

**REPUBLIC OF TÜRKİYE
ERCIYES UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
DEPARTMENT OF MECHANICAL ENGINEERING**

**THE PRODUCTION OF BAMBOO BASED NATURAL
COMPOSITE MATERIALS AND COMPARISON OF
THEIR MATERIAL PROPERTIES WITH
PARTICLEBOARD AND MDF BOARDS**

**Prepared by
Ali GÜMÜŞTEKİN**

**Supervisor
Prof. Dr. Sedat ÖZDEN**

MSc Thesis

**August 2024
KAYSERİ**

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SCIENTIFIC ETHICS SUITABILITY

I declare that all information in this work was obtained in accordance with academic and ethical rules. All results and materials that not been at the essence of this work are also transferred and expressed by giving reference as required by these rules and behavior.

Ali GÜMÜŞTEKİN



The MSc thesis entitled **The Production of Bamboo Based Natural Composite Materials and Comparison of Their Material Properties with Particleboard and MDF Boards** has been obtained in accordance with Erciyes University Graduate Education and Teaching Institute Thesis Preparation and Writing Guide.

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ACKNOWLEDGEMENTS

I would like to express my deepest and most sincere appreciation to my supervisor, Prof. Dr. Sedat ÖZDEN, for his exceptional guidance, unwavering patience, and for shaping my career through his vast knowledge and experience. His mentorship has been instrumental to the success of this thesis, and I am honored to have had the privilege of learning from such a distinguished scholar.

I am also profoundly grateful to Prof. Dr. Fehmi NAİR for his unwavering support, patience, and brilliant ideas. His encouragement and insights have been a continuous source of inspiration, and I hope to continue benefiting from his wisdom throughout my entire engineering career.

A special thank you to Erciyes University Technology and Research and Application Center, especially for their assistance with compression and thermal conductivity tests. Their resources, facilities, and support were essential to the successful completion of this research.

I would also like to extend my sincere appreciation to BELLONA, especially to my manager, Mr. Erkan ŞAHİN, my chief, Mr. Nadir ÖNALAN, as well as the production, research and development, quality, human resources departments and the utilities department and its manager, Mr. Serkan ŞİMŞEK for their invaluable support and the opportunities they provided. Their confidence in my abilities has been crucial in translating my academic research into practical success.

To my family, I owe a profound debt of gratitude that words alone cannot fully express. Their unwavering belief in me, countless sacrifices, and their constant encouragement have been the cornerstone of my success. I am deeply proud to share this achievement with my beloved wife, my sweet daughter, my knowledgeable and dedicated parents and my brother, Dt. Mehmet GÜMÜŞTEKİN, whose creative support has been invaluable.

Ali GÜMÜŞTEKİN

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Erciyes University, Graduate School of Natural and Applied Sciences

MSc. Thesis, August 2024

Thesis Supervisor: Prof. Dr. Sedat ÖZDEN

ABSTRACT

Bamboo is a fast-growing plant. Bamboo-based composite materials offer advantages such as high strength, lightness, thermal conductivity and a low carbon footprint. Particleboard and MDF, commonly used in the furniture industry. This study shows that bamboo-based sandwich composites have significant potential as an alternative due to their notable mechanical properties. In this study, eight types of bamboo-based natural composite materials were produced with stacking methods. While the size and lining parameters of bamboo sticks were kept constant, the type of adhesive and the state of the bamboo (whether hollow or filled) were varied. After being removed from the mold, the material was cut into 12 mm thick strips with a bandsaw. HDF sheets of 3 mm thickness were glued to the top and bottom of these strips. The resulting sandwich composites were tested for compression strength, indentation strength, and thermal conductivity in laboratory conditions. Bamboo-based composite made with D4 wood adhesive and hollow sticks has a density of 430 kg/m³ approximately. The optimal thermal conductivity value of 0.090 W/mK was achieved in composites made with a D3 wood adhesive, with hollow bamboo sticks. The highest compression and indentation strengths were observed in composites using D4 wood adhesive, with an average compression strength of 23.00 N/mm². The best results in the indentation test with a 20 mm diameter steel ball were also achieved with D4 adhesive. As a result, it was shown that the new bamboo-based material possesses improved properties compared to traditional board materials in terms of thermal conductivity and density.

Key Words: Bamboo, Sandwich Composites, Compression Test, Thermal Conductivity Coefficient

BAMBU ESASLI DOĞAL MALZEMELERDEN ÜRETİLEN KOMPOZİT PANELLERİN MALZEME DAVRANIŞLARININ YONGA LEVHALAR VE MDF PLAKALAR İLE KARŞILAŞTIRILMASI

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Yüksek Lisans Tezi, Ağustos 2024
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ÖZET

Bambu, hızlı büyüyen bir bitkidir. Bambu bazlı kompozit malzemeler yüksek mukavemet, hafiflik, ısı iletkenliği ve düşük karbon ayak izi gibi avantajlar sunar. Mobilya endüstrisinde yonga levha ve MDF plakalar yaygın olarak kullanılmaktadır. Bu çalışma, bambu bazlı sandviç kompozitlerin dikkate değer mekanik özelliklerinden dolayı alternatif olarak önemli bir potansiyele sahip olduğunu göstermektedir. Bu çalışmada, istifleme yöntemleriyle sekiz tür bambu bazlı doğal kompozit malzeme üretilmiştir. Bambu çubuklarının boyut ve sıralama parametreleri sabit tutulurken, yapıştırıcı türü ve bambunun durumu (boş veya dolu olup olmadığı) değiştirilmiştir. Kalıptan çıkarıldıktan sonra, malzeme bir şerit testere kullanılarak 12 mm kalınlığında parçalar halinde kesilmiştir. Bu şeritlerin üst ve alt kısımlarına 3 mm kalınlığında HDF levhalar yapıştırılmıştır. Ortaya çıkan sandviç kompozitler, laboratuvar koşullarında basma testi, batma testi ve ısı iletkenliği testlerine tabi tutulmuştur. D4 ahşap yapıştırıcı ve boş çubuklarla yapılan bambu bazlı kompozitin yoğunluğu yaklaşık 430 kg/m³tür. En iyi ısı iletkenlik değeri olan 0.090 W/mK, D3 ahşap yapıştırıcı ve boş bambu çubuklarla yapılan kompozitlerde elde edilmiştir. En yüksek basınç ve ezilme mukavemetleri D4 ahşap yapıştırıcı kullanılarak yapılan kompozitlerde elde edilmiştir; ortalama basınç mukavemeti 23.00 N/mm²'dir. 20 mm çapında bir çelik bilye ile yapılan ezilme testinde de en iyi sonuçlar D4 yapıştırıcı ile elde edilmiştir. Sonuç olarak, yeni bambu bazlı malzemenin, ısı iletkenliği ve yoğunluk açısından geleneksel levha malzemelere kıyasla geliştirilmiş özelliklere sahip olduğu gösterilmiştir.

Anahtar Kelimeler: Bambu, Sandviç Kompozitler, Basma Testi, Isı İletkenlik Testi

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ABBREVIATIONS

BS	: Bamboo Sticks
D3	: MDF-Wood Adhesive
D3+F	: Composite-5, Bamboo Sticks + D3 MDF Adhesive + Filled
D3+H	: Composite-6, Bamboo Sticks + D3 MDF Adhesive + Hollow
D3+S+F	: Composite-7, Bamboo Sticks + 95% D3 MDF Adhesive +5% Saw Dust+ Filled
D3+S+H	: Composite-8, Bamboo Sticks + 95% D3 MDF Adhesive +5% Saw Dust + Hollow
D4	: Marin Adhesive (D4 Water Resistant Wood Adhesive)
D4+F	: Composite-1, Bamboo Sticks + D4 Marin Adhesive + Filled
D4+H	: Composite-2, Bamboo Sticks + D4 Marin Adhesive + Hollow
EPS	: Expanded Polystyrene Insulation
HDF	: High Density Fiberboard
MDF	: Medium Density Fiberboard
PU	: Foamed Polyurethane
PU+F	: Composite-3, Bamboo Sticks + Foamed Polyurethane + Filled
PU+H	: Composite-4, Bamboo Sticks + Foamed Polyurethane + Hollow

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INTRODUCTION

In recent years, there has been a growing interest in sustainable and eco-friendly materials within the construction and furniture industries. This shift is driven by the need to reduce the environmental and cost impact of traditional materials, such as particleboard and MDF (medium-density fiberboard), which often involve high energy consumption, the use of synthetic resins that release harmful emissions and high weight problems. Bamboo, a fast-growing and renewable resource, has emerged as a promising alternative due to its exceptional mechanical properties and minimal environmental footprint. Bamboo fibers are very promising reinforcements for polymer composites production due to their high aspect ratio, renewability, environmentally friendly, non-toxicity, cheap cost, non-abrasives, full biodegradability, and strong mechanical performances [1].

Bamboo's inherent strength, flexibility, and rapid growth cycle make it an ideal candidate for developing natural composite materials. Bamboo-based composites are created by combining bamboo fibers with resins or adhesives, resulting in materials that offer excellent mechanical properties while being environmentally sustainable. These composites can be used in various applications, including construction, furniture, and interior design.

In this thesis, 8 different bamboo-based sandwich composite materials were produced. These composites were evaluated in laboratory conditions. These results were compared with each other and MDF and particleboard.

CHAPTER 1

GENERAL INFORMATION and LITERATURE STUDY

1. General Information

1.1. Problem Status

There are two main traditional products that are used in wide range. Particle board and MDF are main feedstock of today's furniture industry. These materials, while seem easy to use and versatile, pose significant environmental concerns. The main problem with them is weight. The weight makes these materials difficult to handle and transport. Additionally, prices are highly dependent on weight, leading to increased costs. MDF and particle board tend to absorb water and swell, which can lead to warping, expansion, and loss of structural integrity. This makes them less suitable for use in areas with high humidity or exposure to water, like kitchens and bathrooms. The production of MDF and particleboard heavily relies on wood, which contributes to deforestation and habitat destruction.

1.2. Purpose of the research

This study aims to search an alternative material for furniture and construction industry. The primary purpose of this research is to investigate the production and evaluate mechanical properties of bamboo-based natural composite materials. Bamboo is an abundant, fast-growing plant that can be harvested sustainably. They possess high toughness, low density, and adequate specific strength properties. Furthermore, they have great thermal properties, and enhanced energy recovery. It possesses a high strength-to-weight ratio and mechanical properties, making it a viable candidate for composite material production.

1.3. Importance of Research

This research is pivotal in advancing material science and promoting sustainable engineering practices for several reasons:

Bamboo is widely recognized as a rapidly renewable resource and a more sustainable alternative to traditional wood. It can be harvested within 3 to 5 years, which is significantly faster than most hardwoods that often require decades to mature. This rapid growth rate makes bamboo highly renewable and ensures a continuous supply without the risks associated with deforestation [2].

Bamboo's high strength-to-weight ratio makes it an excellent material for various structural applications. Understanding its mechanical properties can lead to the development of strong and lightweight composites.

The adoption of bamboo-based composites can reduce reliance on wood, lower deforestation rates, and minimize the use of harmful adhesives, contributing to a healthier environment.

This research could pave the way for further exploration of natural composites and their potential applications in diverse industries.

1.4. Composite Materials

Composites have developed as a separate class of materials as a result of the production of multiphase composites such as glass fiber polymers. Materials such as adobe, shells, and steel made from straw-reinforced clay have been described as multiphase materials for thousands of years. As the concept of combining different materials during production was accepted by everyone, composites began to be considered as a new material group alongside metals, ceramics and polymers. Composite materials provide a wider range of combinations of material properties than single-phase materials have previously provided.

Special and extraordinary features are needed in high technology applications. These applications are especially in the fields of aviation, underwater, bioengineering and transportation. For example, aeronautical engineers increasingly need low-dense, high-strong, rigid, wear- and impact-resistant and corrosion-free materials. In monolithic

materials, materials with high strength generally have high density. Toughness decreases with increasing strength [3].

The range of material properties and combinations have expanded and continues to evolve. In general, a composite material can be considered as a multiphase material with better properties by combining the properties of both components. This is the combination of two or more materials to provide better properties according to the “combined effect precipitate”. However, it should not be forgotten that while some features improve, others may deteriorate.

Composite materials also exist naturally in nature. For example, wood consists of cellulose fiber and wood sap. The strong and flexible cellulose fiber is held together and supported by a more rigid component called tree sap, and the bone is a composite of strong and soft protein keeper and hard and brittle apatite minerals.

According to the definition made above, a composite material is a material that is artificially produced, as opposed to naturally occurring ones. In addition, the phases that make up the structure are chemically different from each other and separated from each other by a distinct interface.

Most composite materials consist of only two phases. The first phase, called the matrix, surrounds and maintains the continuity of the other phase, usually called the dispersed phase. A simple diagram showing the classification of composite materials is shown in figure 1. Accordingly, composites are divided into 3 main groups: particle reinforced, fiber reinforced and structural composites.

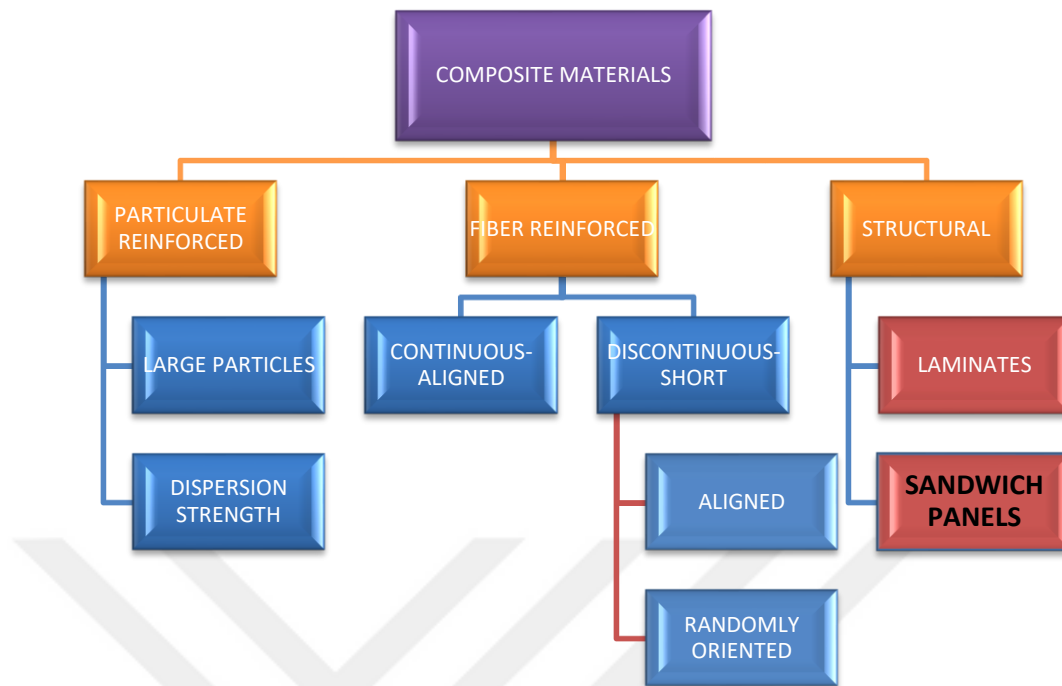


Figure 1. Composite materials.

1.4.1 Particulate Reinforced Composites

It is examined in two parts. In most of these composites, the particle phase is harder and more rigid than the matrix. These strength-enhancing particles prevent movement within the surrounding matrix. Essentially, the matrix transfers some of the applied load to the particles. The improvement of mechanical properties depends on the strength of the bond at the matrix-particle interface. Particles in the composite slow down and prevent dislocation movement. Thus, plastic deformation will be limited, and hardness will increase as well as yield and tensile strength. There are many different forms of particulate composites. The particulates can be very small particles (< 0.25 microns), chopped fibers (such as glass), platelets, hollow spheres (see figure 2), or new materials such as bucky balls or carbon nanotubes. In each case, the particulates provide desirable material properties, and the matrix acts as binding medium necessary for structural applications [4].

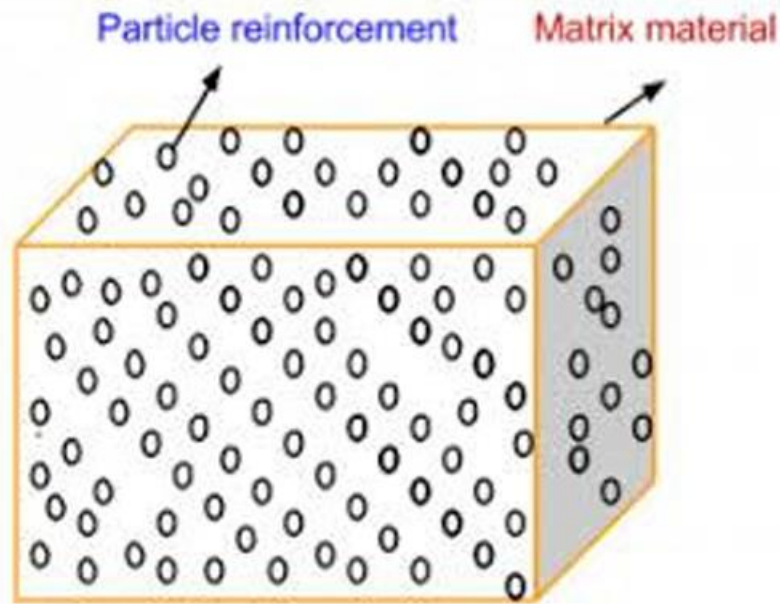


Figure 2. Particulate reinforced composite structure [4].

1.4.1.1 Large Particle Composite

Particles can have very different geometries. However, it is approximately the same size in all directions. To create an effective supplement, the particles must be small and homogeneously distributed. In addition, the volume ratios of both components affect the behavior of the composite.

The most common cermet is sintered carbide. Sintered carbide consists of extremely hard carbides such as tungsten carbide or titanium carbide embedded in a metal matrix such as cobalt or nickel. These composites are widely used as cutting tools.

1.4.1.2 Dispersion-Strength Composites

Distributing very small particles of very hard and stable materials homogeneously in small amounts within metals and metal alloys can increase the hardness and strength of the material. Here the scattered phase can be metallic or non-metallic material. The high temperature resistance of nickel alloys can be increased by adding 3% by volume of fine thoria - ThO_2 particles. This material is called thoria- scattered nickel. The same effect is seen in the aluminum-aluminum oxide system. In the material called sintered aluminum powder, a very thin and sticky alumina coating adheres to the surface of very thin aluminum flakes and then spreads into the aluminum matrix.

1.4.2 Fiber Reinforced Composites

The most technologically important composites are those in which the reinforcement phase is in the form of fibers. The design goal of fiber reinforced composites is generally high strength and high modulus of elasticity combined with low weight. These properties are described in terms of specific free strength and specific modulus of elasticity, defined as the ratio of tensile strength to free weight and the ratio of elastic modulus to specific weight, respectively. Fiber reinforced composites with extraordinary free strength can be produced with low density fiber and matrix materials.

The properties of fiber-reinforced composites depend not only on the properties of the fiber, but also on the amount load transmitted to the fiber through the matrix phase. This load transfer is related to the magnitude of the interfacial bond force between the matrix and fiber phases.

1.4.2.1 Continuous and Aligned Fiber-Reinforced Composites

Variables such as fiber orientation and placement, density, and distribution significantly affect the strength and other properties of fiber-reinforced composites. The strength of composites reinforced with continuous and unidirectionally oriented fibers is largely dependent on the direction. Therefore, these types of composites are subjected to stress along the fiber direction where the strength is highest. However, during operation, loads may also act perpendicular to the fiber direction. In such cases, unexpected early failures may occur because the strength of the composites perpendicular to the fiber direction is extremely low and may even fall below the matrix strength.

1.4.2.2 Discontinuous Fiber-Reinforced Composites

These are divided into two categories: discontinuous oriented and discontinuous randomly oriented fiber composites.

1.4.2.2.1 Discontinuous Aligned

Although the potential increase in strength for discontinuous and oriented fiber composites is lower compared to continuous fiber-reinforced structures, these composites are becoming increasingly important in the commercial market.

1.4.2.2.2 Discontinuous Randomly Oriented

In applications where multi-directional stress is applied, discontinuous fibers randomly oriented within the matrix are generally used. In this case, the reinforcement efficiency obtained is one-fifth of that in the fiber direction, but the mechanical properties are not direction-dependent. When deciding on the orientation and fiber length for a specific composite, attention should be paid to the level and type of applied stress, as well as production costs. Short fiber composites offer both high production speed and the possibility of achieving complex geometries that cannot be produced with continuous fibers.

1.4.3 Structural Composites

A structural composite is composed of homogeneous materials whose properties depend not only on their components but also on their geometry. Laminates composites and sandwich composites are the most common structural composites.

1.4.3.1 Laminates

A laminated composite consists of thin plates or panels with high strength in a specific direction, such as in wood and continuously oriented fiber-reinforced plastics. These layers are stacked on top of each other and bonded in such a way that each layer increases strength in a particular direction. For example, in plywood, the grain directions of the adhered wood layers are placed at right angles to each other. In laminated composites, low cost, high strength, and lightness are prioritized. Examples of laminated composites include vehicle windshield glass, where two layers of glass are bonded with plastic, and furniture components like formica and plywood.

1.4.3.2 Sandwich Panels

Sandwich panels are in the class of structural composites used in the design of entrances or panels that are light but have high rigidity and durability. A sandwich panel consists of a thick intermediate layer and two outer layers or surfaces adhering to it (see figure 3).

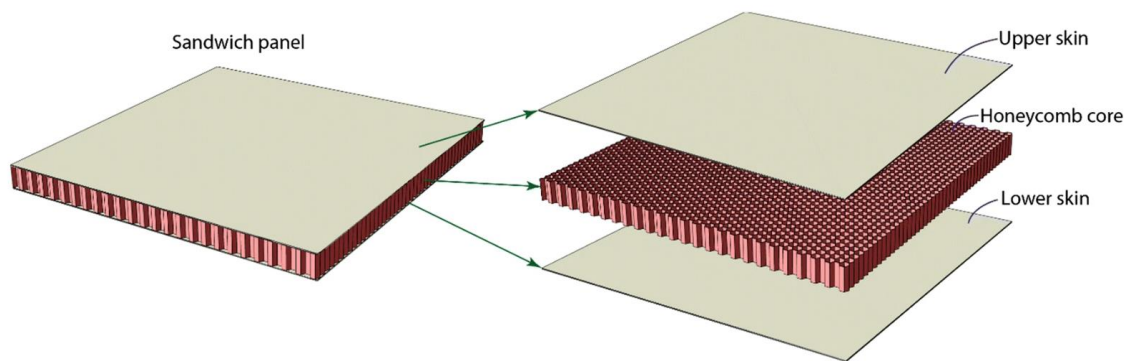


Figure 3. Sandwich panel composite structure [5].

Sandwich panels are a type of structural composite designed to maximize strength, rigidity, and durability while minimizing weight. They consist of three primary components: two strong outer layers (skins) and a lightweight core. The outer layers provide the structural strength needed to withstand tensile and compressive stresses, while the core material helps distribute these stresses and maintain the integrity of the structure. Common materials used for the outer skins include aluminum alloys, fiber-reinforced plastics, and plywood, chosen for their high rigidity and durability. The core materials, such as honeycomb structures, polymer foams, or wood, are selected for their low density and ability to absorb and dissipate energy effectively [6].

1.4.3.2.1 Materials in Sandwich Panels

The core material in a sandwich panel serves multiple functions: it provides shear strength, absorbs impact energy, and supports the outer skins to prevent them from buckling under load. The core is typically made from lightweight materials such as rigid polymer foams (e.g., polyurethane), wood, or honeycomb structures. Each type of core material offers unique mechanical properties:

Rigid polymer foams are lightweight, easy to manufacture, and provide excellent insulation properties. They are used in applications where thermal or acoustic insulation is required alongside structural support. The foam's closed-cell structure also helps resist water absorption, making it suitable for marine applications [7].

Wood cores, especially balsa, is often used as a core material in sandwich panels due to its high strength-to-weight ratio. Balsa wood cores are particularly effective in absorbing impact energy, making them ideal for use in boat hulls and other marine structures. The

natural damping properties of wood also help reduce vibrations, enhancing the comfort and safety of structures in dynamic environments [8].

Honeycomb cores are among the most popular choices for high-performance sandwich panels. These cores consist of thin foils shaped into hexagonal cells that interlock and provide exceptional stiffness and strength with minimal weight. Honeycomb materials are commonly made from aluminum or aramid polymers, which offer good corrosion resistance and thermal stability. The strength and rigidity of the honeycomb structure depend on factors such as cell size, wall thickness, and the material used [9].

1.4.3.2.2 Bamboo-Based Core Materials

Bamboo-based cores are an innovative and sustainable option for sandwich panels, leveraging the natural properties of bamboo to enhance performance. Bamboo is a fast-growing, renewable resource with high tensile strength, making it suitable for use in structural composites. Bamboo fibers can be processed into various forms such as veneers, strips, or woven mats that are then used as core materials in sandwich panels. These bamboo-based cores offer several benefits.

Bamboo fibers have a high strength-to-weight ratio, providing comparable performance to synthetic fibers like glass. This makes bamboo cores highly effective in reinforcing sandwich panels, especially where high rigidity and durability are required.

Bamboo's natural structure allows it to absorb and dissipate impact energy effectively. This characteristic makes bamboo-based sandwich panels suitable for applications that require resistance to dynamic loads, such as in automotive body panels and aircraft interiors.

Using bamboo as a core material aligns with sustainable practices, as bamboo is biodegradable and has a lower carbon footprint compared to synthetic materials. Its use in sandwich panels contributes to reducing the reliance on non-renewable resources and minimizing environmental impact.

1.4.3.2.3 Mechanical Properties of Bamboo-Based Cores

Bamboo-based cores are gaining recognition for their exceptional mechanical properties, which make them suitable for various structural applications in sandwich panels.

Bamboo fibers have a high tensile strength, comparable to synthetic fibers like glass. This characteristic enables bamboo-based cores to provide substantial resistance to stretching forces, making them ideal for reinforcing the outer layers of sandwich panels.

Bamboo-based cores exhibit high flexural strength, allowing them to resist bending forces without breaking. This property is crucial for applications where panels must withstand bending loads, such as flooring, roofing, and other structural elements.

Bamboo's cellular structure provides good shear strength, which is essential for maintaining the integrity of sandwich panels under transverse loads. This helps prevent the layers from sliding relative to each other, ensuring the overall stability of the panel.

Bamboo-based cores offer significant compression strength due to the natural arrangement of bamboo fibers, which are dense and aligned in a manner that can withstand high compressive forces. This property is particularly valuable in applications where panels are subjected to heavy loads or compression forces, such as in construction and transportation.

Bamboo-based cores also possess good indentation strength, which refers to their ability to resist localized deformation or denting under concentrated loads. This characteristic makes bamboo cores suitable for applications where surface durability and resistance to impact are critical, such as in automotive body panels and aircraft interiors.

Bamboo-based cores have relatively low thermal conductivity compared to metallic core materials, which provides excellent insulation properties. This makes them suitable for applications where thermal management is important, such as in building panels for energy-efficient construction or in thermal insulation components for automotive and aerospace applications.

1.4.3.2.4 Applications and Future Directions

Sandwich panels, particularly those utilizing bamboo and natural composites, have a broad range of applications across industries. In aerospace engineering, these panels are used for aircraft interiors, fuselage skins, wings, and tail coverings, thanks to their excellent strength-to-weight ratios and resistance to impact and fatigue. In the automotive sector, sandwich panels are employed in body panels, doors, and other structural components to improve fuel efficiency and reduce emissions by minimizing vehicle weight [10].

In the construction industry, bamboo-based sandwich panels are used in wall panels, roofing, and flooring applications due to their strength, durability, and sustainability. As global emphasis on sustainable development continues to grow, the demand for bamboo and other natural fiber composites in sandwich panels is likely to increase. Future research is expected to focus on optimizing material properties, enhancing manufacturing techniques, and expanding the range of applications for these sustainable composites.

The integration of bamboo and natural composites into sandwich panels offers a promising path toward developing high-performance, sustainable materials for various applications. These materials not only provide excellent mechanical properties but also contribute to environmental sustainability by reducing reliance on non-renewable resources. Continued research and development in this field will further enhance the versatility and performance of sandwich panels, making them a key component in the future of sustainable engineering.

1.5. Composite Production Methods

Composite materials can be produced using various methods described as follows:

1.5.1 Hand Lay-Up

The simplest and most cost-effective composite fabrication method, hand lay-up, is ideal for low to medium volume production. It involves manually placing reinforcement fibers onto a prepared mold and then applying catalyzed resin by brush or spray to saturate the fibers. The process is labor-intensive and relies heavily on the skill of the fabricators to ensure consistent quality. Hand lay-up is particularly useful for producing parts with

complex shapes or where a gel-coated surface finish is required on one side. Despite its simplicity, the method allows for significant flexibility in design changes and is suitable for applications where high precision is not critical.

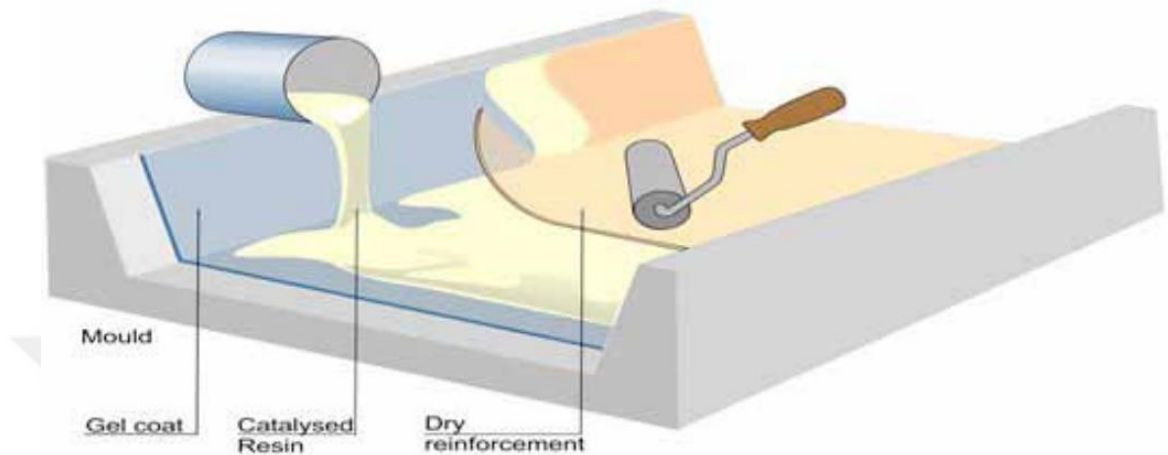


Figure 4. Bamboo based sandwich panel composite structure [11].

1.5.2 Filament Winding

This technique involves winding resin-saturated continuous fibers around a rotating mandrel, typically with a circular cross-section. The fibers are wound under tension, allowing for precise control over fiber orientation and thickness, which directly influences the mechanical properties of the finished product. Filament winding is highly adaptable, capable of producing parts with varying lengths and diameters, such as pipes, tanks, masts, and pressure vessels. The process can be conducted with either a fixed or a continuous mandrel, with the latter being used for larger diameter parts. The ability to adjust winding angles and incorporate materials like sand between layers offers further optimization of mechanical properties, such as burst strength and stiffness.

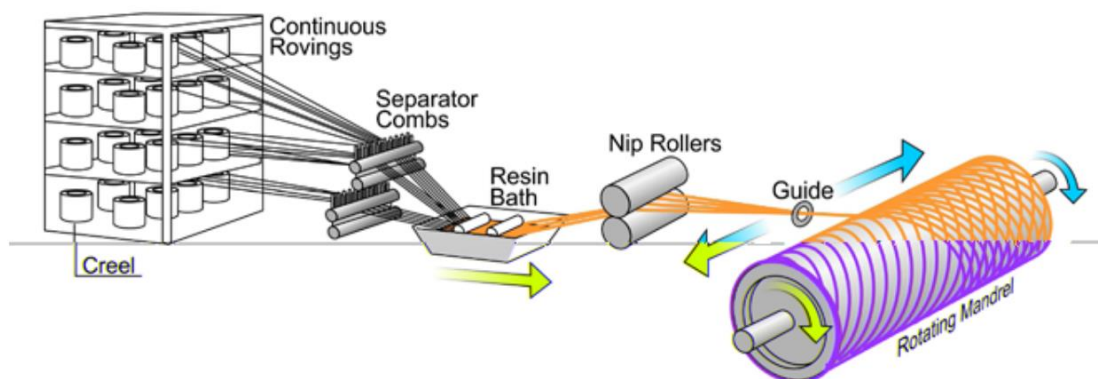


Figure 5. Bamboo based sandwich panel composite structure [11].

1.5.3 Centrifugal Moulding

This process is designed for producing hollow, cylindrical components, such as pipes, through the application of centrifugal force. The process involves preheating a cylindrical mold, which is then rotated at high speeds. As the mold spins, a mixture of resin, chopped glass fibers, and sand is fed into the mold. The centrifugal force consolidates the laminate, compacting it against the mold walls, and forming the pipe. The mechanical properties of the finished product, such as hoop and burst strength, depend on the proportion and arrangement of the resin, glass, and sand layers. This method is suitable for producing low-pressure and jacking pipes, although the mechanical properties are generally lower compared to filament wound pipes.

1.5.4 Hot Moulding Processes (SMC and DMC/BMC)

Sheet Moulding Compound (SMC) and Dough/Bulk Moulding Compound (DMC/BMC) are hot molding processes used for high-volume production of composite parts requiring high dimensional accuracy. SMC involves a mixture of resin, filler, catalyst, and chopped fibers, which is shaped and cured under heat and pressure in matched molds. DMC/BMC follows a similar process but uses a dough-like mixture of resin, filler, and short fibers. Both processes are highly automated, with short cycle times ranging from 30 seconds to 4 minutes, making them ideal for producing automotive components, electrical housings, and other parts where uniformity and surface finish are critical.

1.5.5 Lite-RTM (Resin Transfer Moulding)

Lite-RTM is a variation of the traditional RTM process, designed for lower volume production runs where high-pressure tooling costs are not justified. This method uses lower pressures, making it suitable for molds that are not made from heavy-duty materials. The process involves placing dry fiber reinforcements into a mold, which is then closed and subjected to vacuum pressure to draw resin into the mold cavity. Lite-RTM is ideal for producing components with moderate mechanical requirements and where the cost savings from using less expensive molds outweigh the need for high production volumes.

1.5.6 Pultrusion and Pull Winding

Pultrusion is a continuous process for producing composite profiles with a constant cross-section by pulling fibers through a resin bath and then through a heated die, which shapes and cures the material. This method is efficient and economical for high-volume production of items like beams, rods, and rails, where high strength and stiffness along the length of the part are required. Pull Winding is a variation that introduces fibers in various orientations to enhance the mechanical properties across different directions, making it suitable for applications needing improved transverse properties.

1.5.7 Resin Transfer Moulding (RTM)

A closed mold process that produces composite parts with two finished surfaces, RTM is suitable for medium to high-volume production. The process involves placing dry fibers into a mold, closing the mold, and then injecting catalyzed resin under pressure to saturate the fibers. RTM allows for high fiber volume fractions and low void content, resulting in strong, lightweight parts with high surface finish quality. The process is widely used in the automotive and aerospace industries, where precise control over part geometry and mechanical properties is essential.

1.5.8 Spray-Up

An open mold process that is faster than hand lay-up, spray-up involves spraying catalyzed resin and chopped fibers simultaneously onto a prepared mold surface. This method is well-suited for larger parts such as boat hulls and swimming pools. The process is labor-efficient and allows for quick production, but maintaining consistent quality requires skilled operators. Spray-up is compatible with polyester and vinyl ester resins and is ideal for low to medium volume production runs where surface finish on both sides is not a requirement.

1.5.9 Vacuum Bagging:

A refinement of the hand lay-up process, vacuum bagging involves applying atmospheric pressure to consolidate the wet laminate and remove excess resin. A flexible bag is placed over the laminate and sealed around the edges, and air is evacuated to create a vacuum. This process improves fiber wet-out, reduces void content, and enhances the overall

quality of the part compared to hand lay-up. It is often used for large, complex shapes where other pressurization methods are not feasible and can be combined with prepregs for higher performance applications.

1.5.10 Vacuum Infusion/Resin Infusion

Similar to vacuum bagging but conducted under a fully enclosed mold, vacuum infusion uses vacuum pressure to draw resin into a dry fiber preform. This process results in a high fiber content and superior mechanical properties due to the reduced void content and improved fiber wet-out. Vacuum infusion is ideal for producing large, detailed parts with high structural integrity and is compatible with a wide range of resins and reinforcement materials.

1.5.11 Vacuum Form Acrylic Process

This process involves molding acrylic sheets using vacuum and subsequently reinforcing them with fiberglass for added rigidity. It is used for creating durable, aesthetically pleasing parts such as bathroom fixtures, furniture, and recreational vehicle components. The acrylic provides a tough outer surface, while the fiberglass backing adds strength and durability.

1.5.12 Adhesive Bonding

Adhesive bonding is a crucial production method for assembling sandwich panel composites, ensuring strong and durable connections between face sheets and core materials. This technique is particularly effective for bonding various materials, including bamboo cores and wood-based face sheets, which are increasingly used in sustainable composite designs.

Wood adhesives are ideal for bonding bamboo cores due to their compatibility and ability to penetrate the natural fibers, creating strong, moisture-resistant bonds. The use of bamboo as a core material provides advantages such as high strength-to-weight ratio and sustainability, making it suitable for applications like flooring and lightweight structural panels.

In adhesive bonding, proper surface preparation, such as sanding or chemical treatments, is essential to enhance adhesion and prevent bond failure. The process allows for uniform stress distribution and weight reduction by avoiding mechanical fasteners. This versatility enables the bonding of complex geometries and dissimilar materials, optimizing sandwich panels for diverse applications.

Despite its benefits, adhesive bonding requires careful selection of adhesives to withstand environmental exposure, along with rigorous quality control methods like ultrasonic testing to ensure bond integrity. Overall, adhesive bonding remains a versatile and efficient method for producing high-performance sandwich panel composites.

