample. The assumption of material isotropy results in an independence of diffusivity to the diffusion direction.
- The depth of diffusion is much smaller than the dimensions of the material.
- The initial moisture concentration is uniformly distributed within the foam sample ($C_0 = 0$).
- The concentration only at the surfaces of the foam reaches and remains constant at the maximum moisture concentration (C_m).

Under these assumptions, Fick's second law can be applied to describe the diffusion process primarily in the thickness direction, with consideration for bulk diffusion occurring across the entire volume of the sample.

In the early phases of Fickian absorption, the quantity of moisture absorbed demonstrates a direct proportionality to the square root of time. Following this initial linear moisture increase, the rate of absorption gradually diminishes, eventually plateauing as the material reaches a state of saturation [52]. Hence, the diffusion coefficient can be determined by measuring the slope of the initial linear portion of a typical moisture uptake curve as illustrated in Figure 3.9. The formula for calculating the effective diffusion coefficient is [80]:

$$D = \pi\left(\frac{h}{4M_{sat}}\right)^2\left(\frac{dM(t)}{d\sqrt{t}}\right)^2 \tag{5}$$

Where M_{sat} represents the saturation moisture absorption level.

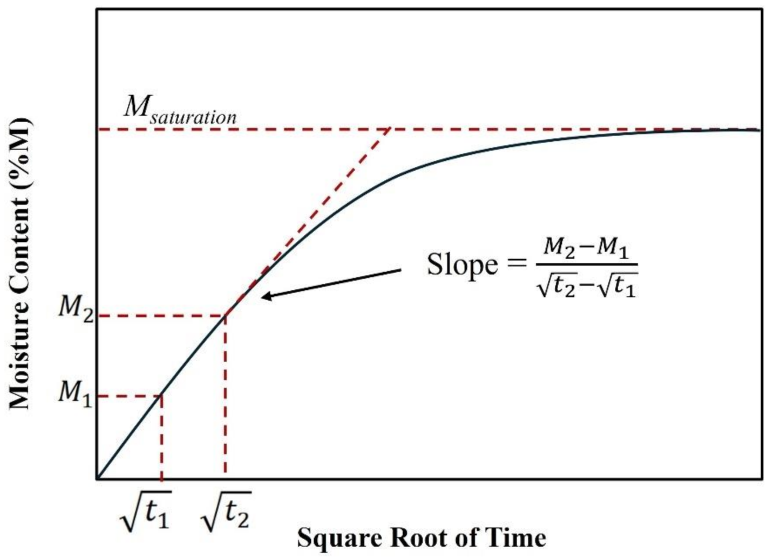


Figure 3.9. Schematic of Fickian diffusion process.

3.3.2 Assumptions for Fickian Diffusion in Facesheet Samples

For facesheet where the thickness is considerably smaller than the other two dimensions, the diffusion can be assumed as one-directional. However, when the directional diffusion is considered for the facesheet specimens, an edge correction factor often needs to be taken into consideration to account for the diffusion from four side edges. Thus, the effective diffusion coefficient along the thickness ($\overline{D}$) of the test specimens can be calculated using Equation (6) [81].

$$\overline{D} = D_z\left(1 + \frac{h}{l}\sqrt{\frac{D_x}{D_Z}} + \frac{h}{w}\sqrt{\frac{D_y}{D_Z}}\right)^2 \tag{6}$$

Where h is the thickness of the specimen, l is the length, and w is the width, and D_x, D_y, and D_z are the diffusion coefficient along the principal axis, as illustrated in Figure 3.10.

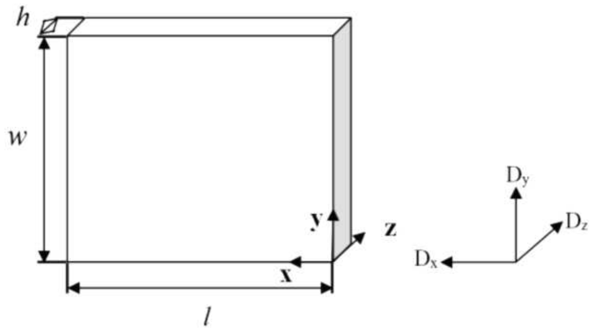


Figure 3.10. Geometry of a composite board.

To determine the effective diffusion coefficient for the facesheet, the slope of the initial linear region of the specimen's moisture uptake curve is used and $\overline{D}$ is calculated from Equation (5).

In this experiment, the glass/PP facesheet is a woven fabric in the x and y directions, and it can be assumed that it shows approximately equal diffusion coefficients in these two orientations. Given this symmetry in the x and y directions, we simplify our calculations by assuming $D_x = D_y$. This results in an approximation where $D_x = D_y \neq D_z$, which simplifies the Equation (6) into this:

$$\sqrt{\overline{D}} = \sqrt{D_z} + \left(\frac{h}{l} + \frac{h}{w}\right)\sqrt{D_x} \tag{7}$$

In this linear relationship $\sqrt{D_z}$ represents the intercept on the vertical axis and $\sqrt{D_x}$ represents the slope as illustrated in Figure 3.11. In this study three sets of facesheet specimens with varying dimensional ratios ($\frac{h}{l} + \frac{h}{w}$) were used to determine diffusivity along the fiber weave directions (*D_x and D_y*) and along the stacking thickness direction (*D_z*).

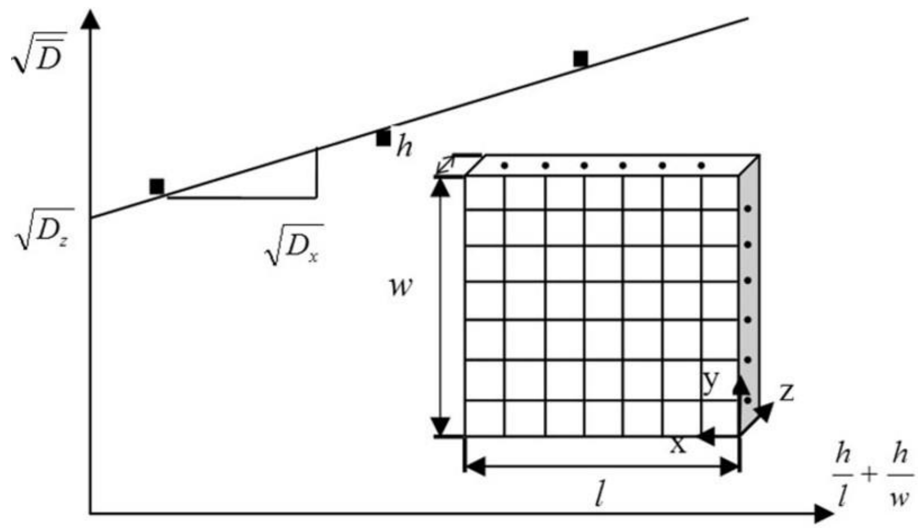


Figure 3.11. Schematic of effective diffusivity as a function of the dimensions of the specimen [48].

Chapter 4: Results and Discussion

4.1 Moisture Diffusion Characteristics of PET Foam

Since the sandwich panels manufactured for the application of prefabricated structures at ICP company are mostly made of Armacell PET foam with a density of 80 Kg/m^3, the main focus of the moisture absorption test was on panels with PET 80. However, to gain a comprehensive understanding of how foam density and cell morphology affect moisture absorption behavior, additional analyses were performed on PET 70, PET 100, and PET 150.

To see the diffusion behavior of PET 80, the percentage of absorbed water (M_t) in three identical specimens was recorded and graphed against the square root of time. The data presented in Figure 4.1 represent the average values from the gravimetric moisture absorption measurements of three samples. As can be seen, there are two distinct stages in the moisture absorption curve of PET 80 during immersion for 3024 hours (126 days). To simplify the approach, closed-cell PET foam was assumed to be uniformly homogeneous and within the framework of time-dependent diffusivity.

During the first two hours of the process of moisture absorption, PET 80 absorbed moisture almost 15% of its weight. The first two hours are characterized by the rapid absorption of water into the cells on the surface that were opened during the cutting process. The main mechanism in this step involves the filling of open cells on the surface, followed by the water flow into adjacent cells with damaged cell walls due to the capillary action. The foam's open cells have a high surface area that creates a powerful capillary action, which draws water into the foam. The damaged cell walls around these open cells create channels for water to penetrate further into the foam. This initial phase sets the conditions for the subsequent absorption process. Open cells on the surface of the foam allow for immediate water entry, and once these cells are saturated, water begins to penetrate deeper into the foam, a process predominantly governed by diffusion and continues until the foam reaches its maximum saturation capacity.

In the second stage (2-3024 hours), the rate of water diffusion slows as moisture diffuses through the cell walls. This stage is governed by Fickian diffusion, where the movement of water molecules is driven by the concentration gradient between the wet outer surface and the drier interior of the foam. The gradual increase in moisture absorption continues until the PET foam reaches a state of equilibrium and becomes fully saturated. This behavior is indicative of the foam's capacity to store water within its closed-cell structure, where the cell walls act as barriers that slow down the rate of moisture ingress [48,82].