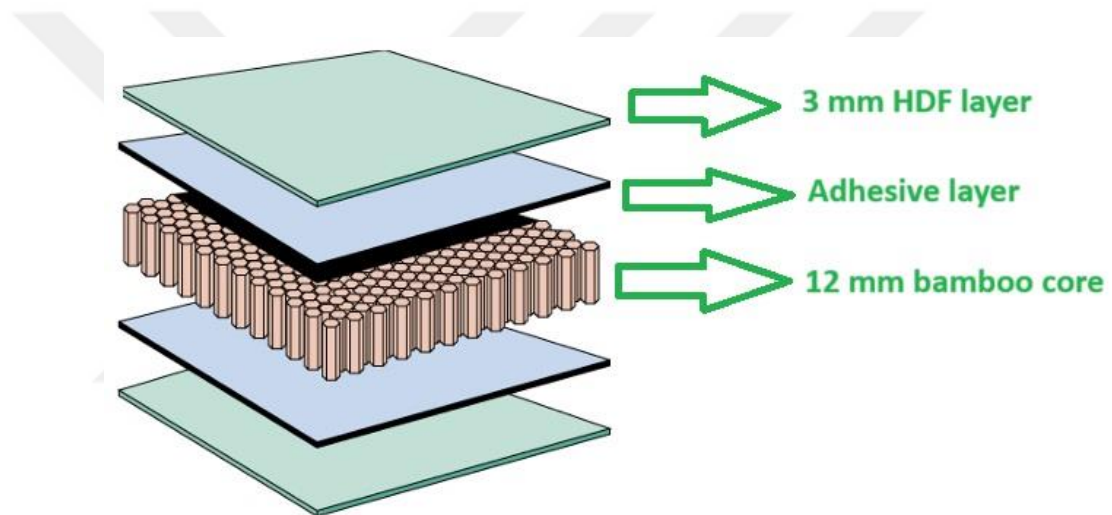


Figure 6. Bamboo Based Sandwich Panel Composite Structure [12].

1.6. MDF Medium-Density Fiberboard

Medium-Density Fiberboard (MDF) is an engineered wood product made by combining wood fibers with resin and pressing them under heat and pressure. MDF is widely used in furniture, cabinetry, and interior applications due to its smooth surface, uniform density, and ease of machining, which make it ideal for decorative finishes like painting and laminating. MDF is known for its high dimensional stability, meaning it resists warping under varying humidity conditions, making it suitable for indoor use. However, MDF is less resistant to moisture, can swell in high humidity, and may release formaldehyde, a potential health risk, from the resins used in its manufacture.

Medium-Density Fiberboard (MDF) typically has a density ranging from 600 to 800 kg/m³, which gives it a balance between strength and workability. The density of MDF affects its mechanical properties, including its strength, stiffness, and resistance to bending. Higher-density MDF panels generally have better mechanical performance but can be more challenging to machine and handle due to their increased weight. MDF's uniform density ensures consistent performance across the entire board, making it ideal for precise cutting and detailed finishing in furniture and interior applications.

The density also impacts MDF's susceptibility to moisture. Higher-density MDF is more resistant to water absorption and swelling compared to lower-density variants, which makes it more suitable for certain applications where exposure to moisture is a concern [13].



Figure 7. Usual MDF BOARD has a smooth surface and side [14].

1.7. High Density Fiberboard (HDF)

High Density Fiberboard (HDF) is a high-quality composite material that is thinner and denser than regular particle board.

1.8. Particleboard

Particleboard, also known as chipboard, is an engineered wood product made from wood particles, such as wood chips, sawmill shavings, or even sawdust, bonded together with a synthetic resin or other suitable binder, which is pressed and extruded. It is widely used in furniture manufacturing, interior construction, and as a base material for decorative laminates.

Particleboard is composed of wood particles of varying sizes mixed with a resin binder. Common binders include urea-formaldehyde, phenol-formaldehyde, and melamine-formaldehyde resins. The wood particles are layered to achieve a uniform thickness and density. The physical and mechanical properties of particleboard depend on the type of wood particles, the adhesive used, and the manufacturing process. Generally, particleboard has lower density, strength, and moisture resistance compared to solid wood or plywood. However, its homogeneity and smooth surface make it suitable for laminating and veneering [15].

The production of particleboard involves three main steps: preparation of raw materials, mixing with adhesives, and hot pressing (see figure 18). The wood particles are first cleaned, sized, and dried. They are then mixed with adhesives and other additives before being formed into mats and compressed under high temperature and pressure to create panels. Recent advancements in manufacturing technology focus on improving the physical and mechanical properties of particleboard by optimizing the particle size distribution, adhesive types, and pressing conditions [16].

Particleboard is primarily used in the furniture industry for items such as cabinets, countertops, shelves, and flat-pack furniture. Its smooth surface is ideal for laminating with decorative surfaces, such as melamine or wood veneer, to improve aesthetics. It is also used in interior construction for non-load-bearing applications, such as wall panels and partitioning, due to its dimensional stability and ease of installation.



Figure 8. Usual Particleboard has a smooth surface [17].

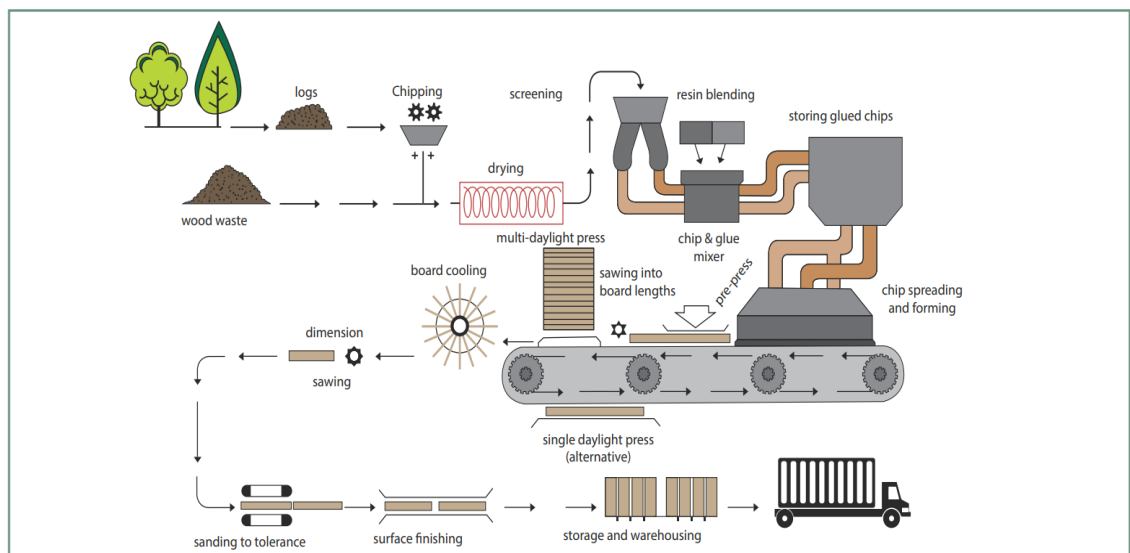


Figure 9. Particleboard manufacturing process [18].

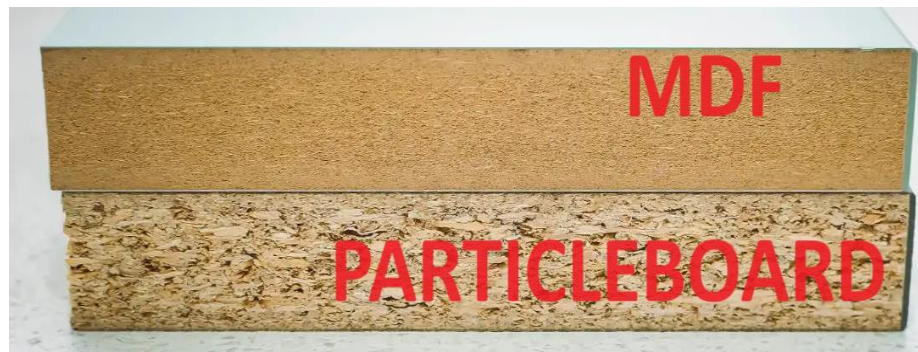


Figure 10. MDF & Particleboard side view.

1.9. Marine Adhesive-D4

Marine Adhesive-D4, classified under the TS EN 204 standard. This classification ensures that the adhesive meets stringent water resistance requirements, particularly for exterior wood composites and applications exposed to moisture and environmental factors. D4 adhesives are widely used in industries such as marine construction and outdoor decking, where continuous or frequent water exposure is expected. According to TS EN 204, D4 adhesives are suitable for applications requiring high durability under conditions involving long-term exposure to running or condensed water.

In addition to their water-resistant properties, Marine Adhesive-D4 offers exceptional bonding strength and flexibility, allowing for effective bonding in wood products that experience expansion and contraction due to moisture and temperature changes. Studies comparing D3 and D4 adhesives show that D4 outperforms in terms of durability and long-term resistance to moisture, making it the adhesive of choice for marine and outdoor structural applications. TS EN 301 further supports the use of D4 adhesives in load-bearing timber structures, ensuring their application in demanding environments [19-20].

3.2 Mixtures

General chemical description:
Adhesive

Base substances of preparation:

Declaration of the ingredients according to CLP (EC) No 1272/2008:

CAS No.	EC No.	Concentration	Classification
4,4'-methylenediphenyl diisocyanate	500-040-3	< 5 %	Canc.2 ;H351 Acute Tox.4*; H332
25686-28-6			STOT Rep. Exp.2; H373** Eye Irrit. 2;H319 BHOT Rep. Exp.3; H335 Skin Irrit. 2;H315 Respiratory Sens.1;H334 Skin Sens.1;H317
Benzoyl Chloride 98-88-4	202-710-8	< 0,05 %	Acute Tox. 4 *;H332 Acute Tox 4 *;H312 Acute Tox 4 *;H302 Skin Irrit. 1B;H314 Skin Sens. 1;H317

See the Section 16 for the full text of the H- and P- Statements.

Figure 11. D4 Marin adhesive substances [21].

1.10. MDF Wood Adhesive-D3

MDF Wood Adhesive-D3, classified under the TS EN 204/D3 standard, is widely used in interior and semi-exterior applications that require moderate water resistance. According to TS EN 204, D3 adhesives are suitable for interior use with frequent short-term exposure to moisture, such as in kitchens or bathrooms, and for exterior use where the product is protected from direct exposure to weather. The balance between cost-effectiveness and performance makes D3 adhesives ideal for manufacturing medium-density fiberboard (MDF), which is a critical material in furniture, cabinetry, and interior paneling.

The TS EN 204 classification ensures that D3 adhesives can withstand intermittent moisture without compromising the integrity of the MDF. However, for applications where long-term moisture exposure is a concern, D4 adhesives might be more appropriate. Research indicates that the use of D3 adhesives in MDF production enhances the material's resistance to delamination and swelling under humid conditions, making it a reliable choice for semi-exterior environments [22].

3.2 Mixtures			
General chemical description:			
Adhesive Emulsion			
Base substances of preparation:			
CAS No.	EC No.	Concentration	Classification
Formaldehyde 50-00-0	200-001-8	< % 0,2	Canc. 2 ;H351 Acute Tox. 3, inh.; H331 Acute Tox. 3, Oral;H301 Skin Corr. 1B ;H314 Skin Sent. 1 ;H317
<i>See the Section 16 for the full text of the H- and P- Statements.</i>			
Declaration of the ingredients according to CLP (EC) No 1272/2008:			
Contains no dangerous substances exceeding the limits of the EU-Regulation			

Figure 12. D3 MDF wood adhesive substances [21].

1.11. Polyurethane Foam

Polyurethane foam plays a significant role in composite material production, particularly in the furniture and insulation industries. Its lightweight, flexible structure, and excellent thermal properties make it suitable for a wide range of applications. Polyurethane foam's ability to adhere effectively to materials like wood and MDF, combined with its resilience and durability, enhances its application in furniture production and thermal insulation.

The foam also meets various standards for thermal insulation materials, contributing to energy-efficient buildings. It is often used in conjunction with adhesives like D3 and D4 to form composite materials that maintain mechanical strength while providing additional properties like soundproofing and impact absorption. This versatility is further supported by its compliance with TS EN 13165, which regulates the use of thermal insulation materials in buildings [23].

3.2 Mixtures

General chemical description:
Polyurethan Foam

Base substances of preparation:

Declaration of the ingredients according to CLP (EC) No 1272/2008:

CAS No.	EC No.	Concentration	Classification
Diphenylmethane-4,4'-diisocyanate 101-68-8	202-966-0	5 % ≤ C < 25	Canc.2 ;H351 Acute Tox.4* ; H332 STOT Rep. Exp.2 ; H373** Eye Irrit. 2;H319 STOT Rep. Exp.3 ; H335 Skin Irrit. 2;H315 Respiratory Sens.1;H334 Skin Sens.1;H317
Propane 74-98-6	200-827-9	-	Flammable Aerosol 1;H220
Butane 106-97-8	203-448-7	-	Flammable Aerosol 1;H220
Dimethyl ether 115-10-6	204-065-8	-	Flammable Aerosol 1;H220

See the Section 16 for the full text of the H- and P- Statements.

Figure 13. Foamed polyurethane substances [21].

1.12. Wood Chips

Wood chips, frequently used in the production of particleboard, form the basis of many engineered wood products. According to the TS EN 312 standard, particleboard made from wood chips must meet certain requirements for mechanical properties such as bending strength and internal bond strength, both of which are enhanced by the use of D3 and D4 adhesives. Wood chips provide bulk and structural integrity to the composite, making them essential in applications like furniture and interior construction.

When combined with D3 or D4 adhesives, wood chips form a composite material that is both cost-effective and sustainable, often utilizing recycled wood waste. The TS EN 204 standard ensures that these adhesives provide sufficient moisture resistance for particleboard used in semi-exterior or protected outdoor applications. Additionally, the environmental benefits of wood chips, particularly when sourced from forestry by-products, contribute to the sustainability of composite production [24].



Figure 14. Wood chips and saw dust [25].

1.13. Bamboo (Arundo Donax)

Bamboo, particularly *Arundo Donax*, is increasingly used in the production of natural composite materials due to its high strength-to-weight ratio, fast growth rate, and sustainability. *Arundo Donax* is one of the fastest-growing plants, capable of reaching heights of 6-10 meters in a single growing season, making it a highly renewable resource. Moreover, bamboo offers environmental benefits such as carbon sequestration and requires fewer chemical inputs compared to traditional wood-based products like particleboard and medium-density fiberboard (MDF). Its application in composite production is further enhanced by its mechanical properties, which are often superior to those of particleboard and MDF [26].

Given its superior mechanical properties, bamboo (*Arundo Donax*) offers numerous advantages over particleboard and MDF in both structural and non-structural applications.

Bamboo is a rapidly renewable resource, typically maturing within 3-5 years, unlike the trees used for particleboard and MDF, which take decades to grow. This makes bamboo a highly sustainable material for composite production [27].

Bamboo's strength, stiffness, and resistance to moisture make it an ideal material for structural applications such as wall panels, flooring, and exterior cladding. Its ability to outperform particleboard and MDF in mechanical properties makes it a viable option for both interior and exterior uses [28].

Bamboo's aesthetic qualities, combined with its durability and resistance to moisture, make it an excellent material for furniture. Bamboo composites are used in applications such as cabinetry, countertops, and outdoor furniture, where moisture resistance is crucial [29].

Despite its many advantages, there are still challenges in using bamboo for large-scale composite production. The initial cost of processing bamboo and the limited availability of *Arundo Donax* in some regions can restrict its adoption. However, advancements in adhesive technologies, such as the use of D3 and D4 adhesives for enhanced moisture resistance and bonding strength, are improving bamboo's applicability in composite materials [30].

As the demand for sustainable materials grows, bamboo is likely to become a key player in the future of eco-friendly building materials, offering a viable alternative to traditional wood-based products like particleboard and MDF.



Figure 15. Bamboo sticks [31].

2. Literature Study

Chaudhary U. [32] explored bamboo's applications in industries such as pulp and paper (see figure 16), noting bamboo's potential as an eco-friendly material with a high strength-to-weight ratio. Bamboo composites have proven to be useful in the production of sustainable materials for various industries (see figure 17).

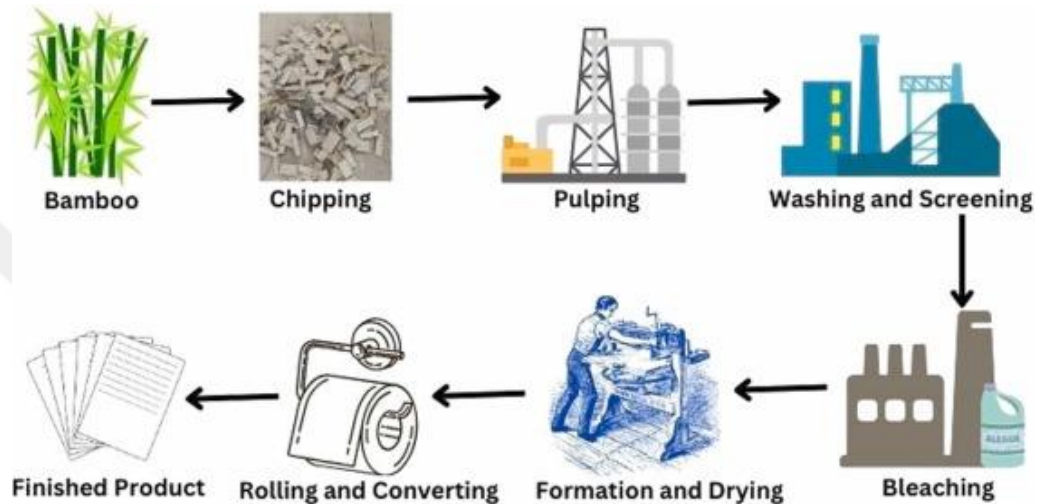


Figure 16. Schematic representation of paper manufacturing process.



Figure 17. Major industrial uses of bamboo.

Martijanti M. [33] investigated the structural properties of bamboo fiber-reinforced composites, revealing their mechanical strength and suitability for various structural

applications. Their research also touched on processing techniques to improve bamboo's adhesion within composite matrices.

Ersin İ. [34] explores how bamboo (*Phyllostachys Bambusoides*) can be used to make Parallel Strand Lumber (PSL), a type of engineered wood. The study tested the strength and physical properties of this bamboo-based PSL, such as how much water it absorbs, how strong it is when bent, and how well screws hold in it. The research found that adding a material called polyol to the adhesive made the PSL stronger and more durable. This suggests that bamboo can be a good material for making strong, reliable wood products for building and construction.

Şahin, H., [35] aimed to explore the thermal insulation properties of different wood and wood-based panels, which are essential for energy conservation in buildings. The research tests ten types of panels, including solid wood panels made from yellow pine and oriental beech, particleboard, medium-density fiberboard (MDF), and oriented strand board (OSB), among others. These panels are commonly used in construction and furniture manufacturing.

Key findings of the study include:

The highest thermal conductivity coefficient was found in the oriental beech plywood (0.137 W/m.K).

The lowest thermal conductivity was observed in the MDF panels coated with resin-impregnated paper (0.083 W/m.K).

The results suggest that surface coating with resin-impregnated paper can significantly reduce the thermal conductivity of wood-based panels, making them more suitable for insulation purposes.

The study concludes that different wood types and surface treatments significantly affect the thermal insulation properties of wood panels. The results can guide material selection in construction to improve energy efficiency.

Chaowana, P. [36] studied the potential of bamboo as an alternative raw material for wood and wood-based composites, emphasizing its abundance in tropical and subtropical zones

and its suitability for various applications, such as pulp and paper, veneer, plywood, particleboard, and fiberboard. The study highlights bamboo's advantages, including its fast growth, high strength, and renewability, which make it a valuable resource amid decreasing global wood supplies. The research also explores the morphological, chemical, physical, and mechanical properties of bamboo, pointing out the need for specialized processing methods and further investigation to optimize its use in composite products. It states that bamboo has higher bending strength, compression strength parallel to grain, and similar shear strength parallel to grain compared to wood used in particleboard manufacturing.

Bansal A. [37] discussed the potential of bamboo as a renewable resource for creating composite materials. Bamboo is highlighted as an environmentally friendly alternative to wood, suitable for various applications like construction, packaging, and furniture. The Indian Plywood Industries Research and Training Institute (IPIRTI) has developed several bamboo-based composites, such as Bamboo Mat Board (BMB), Bamboo Mat Veneer Composite (BMVC), and Bamboo Mat Corrugated Sheets (BMCS), which offer superior strength, dimensional stability, and sustainability compared to traditional wood-based panels. The document emphasizes the economic benefits of bamboo composites, including employment generation in rural areas and reduced dependence on forest resources. It also notes ongoing efforts to scale up production technologies and standardize testing procedures to promote the adoption of bamboo composites in various industries.

Ramos, D [38] investigated the production of fiberboards using *Arundo Donax* fibers without the need for added adhesives. The boards produced exhibit excellent mechanical properties, particularly high Modulus of Elasticity (MOE) values, reaching up to 9552 MPa, and Modulus of Rupture (MOR) values ranging from 11.16 to 53.3 MPa. The density of these boards ranges from 859.9 to 1295.3 kg/m³, classifying them as high-density fiberboards. The pressing pressure applied during production significantly enhances the mechanical properties, making these boards a strong candidate for construction and furniture materials. The study concludes that *Arundo Donax*-based boards can effectively compete with traditional wood-based composite materials.

Ogunbiyi, M [39] compared the tensile strength of bamboo and steel reinforcement bars in building construction. Bamboo demonstrates a lower tensile strength compared to high-yield steel bars, with bamboo tensile strength values of 31.55 MPa versus steel's 792.90 MPa. Despite this, bamboo has a much higher strength-to-weight ratio, making it a viable option for non-load-bearing applications such as walls, ceilings, and partitions. The study concludes that bamboo can be used in non-critical structural applications where lightweight materials are preferred, particularly in low-cost housing projects.

Smith, J. [40] investigated the mechanical properties of bamboo fiber reinforced polymer composites. By incorporating bamboo fibers into polymer matrices, significant improvements in tensile strength, flexural strength, and impact resistance were observed. The findings suggest that bamboo fiber composites are a viable alternative to conventional materials in various engineering applications.

Brown, A. [41] focused on the production and characterization of bamboo-based bio composites. Various fabrication techniques, including hot pressing and extrusion, were utilized to create composite panels. The mechanical properties, thermal stability, and water absorption behavior of the bio composites were evaluated, demonstrating their potential for sustainable material applications.

Johnson, M. [42] presented a comparative study of the mechanical properties and environmental impacts of bamboo-based and wood-based particleboards. Bamboo particleboards exhibited superior flexural strength and dimensional stability compared to conventional wood particleboards. Additionally, the life cycle assessment highlighted the eco-friendly nature of bamboo as a raw material.

Wang, L. [43] explored the development of eco-friendly composite panels using bamboo fibers and recycled polymers for construction applications. The mechanical properties, such as compressive strength and modulus of elasticity, were tested, revealing that bamboo composite panels can serve as a sustainable alternative to traditional building materials.

Lee, K. [44] examined the mechanical and durability properties of bamboo fiber reinforced cement composites. The inclusion of bamboo fibers enhanced the compressive and flexural strengths of the cementitious materials. Durability tests indicated improved

resistance to cracking and water penetration, suggesting their suitability for construction purposes.

Patel, R. [45] investigated the mechanical performance of bamboo mat boards in comparison to medium-density fiberboard (MDF). The results showed that bamboo mat boards possess higher bending strength and impact resistance than MDF, making them a potential alternative for furniture and interior applications.

Kim, D. [46] focused on the development and mechanical testing of bamboo-based sandwich composites for structural applications. The composites were fabricated using bamboo cores and polymer facings. The results demonstrated excellent load-bearing capacity and energy absorption characteristics, highlighting their potential for use in structural components.

Singh, S. [47] explored the thermal and mechanical properties of bamboo fiber reinforced biodegradable composites. The composites were prepared using biodegradable polymer matrices and bamboo fibers. The findings indicated that the composites exhibited good thermal stability and mechanical performance, making them suitable for sustainable product development.

Zhang, T. [48] investigated the potential of bamboo composite materials for automotive applications. The study evaluated the mechanical properties, such as tensile strength and impact resistance, of bamboo fiber reinforced composites. The results suggest that bamboo composites can reduce vehicle weight and improve fuel efficiency while maintaining structural integrity.

Chen, H. [49] evaluated the acoustic insulation properties of bamboo-based composites. Different composite formulations were tested for sound absorption and transmission loss. The results showed that bamboo composites offer effective acoustic insulation, making them suitable for use in building and automotive applications.

Adams, R. [50] assessed the mechanical properties and environmental benefits of bamboo composites. The composites were tested for tensile, flexural, and impact strengths, showing comparable or superior performance to conventional materials. The

environmental analysis highlighted the lower carbon footprint of bamboo composites, emphasizing their sustainability.

Clark, P. [51] explored the use of bamboo fiber reinforced composite panels in furniture manufacturing. The mechanical properties, such as bending strength and surface hardness, were evaluated, demonstrating that bamboo composites are a viable alternative to MDF and particleboard in furniture production.

Davies, L. [52] focused on the fabrication and testing of bamboo fiber reinforced thermoplastic composites. The composites were produced using various thermoplastic matrices and bamboo fibers. Mechanical testing revealed enhanced tensile and impact properties, indicating their potential for diverse applications.

Evans, G. [53] investigated the potential of bamboo-based composite materials for sustainable packaging solutions. The mechanical properties, biodegradability, and moisture resistance of the composites were assessed. The results suggest that bamboo composites can provide environmentally friendly alternatives to conventional packaging materials.

Foster, J. [54] analyzed the mechanical performance of bamboo fiber reinforced epoxy composites. The composites were subjected to tensile, flexural, and impact tests, showing significant improvements in strength and toughness. The findings indicate the suitability of these composites for high-performance applications.

Garcia, S. [55] explored the development of bamboo-based hybrid composites by combining bamboo fibers with other natural fibers. The mechanical properties, such as tensile and flexural strengths, were evaluated, revealing synergistic effects that enhance the overall performance of the composites.

Harris, D. [56] evaluated the use of bamboo composite materials in sports equipment. The mechanical properties, durability, and weight of the bamboo composites were tested, demonstrating their potential for use in sporting goods such as skateboards and bicycles.

CHAPTER 2

MATERIALS AND METHODS

In this study, two different open molding processes were used to produce eight distinct types of bamboo-based sandwich composites. These composites were developed with the aim of exploring the potential of bamboo as a core material in sandwich structures, and to investigate their mechanical properties, including compression strength, indentation resistance, and thermal conductivity.

Bamboo, specifically the species *Arundo Donax*, was chosen due to its availability and natural characteristics, making it a suitable candidate for composite materials. Bamboo sticks were procured from a local supplier in Develi, Kayseri, and were prepared to ensure consistency in size and shape. Different combinations of adhesives and core treatments were employed, varying the state of the bamboo (hollow or filled) and the type of adhesive used, to evaluate the impact of these parameters on the final properties of the composites.

The manufacturing process involved the use of two custom-designed molds to shape and compress the bamboo-based materials. The first mold (Mold-1) was used to produce seven types of composites, while the second mold (Mold-2) was utilized for producing one type of composite filled with polyurethane foam. After molding, the composite materials were further processed and prepared for mechanical testing.

This section outlines the materials used in the composite production, the preparation of the molds, and the detailed methodologies applied during the manufacturing process. It also describes the testing procedures employed to evaluate the mechanical and thermal properties of the bamboo-based composites, including compression testing, indentation testing, thermal conductivity, and specific weight measurements.

2.1. Materials

Bamboo sticks were procured from a company in Develi, KAYSERİ. The type of bamboo is called Arundo Donax. In Turkish it's also called bamboo and kargı.



Figure 18. Arundo Donax plant [57].



Figure 19. Bamboo sticks cut into 100 mm lengths.



Figure 20. Bamboo cut by a band saw.

The thickness of the bamboo sticks is different from each other. With the help of a caliper, bamboo sticks with a thickness of 7,5 mm were selected. As the different thicknesses of the sticks could affect the results, the bamboo sticks closest in size were chosen. Consequently, bamboo sticks of 100 mm in length and $7.5 \text{ mm} \pm 1 \text{ mm}$ in thickness were obtained.



Figure 21. Measurement of bamboo diameters with caliper gauge.

2.1.1 Mold Preparation

Molds were used to ensure the regular bonding of the natural bamboo sticks prepared. Seven different composites were produced using Mold-1, and one different composite was produced using Mold-2.

2.1.1.1 Mold-1

It is designed with dimensions of 100x100x250 mm. The top and two side parts are open. Hinges are used for the closed side parts to be opened and closed easily. The mold is designed to facilitate the arrangement of bamboo sticks, the pouring of adhesive, compression, and easy removal from the mold after drying.



Figure 22. Mold-1.

2.1.1.2 Mold-2

It is produced with dimensions of 100x100x230 mm and includes an 8 mm expansion hole at the bottom. After placing the bamboo sticks inside the mold, polyurethane foam is injected into the mold. The foam is compressed using the top cover, ensuring that it fills the interiors of the bamboo sticks.



Figure 23. Mold-2.

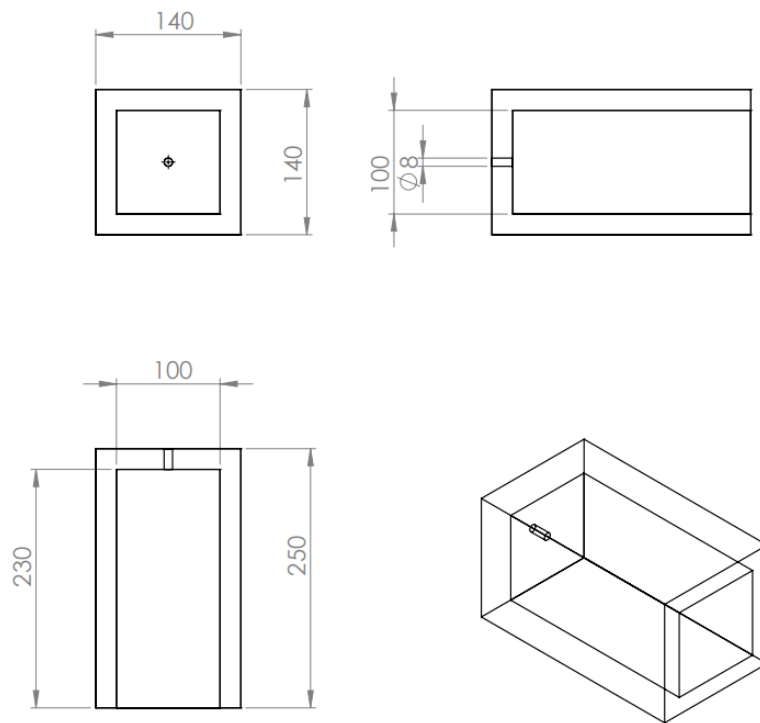


Figure 24. Technical drawing for Mold-2.

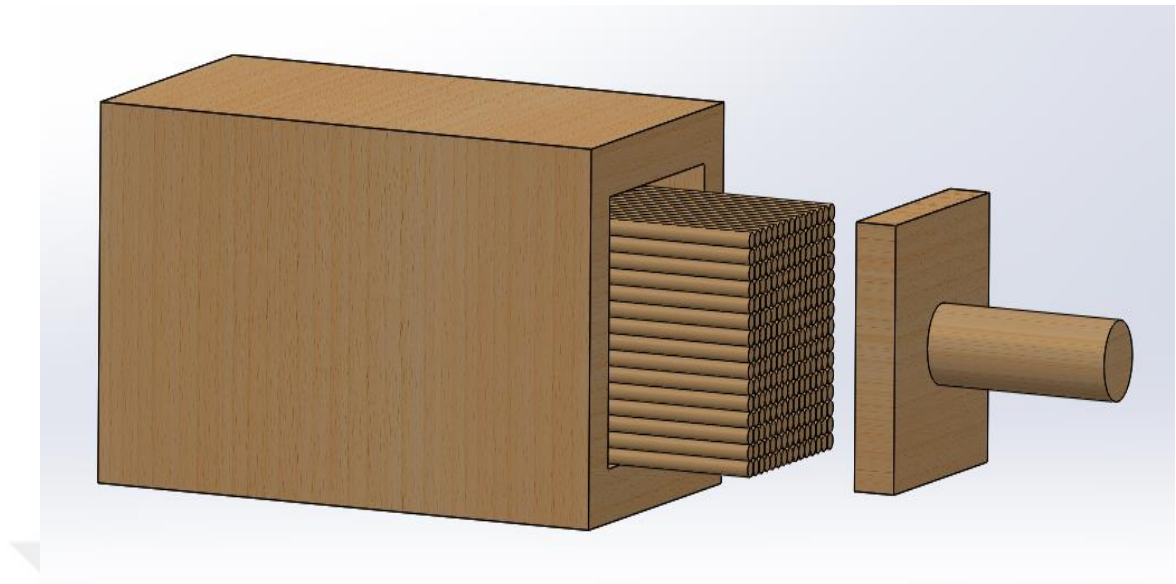


Figure 25. Mold-2 and Bamboo sticks.

2.2. Methods

These strength-increasing, eight types of bamboo-based natural composite materials were produced using two different molds with stacking methods. Workflow is presented in the following chart. While the size and lining parameters of bamboo sticks were kept constant, the type of adhesive and the state of the bamboo (whether hollow or filled) were varied. After being removed from the mold, the material was cut into 12 mm thick strips using a band saw. HDF sheets of 3 mm thickness were glued to the top and bottom of these strips. The resulting sandwich composites were tested for compression strength, indentation strength, and thermal conductivity in laboratory conditions.

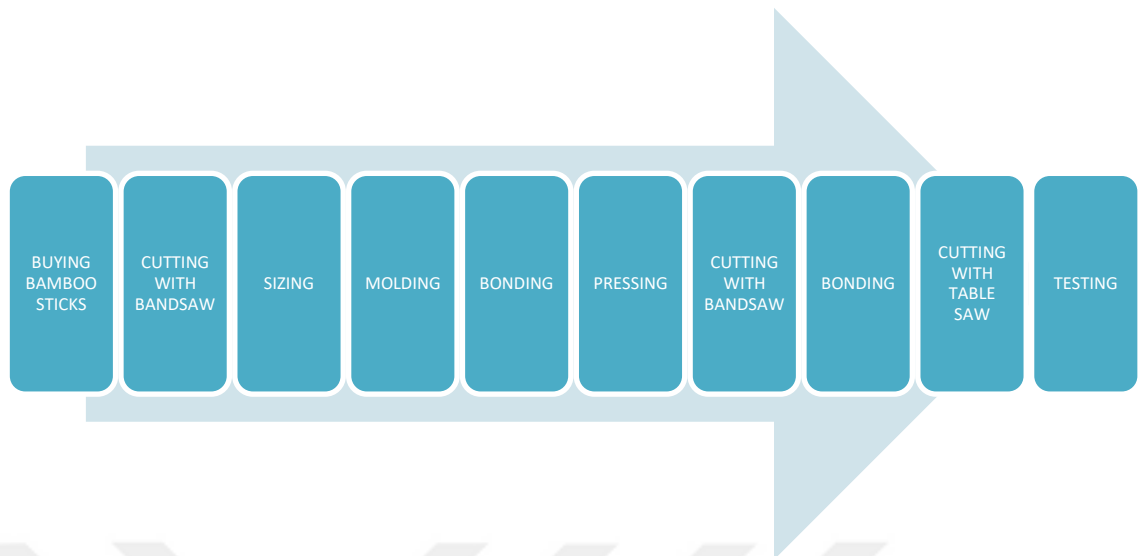


Figure 26. Bamboo Composite Manufacture Process and Workflow.

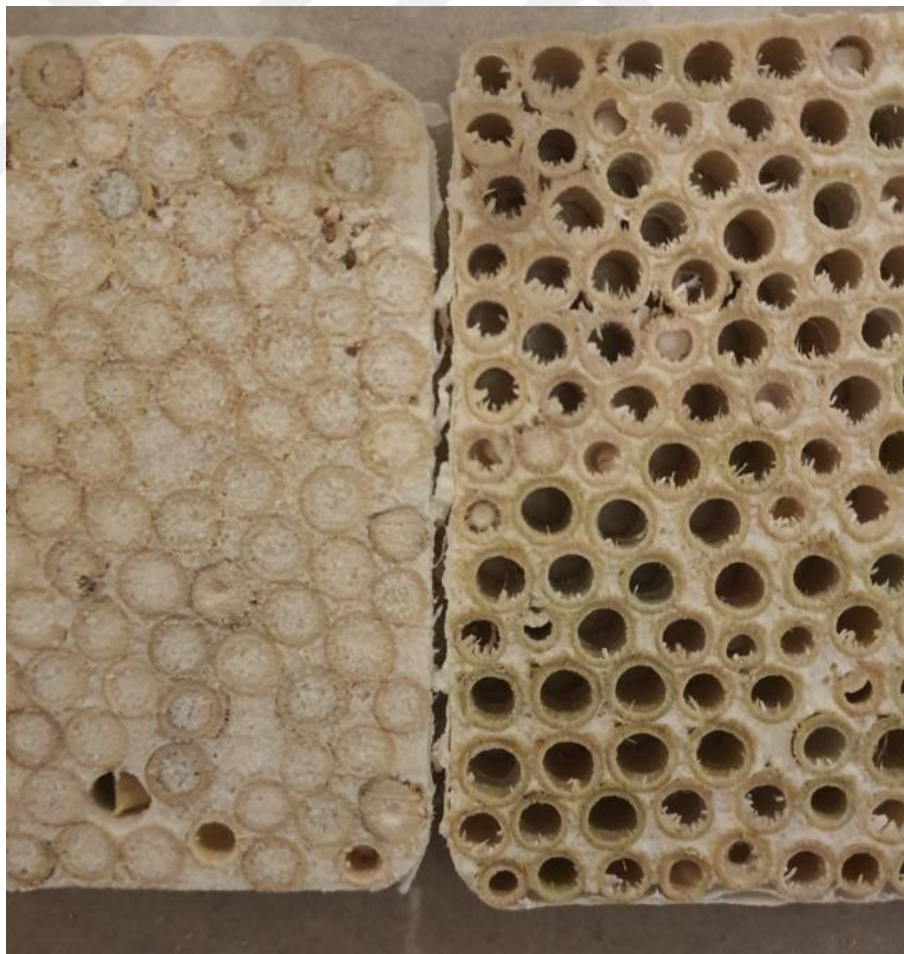


Figure 27. Filled (left) and hollow (right) bamboo core.

2.2.1 Bamboo Based Composites

There are 8 type of bamboo based composite material and in this part these composites are explained in detail.

2.2.1.1 Composite-1 Prepared with D4 Marine Adhesive (D4+F)

In this composite material, bamboo sticks and hardboard were bonded together with an D4 pur marine adhesive. The inside of the bamboo sticks was left empty. First, bamboos with a diameter of 7.5 mm and a length of 100 mm were arranged in Mold-1 in a single row. Enough amount D4 pur marine adhesive was added to the bamboo sticks. The process was repeated until the mold reached a height of 100 mm. Then the mold was compressed and left to dry. D4 pur marine adhesive expands and cures in about 2 hours. It completes its final cure within 24 hours. The dried materials were sliced into 12 mm thick pieces using a band saw. The insides of the bamboo sticks in the obtained 12 mm thick material were left empty. The 3 mm thick HDF was cut to 100 mm x 100 mm dimensions using a table saw.



Figure 28. Mold-1.

Mold-1 Used to bond bamboo sticks together in a specific arrangement. Products measuring 100 mm x 100 mm x 100 mm were obtained.



Figure 29. Mold-1, sticks are lined in a row.