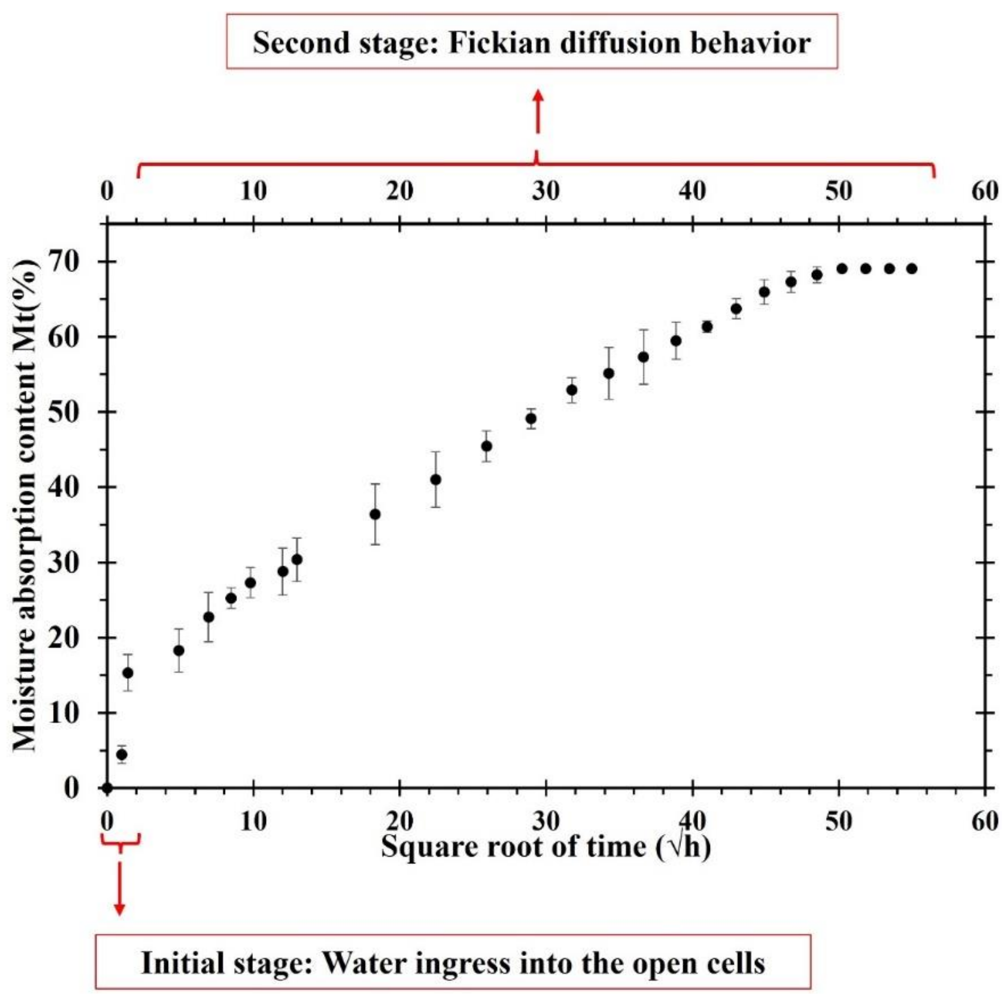


Figure 4.1. Two-stage moisture behavior of PET 80 sample.

To determine the diffusion coefficient of the foam, the water absorption during the initial stage is excluded. This enables the exclusive examination of water absorption into the foam solely through the process of diffusion. Subsequently, the constant diffusivity is calculated for the second stage using Fick's law by determining the slope of the linear portion of the moisture uptake curve, as follows:

$$D_{PET\ 80}\ (mm^2/s) = 2.06\times 10^{-5} \qquad 2 \leq t \leq 3024$$

4.2 Microscopic Observations of PET Foam

The microscopic images of PET 80 in dry and wet conditions demonstrate the foam's capacity to absorb water within its closed-cell structure, as presented in Figure 4.2. In the dry state, the PET foam exhibits a uniform closed-cell structure with distinct, well-defined cell walls. Upon exposure to moisture, the microscopic image reveals the presence of moisture within the cell cavities, indicating that water penetrated beyond the surface and into the deeper layers of the foam. The trapped moisture within the cells does not cause obvious swelling but might contribute to microstructural changes that could affect the foam's mechanical properties over time. These changes include slight deformation and potential weakening of the cell walls, particularly in areas where the cell walls were already thinner or damaged.

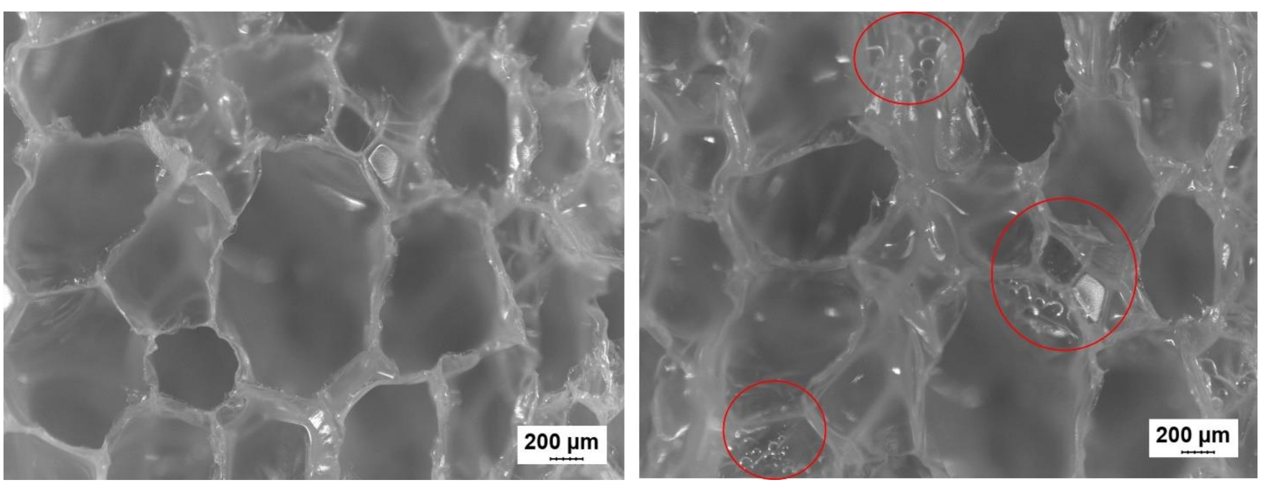


Figure 4.2. Microscopic images of PET 80 microstructure in dry and wet conditions.

To study the effect of the foam density and cell size on moisture penetration, PET foams with densities of 70, 100, and 150 kg/m^3 were exposed to the same conditions as those of PET 80 samples for 3024 hours. The moisture absorption curves plotted over time are illustrated in Figure 4.3. The data represent the mean values collected from three identical samples from each group. As expected, all PET foams exhibited rapid moisture uptake during the initial two hours, followed by a gradual increase in weight from 2 to 3024 hours. As shown in Figure 4.3, PET 70 and PET 80 reached saturation levels of 70.28% and 69.03%, respectively, while PET 100 and PET 150 showed a gradual increase over 3024 hours with maximum absorption of 44.41% and 32.87%, respectively. The diffusion coefficient for each foam was then determined using the slope of the linear region of these curves during the second stage. The diffusion coefficients for PET 70, PET 80, PET 100, and PET 150 were calculated using Equation (5) to be 37.6 × 10^{-6}, 20.6 × 10^{-6}, 10.1 × 10^{-6}, and 6.4 × 10^{-6} mm^2/s, respectively.