The bamboo sticks are arranged in the mold, and enough adhesive is added. Once the mold is filled, it is compressed, and the adhesive is left to dry. After the adhesive has dried, products measuring 100 mm x 100 mm x 100 mm are prepared. These products are then cut with a band saw into 12 mm thick pieces.



Figure 30. Mold-1 compressed bamboo sticks.



Figure 31. Material was cut by bandsaw into 12 mm thick strips.



Figure 32. 12 mm thick strips.

In this thesis, composite materials were prepared using natural bamboo sticks. In all composites, the bamboo sticks and their arrangement parameters are the same. Only the adhesives and whether the bamboo sticks insides were filled, or hollow were changed as parameters.



Figure 33. Hardboard 100x100 cutting with table saw machine.

The prepared plates were bonded to both sides of the 12 mm thick material with D4 pur marine adhesive. A total of 8 samples were prepared using the same method. A weight of 5 kg was placed on the samples to maintain their shape. The weight prevented the material from deforming during the adhesive curing process. The excess adhesive overflowing from the edges of the prepared sandwich composite material was removed by cutting the edges. Each edge was trimmed by 5 mm with a table saw.



Figure 34. Each edge is shortened by 5 mm.

Thus, sandwich composite materials measuring 90 mm x 90 mm x 18 mm were prepared.

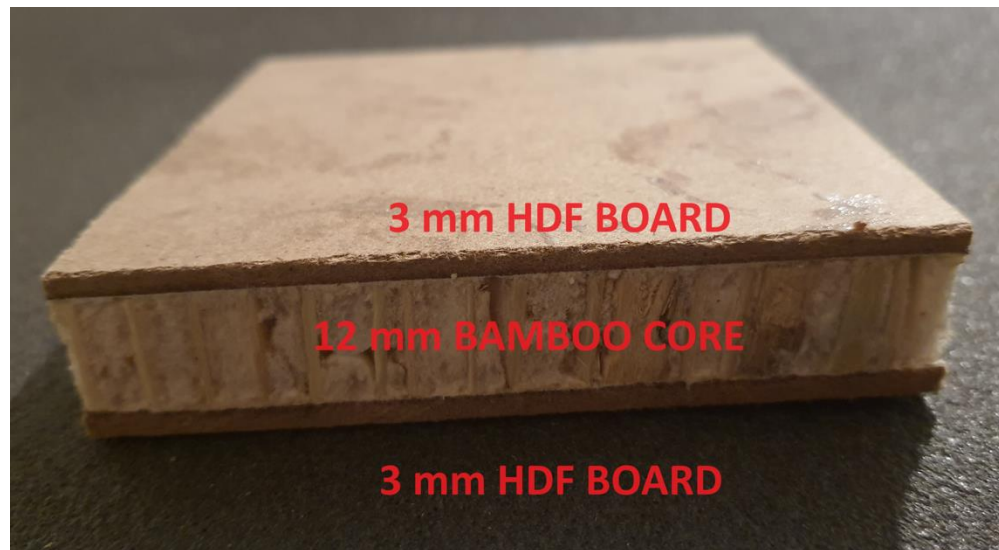


Figure 35. Bamboo based composite side sectional view.

2.2.1.2 Composite-2 Prepared with D4 Marine Adhesive (D4+H)

In this composite material, bamboo sticks and HDF were bonded together with D4 pur marine adhesive. The inside of the bamboo sticks was left hollow.

2.2.1.3 Composite-3 Prepared with Polyurethane Foam (PU+F)

In this composite material, bamboo sticks and hardboard were bonded together with D4 pur marine adhesive. The inside of the bamboo sticks was filled with polyurethane foam.

Mold-2 was used only to produce composite-3 (PU+F). Polyurethane foam was injected into the bamboo sticks using this mold.

The bamboo sticks are arranged in the mold, and enough polyurethane foam is added. Once the mold is filled, it is compressed, and the foam is left to dry. After the foam has dried, products measuring 100 mm x 100 mm x 100 mm are prepared. These products are then cut with a band saw into 12 mm thick pieces.

2.2.1.4 Composite-4 Prepared with Polyurethane Foam (PU+H)

In this composite material, bamboo sticks and hardboard were bonded together with foamed polyurethane. The inside of the bamboo sticks was hollow.

2.2.1.5 Composite-5 Prepared with D3 Wood Adhesive (D3+F)

In this composite material, bamboo sticks and HDF were bonded together with D3 MDF profile adhesive. The inside of the bamboo sticks was filled.

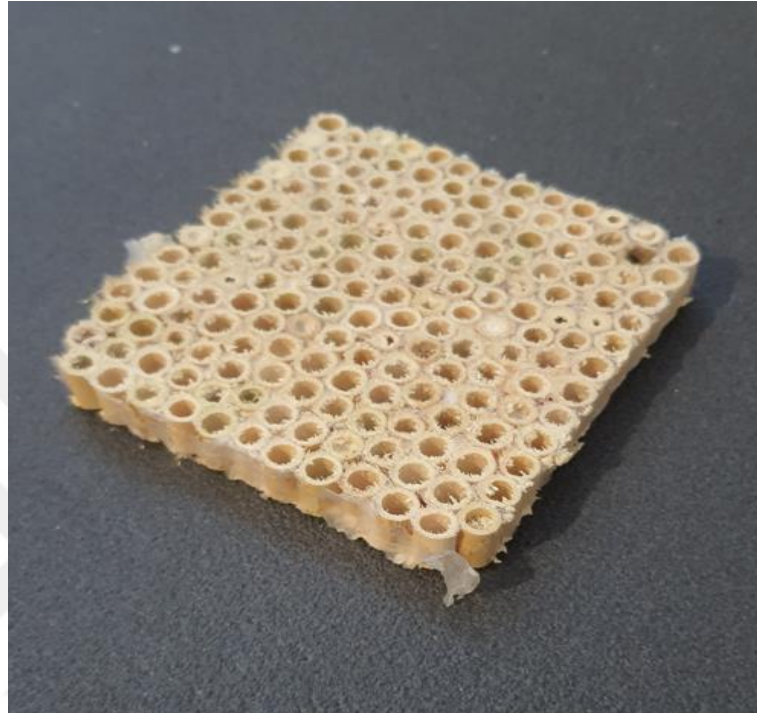


Figure 36. 12 mm thick bamboo core.

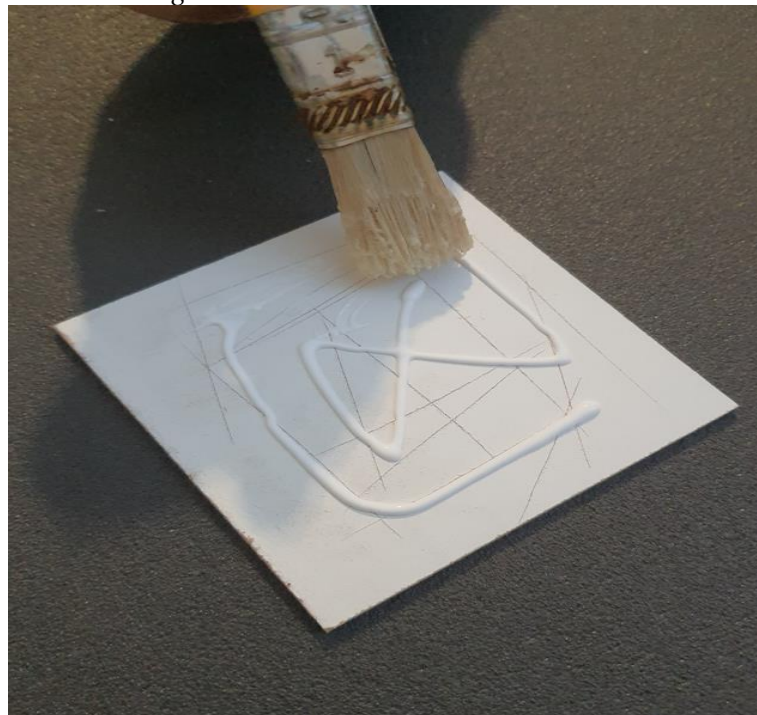


Figure 37. Pasting on HDF layer with D3 adhesive.

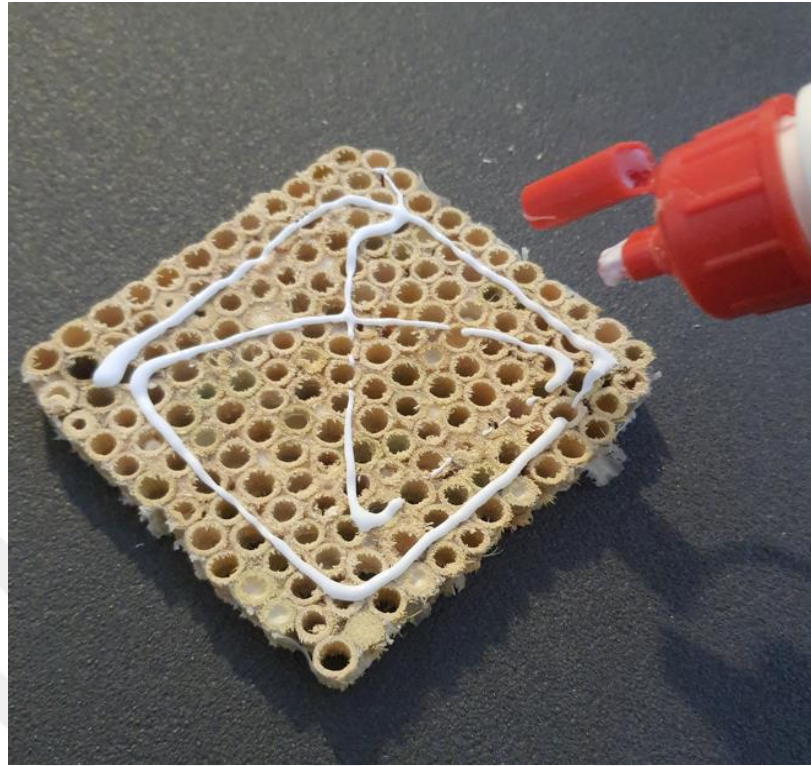


Figure 38. Pouring adhesive on the bamboo core.

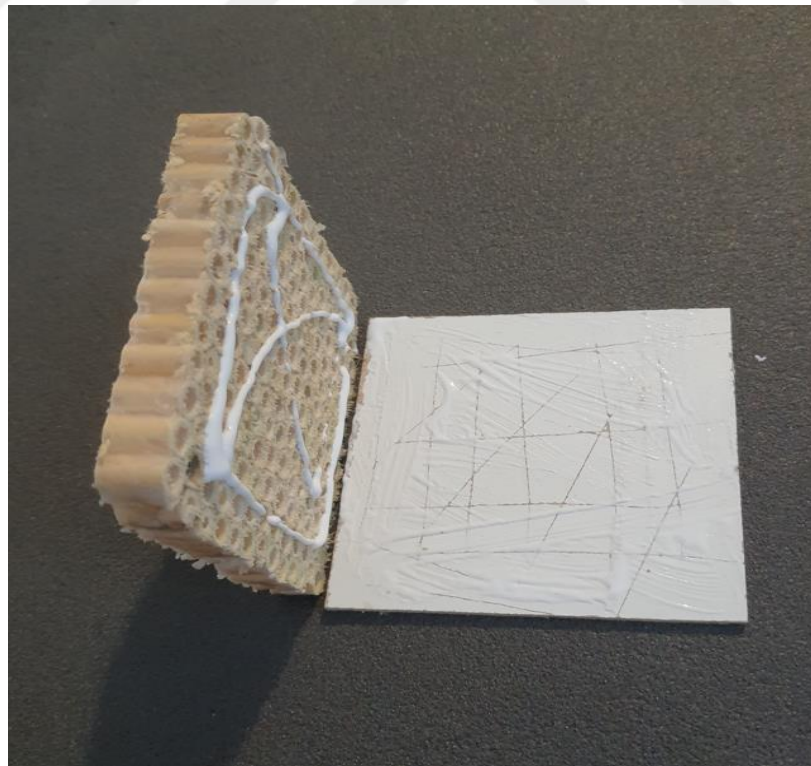


Figure 39. Bamboo core and HDF layer.

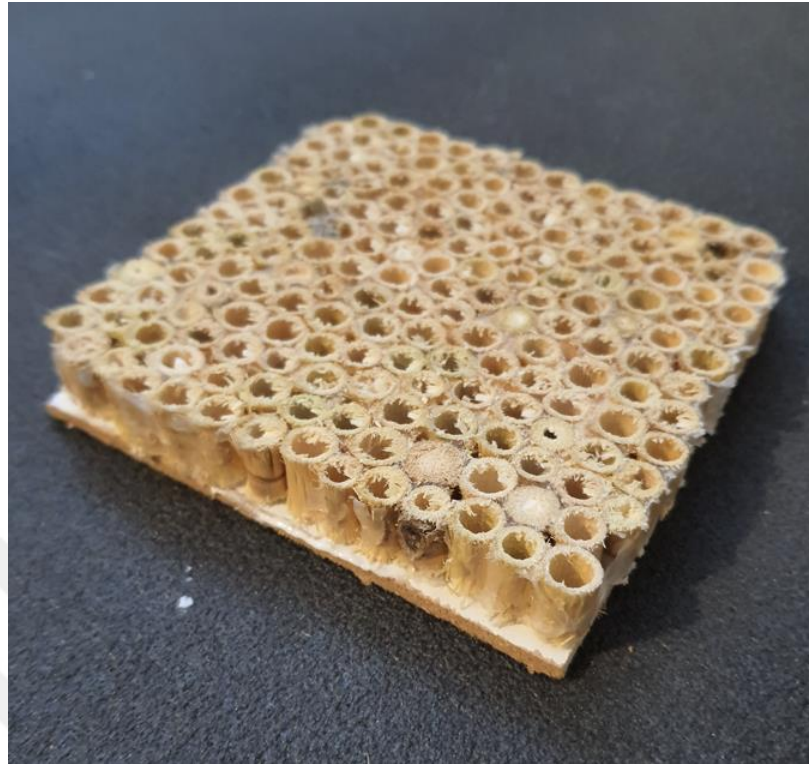


Figure 40. Bamboo core and bottom HDF layer.

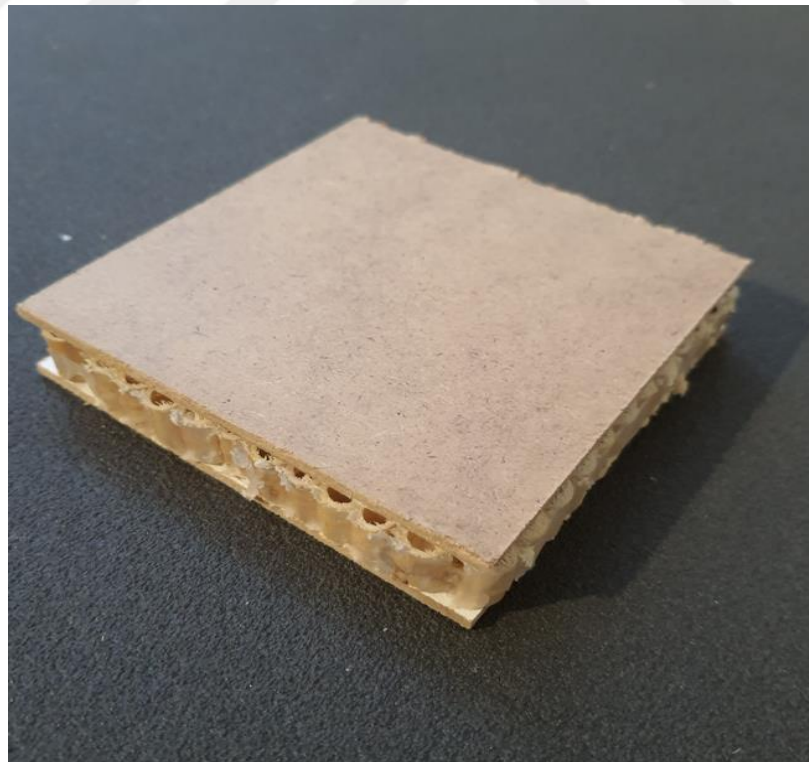


Figure 41. Bamboo core and top and bottom HDF layer.

2.2.1.6 Composite-6 Prepared with D3 Wood Adhesive (D3+H)

In this composite material, bamboo sticks and hardboard were bonded together with D3 MDF profile adhesive. The inside of the bamboo sticks was left hollow.

2.2.1.7 Composite-7 Prepared with D3 Wood Adhesive and saw dust mixture (D3+S+F)

In this composite material, bamboo sticks and hardboard were bonded together with a mixture of 95% D3 MDF profile adhesive and 5% sawdust by weight. The inside of the bamboo sticks was filled with the same adhesive mixture.

2.2.1.8 Composite-8 Prepared with D3 Wood Adhesive and saw dust (D3+S+H)

In this composite material, bamboo sticks and hardboard were bonded together with a mixture of 95% D3 MDF profile adhesive and 5% sawdust by weight. The inside of the bamboo sticks was left hollow.



Figure 42. Pouring adhesive to bamboo core.

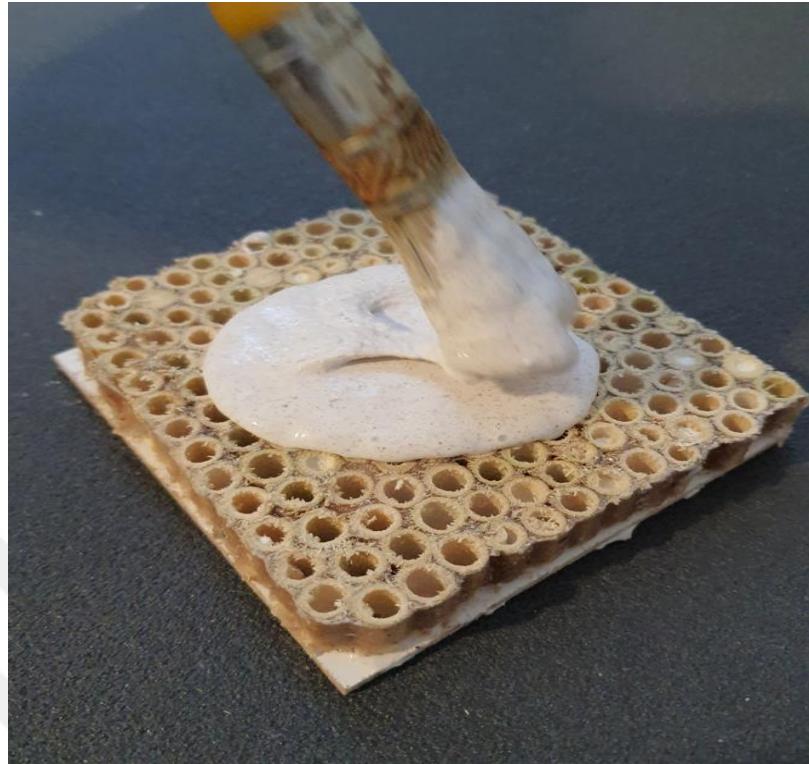


Figure 43. The filling of the bamboo core with D3+saw dust.



Figure 44. Bamboo core filled with d3+saw dust.

2.2.2 Particleboard

18 mm thick raw particleboard plates were cut to 90 mm x 90 mm dimensions using a table saw. Thus, samples of the same dimensions as the composite samples were prepared.

2.2.3 MDF (medium density fiberboard)

18 mm thick raw MDF plates were cut to 90 mm x 90 mm dimensions using a table saw. Thus, samples of the same dimensions as the composite samples were prepared.

2.2.4 Samples

A total of 40 samples were prepared for the compression test. Each sample was assigned a unique number, as detailed in the table below.

Table 1. Compression Test Sample Numbering and Descriptions.

<u>Sample Number</u>	<u>Material Explanation</u>	<u>Short Explanation</u>
1.1		
1.2	BAMBOO+D4 MARIN ADHESIVE+FILLED	D4+F
1.3		
1.4		
2.1		
2.2	BAMBOO+D4 MARIN ADHESIVE+HOLLOW	D4+H
2.3		
2.4		
3.1		
3.2	BAMBOO+POL YURETHANE+FILLED	PU+F
3.3		
3.4		
4.1		
4.2	BAMBOO+POLYURETHANE+HOLLOW	PU+H
4.3		
4.4		
5.1		
5.2	BAMBOO+MDF D3 ADHESIVE+FILLED	D3+F
5.3		
5.4		
6.1		
6.2	BAMBOO+MDF D3 ADHESIVE+HOLLOW	D3+H
6.3		
6.4		
7.1		
7.2	BAMBOO+%95 D3 MDF ADHESIVE+%5 SAW DUST +FILLED	D3+S+F
7.3		
7.4		
8.1		
8.2	BAMBOO+%95 D3 MDF ADHESIVE+%5 SAW DUST +HOLLOW	D3+S+H
8.3		
8.4		
9.1		
9.2	PARTICLEBOARD	PB
9.3		
9.4		
10.1		
10.2	MEDIUM DENSITY FIBERBOARD	MDF
10.3		
10.4		

2.3. Mechanical Testing Methods

2.3.1 Compression Test

Samples of 40 mm x 40 mm dimensions were cut with the band saw. Compression tests were conducted using a Shimadzu, AG-X 50kN testing machine (see figure 45) with these samples (Figure 47). The compression speed was 2 mm/min. After the force reached the top peak value, it dropped smoothly.



Figure 45. Compression testing machine (Brand: Shimadzu, AG-X 50kN).

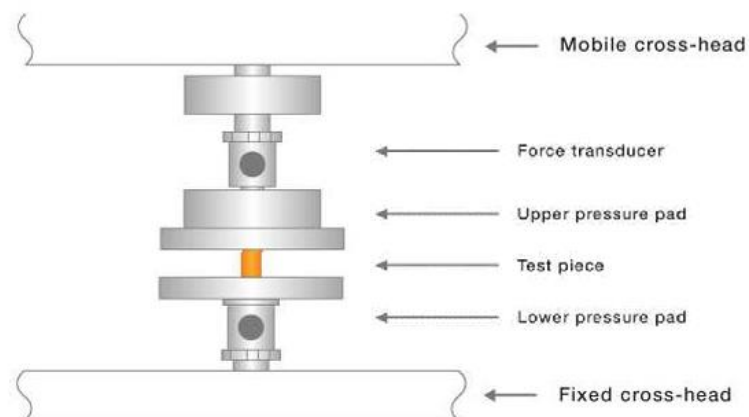


Figure 46. Components of compression test machine.

The compressive stress, in the metric system, is usually measured in N/m² or Pa, such that 1 N/m² = 1 Pa. From the experiment, the value of stress is calculated by dividing the amount of force (P) applied by the machine in the axial direction by its cross-sectional area (A₀), which is measured prior to running the experiment. Mathematically, it is expressed in Equation.

$$\sigma = \frac{P}{A_0}$$

Percentage elongation (shortening) is the highest plastic elongation percentage value. If the sample subjected to the compression test is broken, the final length (L) can be measured after fitting together the broken parts of the sample. Then percentage elongation is calculated by Equation.

$$\% \text{ Elongation} = \frac{L - L_0}{L_0}$$



Figure 47. Compression test samples.

2.3.2. Indentation Test

Indentation test was conducted using a Shimadzu, AG-X 50kN testing machine with samples of 90 mm x 90 mm. The test involved pressing a 20 mm diameter steel sphere into the composite material at a speed of 2 mm/min, and it was stopped after a 9 mm vertical displacement through the samples. The pictures were taken at the surface following the tests.

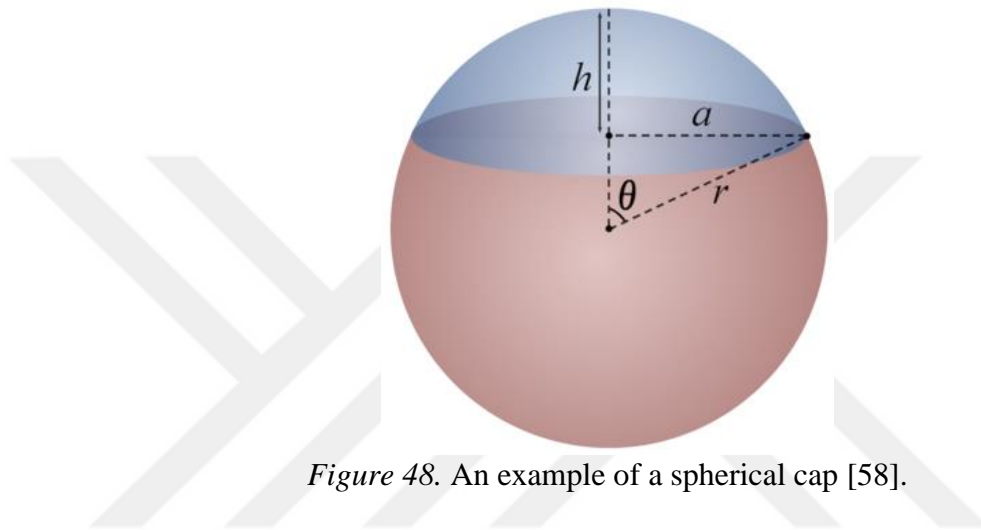


Figure 48. An example of a spherical cap [58].

Spherical cap surface area;

r : a sphere of radius

h : the height of the cap

The surface area of a whole sphere is:

$$A_{\text{sphere}} = 4\pi r^2$$

But we are interested in the area of a portion of the sphere, specifically the cap. To find this, we need to use a method of slicing the sphere and summing the areas of small segments.

Imagine slicing the sphere into thin horizontal rings (differential strips) parallel to the base of the spherical cap. These rings form latitudes on the surface of the sphere.

The radius of a ring at a latitude angle θ from the vertical axis of the sphere is $r \sin \theta$. This is the distance from the vertical axis to the edge of the ring.

The circumference of this ring is $2\pi(r\sin\theta)$.

$$S=2\cdot\pi\cdot r\cdot h$$

This function computes the surface area of a spherical cap. A spherical cap, also known as a spherical dome, is the portion of a sphere that lies above (or below) a given plane. It is a spherical segment with a single base, defined by the intersection of the sphere and the plane.

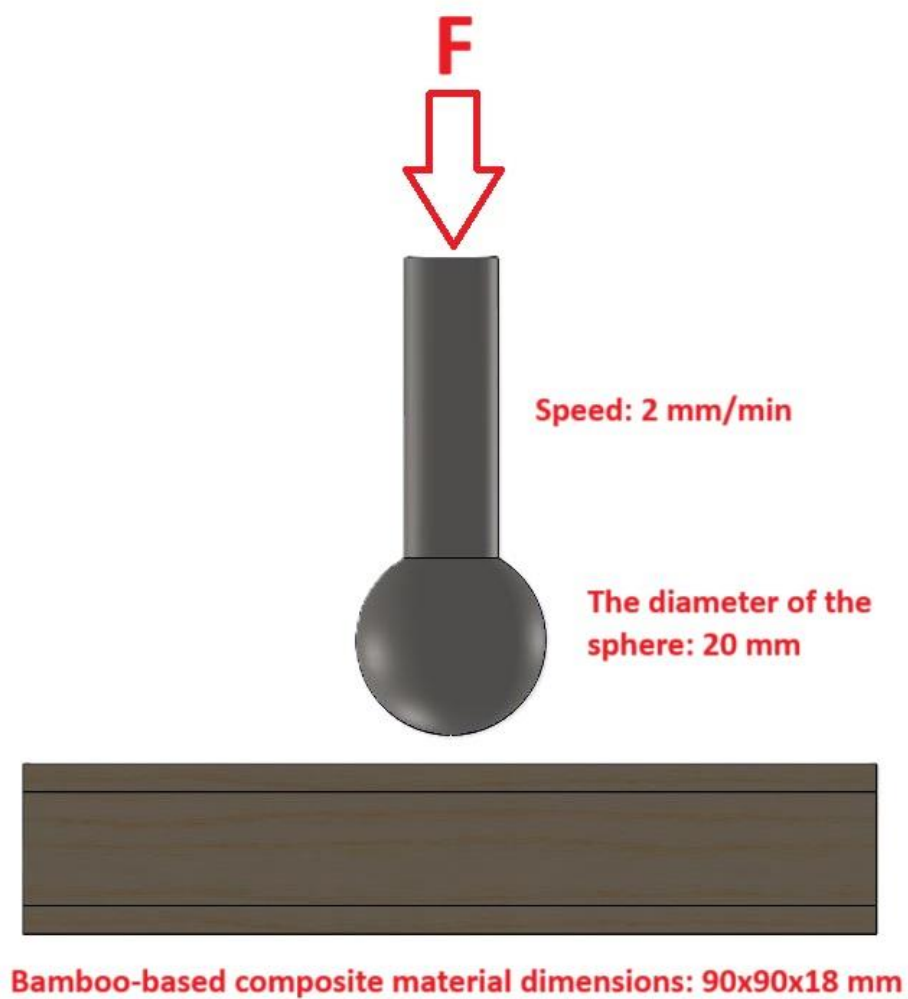


Figure 49. Indentation test schematic drawing.

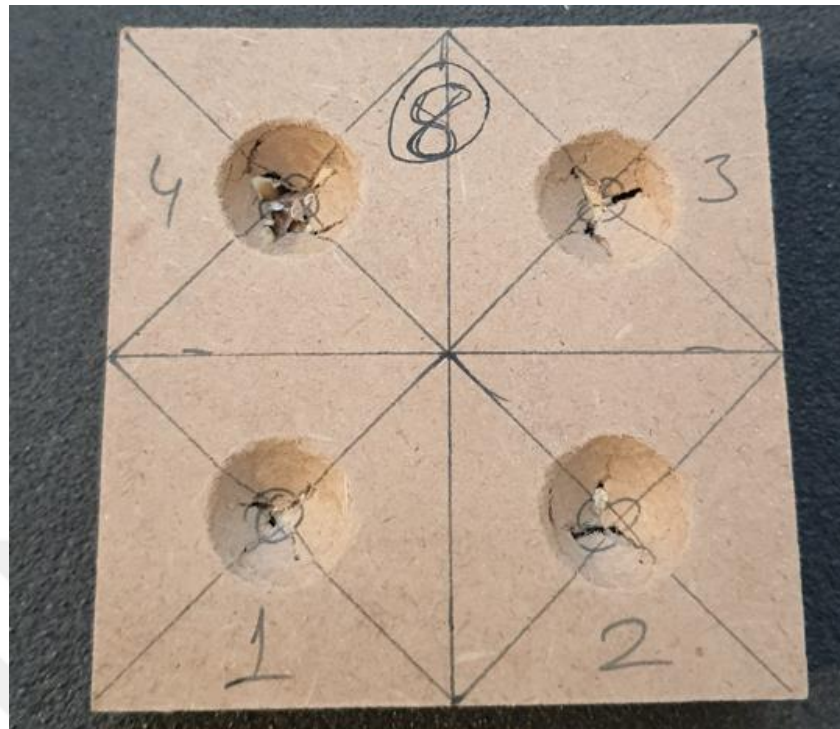


Figure 52. The surfaces of the composites after indentation test.

2.3.3. Thermal Conductivity Test

Thermal conductivity tests were conducted using a Thermtest HFM-100 machine (Figure 53). A minimum sample size of 150 mm x 150 mm was required for the test. Therefore, composite materials were enlarged by using a 20 mm thick EPS board, expanding from 90 mm x 90 mm to 150 mm x 150 mm in size.



Figure 53. Thermal conductivity test machine (Brand: ThermtestHFM-100).

2.3.4. Specific Weight Test

Specific weight calculations were made by using a Precisa LS 220A SCS scale (Figure 44) and a caliper with an accuracy of 0,05 mm and range of 0-150 mm.

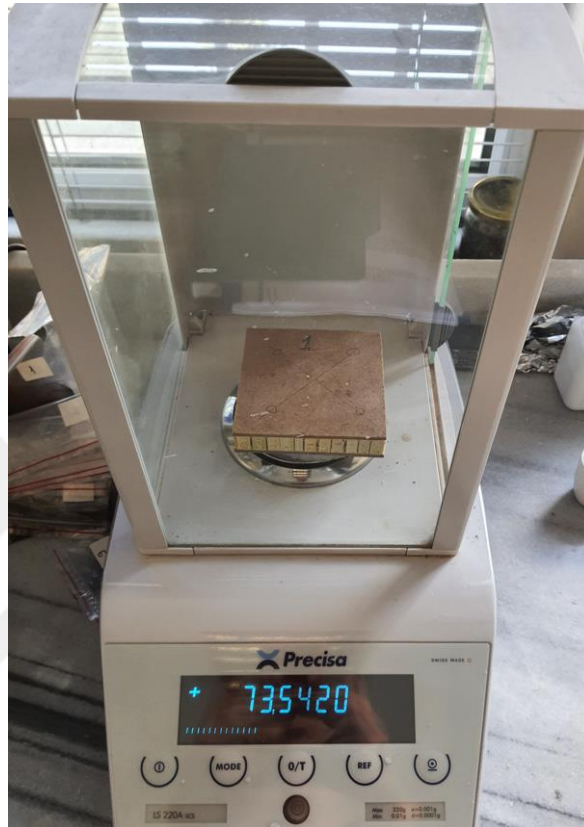


Figure 54. Scale used for specific weight calculation (Brand: Precisa LS 220A SCS).

CHAPTER 3

RESULTS

3.1 Research Model

This study was conducted using a quantitative research method. Compression, indentation, and thermal conductivity tests were applied to samples obtained from 8 different bamboo-based composite materials. Additionally, samples of the same dimensions were prepared from traditionally widespread particleboard and MDF, and the same tests were conducted on these samples.

3.2 Population and Sample

For the compression test, 4 samples with dimensions of 40x40x18 mm were tested. For the indentation test, 4 points equally spaced on a sample with dimensions of 90x90x18 mm were subjected to the indentation test. For the thermal conductivity test, the test samples with dimensions of 90x90x18 mm were extended to 150x150x18 mm by adhering them to an 18 mm thick EPS frame using polyurethane foam, according to the minimum sample size required by the device. More detailed information about the samples is provided in the materials section.

3.2.1 Compression Test Results

The D4+F composite had the highest compression strength (see table 2). The compressive strength of D4+F was 74%, 46%, and 19% higher than the compressive strengths of PU+F, D3+F, and D3+S+F, respectively. Hollow composites made with D3 adhesive and foamed polyurethane showed better results compared to filled ones.

Table 2. Compression test results (MPa).

COMPRESSION TEST (MPa)	FILLED	HOLLOW
D4	23.00	21.51
PU	11.83	17.17
D3	14.06	16.83
D3+S	17.24	20.74

As a result of the tests applied to four samples of D4+F composite with dimensions of 40 mm x 40 mm, the following stress-displacement graph was obtained (see figure 55). The average stress-displacement graph for the four samples is also shown below. The highest value of the average graph is 23 MPa. This test result indicates that the D4+F composite has better compressive strength compared to the D4+H composite and all other composite samples.

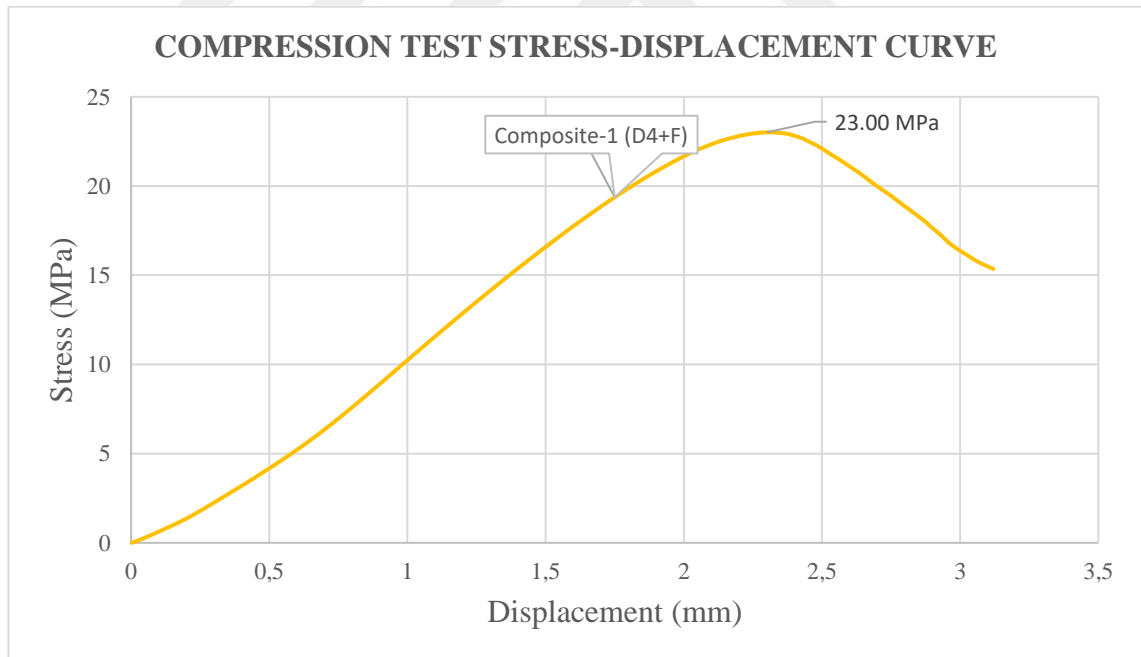


Figure 55. Composite-1 (D4+F) compression test average curve.

The average graph value obtained from the test results of the D4+H composite samples is as follows (see figure 56). According to this test result, D4+H has 6% lower compressive strength than D4+F. Therefore, in materials where D4 adhesive is used, a filled structure plays a role in enhancing compressive strength.

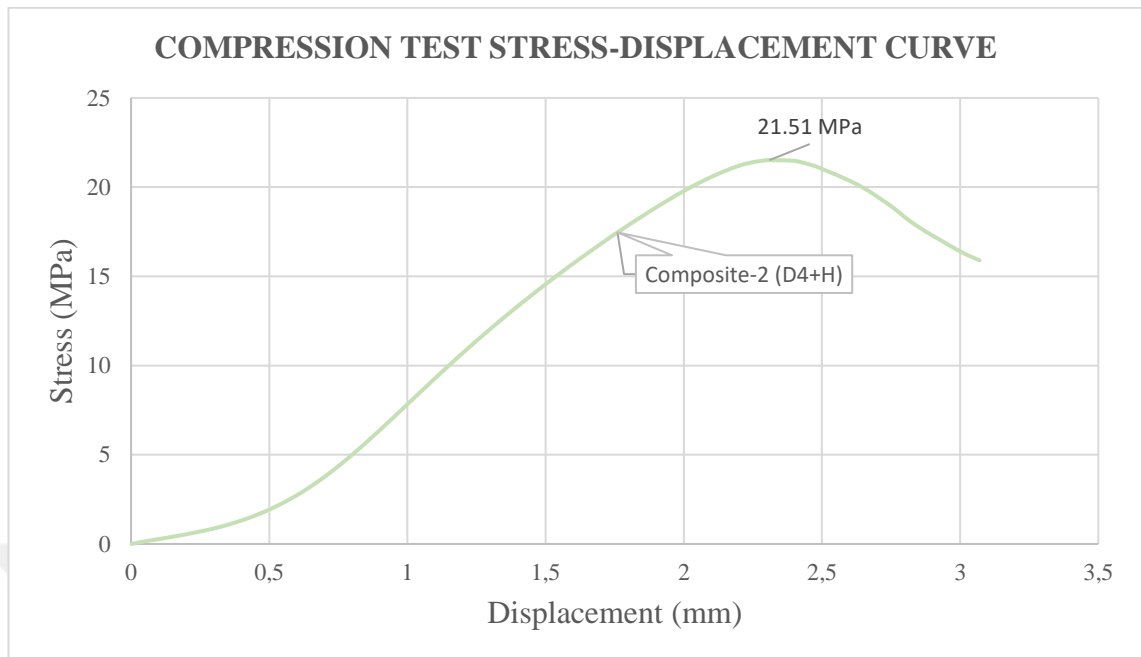


Figure 56. Composite-2 (D4+H) compression test average curve.

The stress-displacement graph for Composite-1 and Composite-2 (see figure 57) indicates that Composite-1, which is filled with D4 adhesive, exhibits higher values than Composite-2, which is left hollow.

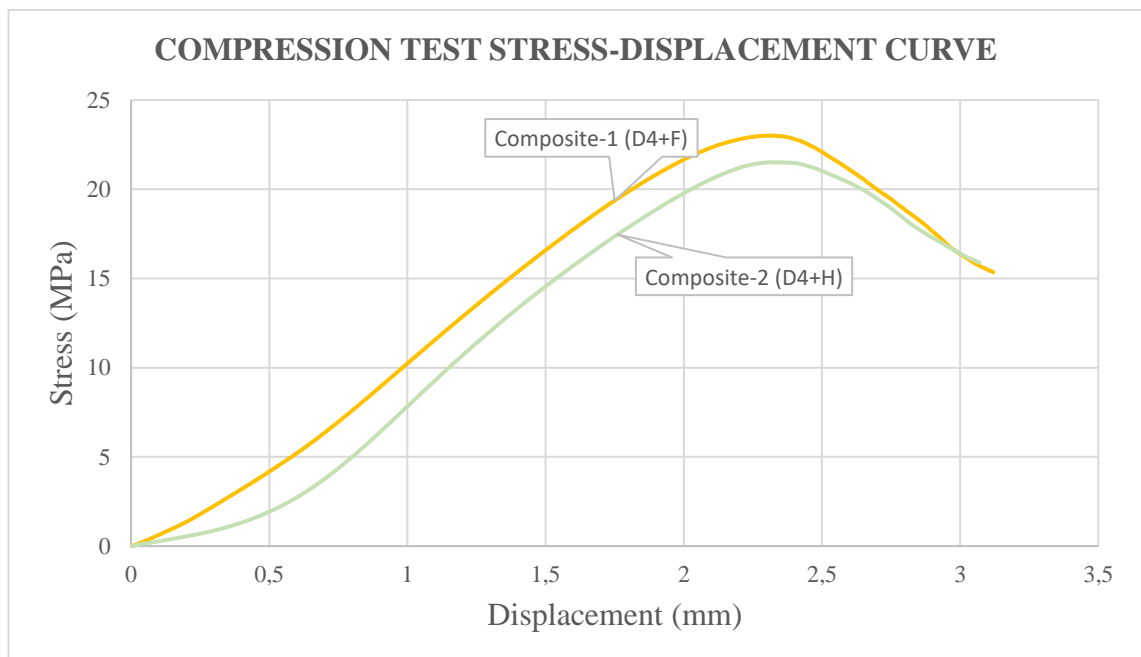


Figure 57. Compression test curves for Composite-1 and Composite-2.

The stress-displacement graph of the PU+F composite is shown below (see figure 58). The highest value of the average stress-displacement curve is 11.83 MPa. This test result shows that PU+F has the lowest compressive strength among the composite materials.

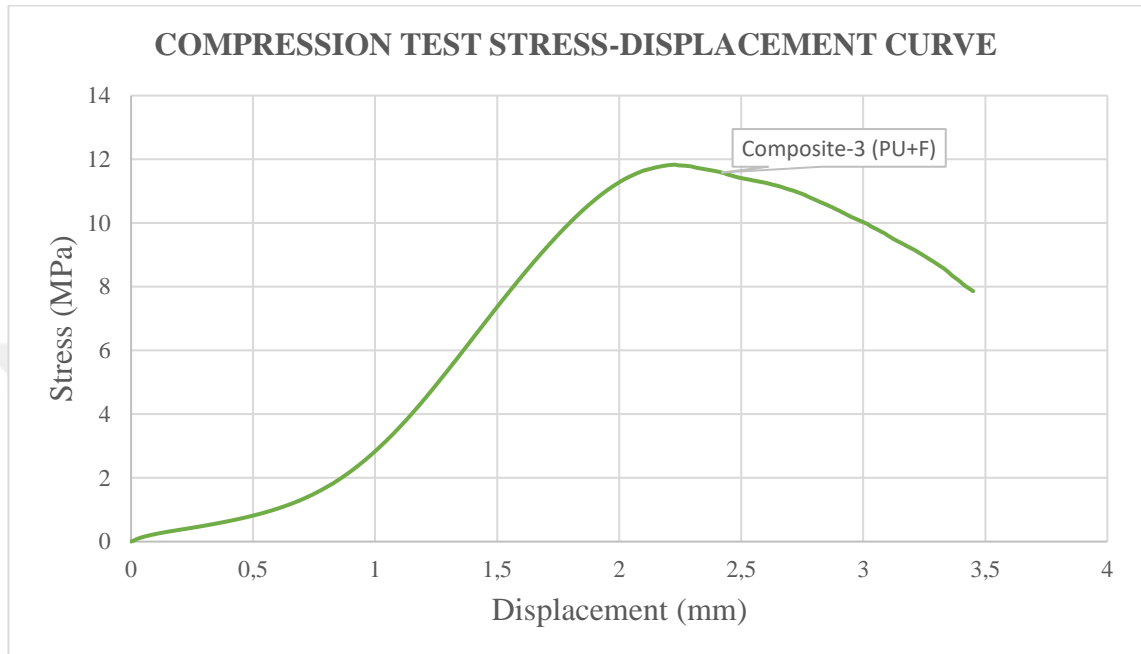


Figure 58. Composite-3 (PU+F) compression test average curve.

The average graph value obtained from the test results of the PU+H composite samples is as follows (see figure 59). According to this test result, PU+H has 45 % higher compressive strength than PU+F. Therefore, in materials where PU is used, a hollow internal structure increases compressive strength.

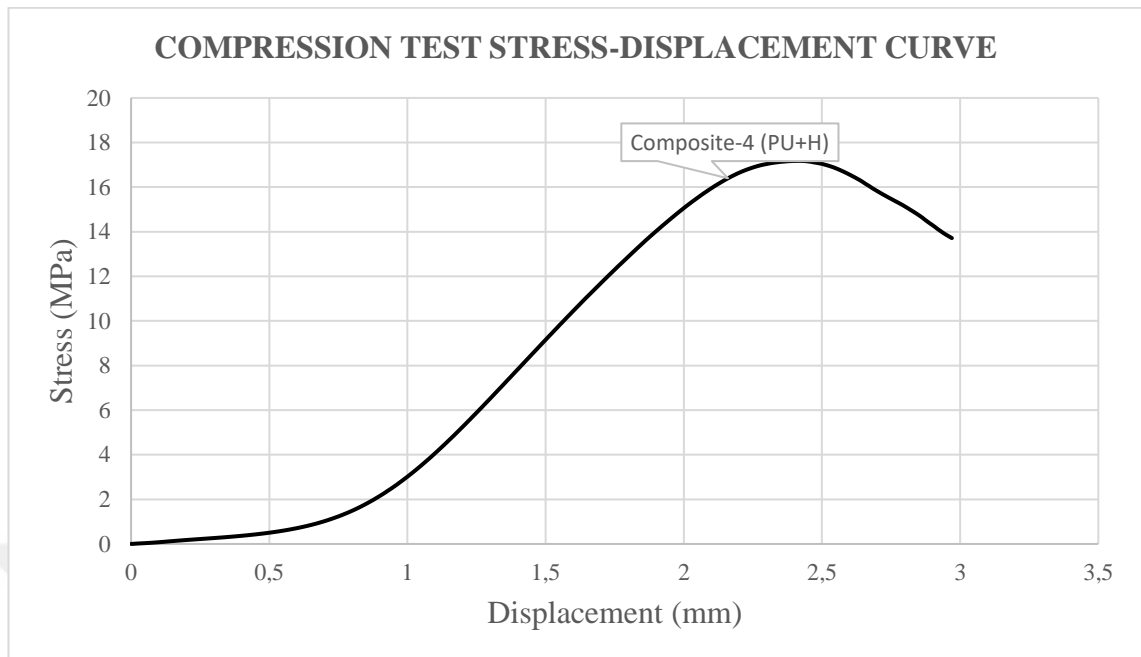


Figure 59. Composite-4 (PU+H) compression test average curve.

The stress-strain graph for Composite-3 and Composite-4 (see figure 60) indicates that Composite-4, which is left hollow, exhibits higher values than Composite-3, which is filled with PU.

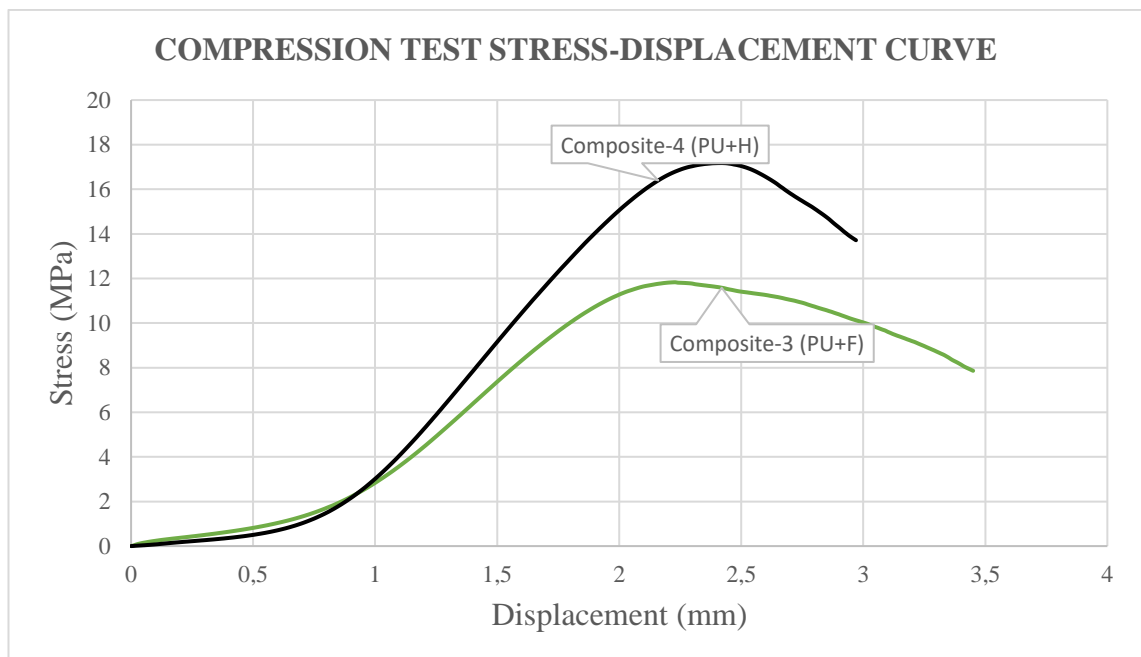


Figure 60. Compression test curves for Composite-3 and Composite-4.

The stress-displacement graph of the D3+F composite is shown below (see figure 61). The top value of the average stress-displacement curve is 14.06 MPa. This test result

shows that D3+F has better compressive strength than PU+F, but 46% lower compressive strength compared to D4+F.

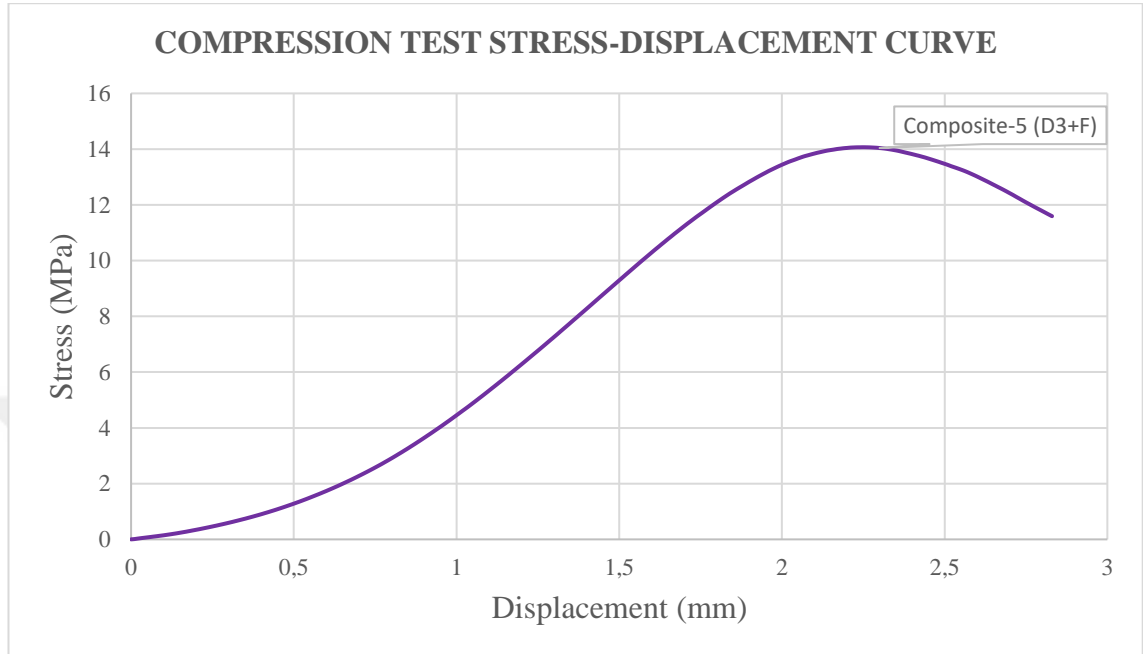


Figure 61. Composite-5 (D3+F) compression test average curve.

The average graph value obtained from the test results of the D3+H composite samples is as follows (see figure 62). According to this test result, D3+H has 20% higher compressive strength than D3+F. Therefore, in materials where D3 adhesive is used, a hollow internal structure enhances compressive strength.

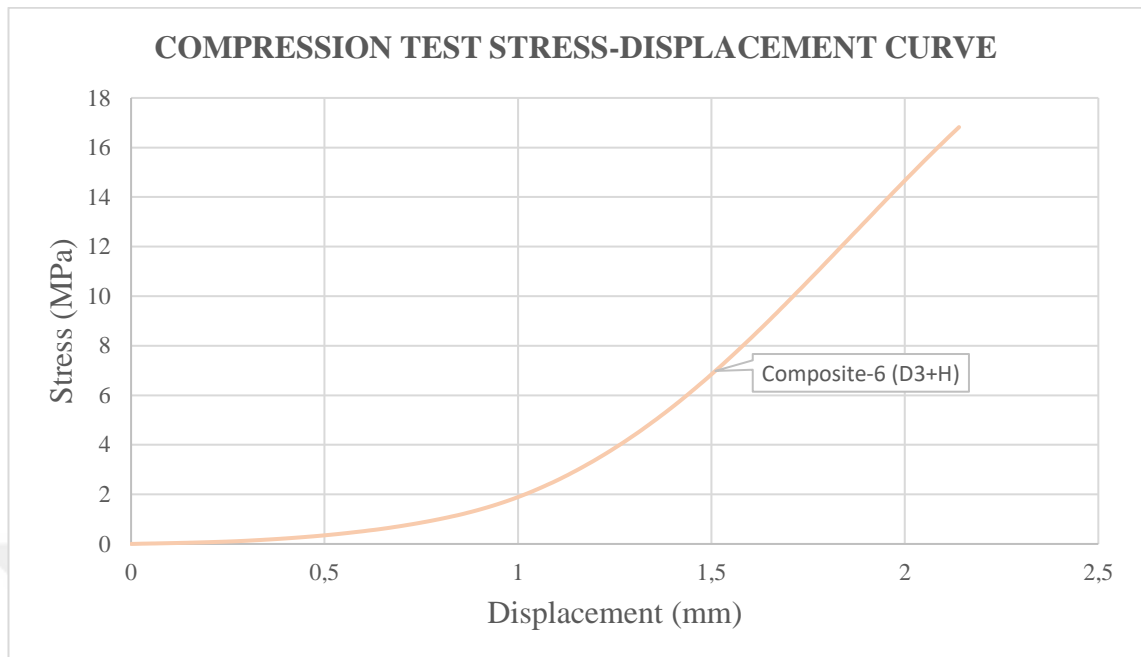


Figure 62. Composite-6 (D3+H) compression test average curve.

The stress-strain graph for Composite-5 and Composite-6 (see figure 63) indicates that Composite-6, which is left hollow, exhibits higher values than Composite-5, which is filled with D3 adhesive.

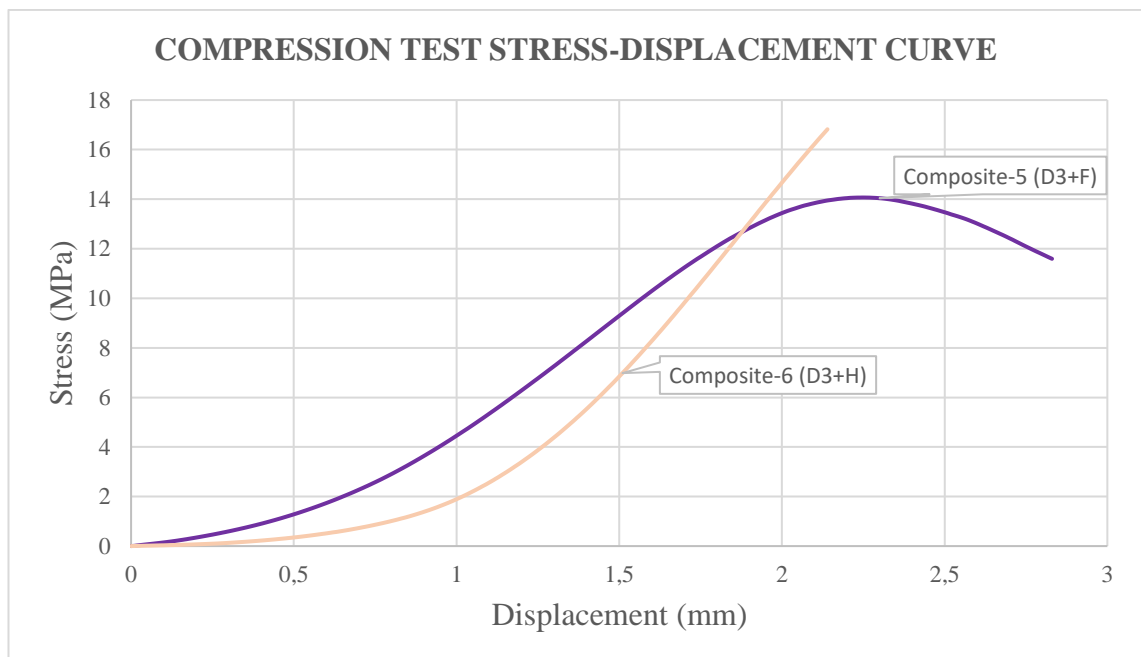


Figure 63. Compression test curves for Composite-5 and Composite-6.

The stress-displacement graph of the D3+S+F composite is shown below (see figure 64). The top value of the average stress-displacement curve is 17.24 MPa. This test result

indicates that D3+S+F has better compressive strength compared to D3+F. It was observed that the composite produced with an adhesive containing 5% by weight of sawdust mixed into the D3 adhesive has 23% better compressive strength.

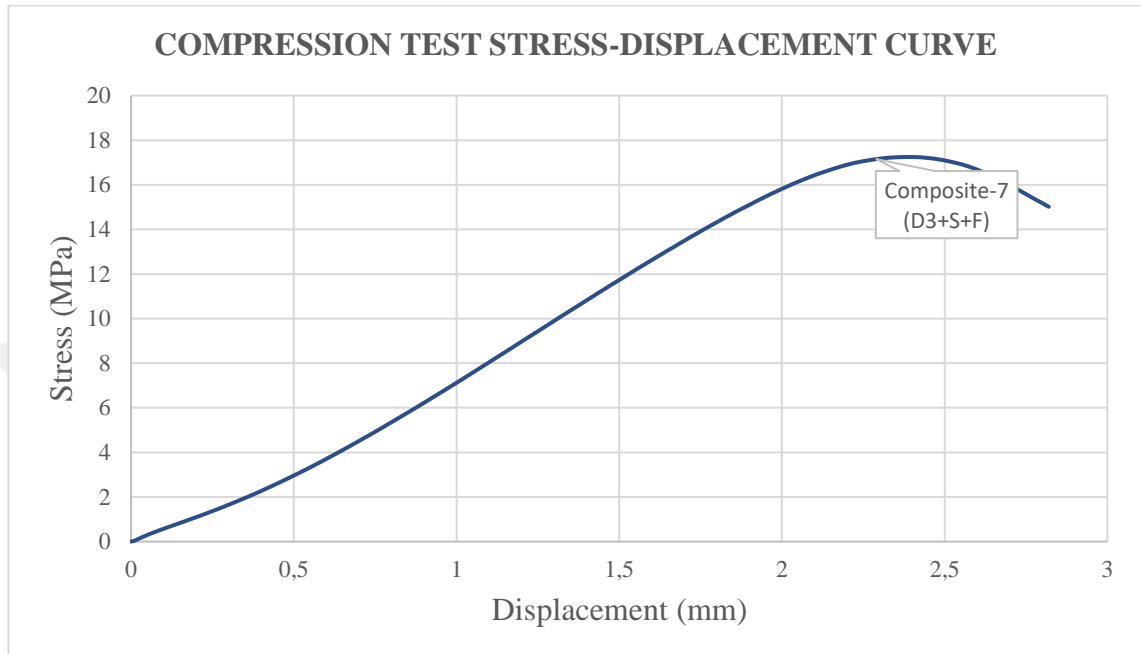


Figure 64. Composite-7 (D3+S+F) compression test average curve.

The average graph value obtained from the test results of the D3+S+H composite samples is as follows (see figure 65). According to this test result, D3+S+H has 20% higher compressive strength than D3+S+F. Therefore, in materials where D3+S is used, a hollow internal structure increases compressive strength.

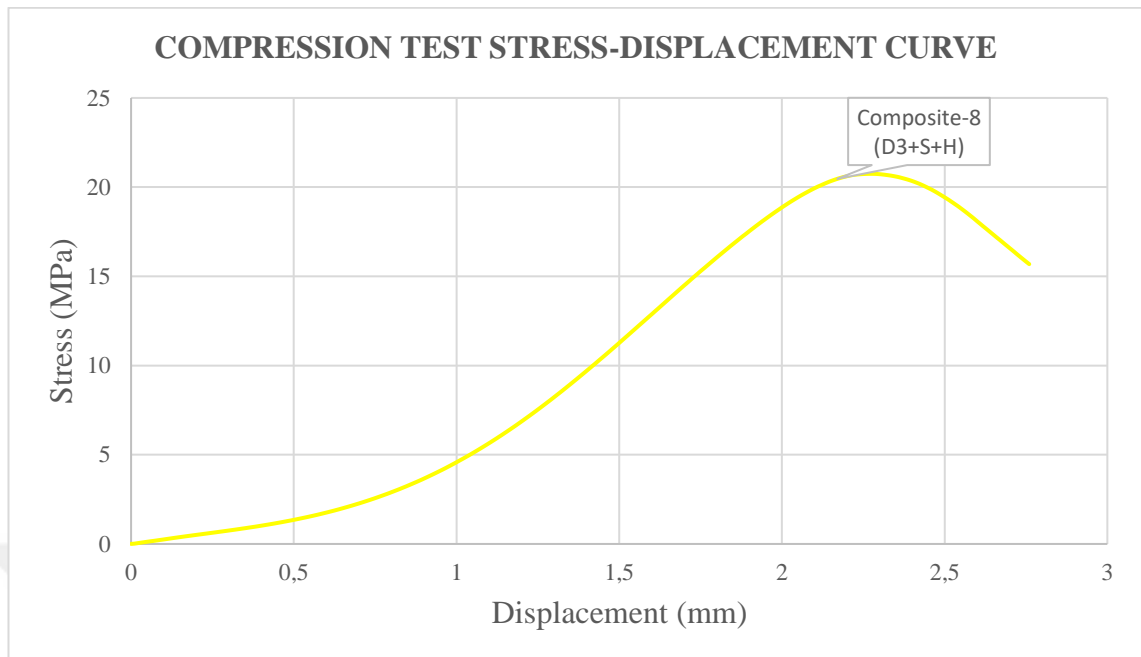


Figure 65. Composite-8 (D3+S+H) compression test average curve.

The stress-strain graph for Composite-7 and Composite-8 (see figure 66) indicates that Composite-8, which is left hollow, exhibits higher values than Composite-7, which is filled with D3 adhesive and saw dust mixture.

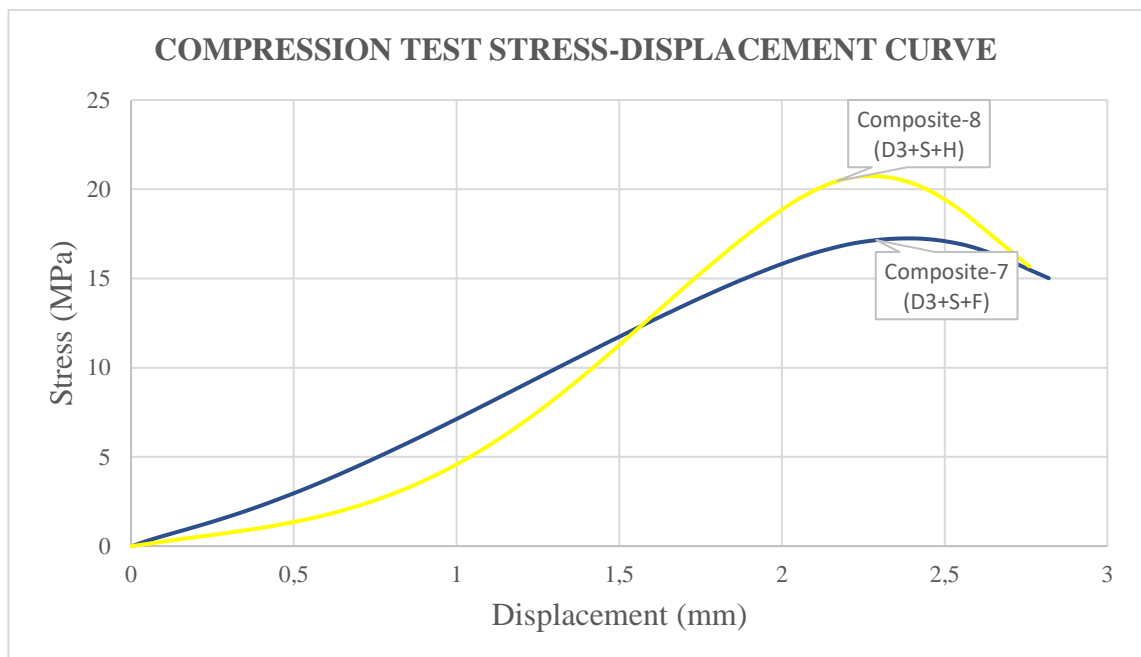


Figure 66. Compression test curves for Composite-7 and Composite-8.

The particleboard tests exhibited a distinct behavior. The stress increased with compression and then rapidly decreased, whereas in bamboo-based composites, the reduction in force occurred more gradually. This indicates that the failure of bamboo-based composites under impact forces is slower, suggesting that the composite material has greater resistance to deformation compared to particleboard. After the compression test, the height of the particleboard decreased from 18 mm to 14 mm, compromising the material's structural integrity.

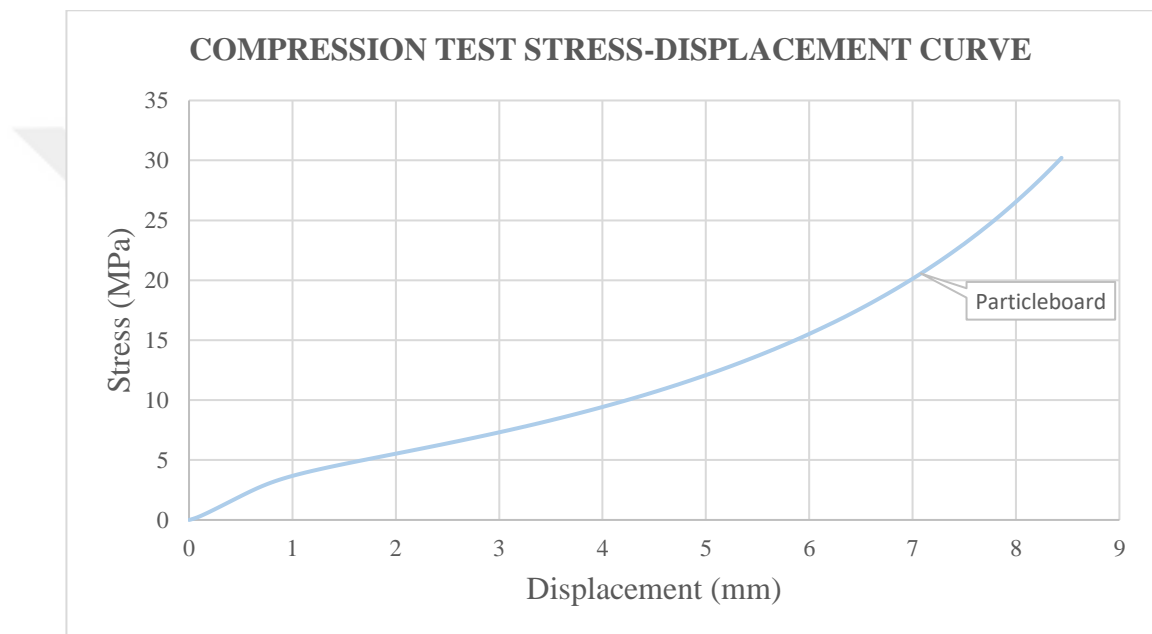


Figure 67. Particleboard compression test average curve.

MDF displayed a lower slope angle under stress compared to other composite materials. This indicates that MDF has lower deformation resistance than the composite materials. Unlike the graphs of other composite materials, the graph for MDF consistently continued to rise, showing that the material underwent plastic deformation without fracturing due to its structure. As a result of the test, it was observed that the height of the material decreased from 18 mm to 16 mm, compromising its structural integrity.

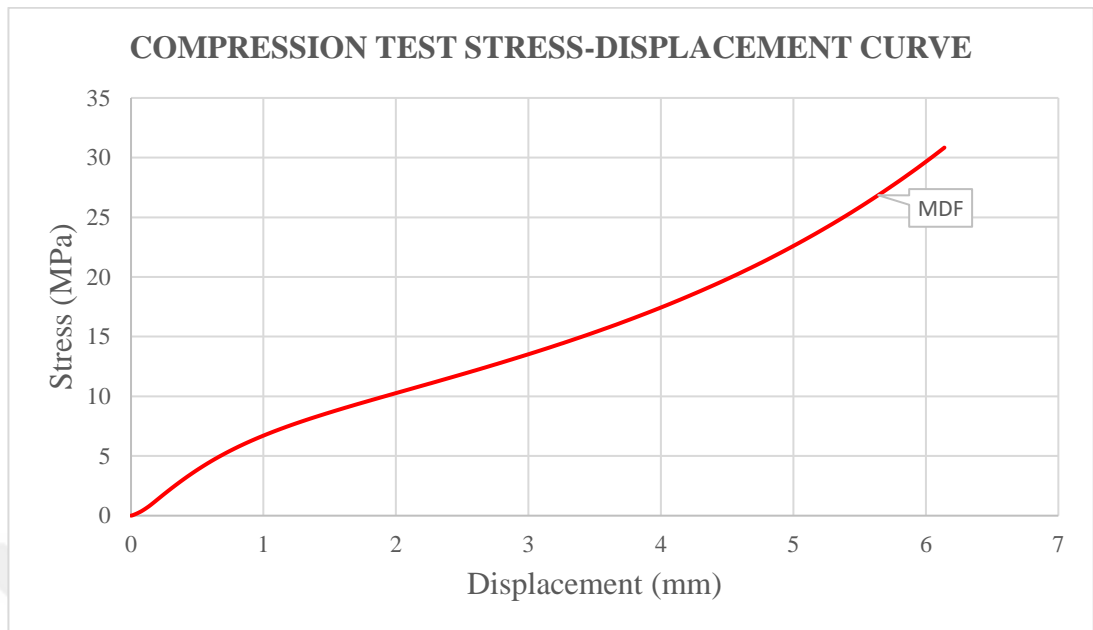


Figure 68. MDF compression test average curve.

The stress-strain graph for particleboard and MDF (see figure 69) indicates that MDF exhibits higher values than particleboard. This is due to its finer and denser fiber structure, more uniform adhesive distribution, smoother surface finish, and the more rigorous manufacturing conditions, all of which contribute to a stronger and more stable material.

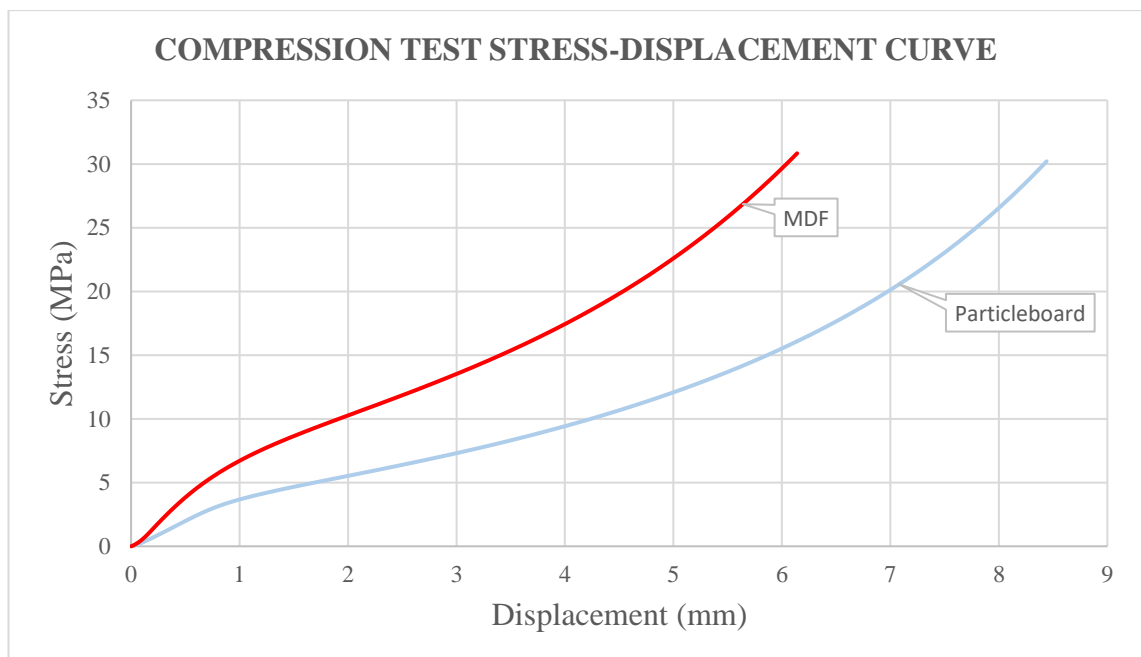


Figure 69. Compression test curves for Particleboard and MDF.

Composite-1, Composite-2, particleboard, and MDF were compared in Figure 70. Composite-1 demonstrated the highest results after a 2 mm displacement.

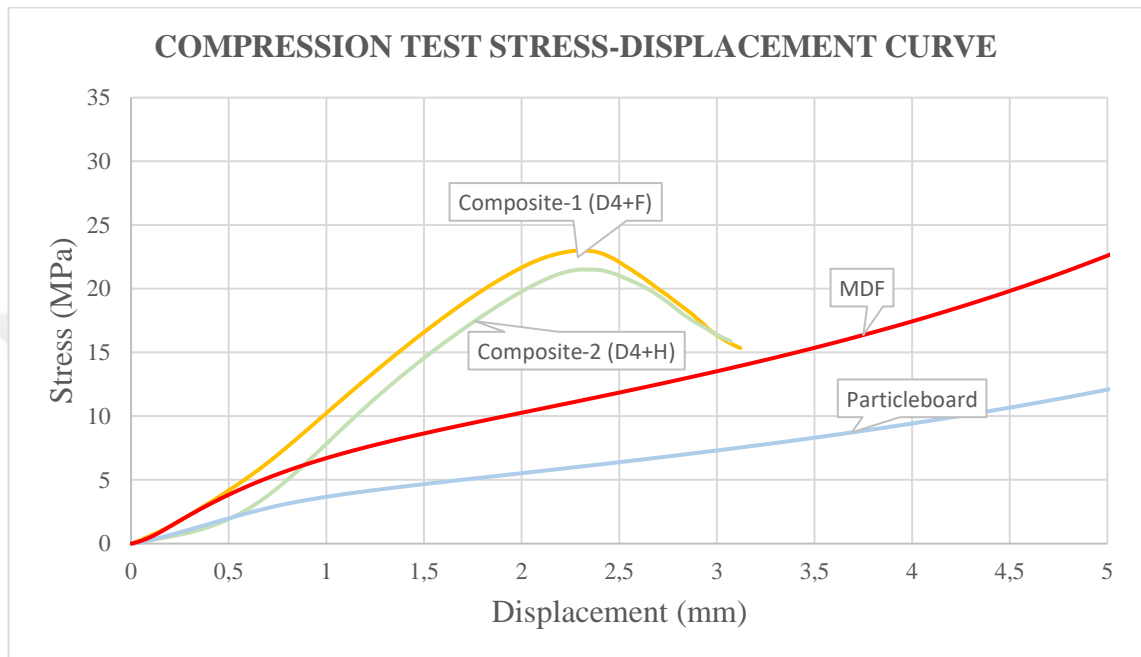


Figure 70. Compression test curves for Com.-1, Com.-2, Particleboard and MDF.

Composite-1, Composite-2, particleboard, and MDF were compared with specific stress values in Figure 71. Composite-2 demonstrated the highest value after a 2 mm displacement.