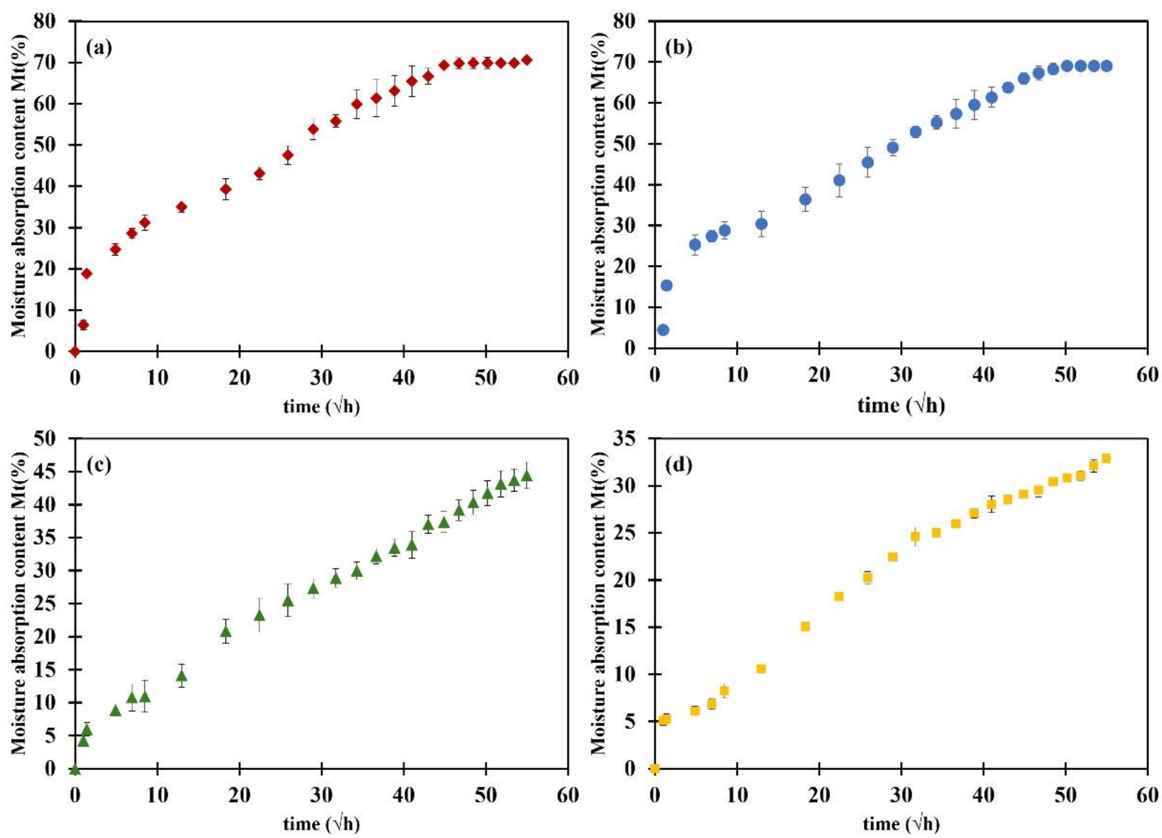


Figure 4.3. Short-term moisture absorption curve of (a) PET 70, (b) PET 80, (c) PET 100, and (d) PET 150 kg/m^3.

4.3 Effect of Foam Density and Cell Size on Moisture Diffusion Behavior of PET Foams

The results show that the diffusion coefficient in PET samples decreases with the increase in foam densities. To investigate the effect of foam density and cell microstructure on the diffusion behavior of foams and the rate and extent of water uptake, microscopic analysis was conducted. Microscopic examinations of the foam surfaces provided insights into the cell structures. As can be seen in Figure 4.4, the density of the foam is inversely proportional to the cell size. Higher-density foams, such as PET 150 (Figure 4.4d), exhibit smaller cell sizes due to the increased amount of polymer material present per unit volume. This results in thicker cell walls and a more compact cell structure. In contrast, lower-density foams like PET 70 (Figure 4.4a) have larger cells with thinner walls.

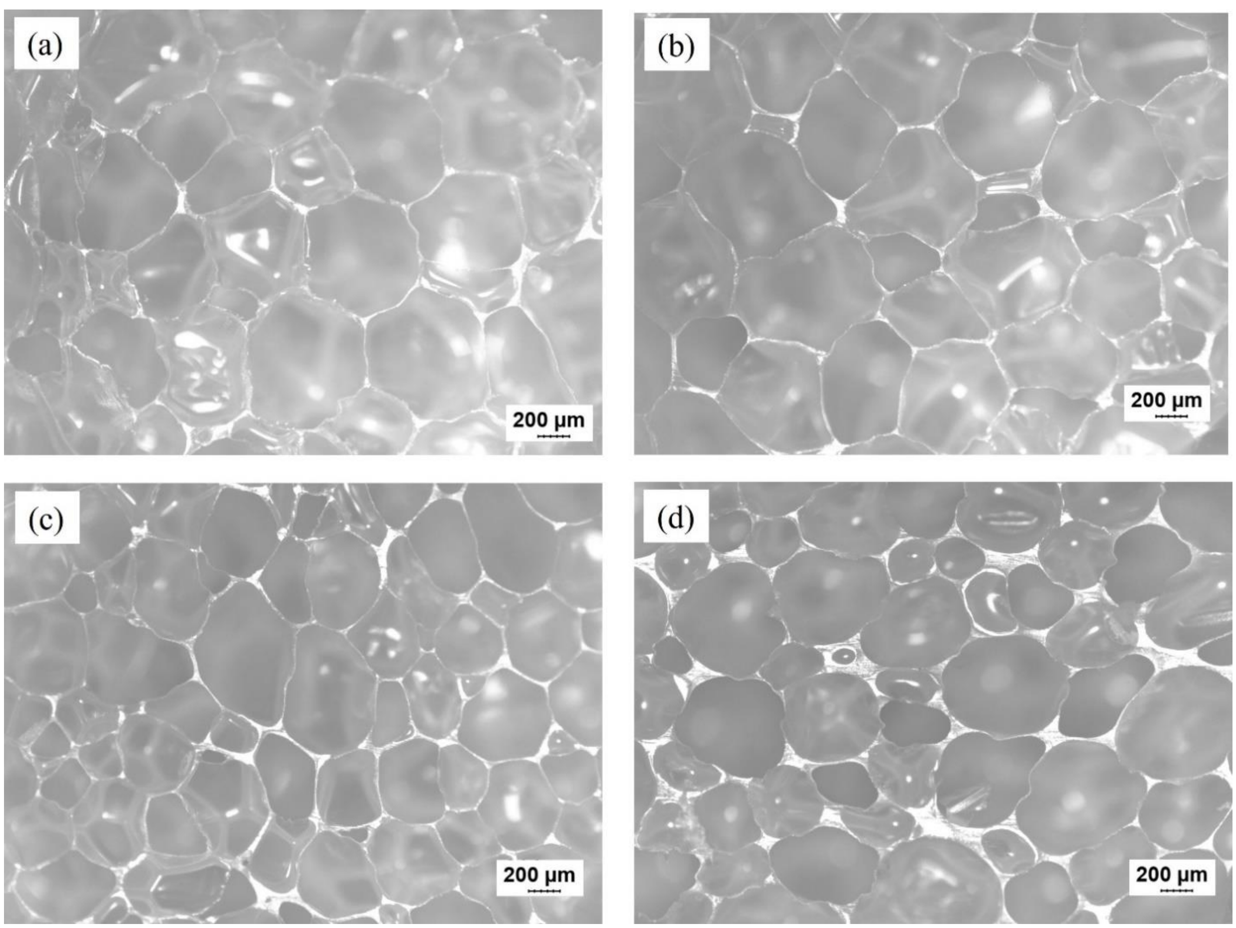


Figure 4.4. Microscopic images of (a) PET 70, (b) PET 80, (c) PET 100, and (d) PET 150.

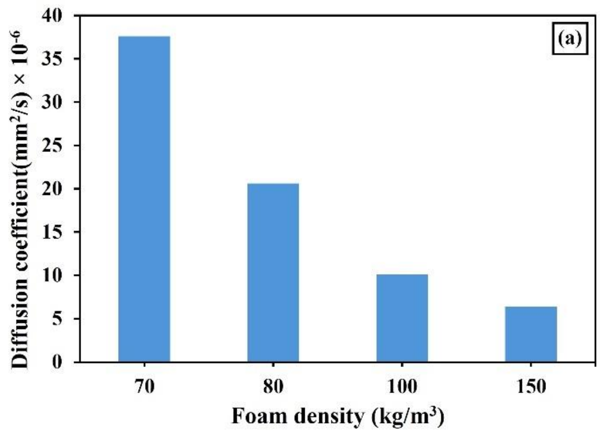
To accurately compare the size of cells, the equivalent diameter was calculated to account for the irregular shape of the cells. The cell size was estimated by measuring the equivalent diameter based on the measurement of 150 cells. The variations in diffusion coefficients among foams with different densities can be related to differences in cell size and thickness of cell walls. The equivalent diameter (D_e) of the cells is calculated using the formula [83]:

$$D_e = \frac{1}{n}\sum_{1}^{n} 2\sqrt{\frac{S}{\pi}} \tag{9}$$

Where *S* is the area of the cell, and *n* is the number of cells measured (*n=150*).

By comparing the results of foam cell size and microscopic images, it becomes evident that higher-density foams possess smaller cells which affects the diffusion coefficient of the PET foams. Figure 4.5 demonstrates the relationship between the diffusion coefficient, foam density, and cell size.

As depicted in Figure 4.5b, PET 70 has the largest cells with an equivalent diameter of approximately 597 microns. The cell walls are thinner, which makes the foam more susceptible to water absorption due to the larger surface area of the cells and the higher probability of cell wall breakage. PET 80 displays relatively smaller cells, with an equivalent diameter of approximately 558 microns. The cells of PET 100 are smaller with thicker walls, having an equivalent diameter of around 458 microns. This configuration enhances the foam's mechanical strength and reduces moisture uptake due to the reduced cell size and increased material density. PET 150 has the smallest cells, with an equivalent diameter of about 433 microns. The thick cell walls make this foam highly resistant to mechanical deformation and moisture absorption.