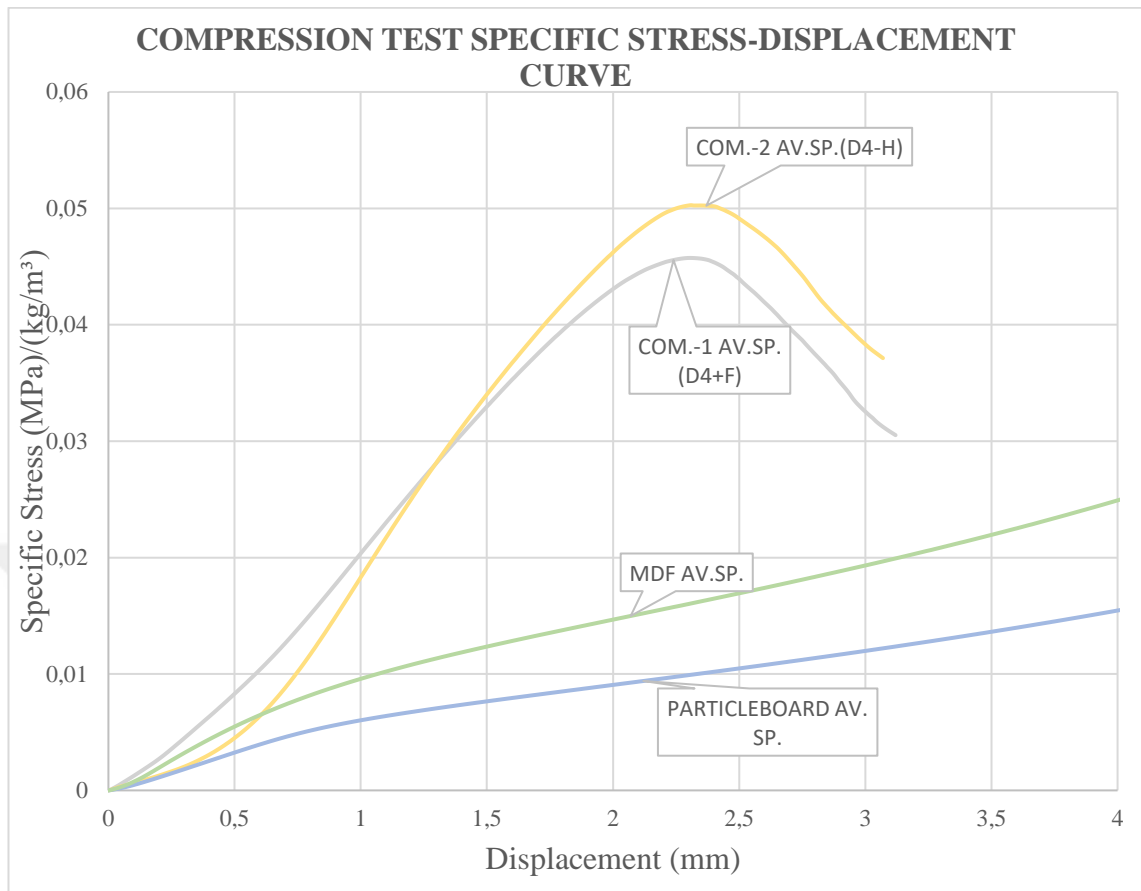


Figure 71. Compression Test Specific Stress Curves.

Ten materials were compared in Figure 72. Composite-1 and Composite-2, which were made using a D4 adhesive, exhibited higher resistance to deformation. Additionally, the D3 and sawdust mixture showed higher results compared to composites made with D3 and PU adhesives.

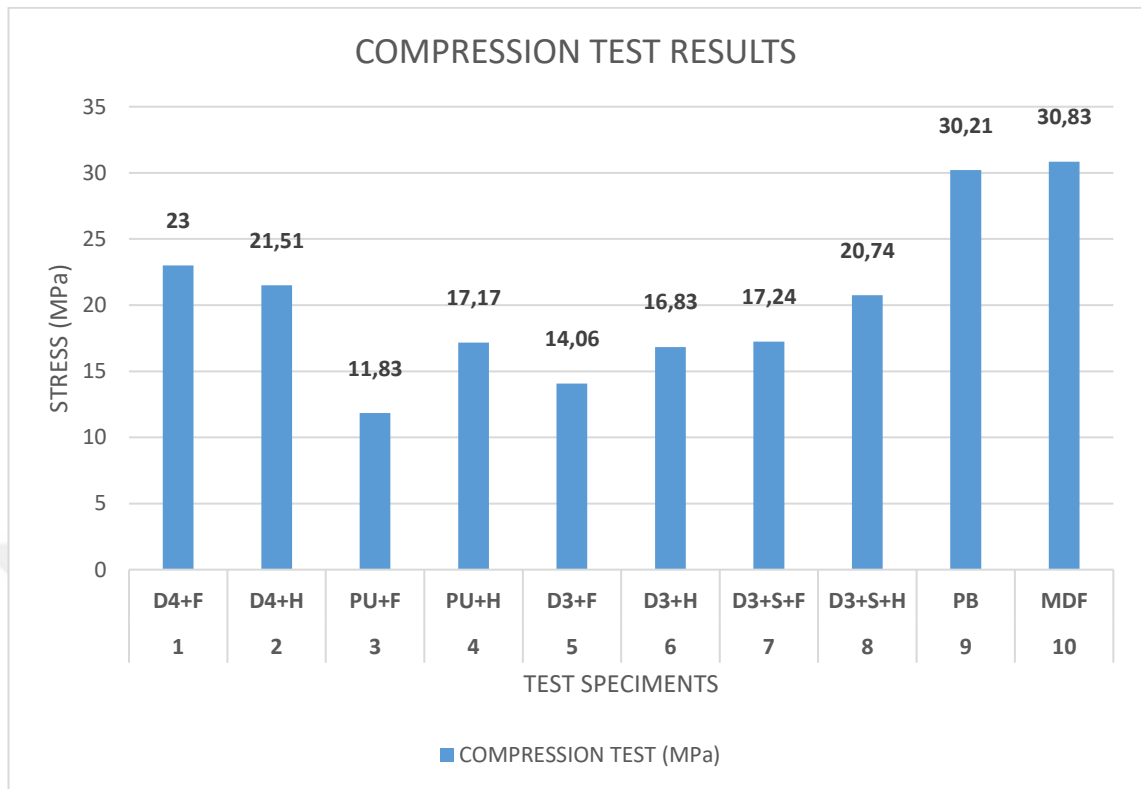


Figure 72. Compression Test Top Stress Values.

3.2.2 Indentation Test Results

Similarly, the D4+F composite had the highest indentation strength (see table 3). The indentation strength of D4+F was 95%, 75%, and 63% greater than the indentation strengths of PU+F, D3+F, and D3+S+F, respectively. Hollow composites made with D3 adhesive and foamed polyurethane performed better in indentation tests compared to filled ones.

Table 3. Indentation test results.

INDENTATION TEST (MPa)	FILLED	HOLLOW
D4	20.53	16.97
PU	10.53	17.60
D3	11.76	14.24
D3+S	12.57	19.48

As a result of the tests applied to a sample of D4+F composite with dimensions of 90 mm x 90 mm, the following stress-displacement graph was obtained (see figure 73). The average stress-displacement graph for the four points is also shown below. The highest value of the average graph is 20.53 MPa. This test result indicates that the D4+F composite has better indentation strength compared to the D4+H composite and all other composite samples.

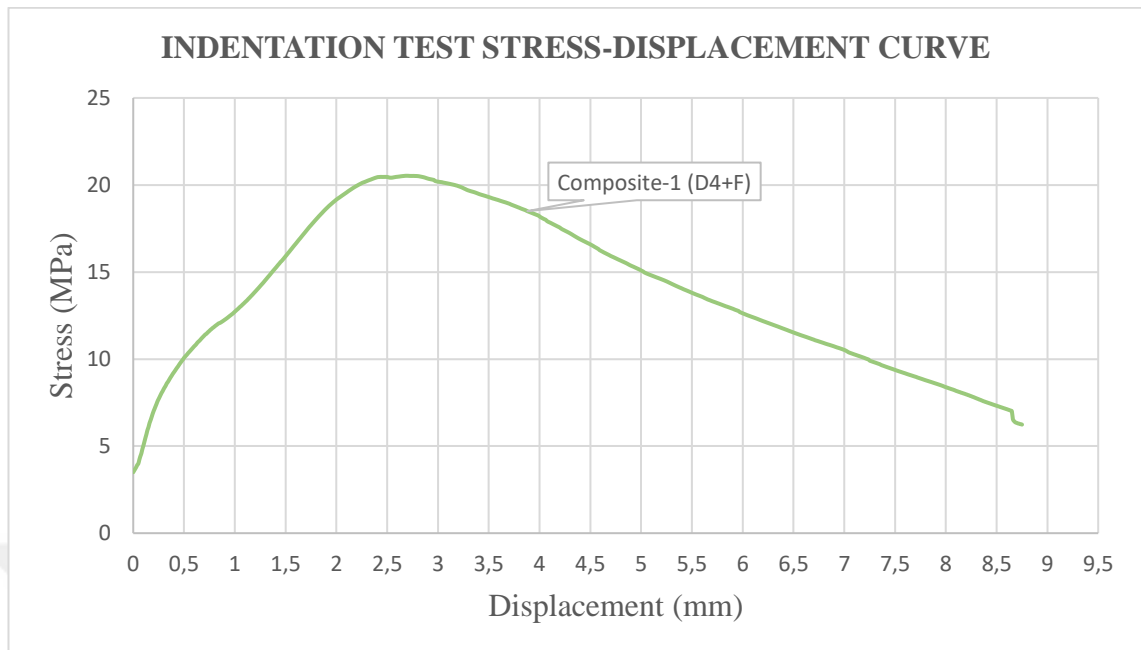


Figure 73. Composite-1(D4+F) compression test samples & average curves.

The average graph value obtained from the test results of the D4+H composite sample is as follows (see figure 74). According to this test result, D4+H has 17 % lower indentation strength than D4+F. Therefore, in materials where D4 adhesive is used, a filled internal structure plays a role in enhancing indentation strength.

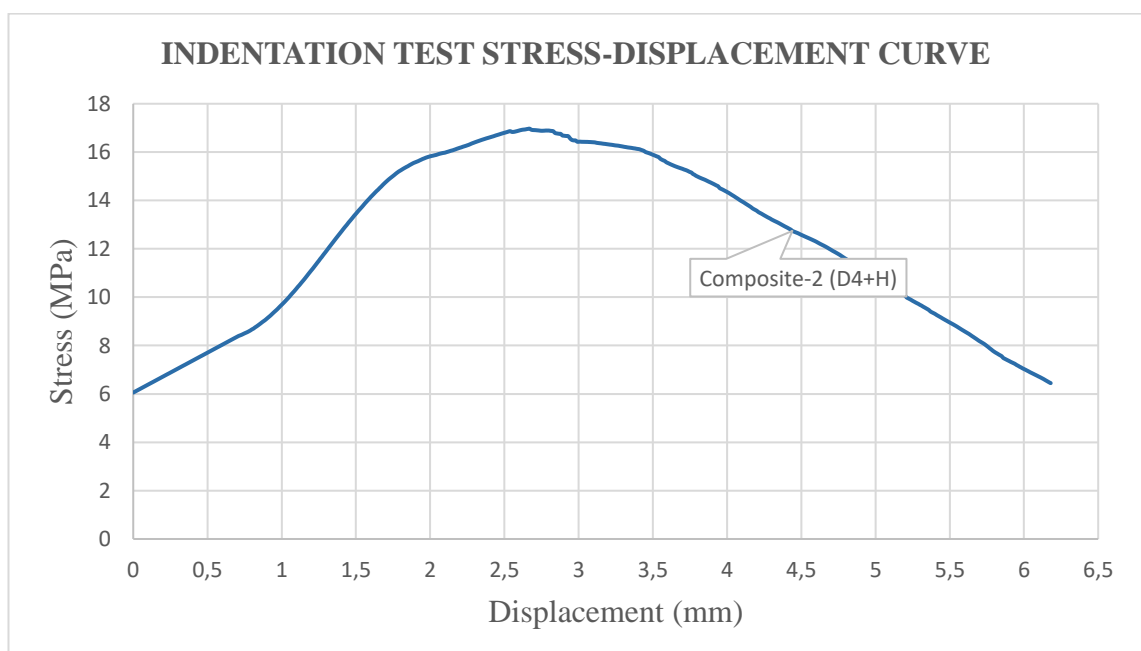


Figure 74. Composite-2 (D4+H) indentation test samples & average curves.

The stress-displacement graph for Composite-1 and Composite-2 (see figure 75) indicates that Composite-1, which is filled with D4 adhesive, exhibits higher values than Composite-2, which is left hollow.

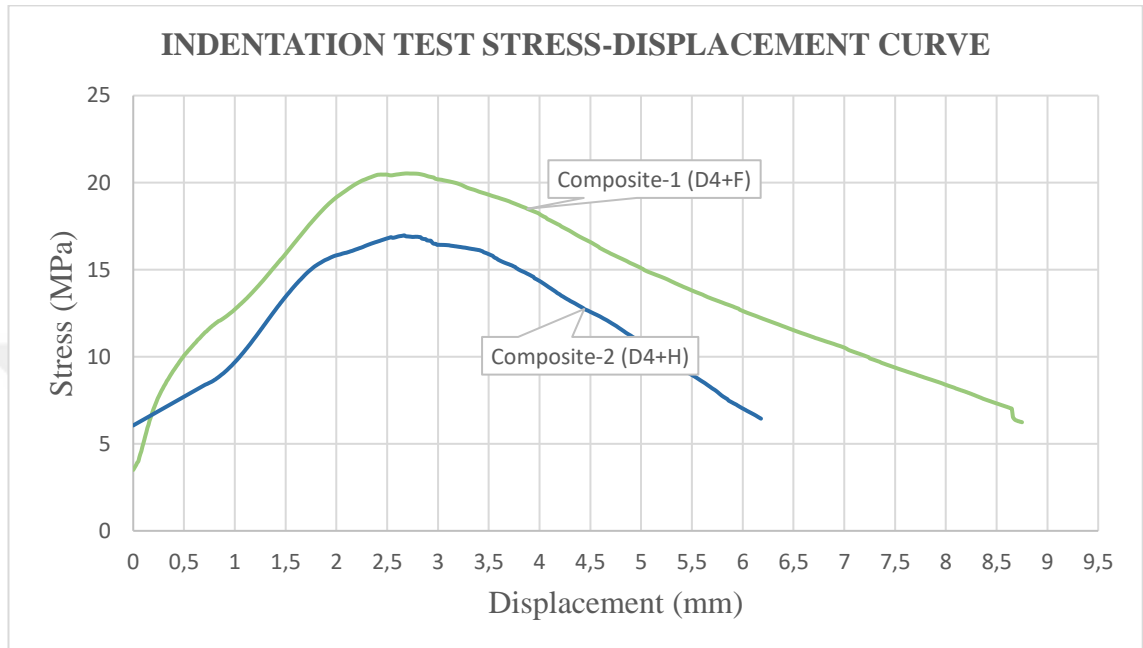


Figure 75. Composite-1 & Composite-2 indentation test average curves.

The stress-displacement graph of the PU+F composite is shown below (see figure 76). The highest value of the average stress-displacement curve is 10.53 MPa. This test result shows that PU+F 67% lower indentation strength than D4+F composite.

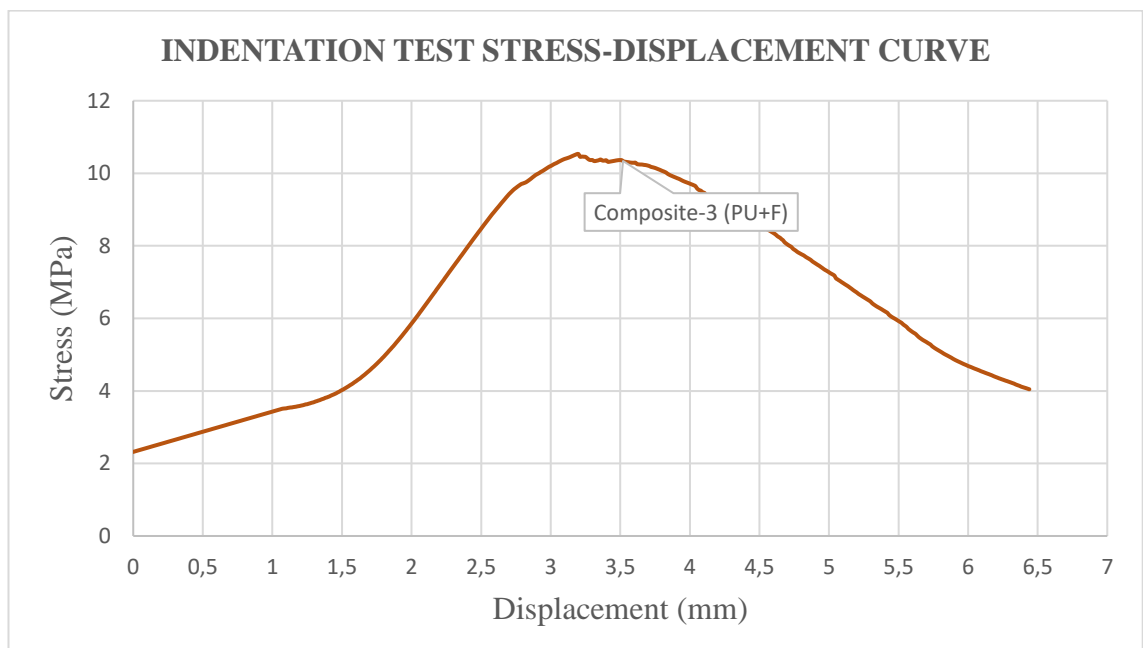


Figure 76. Composite-3 (PU+F) indentation test samples & average curves.

The average graph value obtained from the test results of the PU+H composite sample is as follows (see figure 77). According to this test result, PU+H has 67 % higher indentation strength than PU+F. Therefore, in materials where PU is used, a hollow internal structure increases indentation strength.

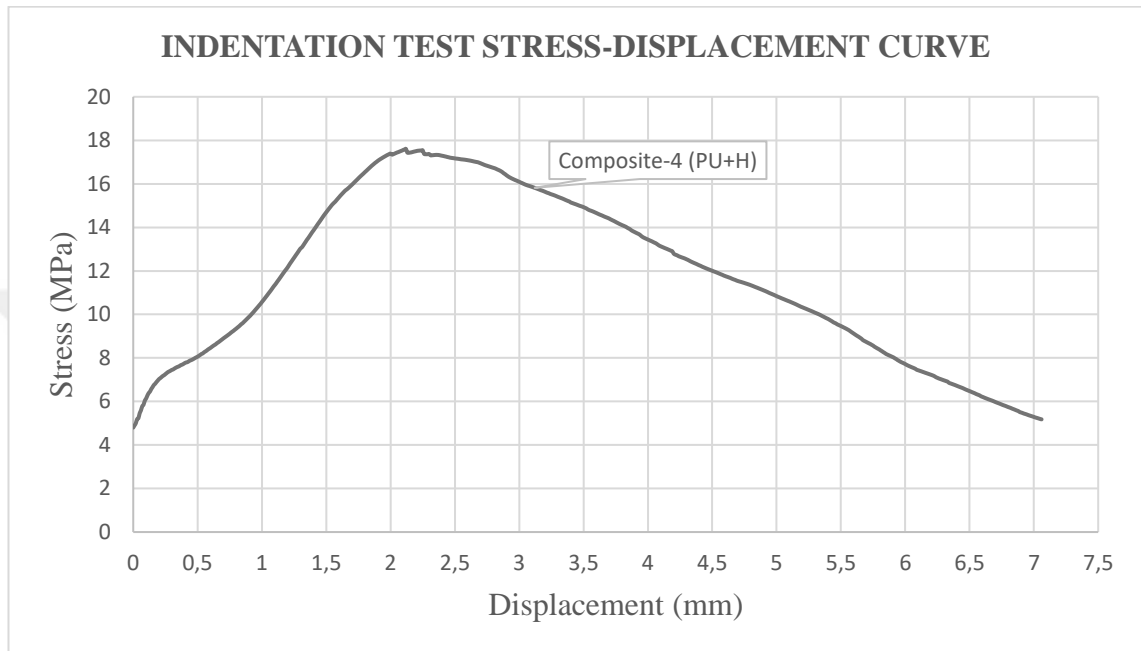


Figure 77. Composite-4 (PU+H) indentation test samples & average curves.

The stress-strain graph for Composite-3 and Composite-4 (see figure 78) indicates that Composite-4, which is left hollow, exhibits higher values than Composite-3, which is filled with PU.

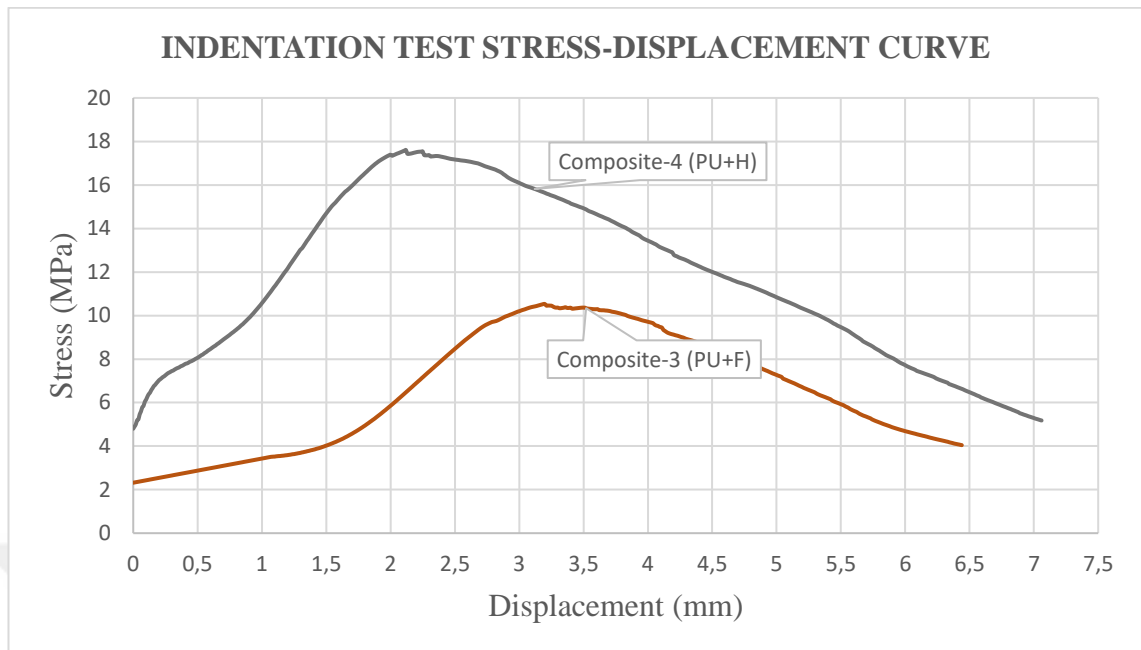


Figure 78. Composite-3 & Composite-4 indentation test average curves.

The stress-displacement graph of the D3+F composite is shown below (see figure 79). The highest value of the average stress-displacement curve is 11.76 MPa. This test result shows that D3+F has the lowest indentation strength after PU+F compared to all other composites.

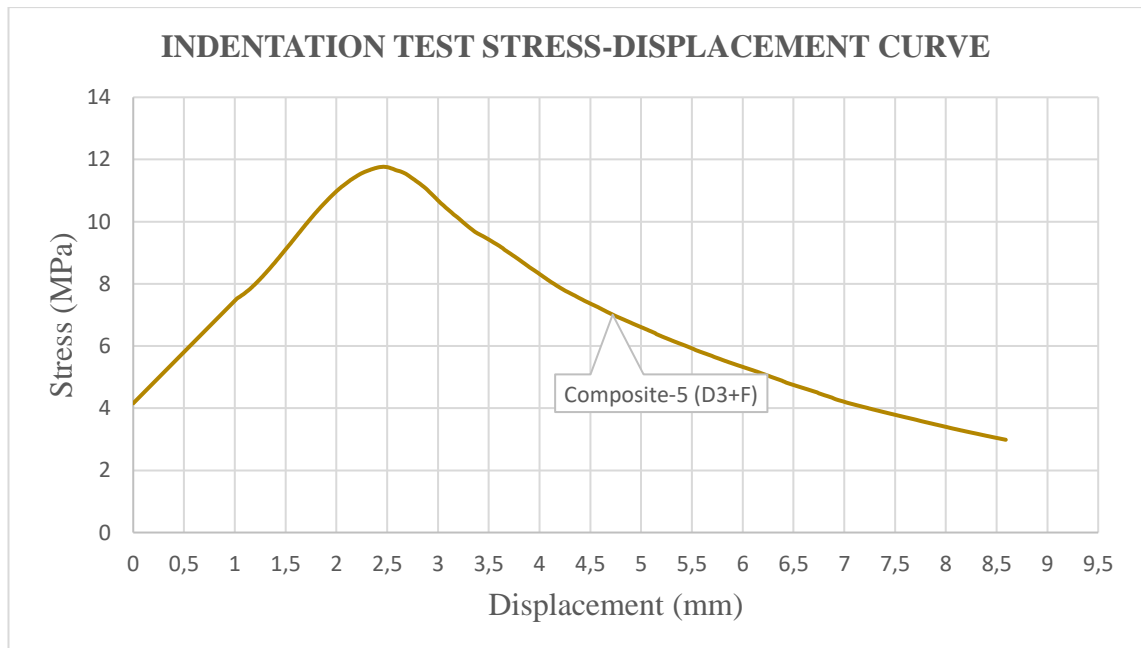


Figure 79. Composite-5 (D3+F) indentation test samples & average curves.

The average graph value obtained from the test results of the D3+H composite sample is as follows (see figure 80). According to this test result, D3+H has 21 % higher indentation

strength than D3+F. Therefore, in materials where D3 is used, a hollow internal structure enhances indentation strength.

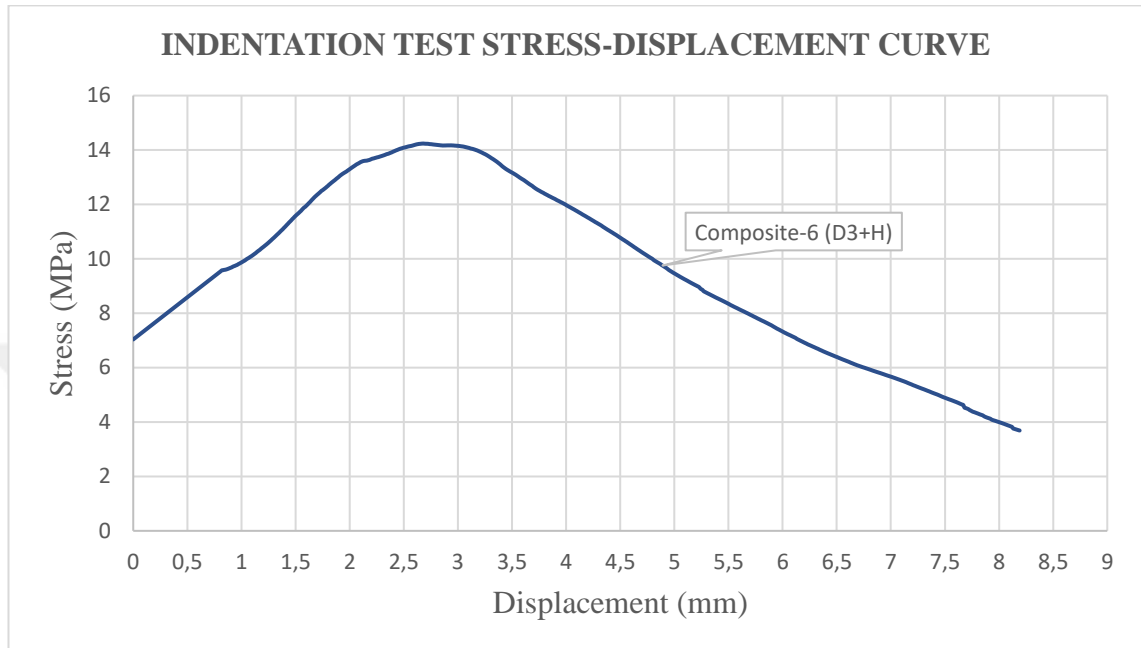


Figure 80. Composite-6 (D3+H) indentation test samples & average curves.

The stress-strain graph for Composite-5 and Composite-6 (see figure 81) indicates that Composite-6, which is left hollow, exhibits higher values than Composite-5, which is filled with D3 adhesive.

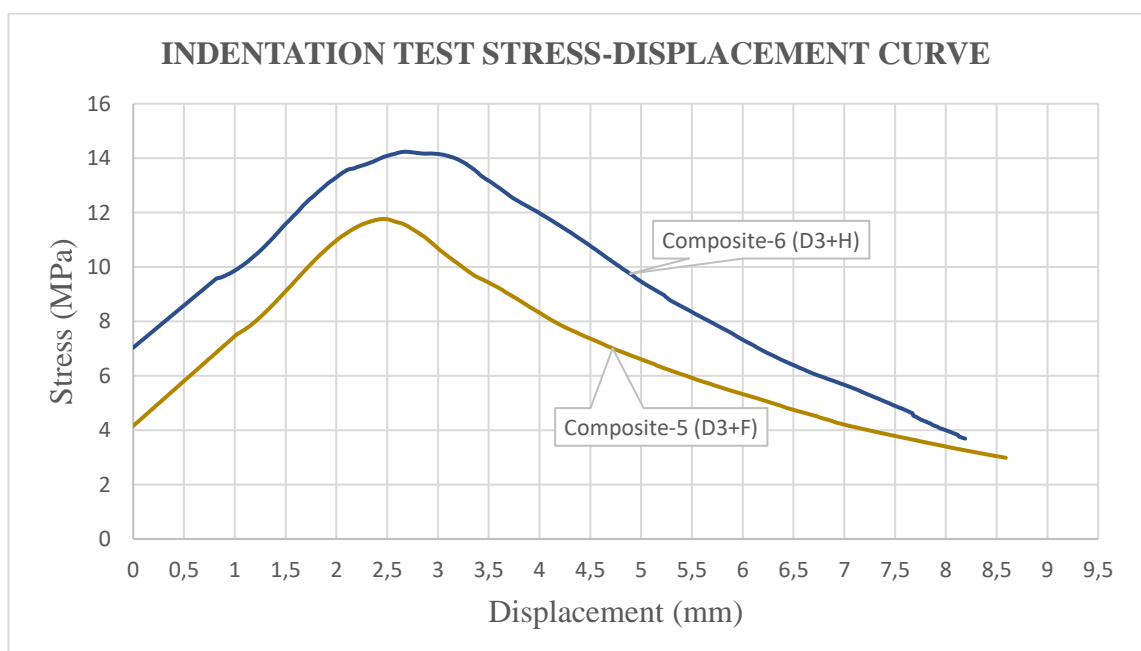


Figure 81. Composite-1 & Composite-2 indentation test average curves.

The stress-displacement graph of the D3+S+F composite is shown below (see figure 82). The highest value of the average stress-displacement curve is 12.57 MPa. This test result indicates that D3+S+F has better indentation strength compared to D3+F. It was observed that the composite produced with an adhesive containing 5% by weight of sawdust mixed into the D3 adhesive has 7% better indentation strength.

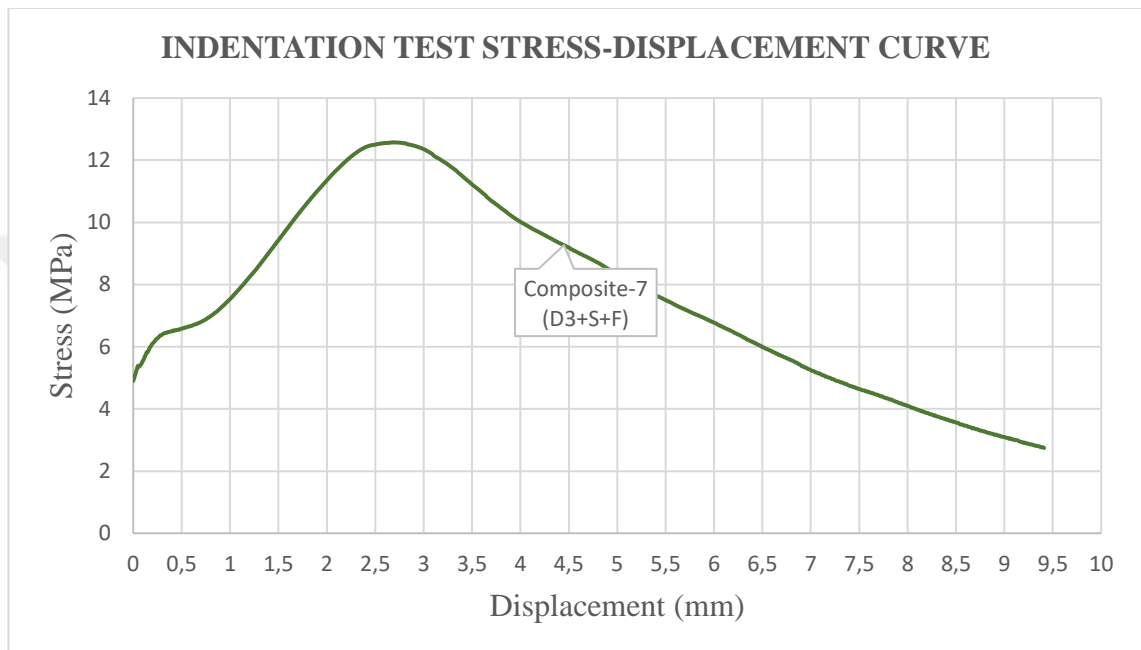


Figure 82. Composite-7 (D3+S+F) indentation test samples & average curves.

The average graph value obtained from the test results of the D3+S+H composite samples is as follows (see figure 83). According to this test result, D3+S+H has 55 % higher indentation strength than D3+S+F. Therefore, in materials where D3+S is used, a hollow internal structure increases indentation strength.

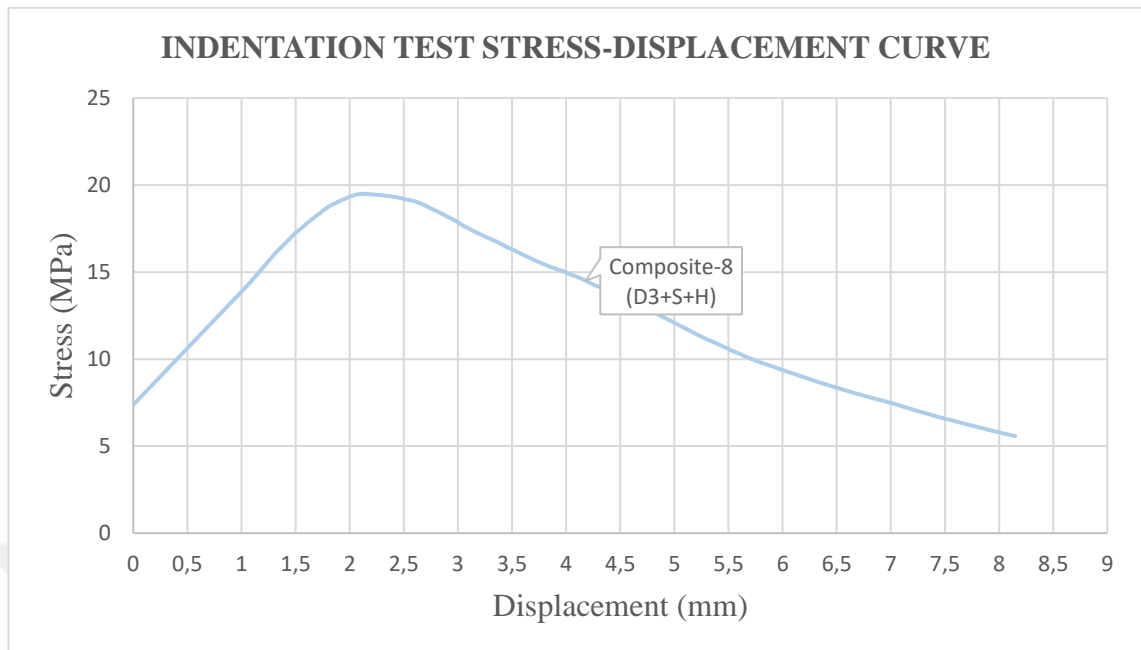


Figure 83. Composite-8 (D3+S+H) indentation test samples & average curves.

The stress-strain graph for Composite-7 and Composite-8 (see figure 84) indicates that Composite-8, which is left hollow, exhibits higher values than Composite-7, which is filled with D3 adhesive and saw dust mixture.

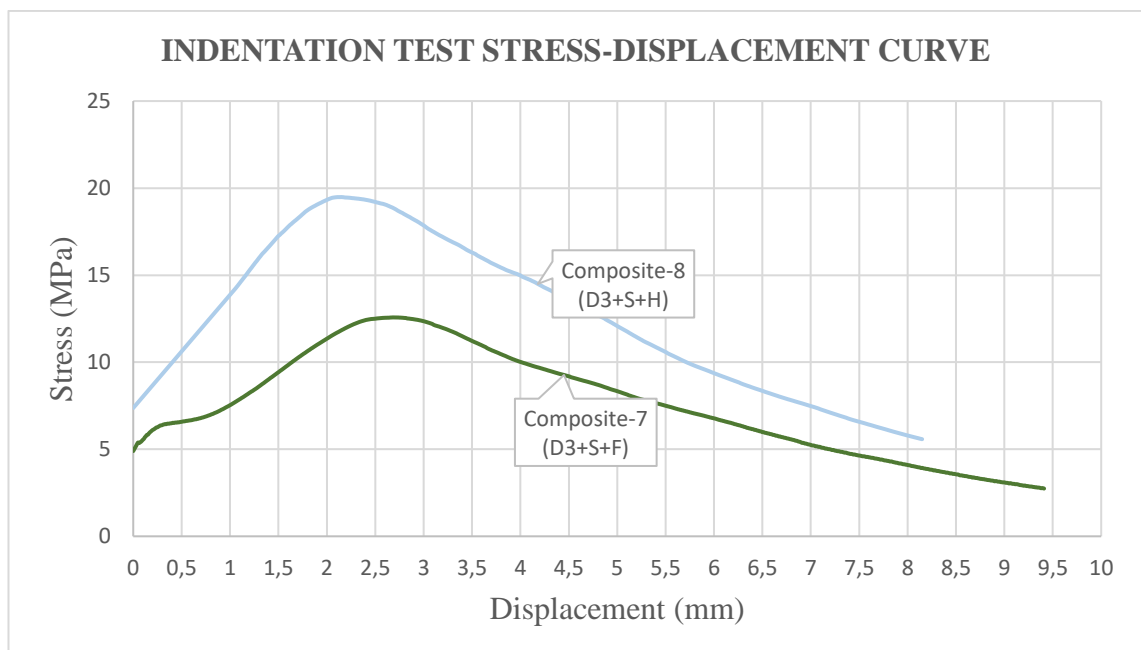


Figure 84. Composite-1 & Composite-2 indentation test average curves.

The particleboard tests revealed a different behavior. The force increased with contraction and then sharply decreased (see figure 85). While in bamboo-based composites the reduction of the force was much slower. It shows that the failure of the composites under impact forces is slower. The structural integrity of the particleboard was compromised.

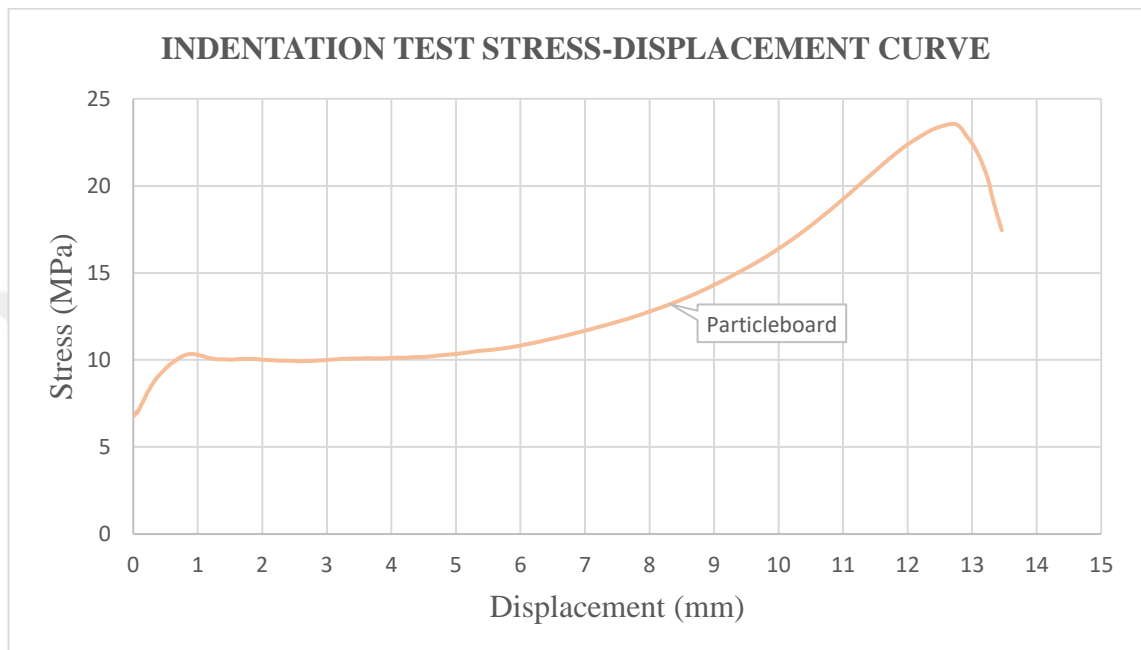


Figure 85. Particleboard indentation test samples & average curves.

The MDF tests revealed a different behavior. The force increased with contraction and then sharply decreased (see figure 86). While in bamboo-based composites the reduction of the force was much slower. It shows that the failure of the composites under impact forces is slower. The structural integrity of the MDF was compromised after testing.

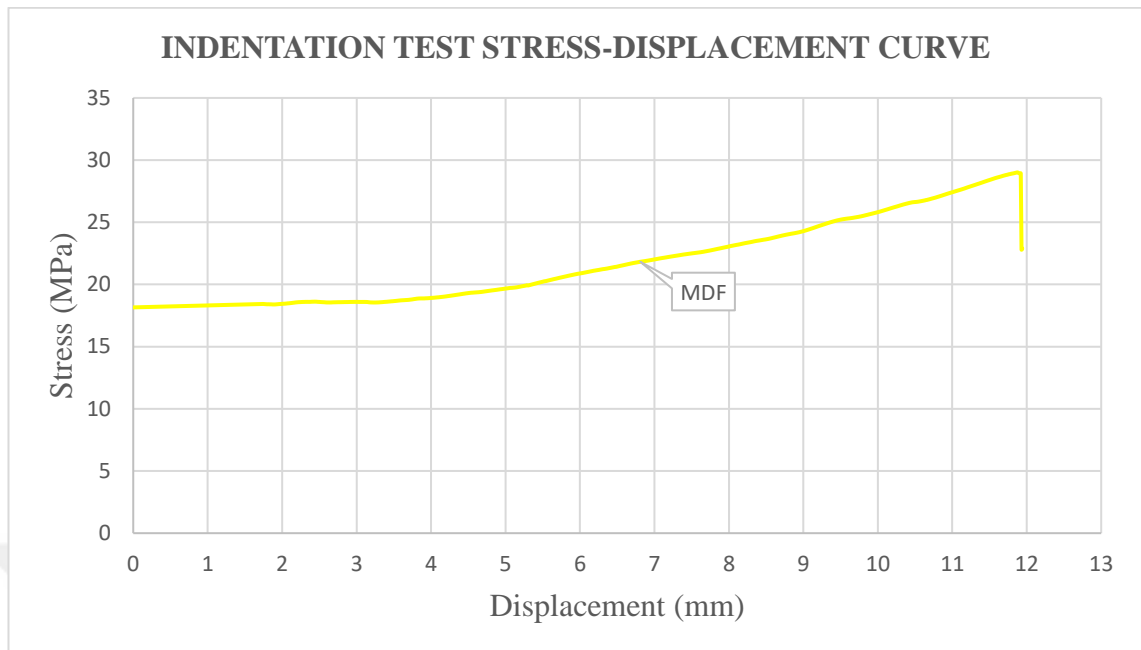


Figure 86. MDF indentation test samples & average curves.

The stress-strain graph for particleboard and MDF (see Figure 87) shows that MDF demonstrates higher values compared to particleboard. This is attributed to its finer, denser fiber composition, more even adhesive distribution, smoother surface texture, and the stricter manufacturing processes, all of which result in a stronger and more stable material.

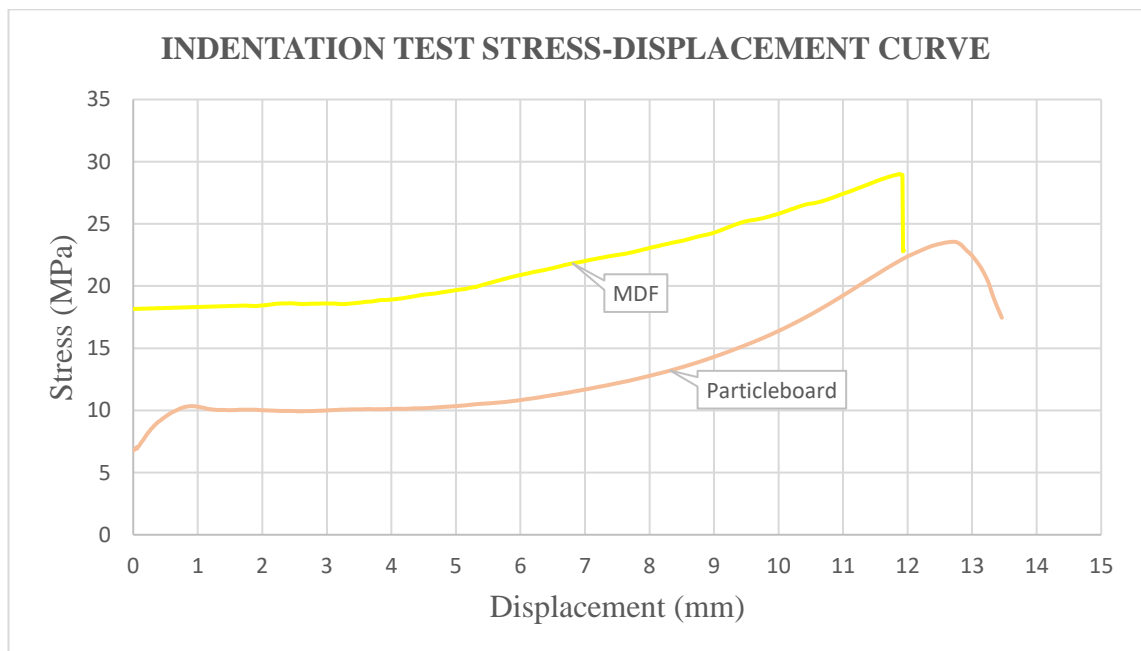


Figure 87. Composite-1 & Composite-2 indentation test average curves.

Composite-1, Composite-2, particleboard, and MDF were compared in Figure 88. Composite-1 demonstrated the highest results after a 2 mm displacement followed by MDF, Composite-2 and particleboard.

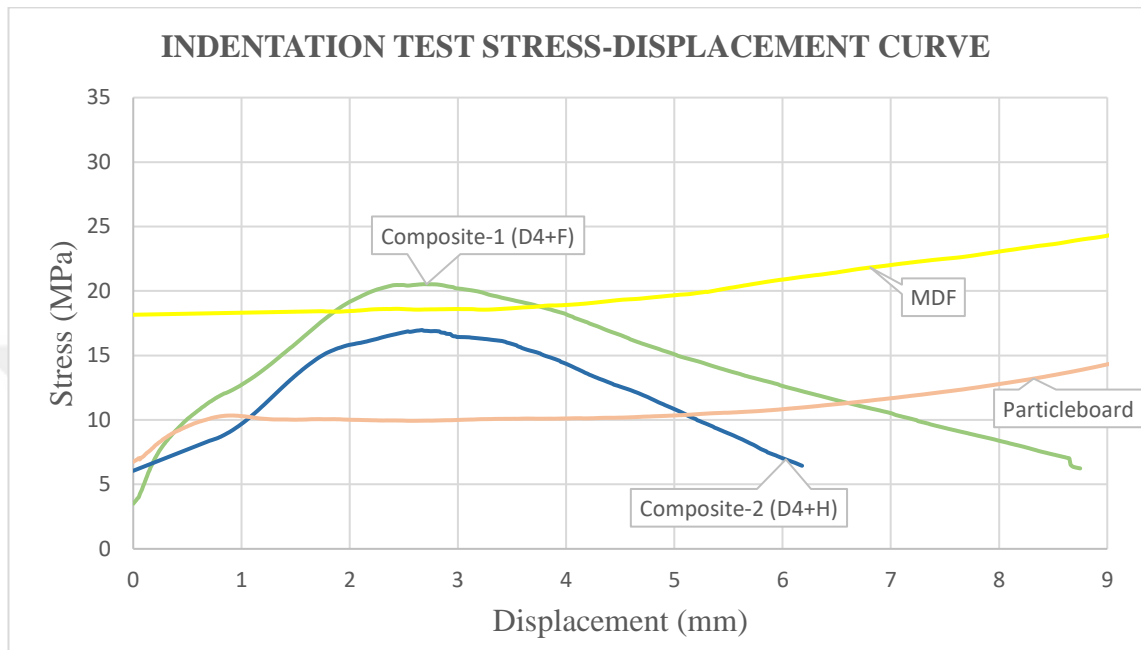


Figure 88. Composite-1, Composite-2, Particleboard and MDF indentation test average curves.

Composite-1, Composite-2, particleboard, and MDF were compared based on specific stress values in Figure 89. Composite-1 exhibited the highest value after a 2 mm displacement, with Composite-2 following closely, showing a 3% lower result than Composite-1. Additionally, Composite-1 was 132% higher than particleboard and 45% higher than MDF.

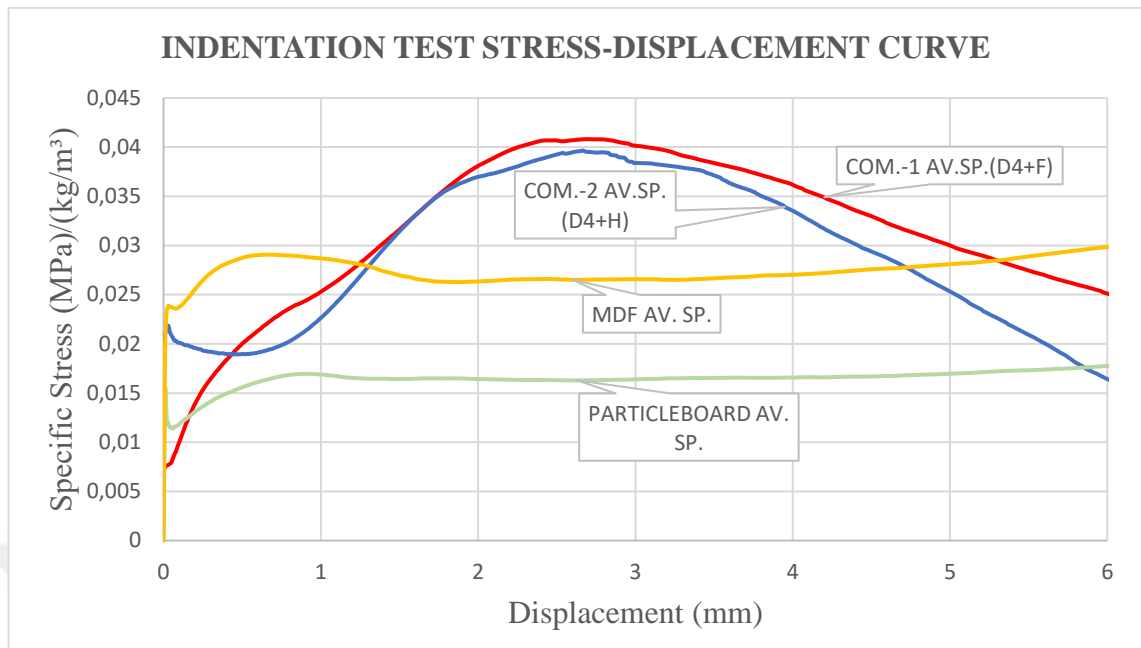


Figure 89. Composite-1, Composite-2, Particleboard and MDF indentation test specific stress curves.

Compression and indentation test results showed similar trends (see figure 90). Composite-1 was 7% higher than Composite-2 in the compression test and 21% higher in the indentation test. Composite-4 was 45% higher than Composite-3 in the compression test and 67% higher in the indentation test. Composite-6 was 20% higher than Composite-5 in the compression test and 21% higher in the indentation test. Composite-8 was 20% higher than Composite-7 in the compression test and 55% higher in the indentation test. MDF was 2% higher than particleboard in the compression test and 23% higher in the indentation test.

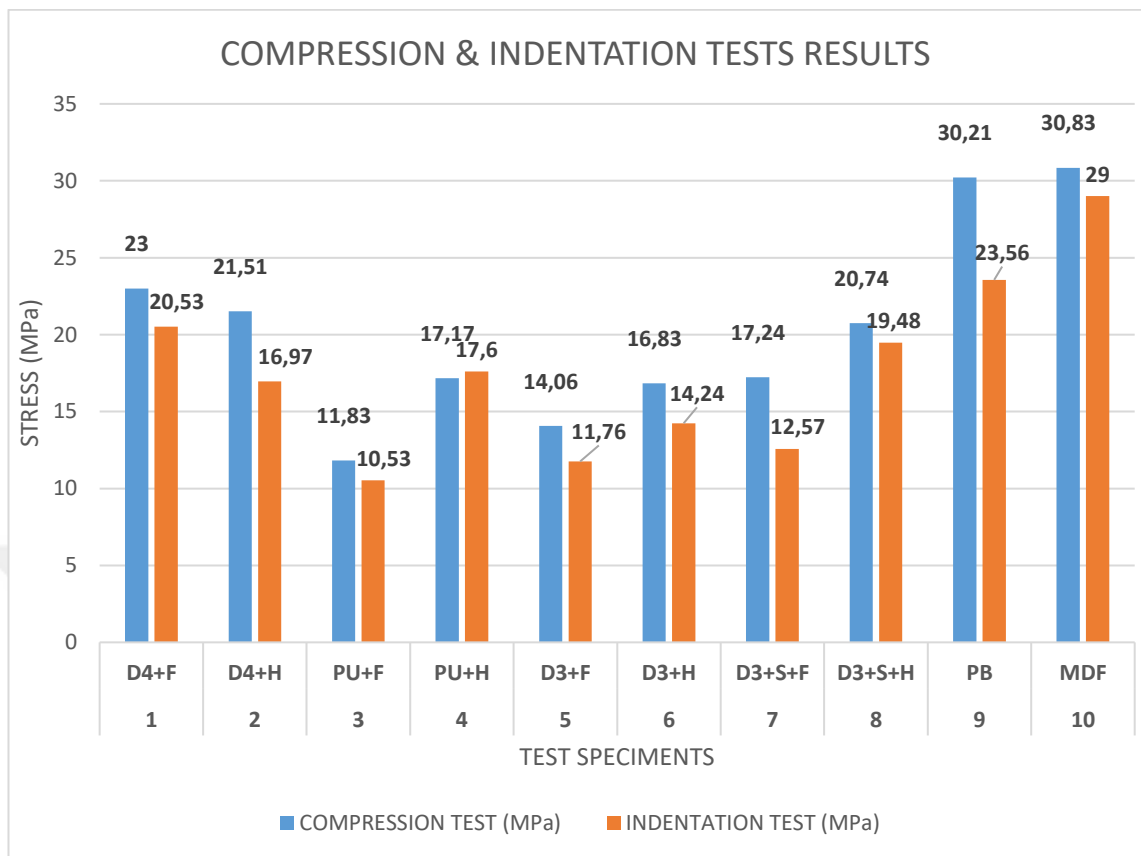


Figure 90. Indentation & Compression test stress values.

3.2.3 Compression and Indentation Test Failure Results

The images below present side views of the specimens used in the compression test. For the indentation test specimens, a band saw was used to make cuts through the central axis of the circular indentation area where the tests were conducted. These images showcase the sections from these cuts. The main failure modes observed during testing were barreling, buckling (see figure 91), lateral spreading, cracking, and core crushing. The failure results for the indentation and compression tests are shown side by side for comparison.

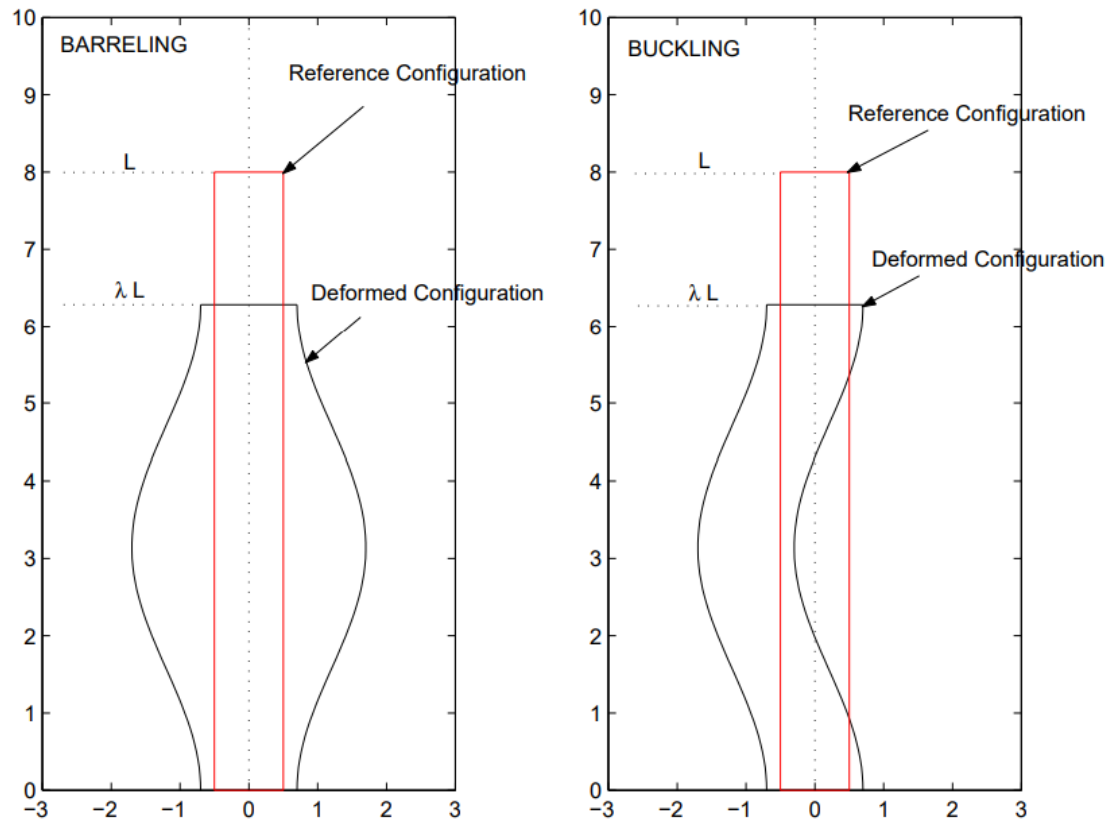


Figure 91. Comparison of barreling and buckling deformations under compressive load [59].

3.2.3.1 Composite-1 Failure Result

The core of Composite-1, made from filled bamboo sticks, achieved the highest values in both the compression and indentation tests. An analysis of the fracture structure revealed that the core crushing from the indentation test was confined solely to the test area. In contrast, the compression test resulted in a barreling-shaped failure (see Figure 92).

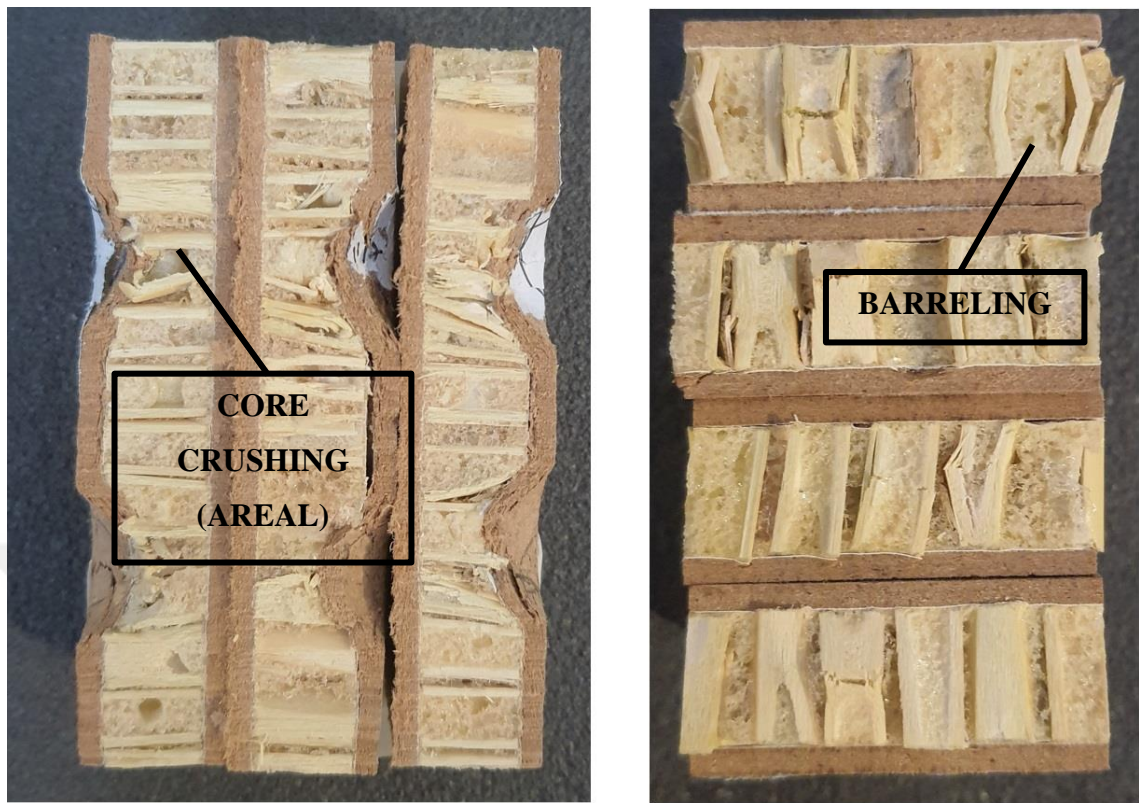


Figure 92. Side Views of Composite-1 After Indentation (left) and Compression (right) Tests.

3.2.3.2 Composite-2 Failure Result

The core of Composite-2, made from hollow bamboo sticks, achieved the second-highest values in both the compression and indentation tests. An analysis of the fracture structure revealed that core crushing from the indentation test was confined solely to the test area. Additionally, face sheet debonding was observed as a secondary failure mode following the indentation test. In contrast, the compression test resulted in a buckling failure (see Figure 93).

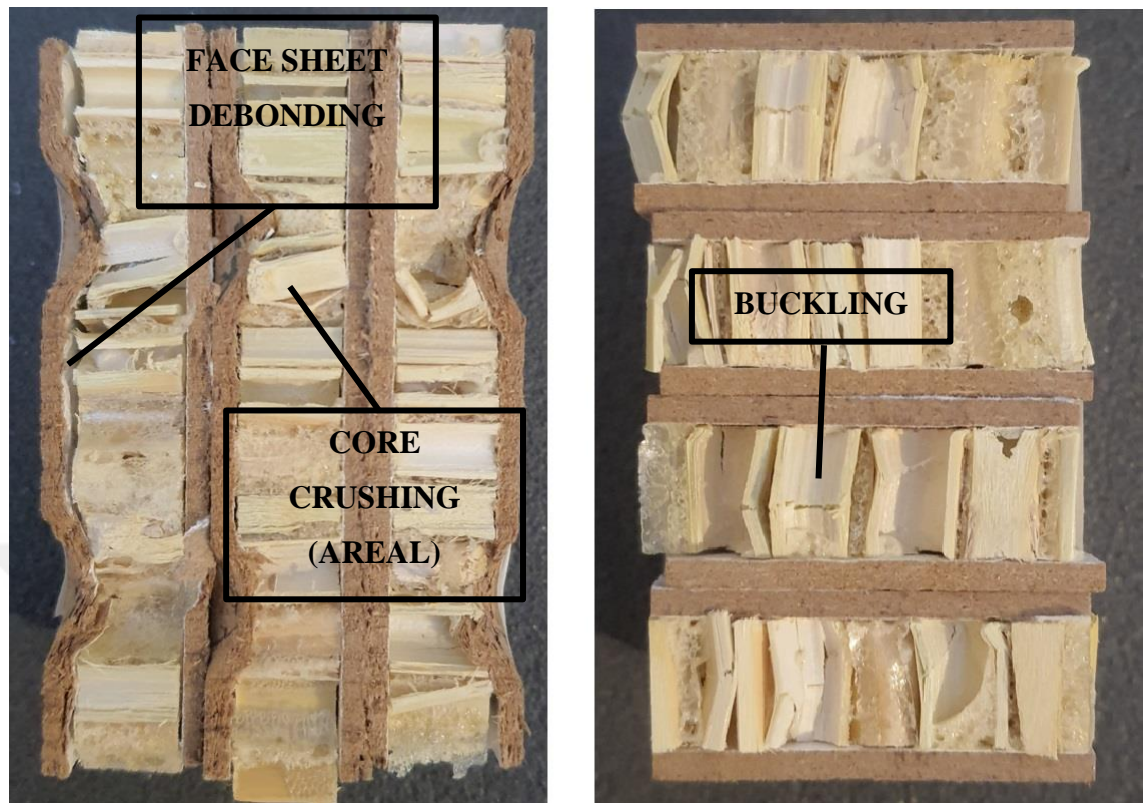


Figure 93. Side Views of Composite-2 After Indentation (left) and Compression (right) Tests.

3.2.3.3 Composite-3 Failure Result

The core of Composite-3, made from filled bamboo sticks, resulted in lower values compared to Composite-4 in both the compression and indentation tests. An analysis of the fracture structure revealed that the core crushing caused by the indentation test was confined solely to the test area. In contrast, the compression test led to a lateral spreading failure (see figure 94).

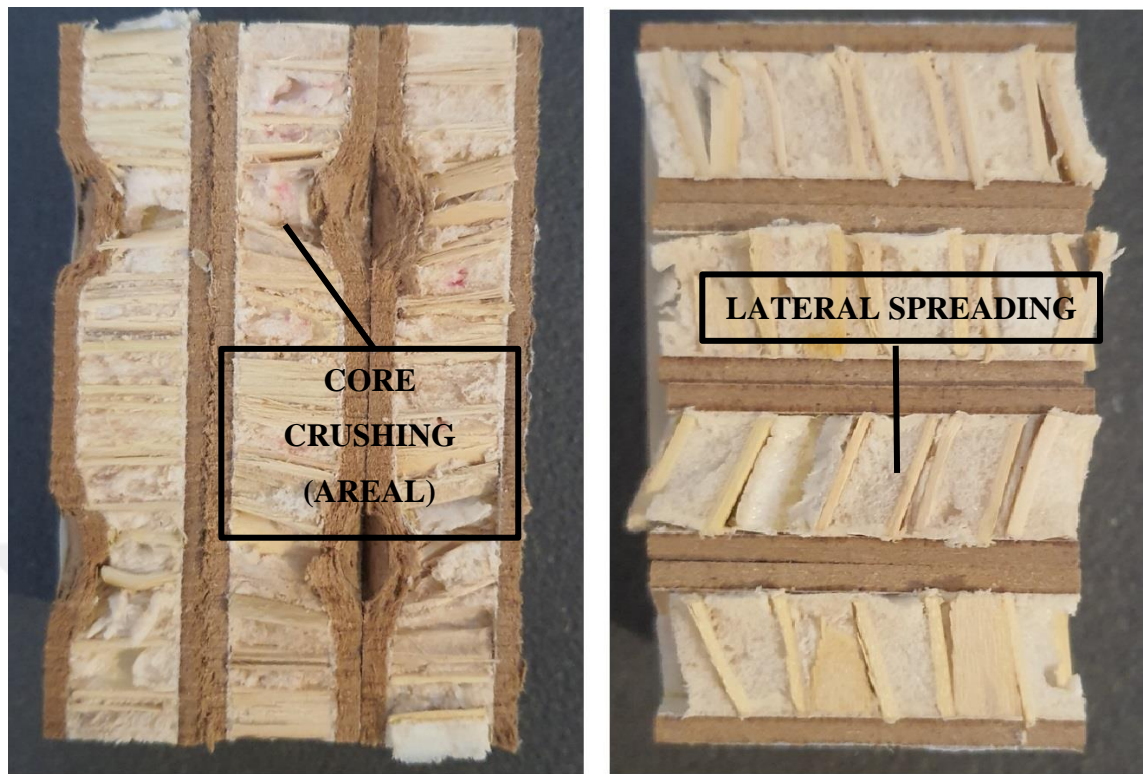


Figure 94. Side Views of Composite-3 After Indentation (left) and Compression (right) Tests.

3.2.3.4 Composite-4 Failure Result

The core of Composite-4, made from hollow bamboo sticks, resulted in higher values compared to Composite-3 in both the compression and indentation tests. An analysis of the fracture structure revealed that the core crushing caused by the indentation test was confined solely to the test area. In contrast, the compression test led to both lateral spreading and barreling failures.



Figure 95. Side Views of Composite-4 After Indentation (left) and Compression (right) Tests.

3.2.3.5 Composite-5 Failure Result

The core of Composite-5, made from filled bamboo sticks, resulted in lower values in both the compression and indentation tests compared to Composite-6. An analysis of the fracture structure revealed that the core crushing from the indentation test was confined solely to the test area. In contrast, the compression test resulted in barreling failures.

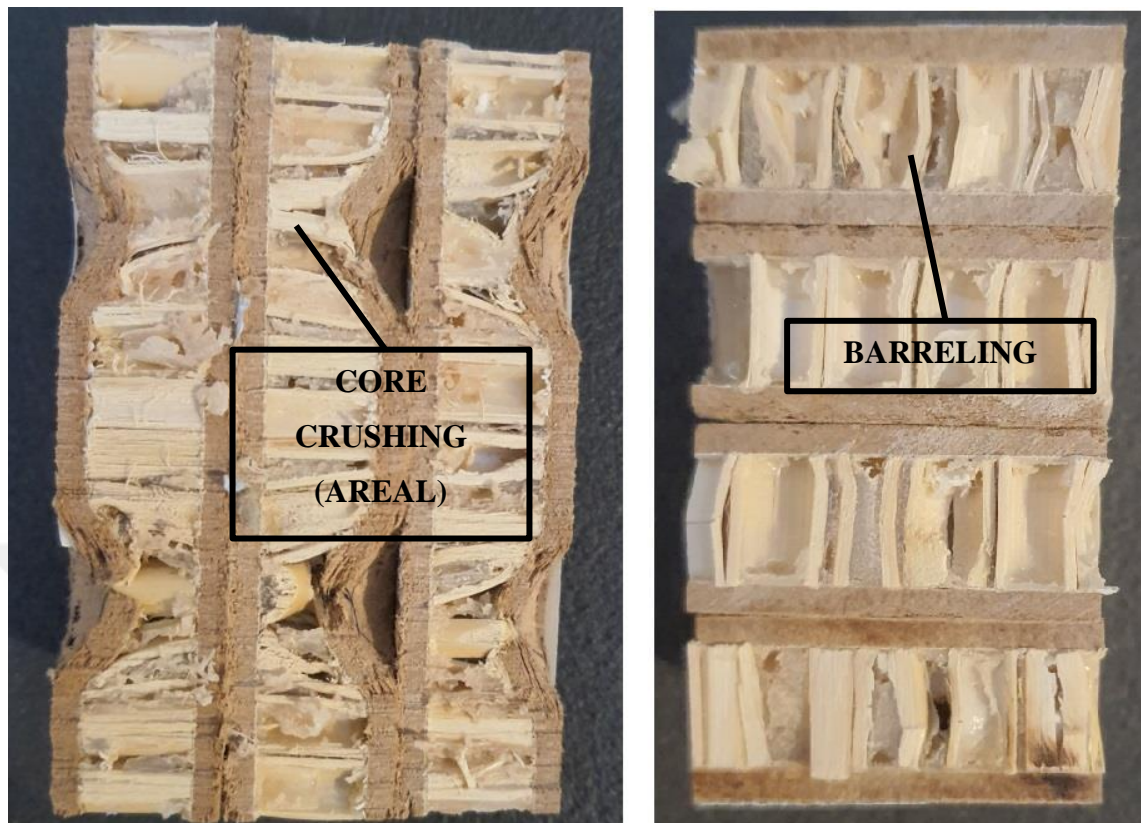


Figure 96. Side Views of Composite-5 After Indentation (left) and Compression (right) Tests.

3.2.3.6 Composite-6 Failure Result

The core of Composite-6, made from hollow bamboo sticks, resulted in higher values in both the compression and indentation tests compared to Composite-5. An analysis of the fracture structure revealed that the core crushing from the indentation test was confined solely to the test area. In contrast, the compression test led to buckling failures.

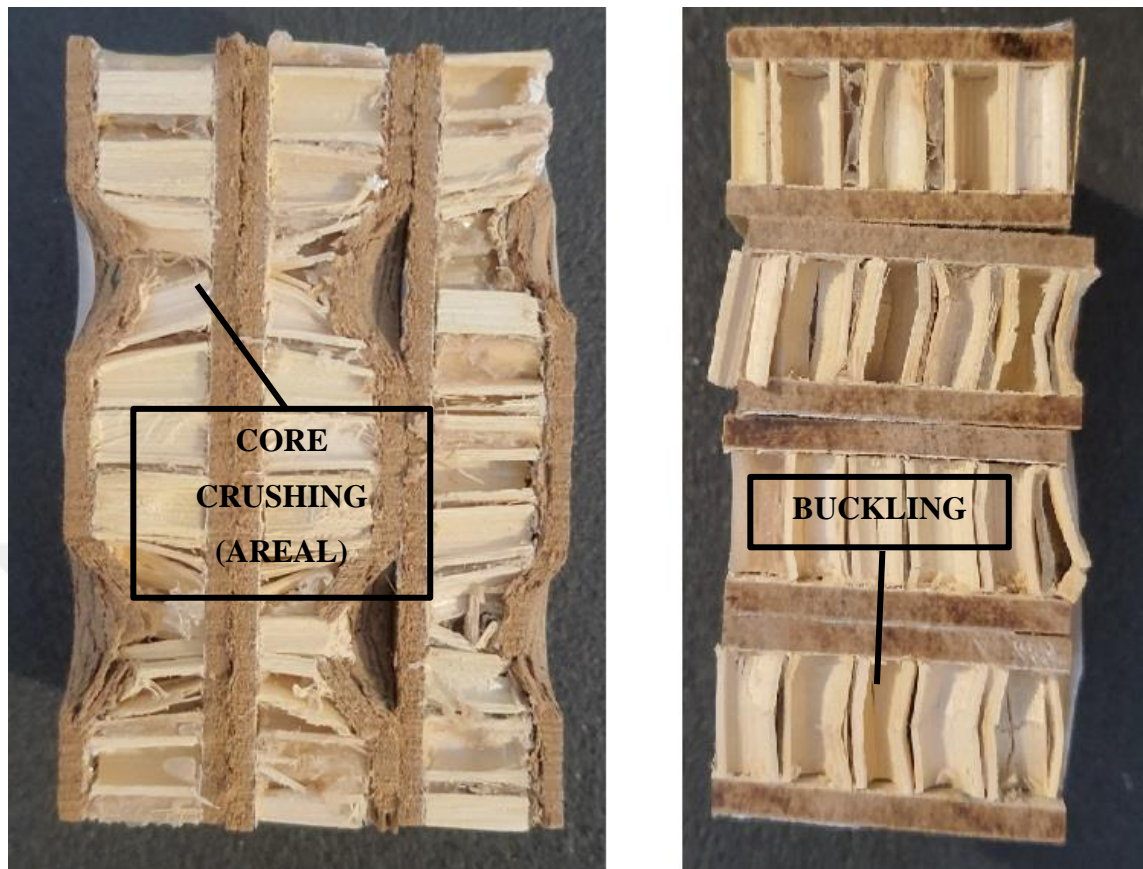


Figure 97. Side Views of Composite-6 After Indentation (left) and Compression (right) Tests.

3.2.3.7 Composite-7 Failure Result

The core of Composite-7, made from filled bamboo sticks, resulted in lower values in both the compression and indentation tests compared to Composite-8. An analysis of the fracture structure revealed that the core crushing from the indentation test was confined solely to the test area. In contrast, the compression test led to cracking failures.