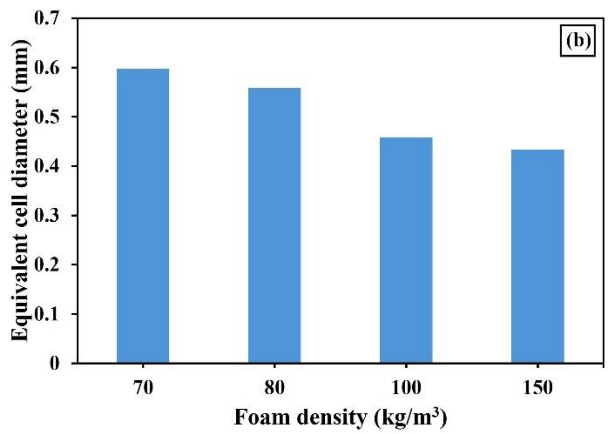


Figure 4.5. A bar chart of (a) Diffusion coefficient as a function of foam density and (b) Equivalent cell diameter as a function of foam density.

4.4 Effect of Moisture on the Compressive Properties of the PET Foam

In this section, the compressive properties of PET foam cores with densities of 70, 80, 100, and 150 kg/m^3 were evaluated, focusing on the impact of foam density and moisture exposure. The tests were conducted on two groups of specimens: dry specimens and specimens immersed in a water environment at 40°C for 3024 hours, and three specimens were tested in each group.

The compressive stress-strain curves for both dry and wet specimens are shown in Figure 4.6. Upon analysis, it was observed that the compression curves of PET foams align with those reported in the literature and display three distinct stages: I) elastic region, II) plateau region, and III) densification region. In the initial stage, the PET foams demonstrate elastic behavior, defined by a linear relationship between stress and strain. The deformation in this stage is mainly due to the bending of cell walls. During the plateau region, the cell walls of the PET foam begin to buckle, leading to relatively constant stress despite increasing strain. This stage is marked by significant energy absorption as the foam deforms plastically. The PET foam cells shrink as the compression deformation increases, resulting in irreversible changes to the foam structure. In the densification region, the collapsed cells are compressed further, leading to a sharp increase in stress. This stage represents the densification of the foams as the cell walls are compacted [84]. Figure 4.8 illustrates the condition of the dry and wet samples subjected to compressive testing in the plateau region.

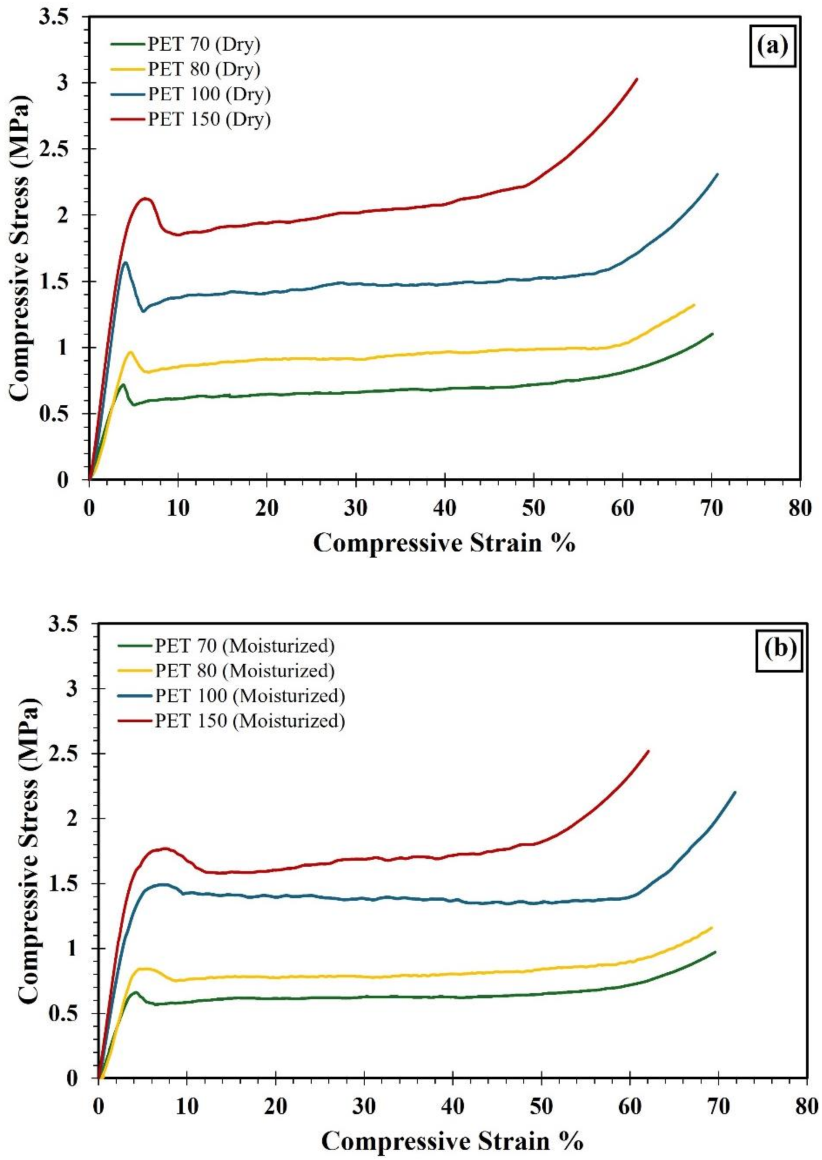


Figure 4.6. Compressive stress-strain curves of (a) Dry specimens and (b) Moisturized specimens.

Upon analyzing Figure 4.6, it becomes evident that higher-density PET foam demonstrates greater stress at the same strain, indicating higher yield strength and elastic modulus. This is due to the increased material content and thicker cell walls, which enhance strength and stiffness. Additionally, foams with higher density undergo earlier densification and exhibit a shorter stress plateau because of their lower porosity levels [85]. The evaluation of the compressive test results also revealed that moisture absorption deteriorates the compressive properties of the foam, as indicated by notable reductions in yield stress and the stress response in the plastic plateau phase. Specifically, yield strength decreased by 8.3%, 12.5%, 9.14%, and 16.5% for PET 70, PET 80, PET 100, and PET 150, respectively, after 3024 hours of conditioning (see Figure 4.7a). A comparison of the peak stress regions in Figure 4.6a and Figure 4.6b shows a broader peak and softer load drops for wet specimens, which is due to cell softening and plasticization from prolonged moisture exposure [40].

Figure 4.7b shows the comparison of the elastic modulus between dry and conditioned PET foam samples. The results show a slight reduction in stiffness for all foam densities after 3024 hours of moisture exposure. The observed variations in elastic modulus values between the dry and wet samples remain below 10%, highlighting the relatively minor impact of moisture absorption on the stiffness of the PET foams.

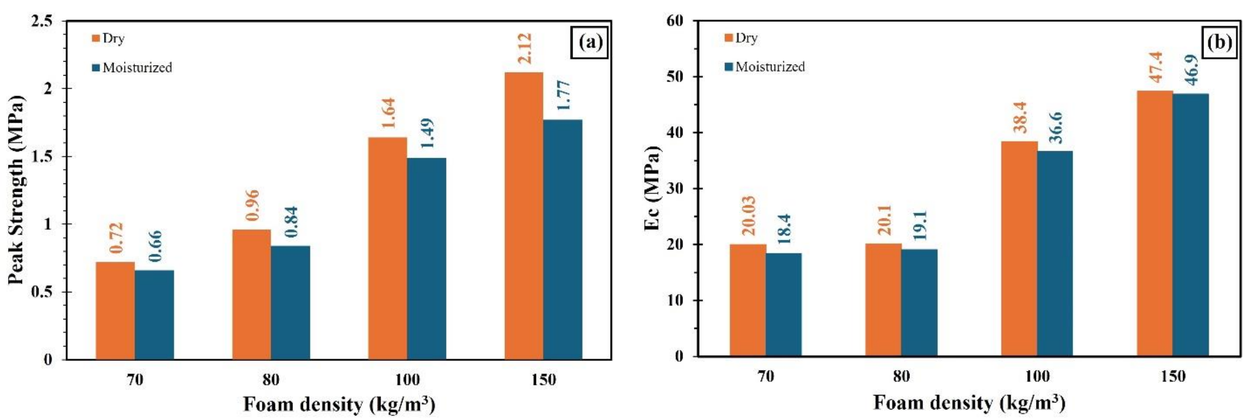


Figure 4.7. A bar chart of (a) compression peak strength as a function of foam density, and (b) stiffness as a function of foam density

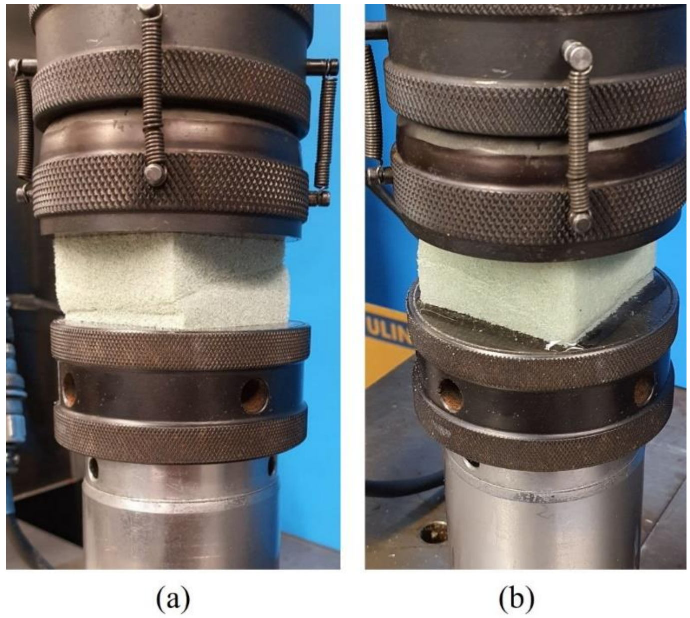


Figure 4.8. Images of PET foam samples subjected to compressive testing in the plateau region: (a) Dry sample, (b) Sample conditioned for 3024 hours.