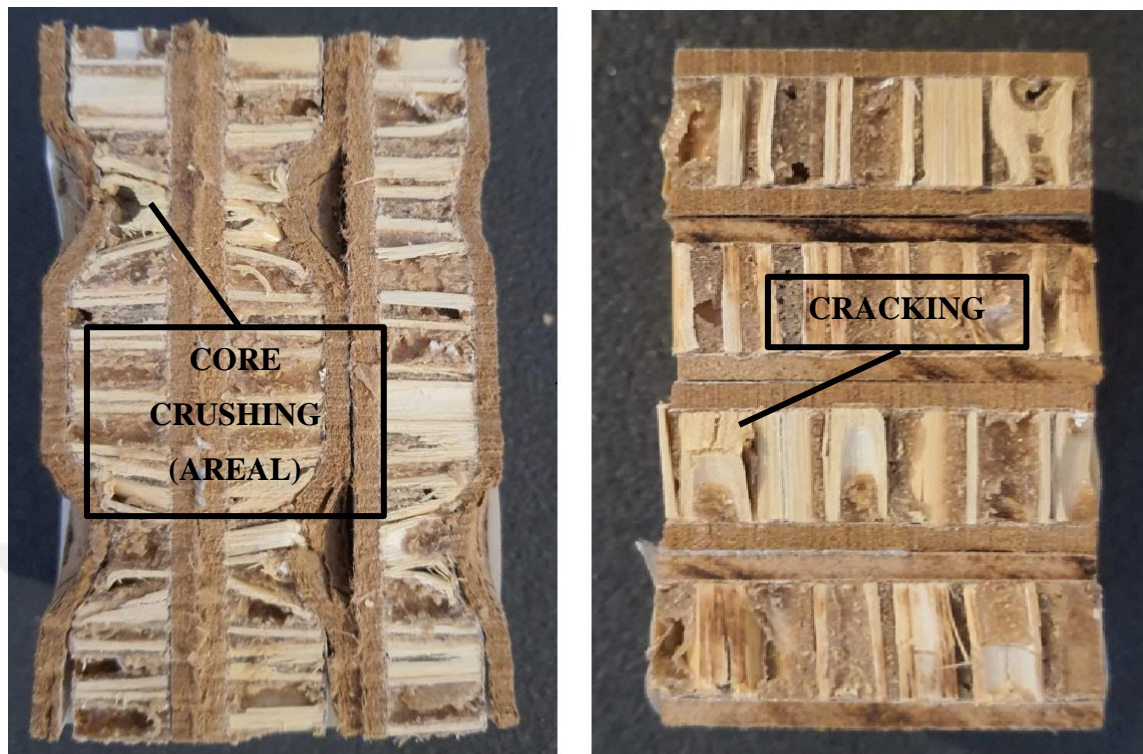


Figure 98. Side Views of Composite-7 After Indentation (left) and Compression (right) Tests.

3.2.3.8 Composite-8 Failure Result

The core of Composite-8, made from hollow bamboo sticks, achieved higher values in both the compression and indentation tests compared to Composite-7. An analysis of the fracture structure revealed that the core crushing from the indentation test was confined solely to the test area. In contrast, the compression test resulted in buckling failures.

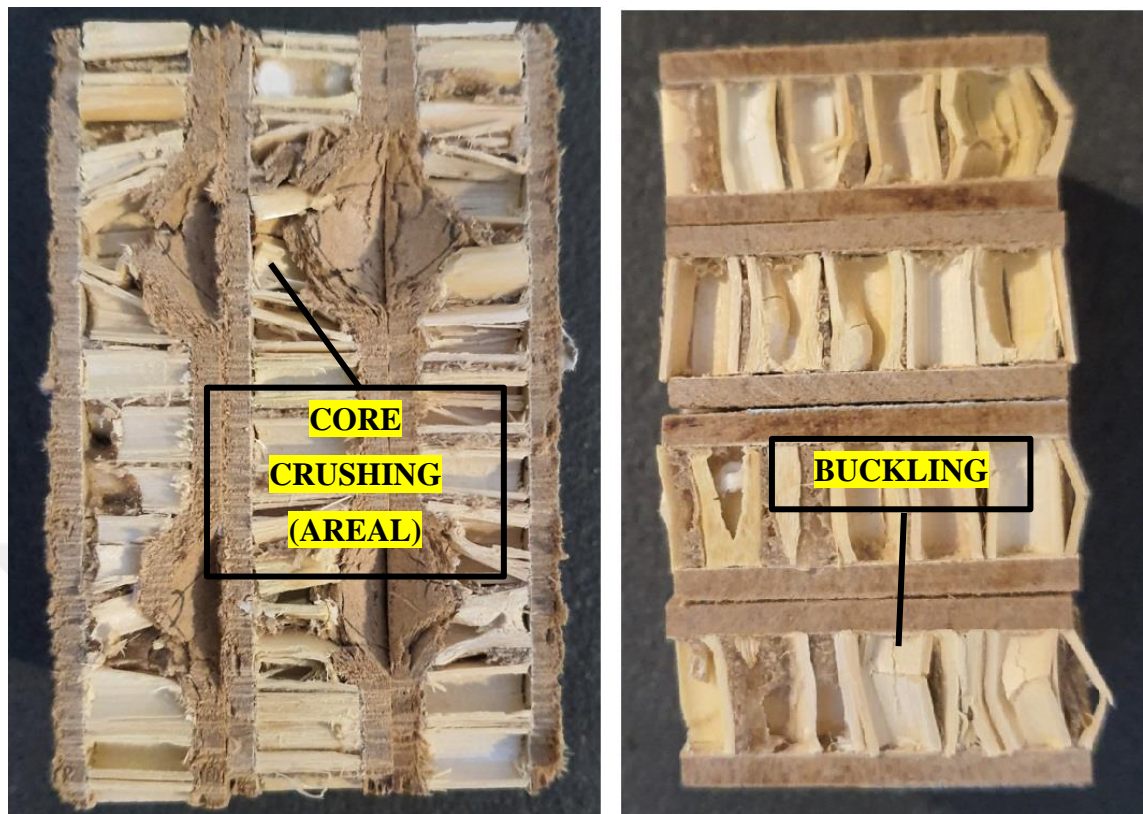


Figure 99. Side Views of Composite-8 After Indentation and Compression Tests.

3.2.3.9 Particleboard Failure Result

The particleboard made from wood chips achieved lower values in both the compression and indentation tests compared to MDF. An analysis of the failure structure revealed that the crushing caused by the indentation test affected the entire sample and compromised the material's structural integrity. On the other hand, the compression test exhibited both crushing and slight barreling failures. After the compression test, the height of the particleboard decreased from 18 mm to 14 mm.

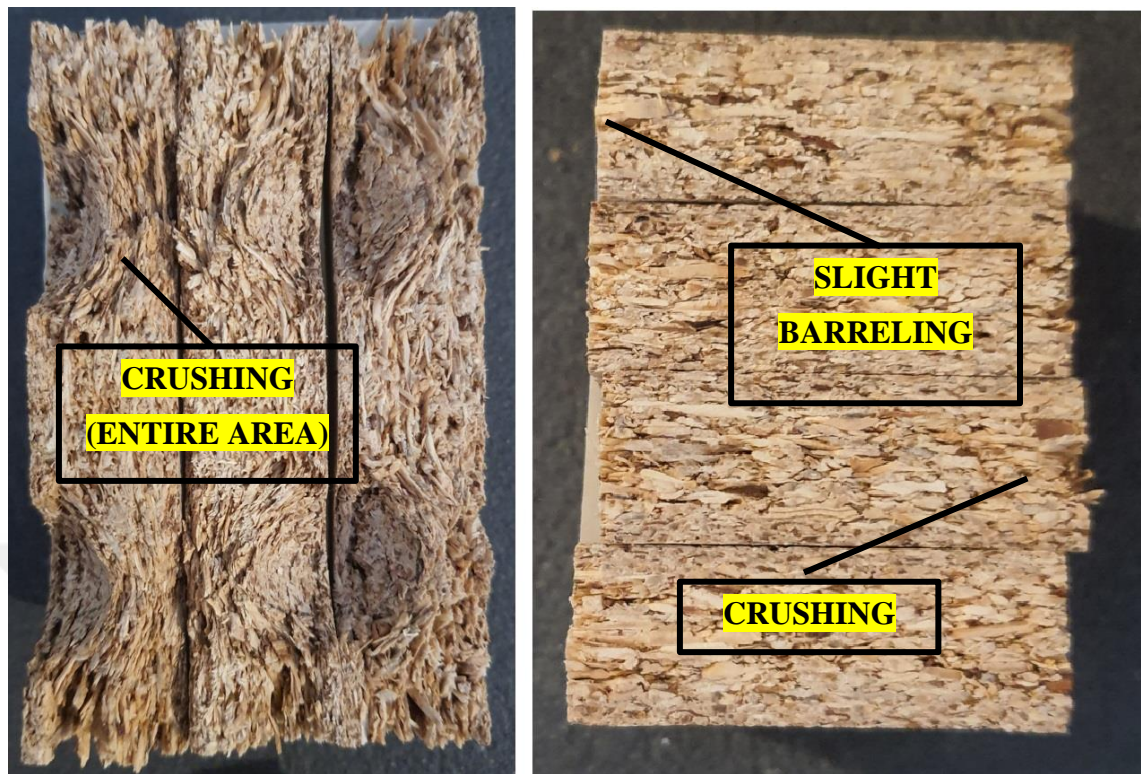


Figure 100. Side Views of Particleboard After Indentation (left) and Compression (right) Tests.

3.2.3.10 MDF Failure Result

The MDF made from wood fibers achieved higher values in both the compression and indentation tests compared to particleboard. An analysis of the failure structure revealed that the crushing caused by the indentation test affected the entire sample and compromised the material's structural integrity. In contrast, the compression test resulted in plastic deformation. After the compression test, the height of the MDF decreased from 18 mm to 16 mm.

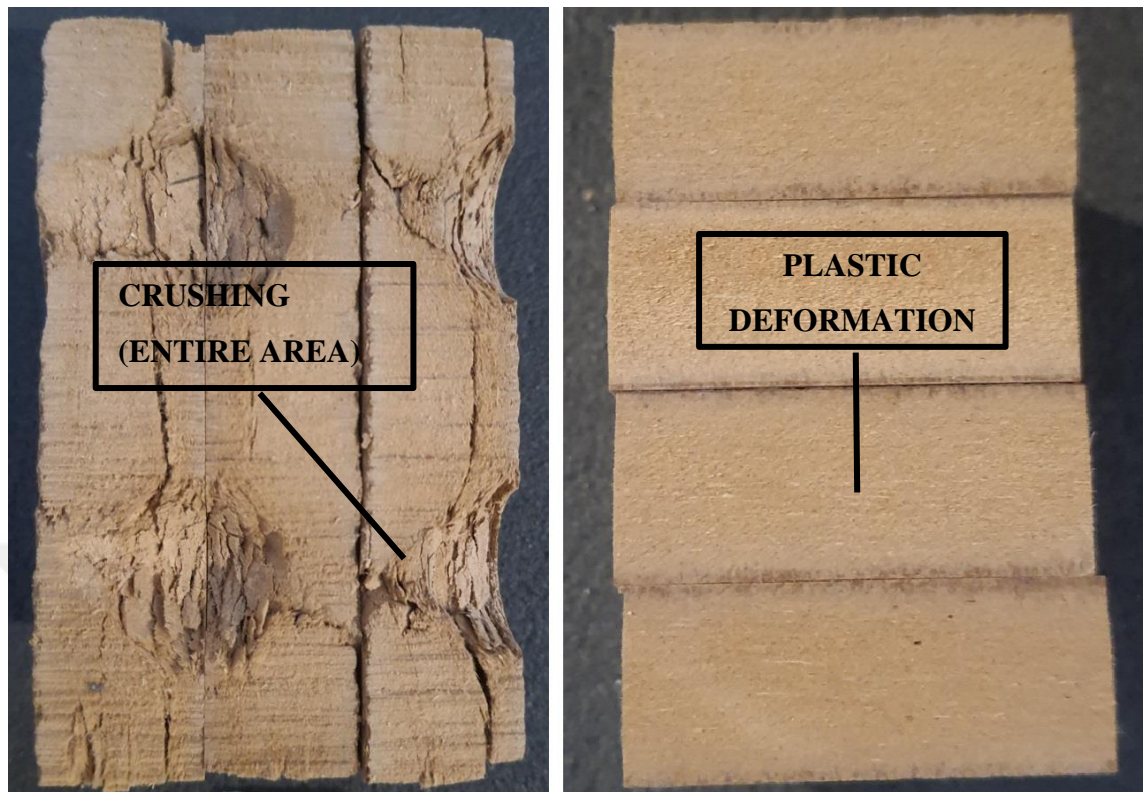


Figure 101. Side Views of MDF After Indentation (left) and Compression (right) Tests.

3.2.4 Thermal Conductivity Test Results

Thermal conductivity test results are shown in the chart below. Hollow bamboo composites consistently revealed lower thermal conductivity results compared to filled ones. The lowest and most optimal thermal conductivity value, 0.0900 W/mK, was observed in the D3+H composite. The highest value, 0.1214 W/mK, was obtained with the D3+S+F composite.

Table 4. Thermal conductivity test results.

Thermal Conductivity W/mK	FILLED	HOLLOW
D4	0,1005	0,0933
PU	0,1031	0,0978
D3	0,1182	0,0900
D3+S	0,1214	0,1194

3.2.5 Specific Weight Test Results

The lightest average specific weight, 428 kg/m³, was obtained with the D4+H composite, making it nearly 39% lighter than MDF.

Table 5. Average specific weights (density).

DENSITY (kg/m ³)	FILLED	HOLLOW
D4	503	428
PU	464	463
D3	687	476
D3+S	645	586
PARTICLEBOARD		610
MDF		700

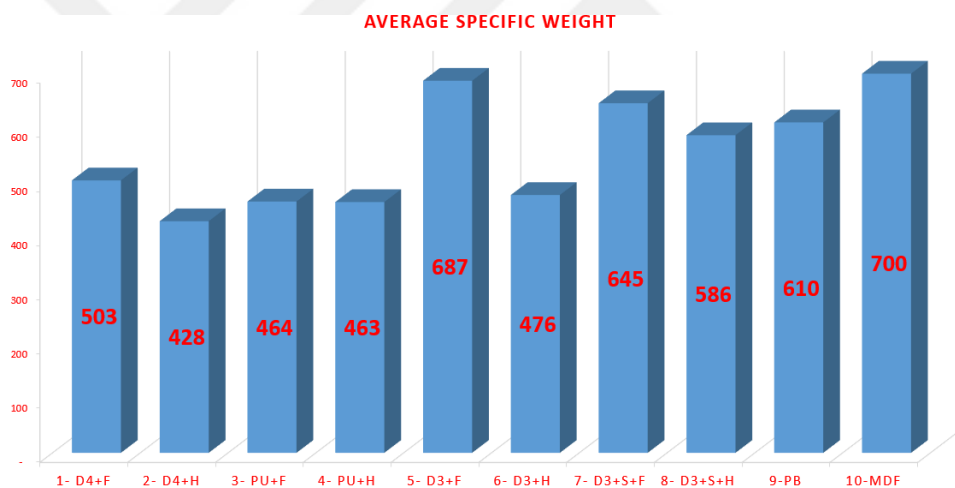


Figure 102. Average specific weights.

CHAPTER 4

DISCUSSION-CONCLUSION AND RECOMMENDATIONS

4.1. Discussion

The experimental results from this study reveal that bamboo-based sandwich composites possess remarkable potential as sustainable and high-performance alternatives to traditional particleboard and MDF. The following discussion delves into the implications of the findings and their relevance to engineering and material science.

4.1.1 Mechanical Properties:

Compression Strength of the bamboo composites exhibited sufficient compression strength compared to traditional materials. Notably, the D4+F composite demonstrated the highest compression strength, which can be attributed to the synergy between the D4 adhesive and the filled bamboo structure. This finding suggests that bamboo composites could replace particleboard and MDF in applications where high compressive loads are expected.

Indentation strength, similarly, the indentation tests showed that the D4+F composite outperformed other samples. This highlights the potential of bamboo composites for applications that require resistance to localized pressure, such as flooring and furniture surfaces. The improved performance with D4 adhesive suggests that adhesive selection is critical for optimizing the mechanical properties of bamboo composites.

The study found that hollow bamboo composites generally had lower thermal conductivity than filled ones, with the D3+H composite exhibiting the best thermal insulation properties. This characteristic is particularly advantageous for applications in building insulation, where reducing thermal conductivity is crucial for energy efficiency.

The ability to manipulate thermal properties by varying the internal structure of the bamboo composites adds versatility to their application potential.

Specific weight of the bamboo-based composites were significantly lighter than MDF, with the D4+H composite being the lightest. This weight reduction, coupled with high mechanical strength, makes bamboo composites highly suitable for lightweight construction applications, such as portable structures and transportable furniture. The reduced weight also implies lower transportation costs and easier handling during construction and installation.

The orientation of bamboo sticks (vertical) and the internal state (hollow or filled) play crucial roles in determining the overall properties of the composites. The study's results suggest that vertically oriented bamboo sticks with filled interiors (D4+F) provide the best combination of mechanical strength and structural integrity. This insight can guide future production processes to tailor bamboo composites for specific engineering requirements.

Bamboo is a fast-growing and renewable resource, making it an environmentally friendly alternative to wood-based materials like particleboard and MDF. The use of bamboo reduces the carbon footprint of composite materials and promotes sustainable forestry practices. Additionally, bamboo-based composites can be produced with minimal environmental impact, aligning with global efforts to combat climate change and promote sustainable development.

4.2. Conclusion and Recommendations

This study conclusively demonstrates the significant potential of bamboo-based sandwich composites as sufficient alternatives to traditional particleboard and MDF. The findings highlight the advantages of bamboo composites in terms of mechanical properties, thermal conductivity, and specific weight, underscoring their suitability for various applications in the furniture and construction industries.

Mechanical Properties of the bamboo-based composites, particularly those using D4 adhesive and filled bamboo sticks (D4+F), exhibited the highest compression and

indentation strengths. These properties make them highly suitable for applications requiring high load-bearing capacity and surface durability.

Composite-1 (D4+F) demonstrated 194% higher results than MDF in the compression test after a 2 mm displacement, and 45% higher results in the indentation test, according to the specific stress-displacement graph. This indicates that Composite-1 has greater resistance to deformation forces.

The hollow bamboo composites, particularly those using D3 adhesive (D3+H), demonstrated the best thermal conductivity with a rate of 0,0900 W/mK. This makes them ideal for applications where effective thermal insulation is essential.

The specific weight of the bamboo-based composites, particularly the D4+H composite with a density of 428 kg/m³, was 39% lighter than MDF, making them ideal for lightweight applications where weight savings are crucial.

The type of adhesive used in the composites played an important role in determining the mechanical properties. D4 adhesive consistently produced the best results in both compression and indentation tests, while D3 adhesive offered the best thermal conductivity when used with hollow bamboo sticks.

The orientation of bamboo sticks sorted vertically, and the use of different adhesives and states (hollow or filled) have significant impacts on the performance of the composite materials. These variables provide flexibility in tailoring the properties of the composites to specific applications.

In conclusion, bamboo-based natural composite materials represent a promising advancement in the development of sustainable and high-performance engineered wood products. Their application in the furniture industry can offer substantial benefits, including sufficient mechanical properties, lightness, and a low carbon footprint. These advantages not only support the industry's transition towards more sustainable practices but also enhance product performance and environmental responsibility. Continued research and development in this field could unlock even greater potential, solidifying bamboo as a key material in the future of sustainable manufacturing.

4.2.1 Recommendations

Continued research should focus on optimizing the adhesive formulations and exploring other natural adhesives to enhance the mechanical properties and sustainability of bamboo composites further.

Industries should consider adopting bamboo-based composites for applications requiring high strength, durability, and thermal insulation. Potential areas include flooring, furniture, and structural panels.

Further studies should explore the effects of different orientations of bamboo sticks (vertical and horizontal) on the composite properties to optimize performance for specific applications.

Promoting the use of bamboo-based materials can significantly reduce the carbon footprint of the construction and furniture industries. Policymakers and industry leaders should advocate for integrating bamboo composites into building codes and material standards.

Conduct a detailed cost analysis comparing bamboo-based composites with traditional materials to evaluate economic feasibility and identify cost-saving opportunities in large-scale production.

Develop and test new product prototypes using bamboo-based composites to expand their application range and demonstrate their practicality and benefits in real-world scenarios.

Implement standardized testing protocols, like the TSE tests conducted for MDF and particleboards, for bamboo composites to establish benchmarks and ensure consistent quality and performance across different applications.

By focusing on these areas, the adoption of bamboo-based composites can be accelerated, leading to more sustainable, efficient, and high-performance materials in the furniture and construction industries.

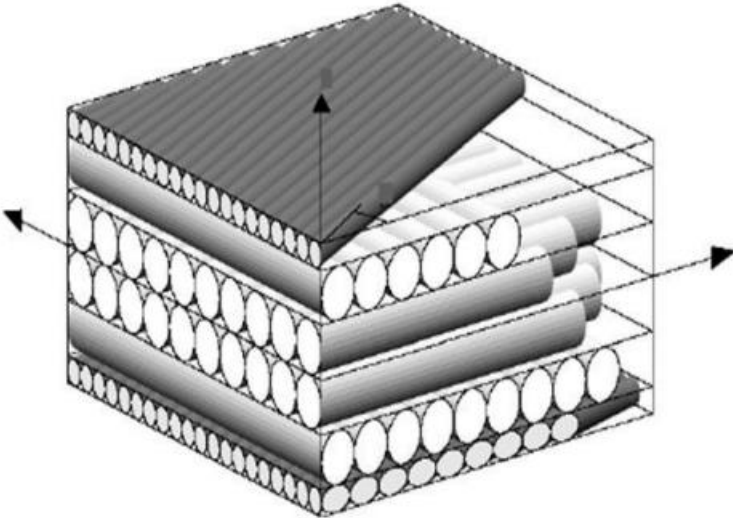
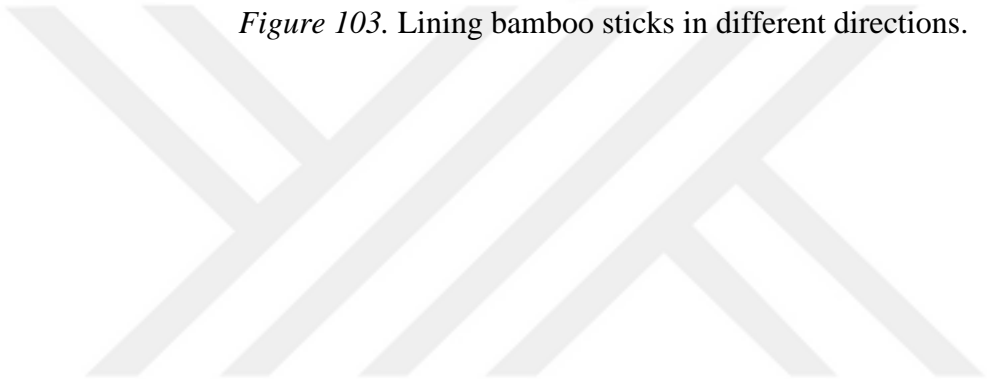


Figure 103. Lining bamboo sticks in different directions.



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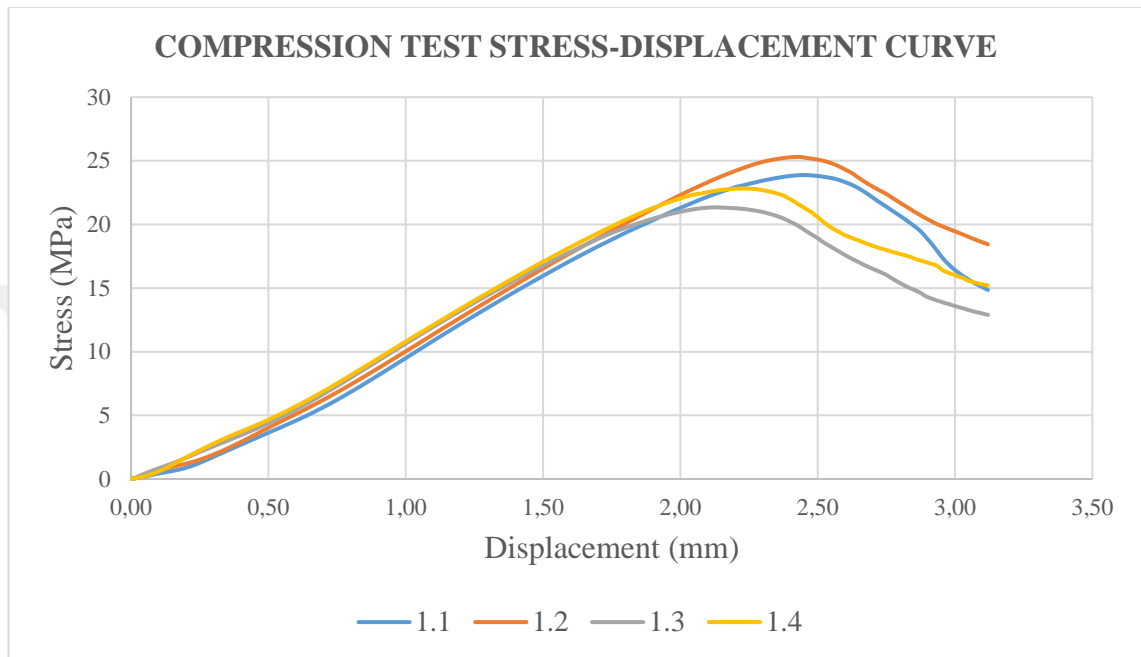
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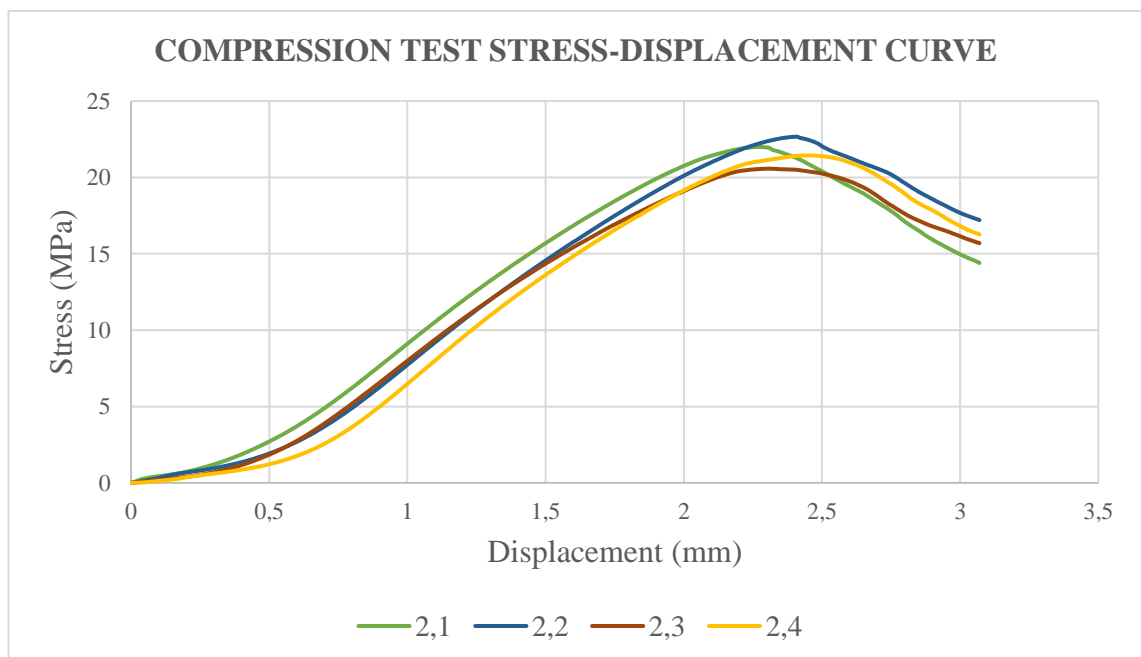
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APPENDICES

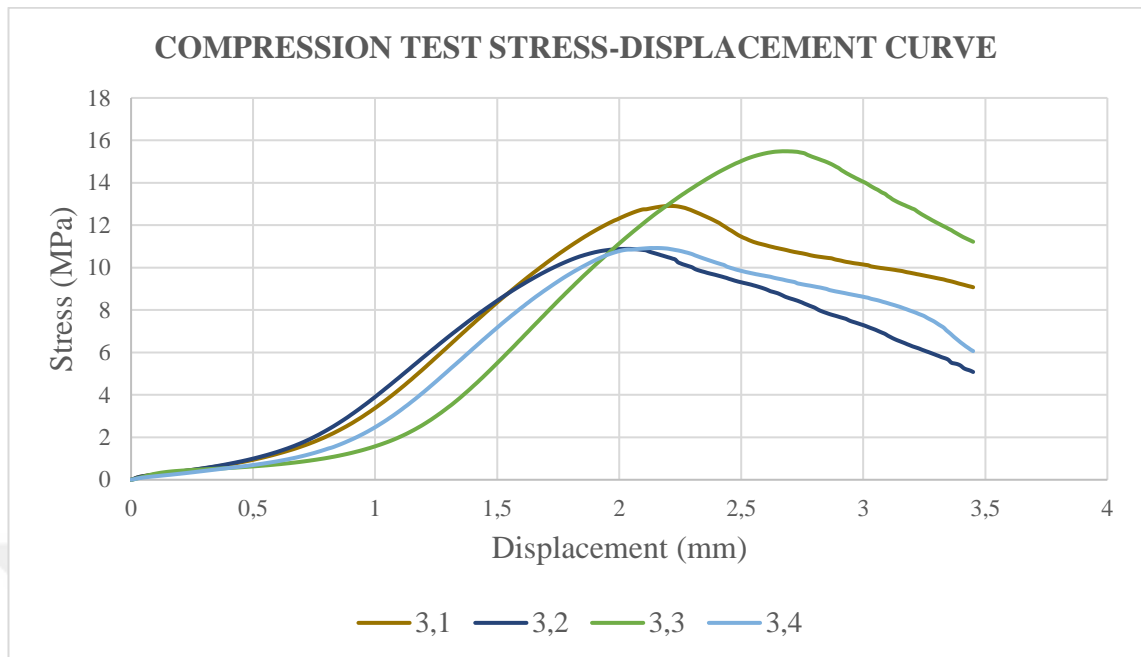
Annex 1. Compression Test Results



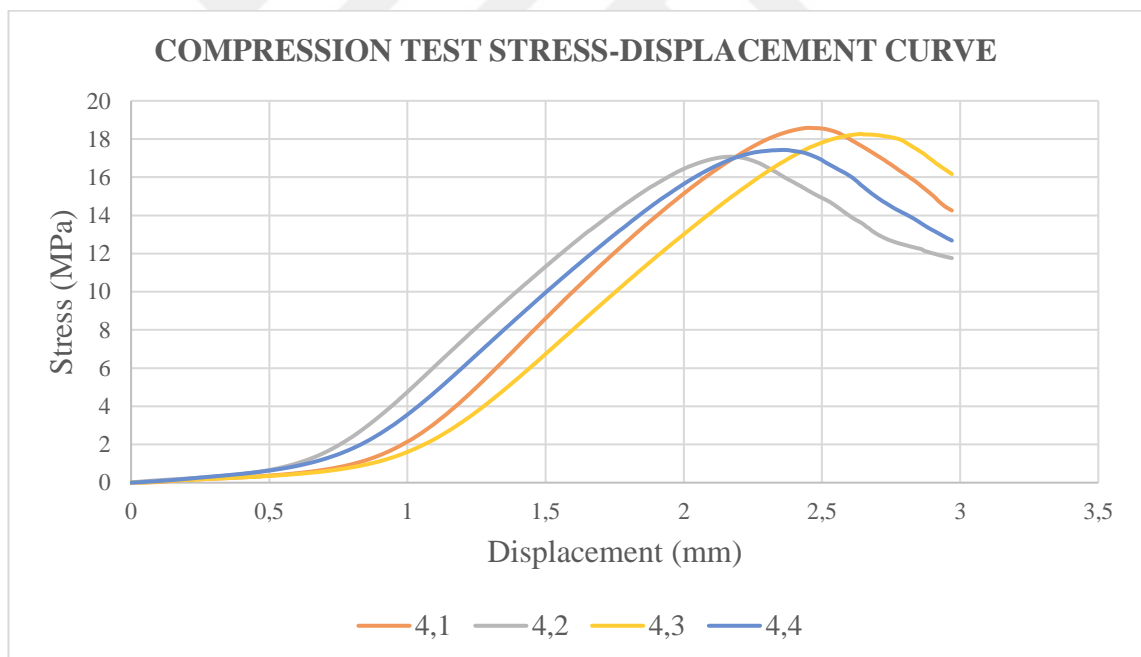
Composite-1 (D4+F) compression samples curves.



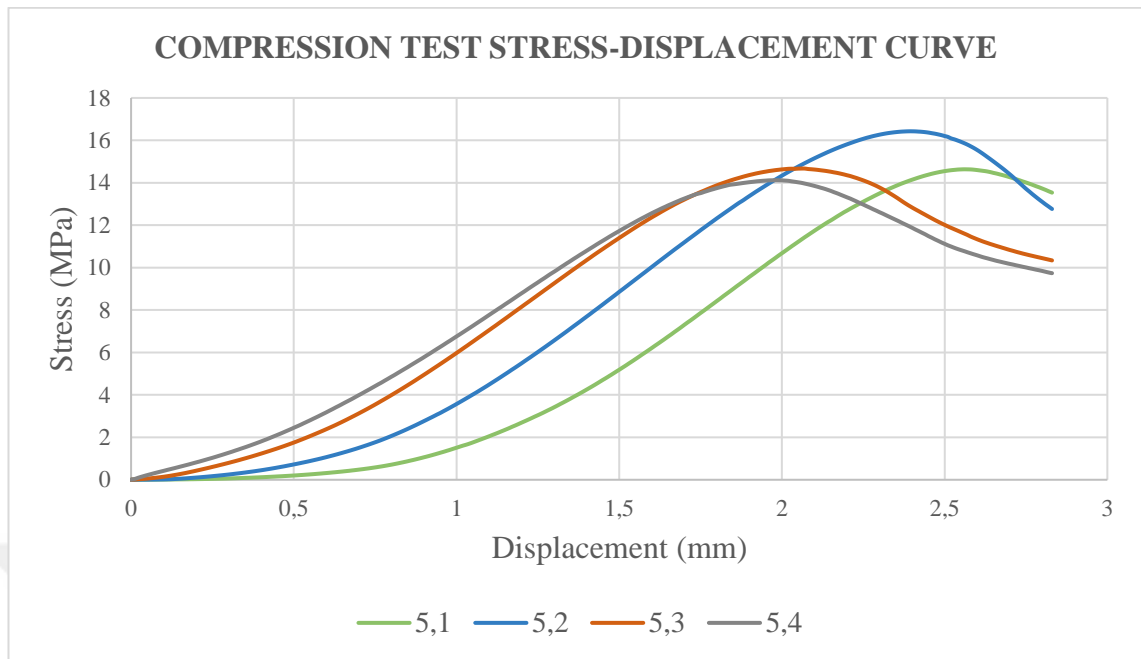
Composite-2 (D4+H) compression test samples curves.



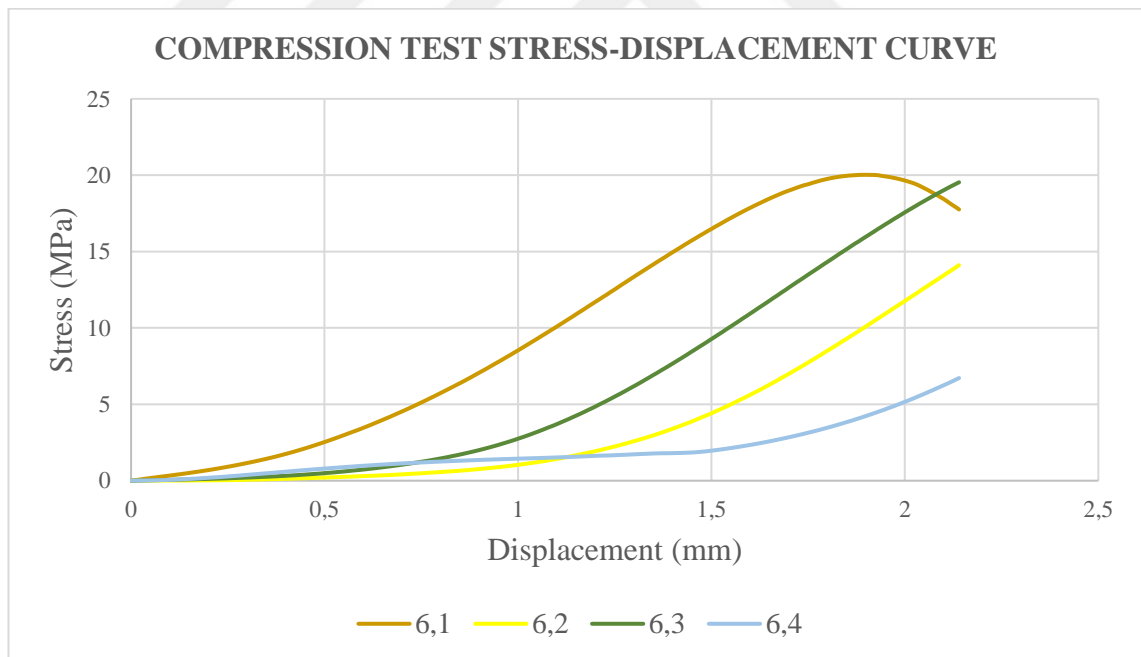
Composite-3 (PU+F) compression test samples curves.



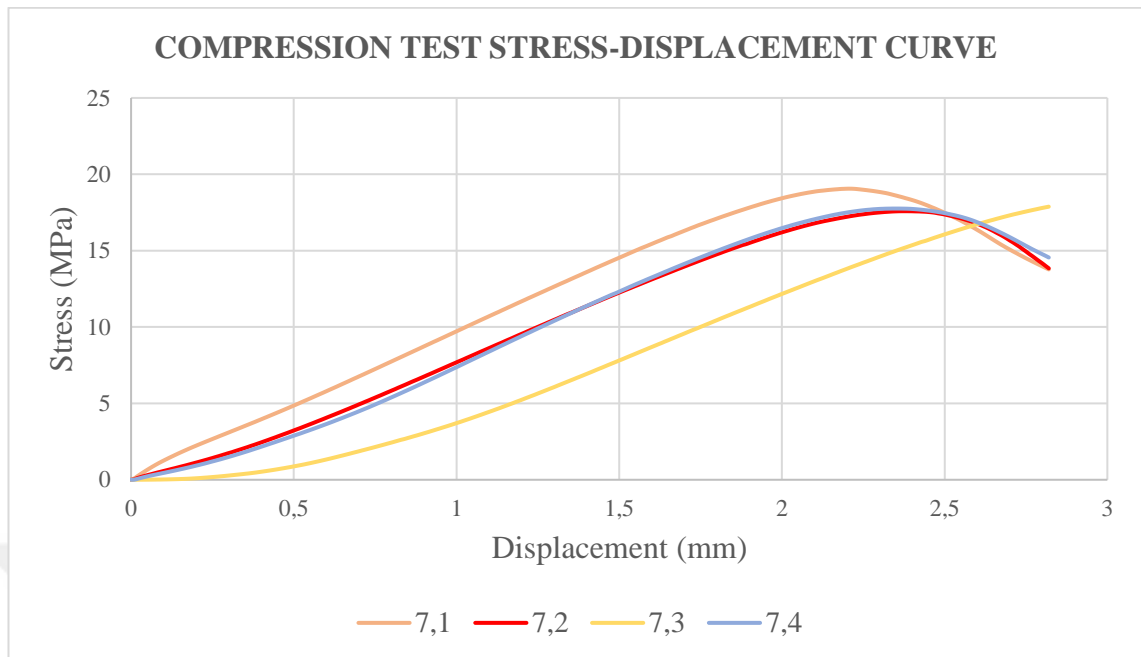
Composite-4 (PU+H) compression test samples curves.