4.5 Moisture Diffusion Characteristics of Facesheet

Understanding the moisture absorption behavior of facesheets is essential for comprehending their performance in conditions with high humidity. The complexity of moisture ingress in woven glass/polypropylene facesheets is considered in this study when employing the three-dimensional diffusion approximation. The experimental results indicate that the moisture absorption conforms to a Fickian diffusion model, which is characterized by an initial rapid uptake followed by a gradual approach to saturation.

By considering 3D diffusion approximation for facesheets, 3 sets of specimens with different thickness ratios were prepared and immersed in the same water condition to calculate the directional diffusion coefficients. Figure 4.9 displays the moisture absorption curves of three distinct sizes of GFRP A (1.2 mm×50.8 mm×50.8 mm), GFRP B (1.2 mm×25.4 mm×25.4 mm), and GFRP C (1.2 mm×25.4 mm×12.7 mm) samples over a period of 1848 hours of conditioning. The data represents the mean values collected from three identical samples from each group.

Upon analyzing the moisture absorption curves of each group of glass/PP boards, it is evident that the moisture absorption process follows a classical Fickian model. As can be seen in Figure

4.9 the initial sharp increase in moisture absorption for all three GFRP samples, indicates the quick response of the material to water exposure in the first few hours. This rapid uptake phase is primarily attributed to the initial filling of microvoids and capillary action within the woven fabric structure, as well as the initial diffusion of moisture into the polymer matrix. Once all the voids are filled, the water uptake becomes governed only by moisture diffusion, with moisture migrating through the polymer matrix and along the fiber-matrix interfaces. This is characterized by a slower rate of absorption until saturation is reached.

To calculate the effective diffusivity for GFRP A, GFRP B, and GFRP C, Equation (5) is used, utilizing the initial linear portion of the corresponding moisture absorption curves in Figure 4.9. The effective diffusion coefficient for the GFRP A, GFRP B, and GFRP C panels are listed in Table 4.1. Subsequently, the square root of effective diffusivity was plotted against the ratio of thickness to length plus the ratio of thickness to width (h/l + h/w) for each set of facesheets, as illustrated in Figure 4.10. This allowed for the calculation of the square root of diffusivity along the x-axis (or y-axis) by determining the slope of the linear fitting curve. In addition, the square root of the diffusivity along the z-axis was calculated based on the intercept value. As a result, the diffusion coefficients in three directions are D_x and $D_y = 6.7 \times 10^{-6}$ mm^2/s , and $D_z = 9 \times 10^{-8}$ mm^2/s.

As expected, the diffusion coefficient of the GFRP panel in the thickness direction is comparatively lower than the diffusivity along the fiber directions [86]. This is attributed to the anisotropic nature of the GFRP facesheet. The presence of spaces between fibers creates pathways that facilitate moisture diffusion along the fiber weave directions. The narrow gaps between fibers act as capillaries, allowing water to be drawn along the length of the fibers. Conversely, diffusion through the thickness is more difficult as the fibers can act as a barrier, impeding water ingress.

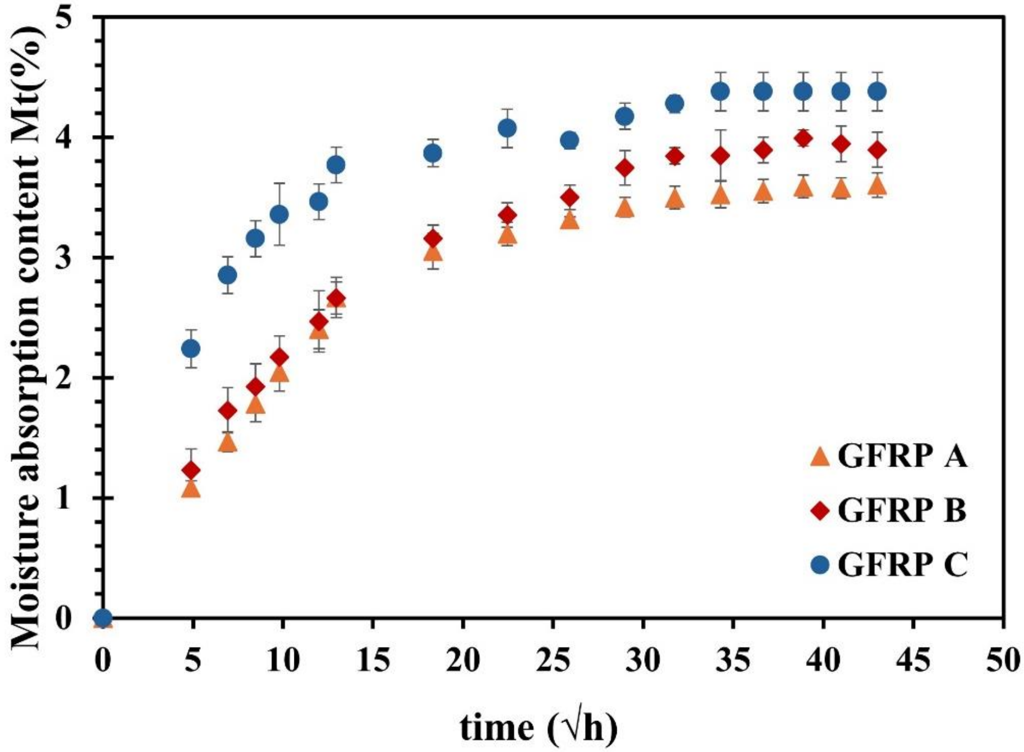


Figure 4.9. Moisture absorption curve for glass/PP facesheets with different dimensions.

Table 4.1. Effective diffusivity of facesheets with different dimensions.

Label	Dimensions (mm)	Effective Diffusivity (mm^2/s)
GFRP A	1.2 × 50.8 × 50.8	1.76×10^{-7}
GFRP B	1.2 × 25.4 ×25.4	2.29×10^{-7}
GFRP C	1.2 × 25.4 × 12.7	4.38×10^{-7}

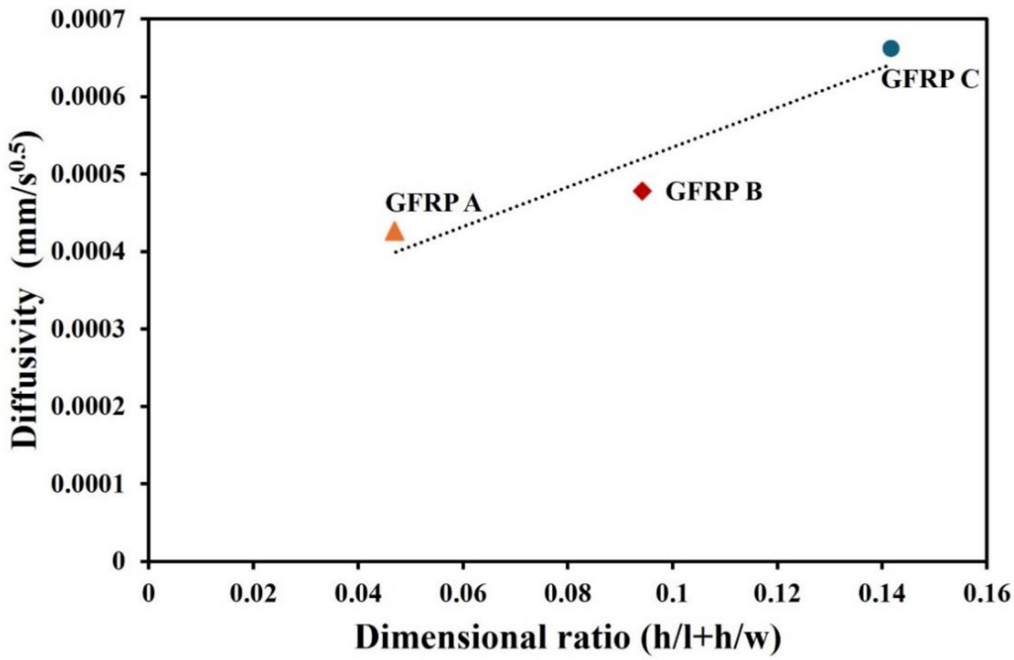


Figure 4.10. The square root of effective diffusivity versus (h/l+h/w) for three sets of face sheets.

4.6 Microscopic Observations of Facesheet

The facesheet is a critical element of the PET foam sandwich panel, acting as the primary barrier against moisture ingress. However, there are different factors that could potentially adversely impact its effectiveness. Figure 4.11 shows the SEM image of the facesheet cross-section.

The SEM image reveals the presence of voids and imperfections within the facesheet material. These voids are essentially small gaps or air pockets that were not filled during the manufacturing process. Such imperfections are typically caused by inadequate pressure during the lamination process or insufficient resin flow. During the manufacturing process of GFRP composites, the formation of tiny, irregularly shaped voids is unavoidable. In the doublet-belt lamination process at a 40% glass content, the molten PP matrix exhibits capillary effects, causing the resin to pull away from the fibers and coalesce. This can create areas with insufficient resin and potential voids, leading to poor impregnation of the glass fibers and negatively impacting the composite's mechanical properties.

These voids significantly affect the moisture barrier properties of the facesheet. The rate of moisture diffusion in the voids is about 1×10^{-3} mm²/s, which is thousands of times faster than in the pure resin [87]. Consequently, the presence of voids facilitates water diffusion through the facesheet, compromising its ability to protect the core material from moisture ingress. This rapid moisture diffusion through voids can lead to localized areas of high moisture content, accelerating degradation processes such as reducing the overall mechanical performance of the composite.

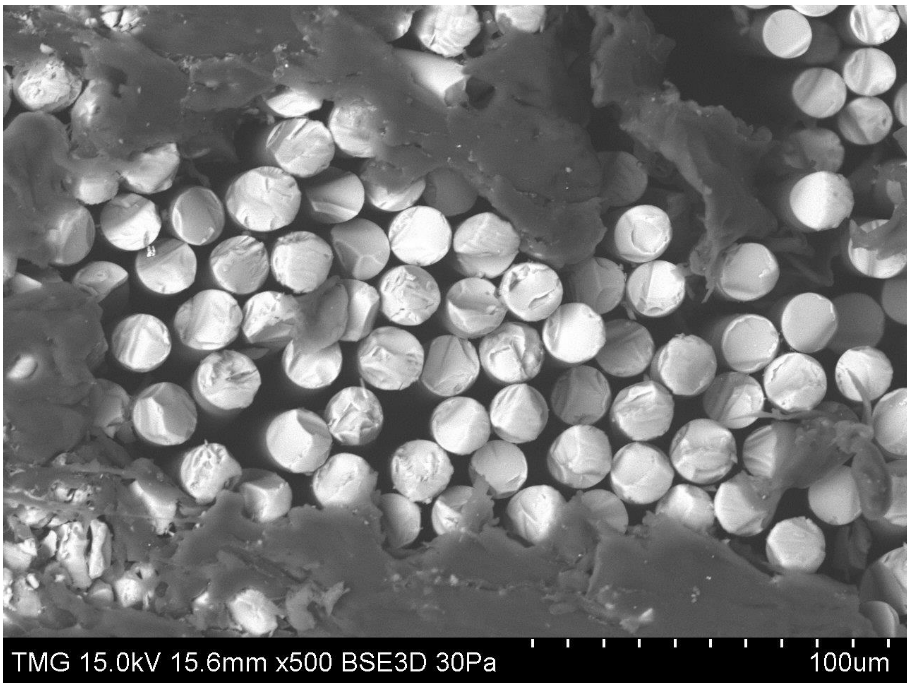


Figure 4.11. SEM image of glass/PP cross-section.

4.7 Moisture Diffusion Characteristics of PET Foam Sandwich Panel

Figure 4.12 illustrates the progression of water absorption in the PET sandwich panel fabricated using PET foam 80. The water diffusion curve is plotted as a function of the squared root of time over 3024 hours. The quantity of absorbed water which is represented as $\%M_t$ at each time is the average value based on the measurements from three PET sandwich specimens. The figure shows that during the first hour of soaking, the water uptake of the PET sandwich specimen increased rapidly. Following this, water diffuses at a reduced rate for the next 3024 hours, until the specimen reaches its saturation level of approximately 37%.

When comparing the moisture absorption curves of the PET sandwich sample with its PET foam counterpart (PET 80), it's evident that both curves follow a similar trend. However, the initial increase in moisture for the sandwich sample is less pronounced and occurs over a shorter duration. Moreover, the saturation level of the sandwich sample is approximately 37%, which is significantly lower than the foam's saturation point of about 69%. This difference can be attributed to the presence of the GFRP panel in the sandwich structure, which exhibits significantly lower moisture absorption capacity and a smaller diffusion coefficient. This barrier effect is evident in the reduced initial moisture uptake and the lower overall saturation level observed in the PET sandwich panels compared to the PET foam alone.

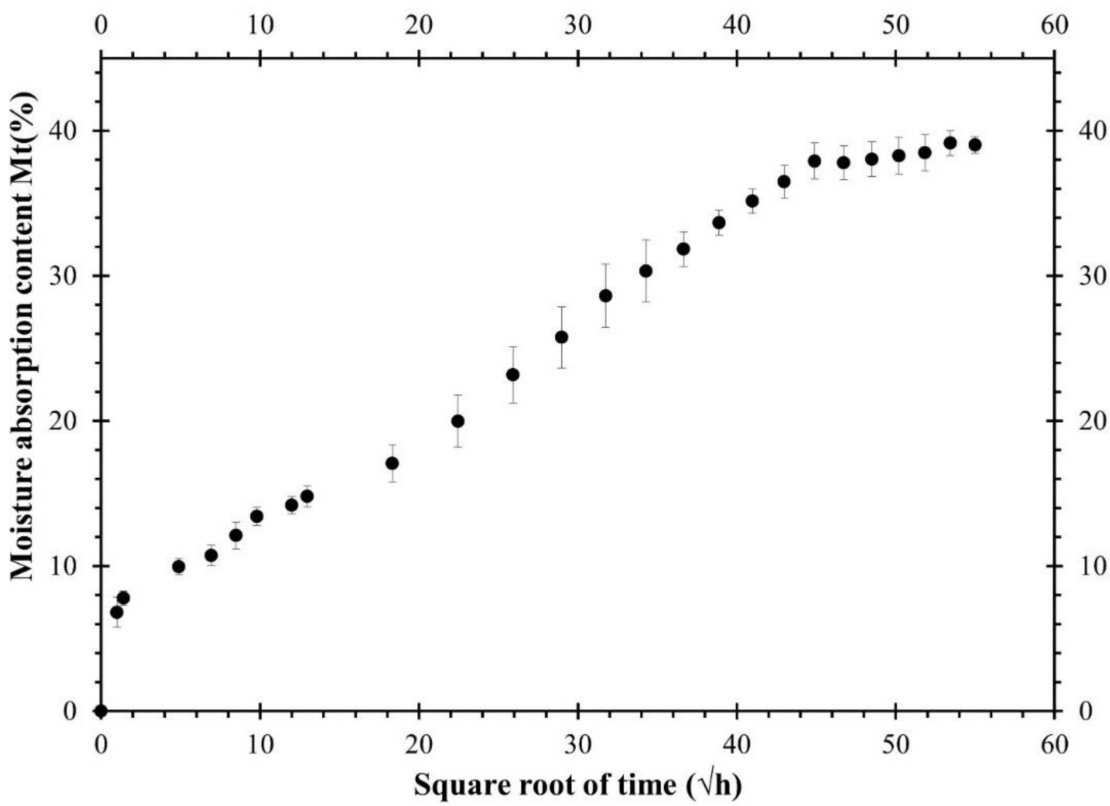


Figure 4.12. Moisture absorption curve for PET sandwich panel

However, it is important to note that while the facesheet significantly reduces moisture ingress from the top and bottom faces, it does not completely prevent it from these sides. Moisture can still penetrate the facesheet and interfaces between the facesheet and the foam core. These locations may have voids, imperfections, or insufficient bonding, which can serve as pathways for moisture to enter and become trapped within the structure. The presence of these pathways can compromise the moisture barrier effect of the facesheet, allowing moisture to diffuse into the interface between the facesheet and the foam and accumulate in these areas.

4.8 Microscopic Observations of PET Sandwich Panel

The SEM images from the interface between the foam and facesheet (see Figure 4.13) provide microstructural details, highlighting areas where moisture can penetrate and accumulate. Figure 4.13 depicts an area where the bonding between the facesheet and the PET core is insufficient. These microstructural imperfections are important because they create pathways for moisture ingress. Moisture can penetrate these weakly bonded areas and become trapped, leading to localized accumulation. This accumulation of moisture can initiate and propagate micro-cracks, further degrading the structural integrity of the interface.

A flatwise tensile test was conducted to explore the impact of moisture that penetrates the interface and its effect on bonding strength. The results of this test are detailed in the following section.

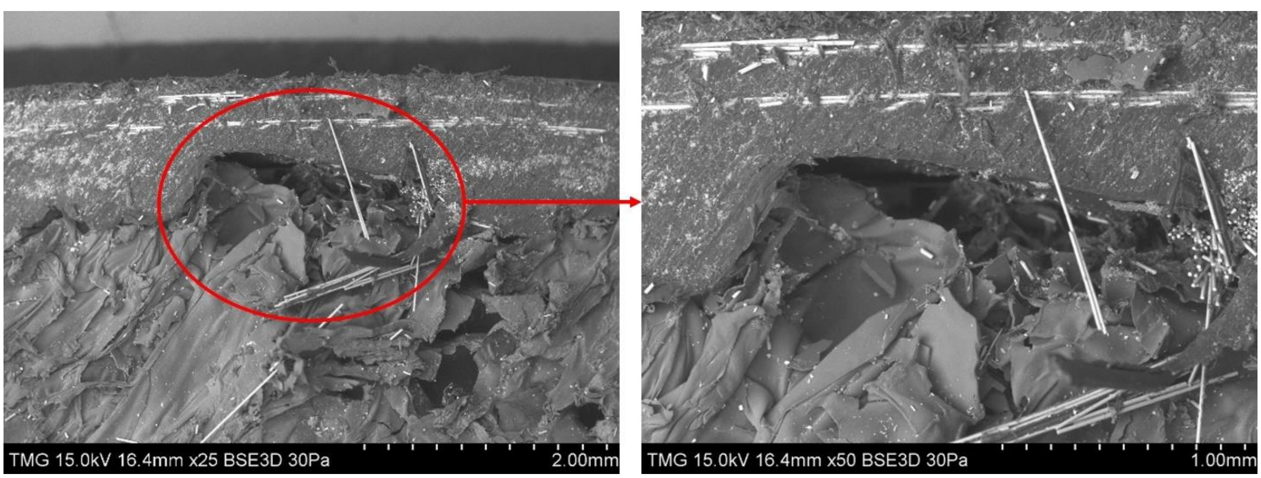


Figure 4.13. SEM of the interface between the facesheet and PET foam core.

4.9 Effect of Moisture on the Interfacial Bonding Properties of PET Foam Sandwich Panels

The interfacial bonding properties of PET foam sandwich panels are critical to their overall performance. This section explores how prolonged exposure to moisture affects the adhesion bonding strength between the PET foam core and the Glass/PP facesheets. By exposing the samples to moisture from all directions, the testing process ensures a thorough evaluation of the panels' moisture resistance, even if it slightly overestimates the exposure scenario. This method allows us to observe potential failure modes and degradation mechanisms that might develop over extended periods in actual service conditions, where moisture ingress through the facesheets could lead to similar long-term effects. This approach helps us better understand the durability of the panels and contributes to the development of panels with enhanced moisture-resistant properties.

The effect of moisture on the mechanical properties of PET sandwich panels was evaluated by a flatwise tensile test. Flatwise tests were conducted on both dry samples and samples that were immersed in water for durations of 24 and 730 hours. Figure 4.14 shows the response of the flatwise test for sandwich specimens subjected to tensile load. The results demonstrated in Table 4.2 show a significant decrease in mechanical properties following water absorption. The bonding strength of the dry samples, samples immersed for 24 hours, and samples immersed for 730 hours was evaluated at 0.93 MPa, 0.56 MPa, and 0.42 MPa, respectively. This decline can be attributed to localized insufficient adhesion strength between the foam core and facings.

During the manufacturing process, achieving a perfect bond between the foam core and the facesheets is challenging due to the significant difference in melting points between PET and PP, which is around 100 degrees Celsius. This temperature disparity makes it difficult to achieve complete fusion bonding at a relatively fast production rate, especially given the waviness of the facesheet. Any waviness or irregularity in the facesheet can create gaps or areas where fusing PET into PP is problematic, leading to insufficient bonding. These defect sites might not significantly affect bonding strength under dry conditions, but they become susceptible to moisture ingress.

When the sandwich panels are exposed to moisture, water can diffuse through the interfaces and penetrate these defect sites. The presence of water at the interface between the foam core and facesheet exacerbates the weak adhesion. Water can act as a plasticizer, weakening the adhesive bonds and facilitating the initiation and propagation of cracks at the interface, leading to a reduction in bonding strength.

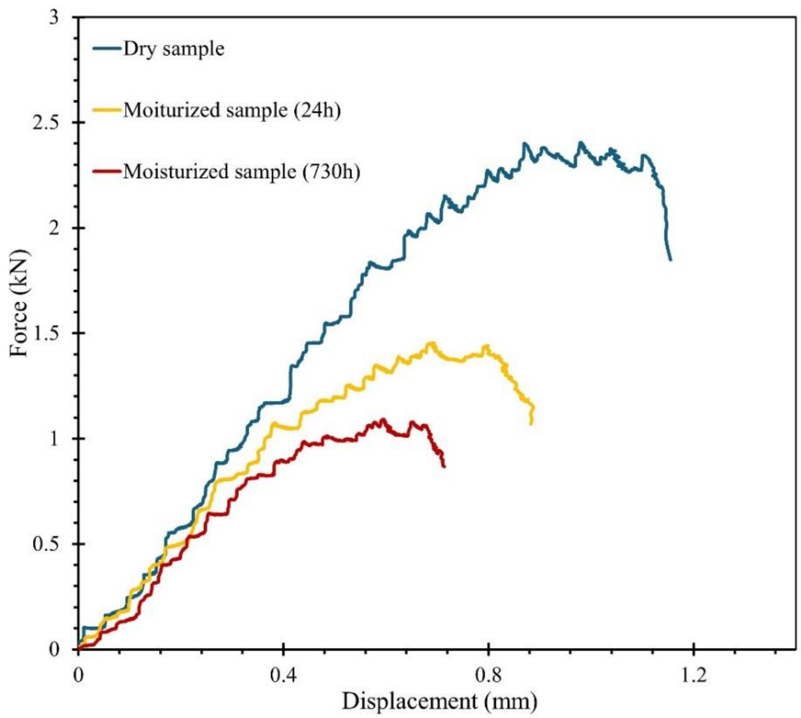


Figure 4.14. Load-displacement curves of flatwise tensile test of samples in dry and moisturized (for 24 and 730 hours) states.

Table 4.2. Results of flatwise tensile test of sandwich samples

Label	Condition	Maximum Force (N)	Ultimate Flatwise Tensile Strength (MPa)
PET foam sandwich	Dry	2404.95	0.93
	Conditioned for 24 hours	1452.63	0.56
	Conditioned for 730 hours	1090.81	0.42

The Examination of fracture surfaces of flatwise tensile tests indicates that the failure mechanism changes from substrate failure to adhesive failure over moisturizing. Figure 4.15 and Figure 4.16 depict the surface characteristics and failure modes under different moisture exposure conditions from top and side perspectives, respectively.

As shown in these figures the failure in the dry sample predominantly occurred within the foam core. In contrast, the sample exposed to water for 24 hours exhibited a combination of substrate and adhesive failure, with the failure plane propagating closer to the interface between the facesheet and foam. With extending immersion time of up to 730 hours, the interfacial strength decreases, leading to a complete separation between the facesheet and PET foam.

This is especially important in terms of bonding structural stability, as weakened interface adhesion becomes the primary factor contributing to failure. This weakening can be attributed to the formation and propagation of micro-cracks induced by swelling at the interface, ultimately resulting in diminished bond strength and loss of mechanical properties.

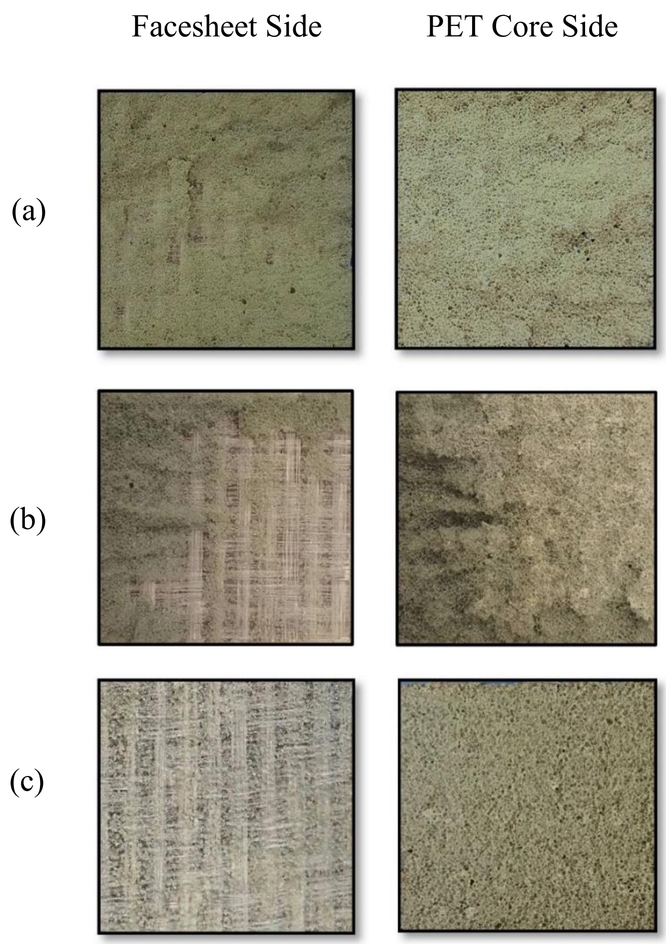
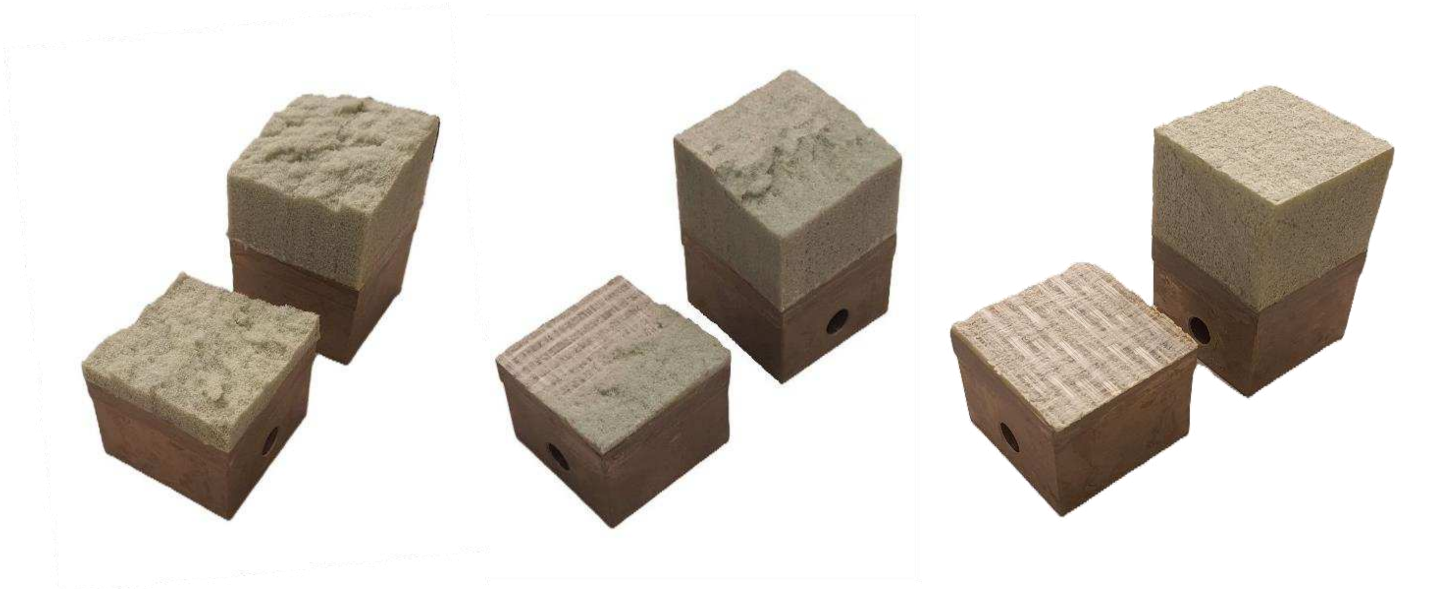


Figure 4.15. Top-view fractography of sandwich samples after failure: (a) Dry condition, (b) After 24 hours of moisture conditioning, (c) After 730 hours of moisture conditioning.



(a) **(b)** **(c)**

Figure 4.16. Isometric-view fractography of sandwich samples after failure: (a) Dry condition, (b) After 24 hours of moisture conditioning, (c) After 730 hours of moisture conditioning.

Chapter 5: Conclusion and Contribution

In this research, the moisture absorption characteristics of PET foam-cored sandwich panels with Glass/PP facesheets, manufactured using the double-belt lamination technique, were thoroughly investigated. The moisture absorption of the foams with densities of 70, 80, 100, and 150 kg/m^3, as well as the facesheet, and sandwich samples was monitored in a water bath maintained at 40˚C over an extended period. Observations of the moisture absorption curves revealed Fickian behavior in both the facesheet and foam samples. Based on this model, the diffusion coefficients of the samples were calculated. Investigation of the microstructures of foams with different densities revealed the relationship between foam density, cell size, and the diffusivity of PET closed-cell foams.

Additionally, the study examined the effect of moisture on the mechanical properties of these panels. The primary objective was to evaluate the suitability of these panels for use in challenging environmental conditions, such as prefabricated constructions on farms and storage cabins that are frequently exposed to humid environments. The findings provide insights into the moisture absorption mechanisms within the PET foam with different densities and the glass/PP facesheet and explain how moisture adversely affects the durability and performance of PET foam cored sandwich structures.

The detailed findings from all the experiments conducted in this study are summarized as follows:

- The experimental results indicate that the PET foams in different densities exhibit water absorption behavior that conforms to Fick's classical diffusion model. The PET foam demonstrates a two-stage absorption mechanism, characterized by an initial phase of high moisture absorption followed by a gradual decrease in absorption rate as the material approaches its moisture saturation level.

- the diffusion coefficients of PET foam at four densities were determined as follows:
  PET 70: 37.6×10^{-6} mm²/s
  PET 80: 20.6×10^{-6} mm²/s
  PET 100: 10.1×10^{-6} mm²/s
  PET 150: 6.4×10^{-6} mm²/s
- Microscopic observations revealed that higher-density PET foams have smaller, more uniformly distributed cells. These smaller cells, with thicker walls, contribute to lower moisture absorption. The comparison of foam density and diffusion coefficients demonstrated this relationship clearly: higher-density foams exhibit lower diffusion coefficients due to their smaller cell size and thicker walls, which enhance resistance to moisture absorption. This finding is critical for optimizing the performance of PET foams in moisture-prone environments.
- The compressive stress-strain curves of the PET foams in the dry state and after conditioning were compared, highlighting the detrimental impact of prolonged moisture exposure on the mechanical properties of the PET foam.
- The moisture absorption behavior of the Glass/PP facesheet was investigated and found to follow Fick's second law. The saturated moisture absorption of the GFRP panels was determined to be less than 5%. The effective diffusivity of the facesheet was calculated in both the thickness direction and the directions parallel to the thickness, with the following results: D_x and $D_y = 6.7 \times 10^{-6}$ mm^2/s, and $D_z = 9 \times 10^{-8}$ mm^2/s
- The presence of the facesheet significantly reduced moisture absorption in the sandwich panels, with the panels exhibiting a maximum saturation point of 37%, which is substantially lower than that of the foam alone. This decelerating effect highlights the protective role of the facesheet against moisture ingress. However, while the facesheet reduces the rate of moisture reaching the PET foam, it does not completely prevent it. Moisture that penetrates becomes trapped within the interface, revealing potential weaknesses in the bonding areas.
- The results of the flatwise tensile test of sandwich panels revealed that although the interfacial bonding is sufficiently strong in dry conditions, the flatwise tensile tests

indicate a significant decrease in bonding strength following moisture exposure, with a reduction of approximately 55% after being immersed for 730 hours.

- The change in failure mode observed during flatwise tensile tests further highlights the impact of moisture on the structural integrity of the PET foam core sandwich panels. In dry conditions, failure predominantly occurred through substrate failure. However, after prolonged exposure to moisture, the failure mode shifted to adhesive failure.

Chapter 6: Future Work

While this research has provided insights into the moisture absorption characteristics and mechanical degradation of PET foam-cored sandwich panels with Glass/PP facesheets, there are still several aspects that require further investigation to improve and enhance the performance of these structures in environments with high moisture levels.

To enhance moisture resistance, applying advanced surface treatments to the Glass/PP facesheets, such as hydrophobic coatings or water-repellent films, needs to be explored. Such coatings may significantly reduce moisture ingress and help maintain interfacial bonding strength at levels similar to dry conditions.

To provide a more accurate representation of environmental conditions commonly encountered on farms and in storage cabins, future research should focus on examining cyclical moisture absorption and its impact on the mechanical properties of sandwich panels. Incorporating different thermal and cooling cycles that mimic the effect of precipitation, such as rain and snow, as well as fluctuations in temperature throughout the day, can more accurately replicate real-life circumstances. To gain a more thorough understanding of the durability and performance of the sandwich panels, it would be beneficial to conduct long-term exposure studies in real environmental conditions.

Furthermore, utilizing Finite Element Analysis (FEA) to simulate moisture absorption and mechanical behavior of the sandwich panels can assist in predicting moisture distribution within the material, identifying areas susceptible to moisture accumulation, and assessing the impact of moisture on the mechanical properties and overall performance of the panels.

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