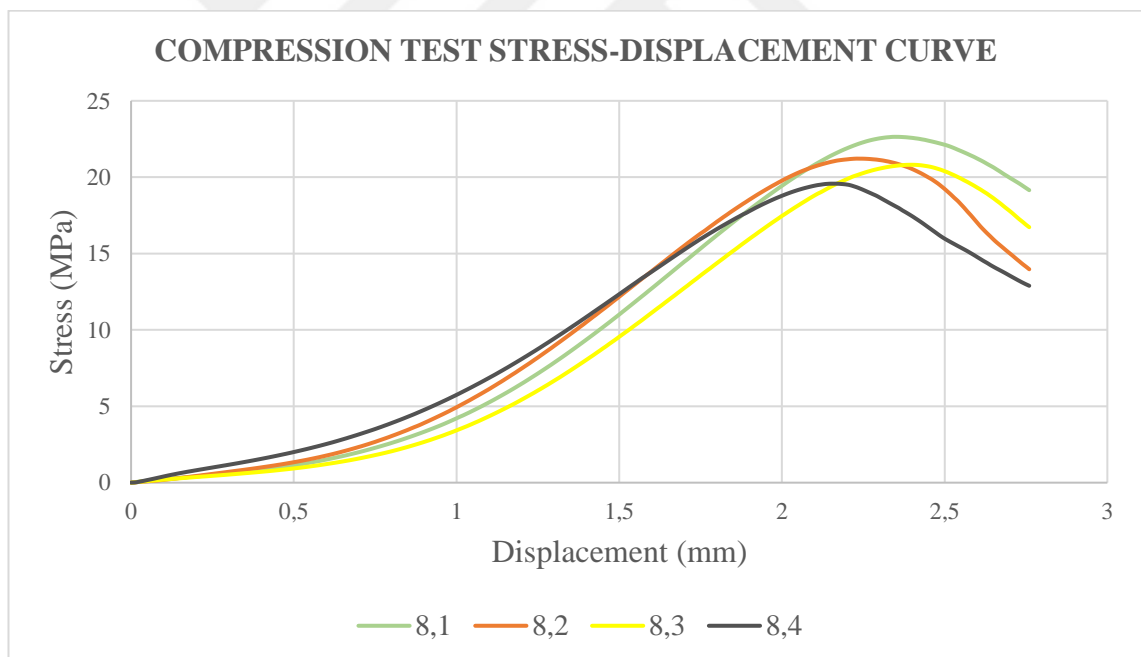
Composite-5 (D3+F) compression test samples curves.



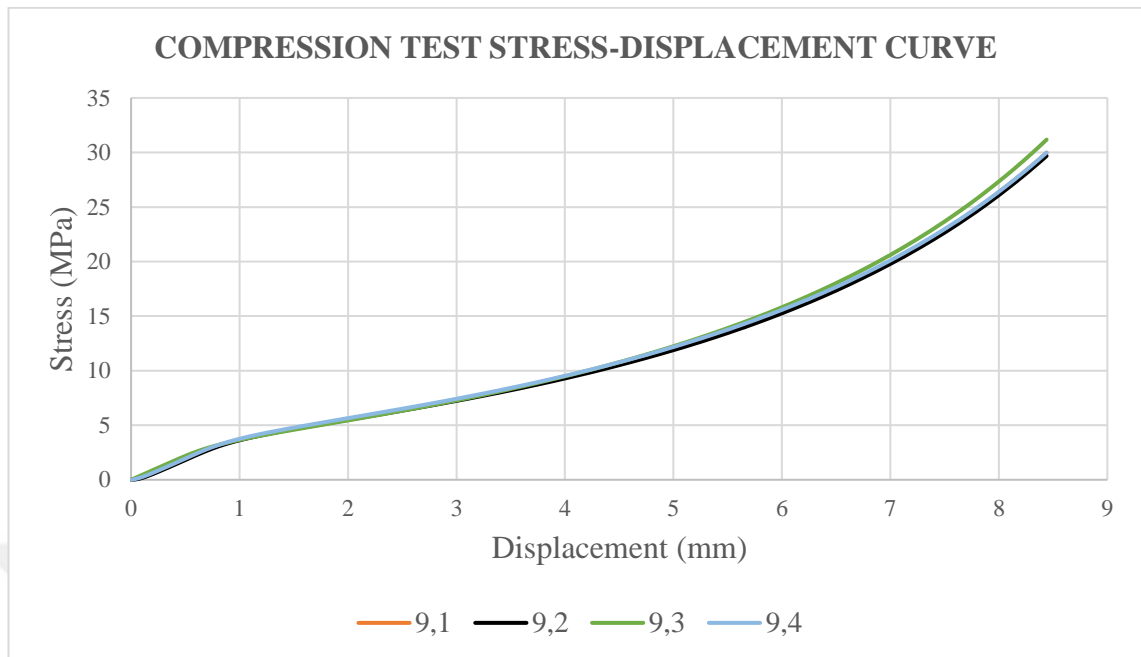
Composite-6 (D3+H) compression test samples curves.



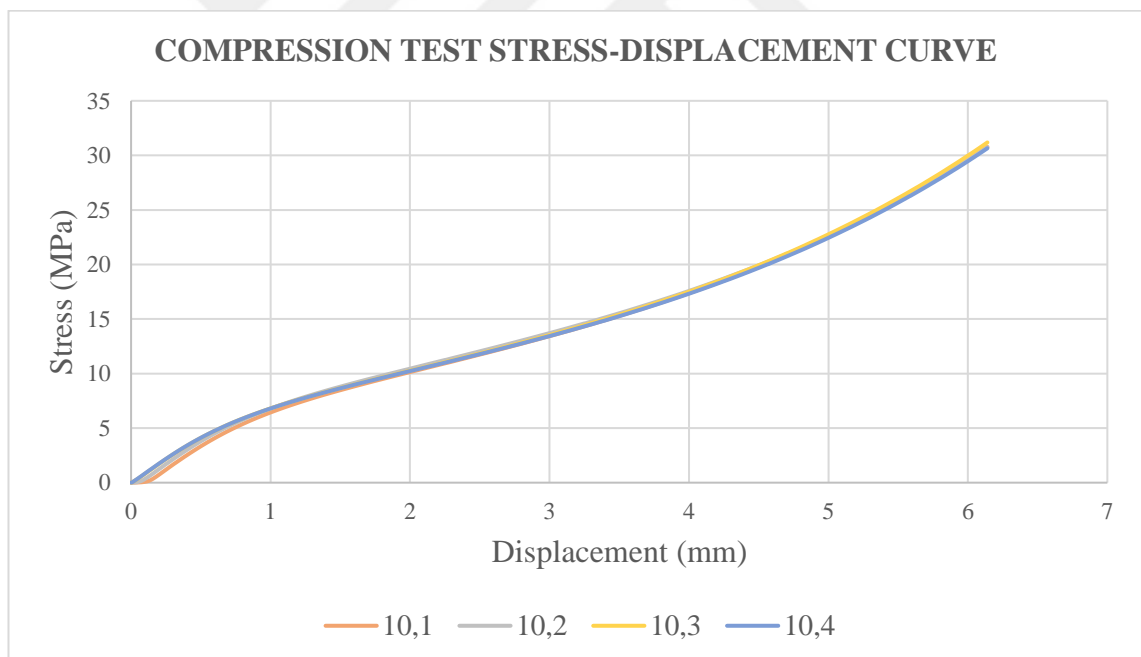
Composite-7 (D3+S+F) compression test samples curves.



Composite-8 (D3+S+H) compression test samples curves.

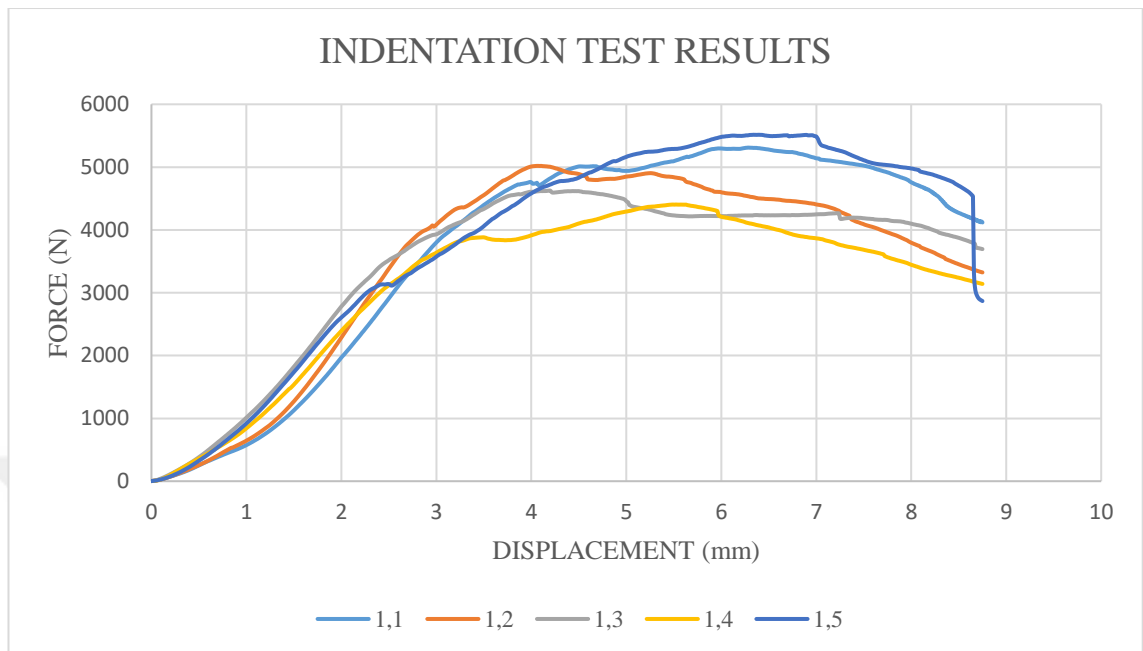


Particleboard compression test samples curves.

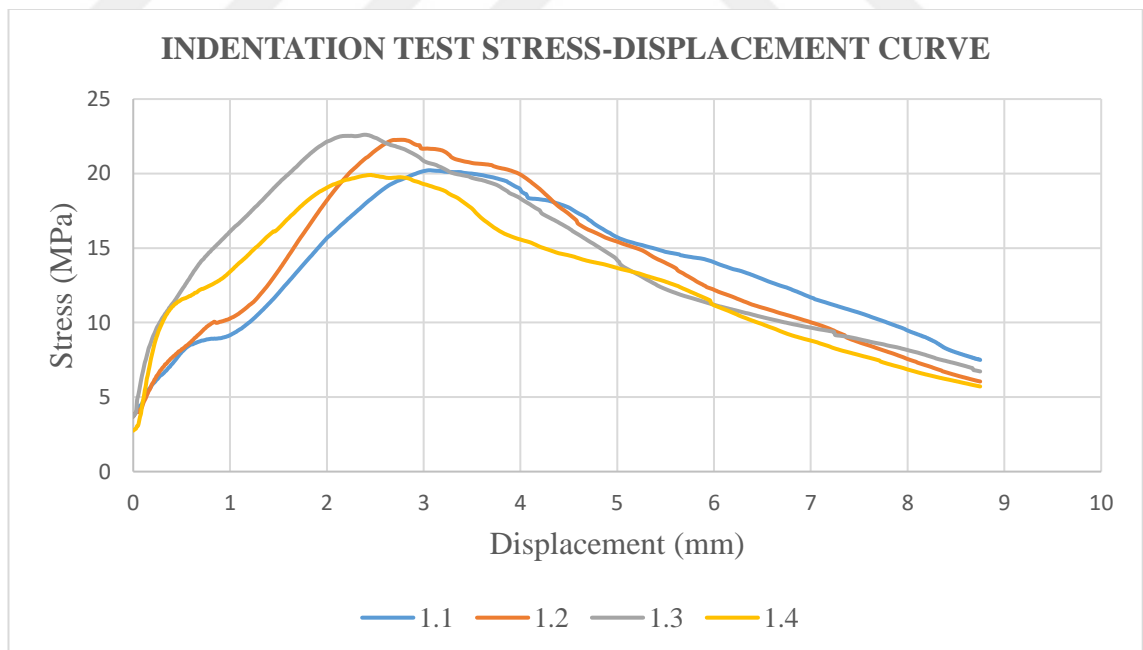


MDF compression test samples curves.

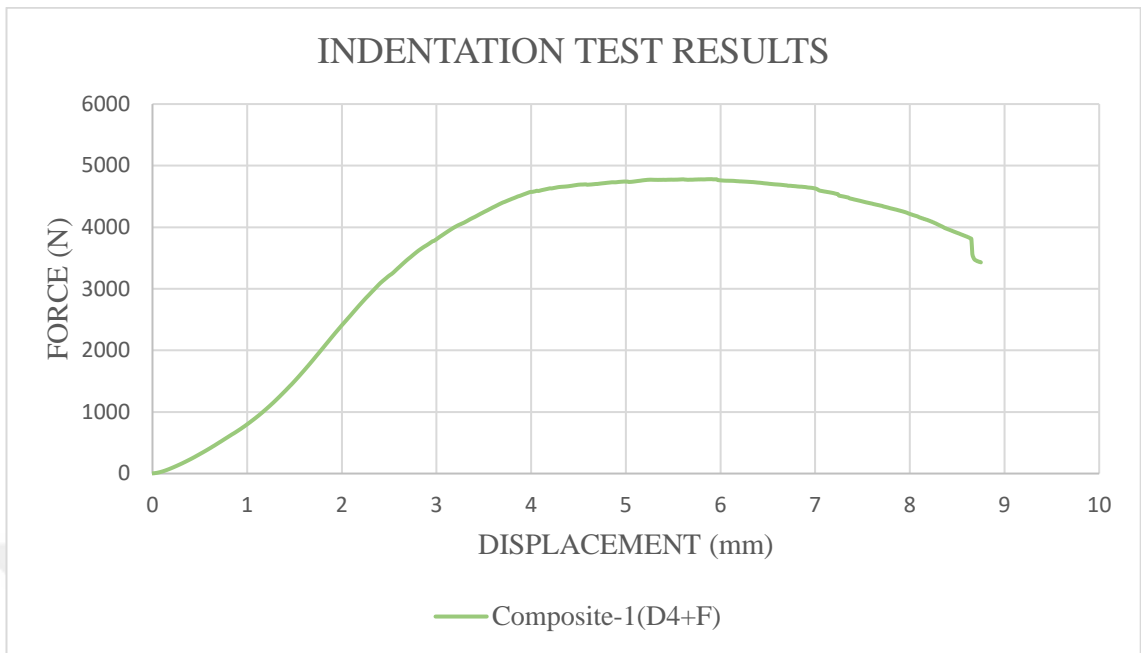
ANNEX 2. Indentation Test Results



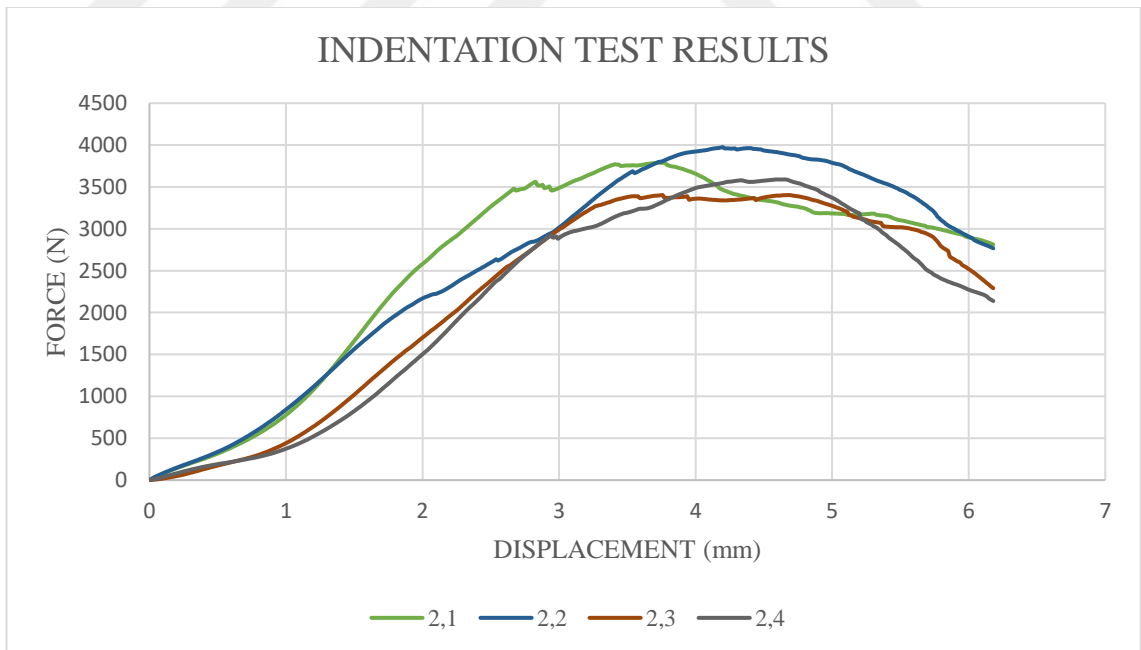
Composite-1 (D4+F) indentation test samples curves.



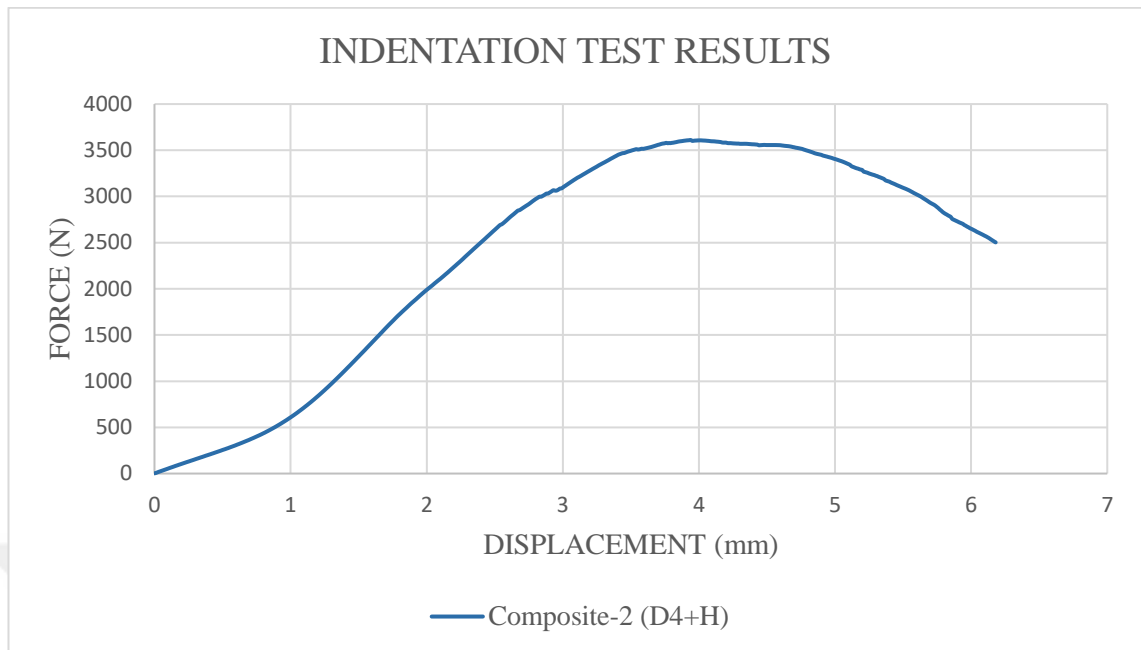
Composite-1 (D4+F) indentation test samples curves (stress-displacement).



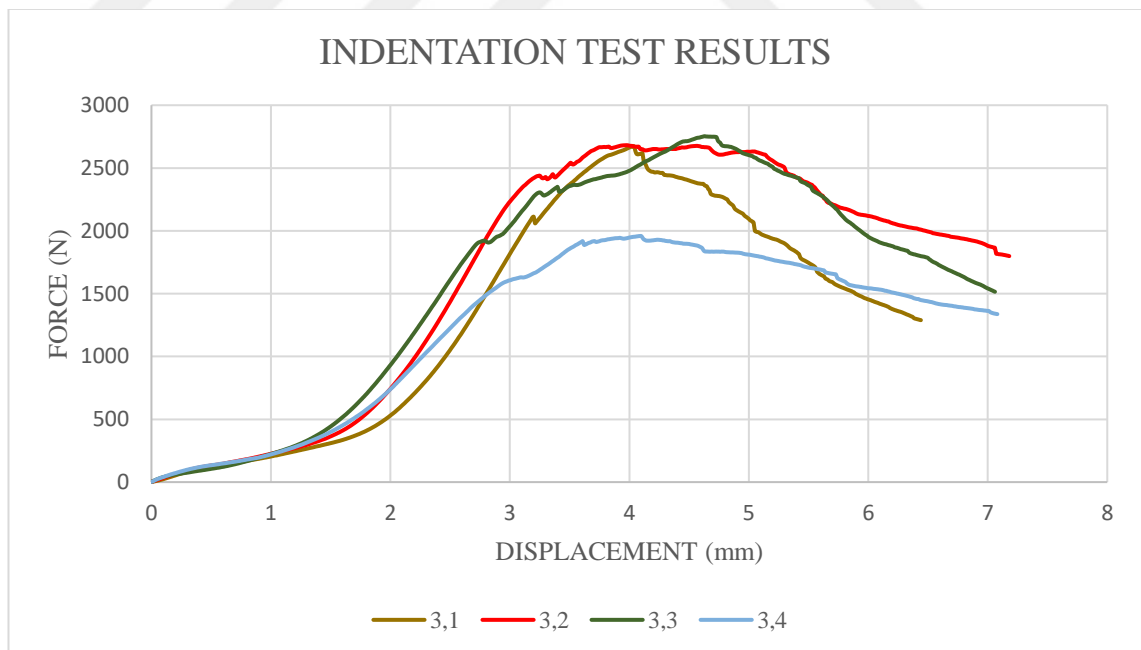
Composite-1(D4+F) compression test average curve.



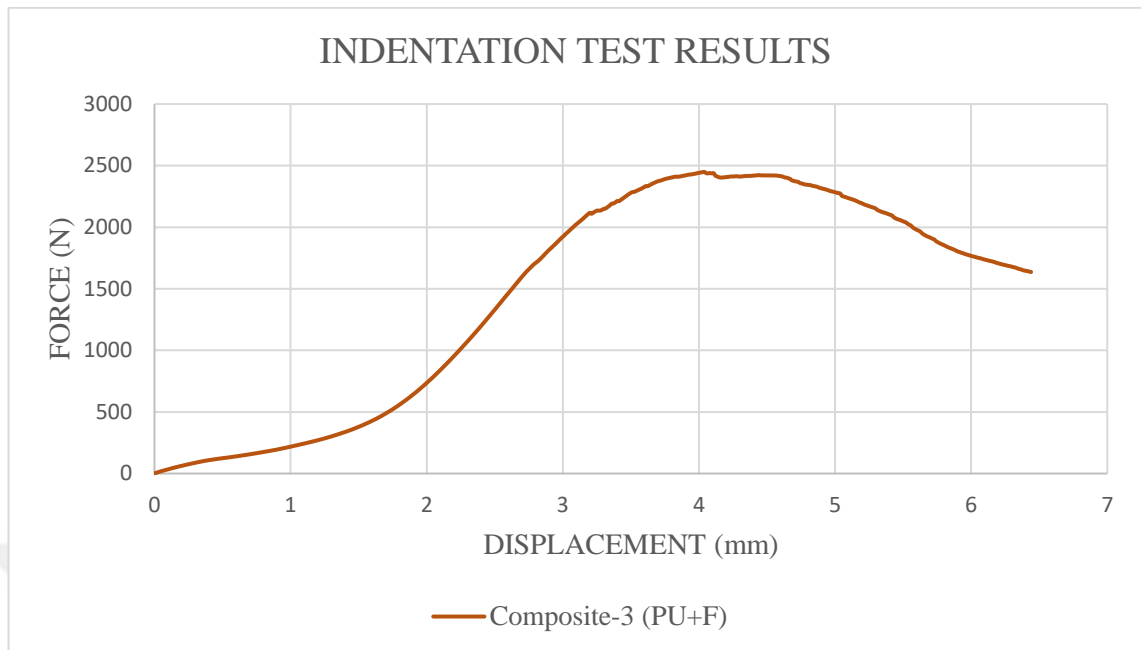
Composite-2 (D4+H) indentation test samples curves.



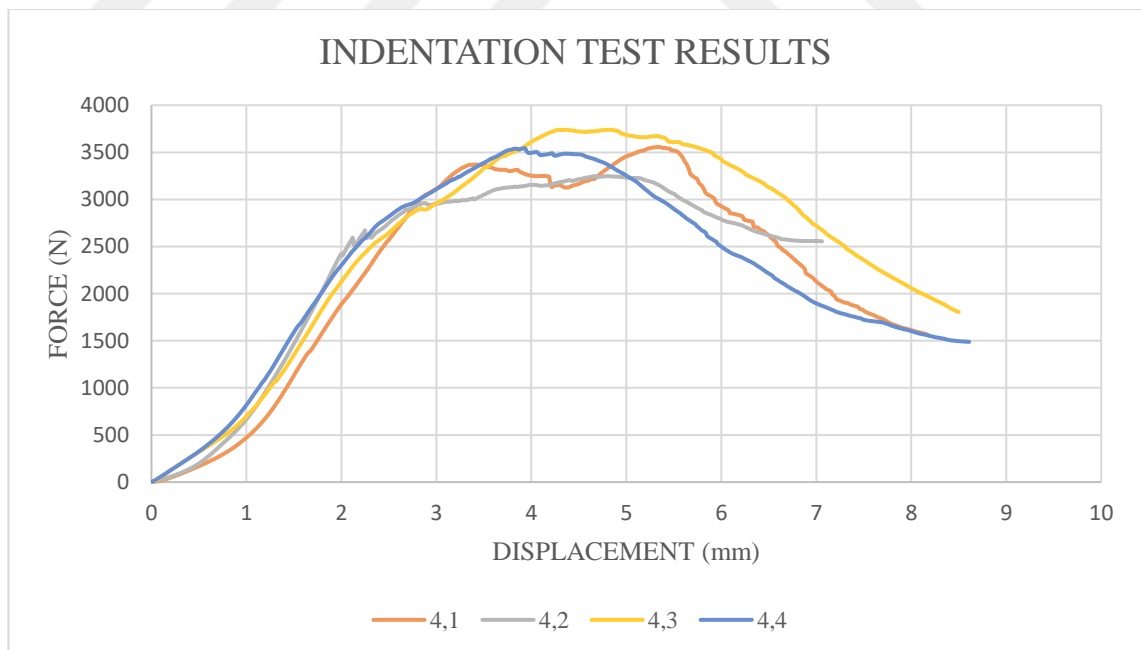
Composite-2 (D4+H) indentation test average curve.



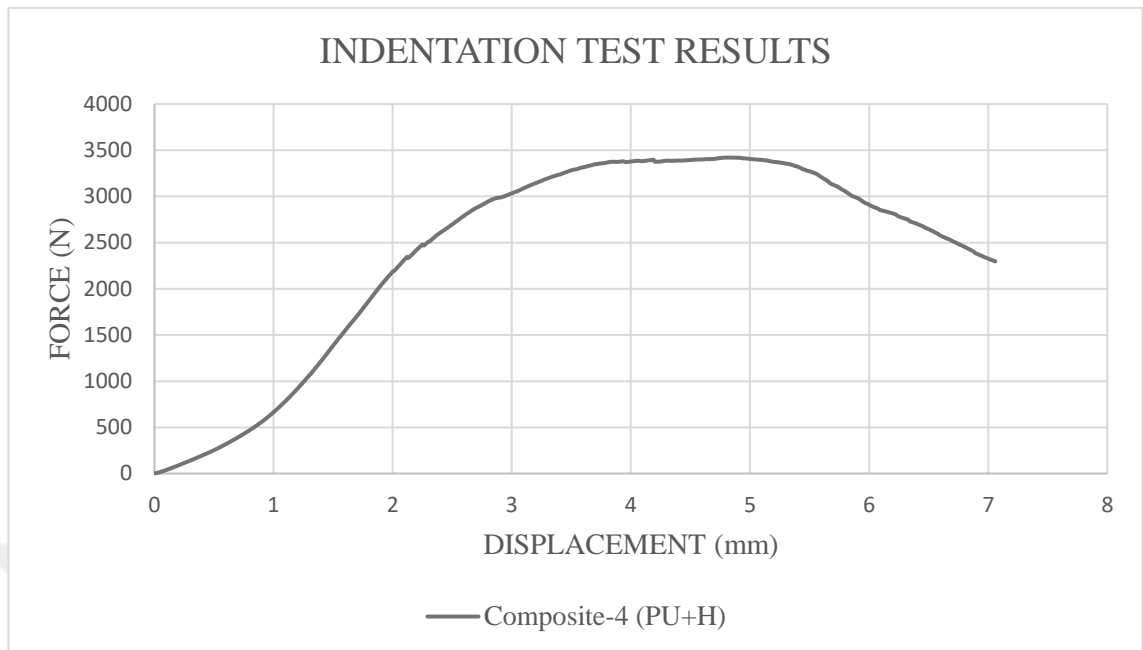
Composite-3 (PU+F) indentation test samples curves.



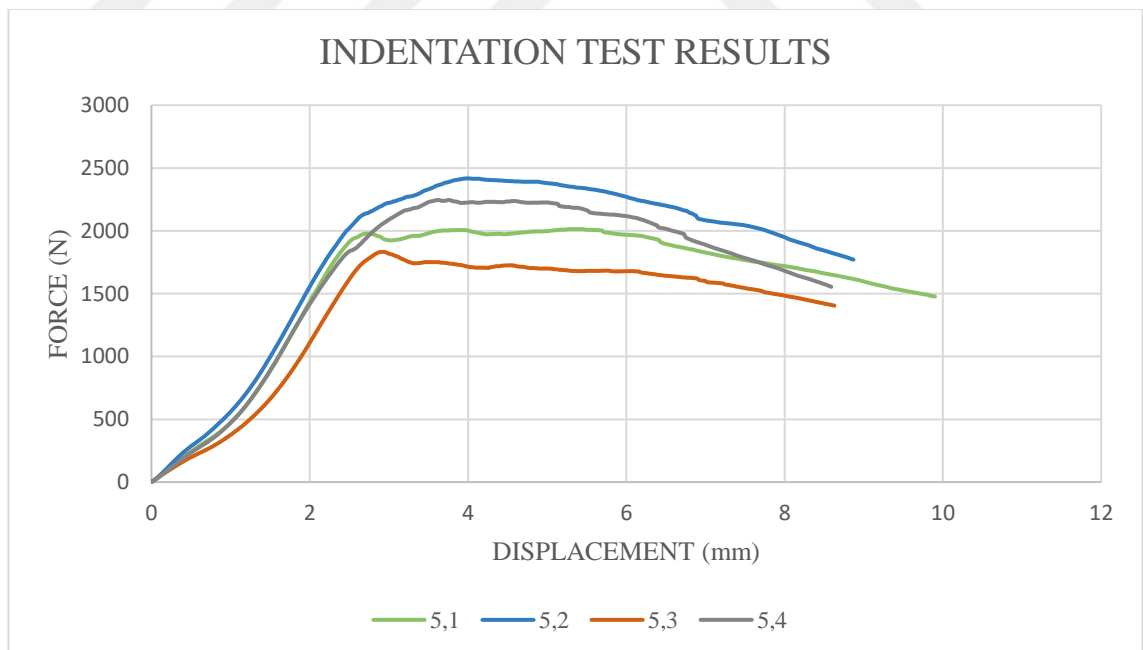
Composite-3 (PU+F) indentation test average curve.



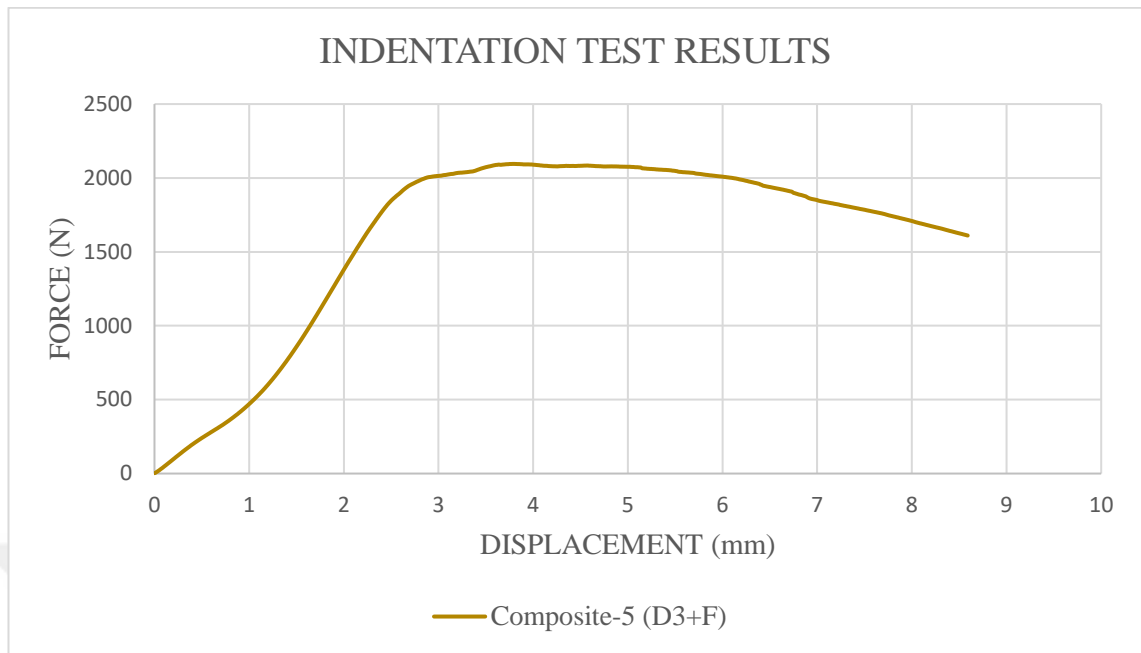
Composite-4 (PU+H) indentation test samples curves.



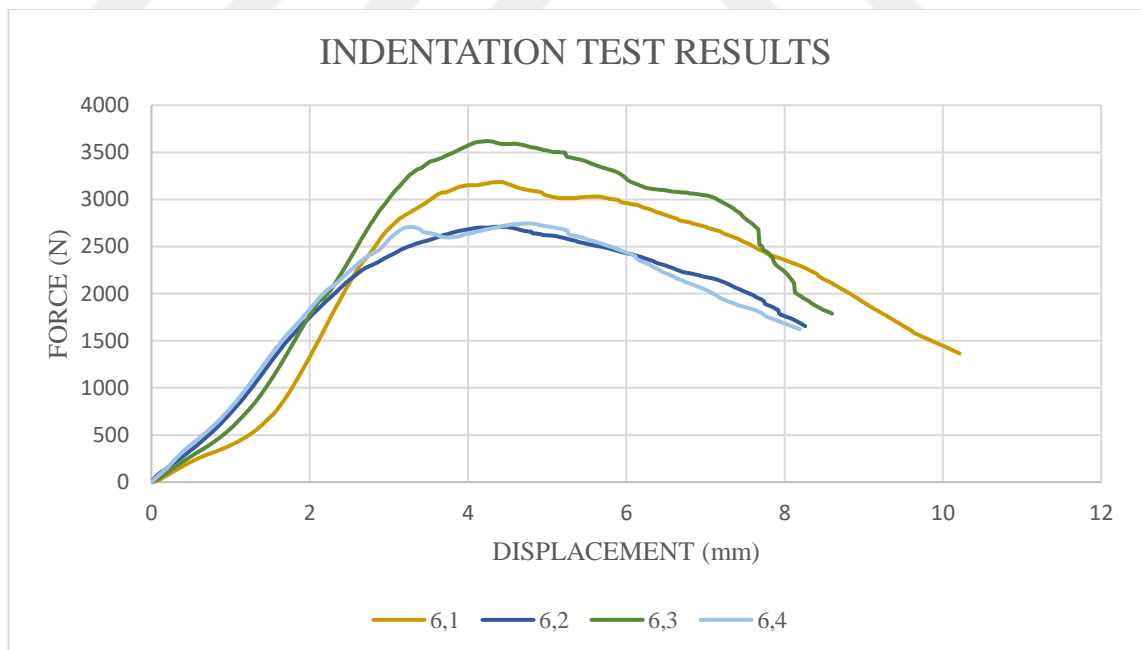
Composite-4 (PU+H) indentation test average curve.



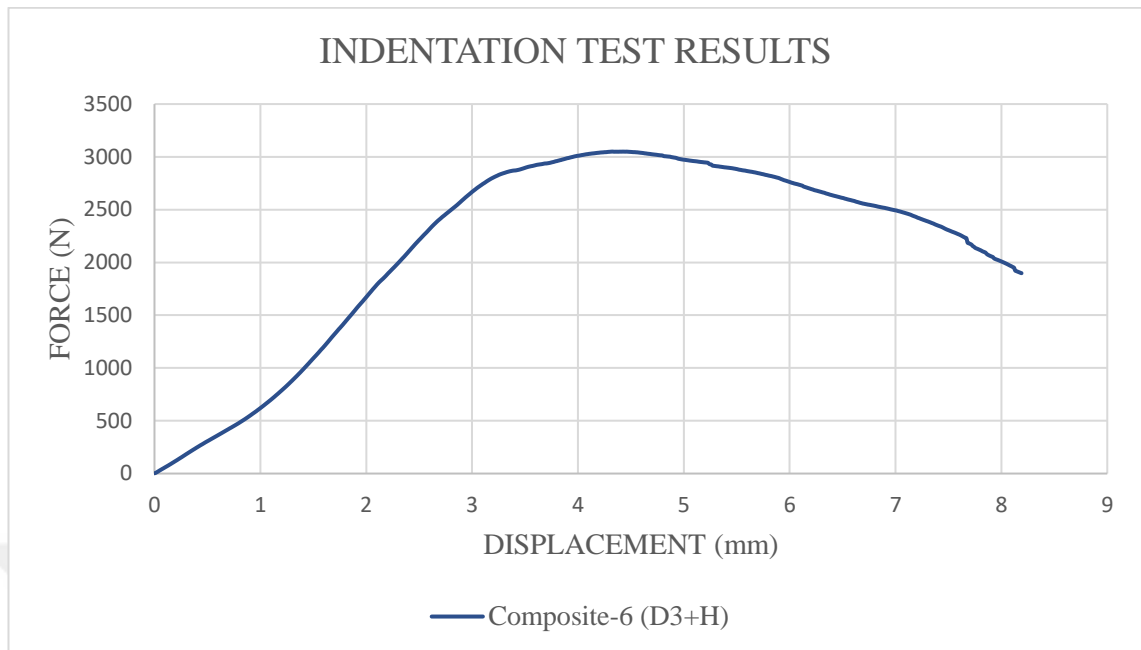
Composite-5 indentation test samples curves.



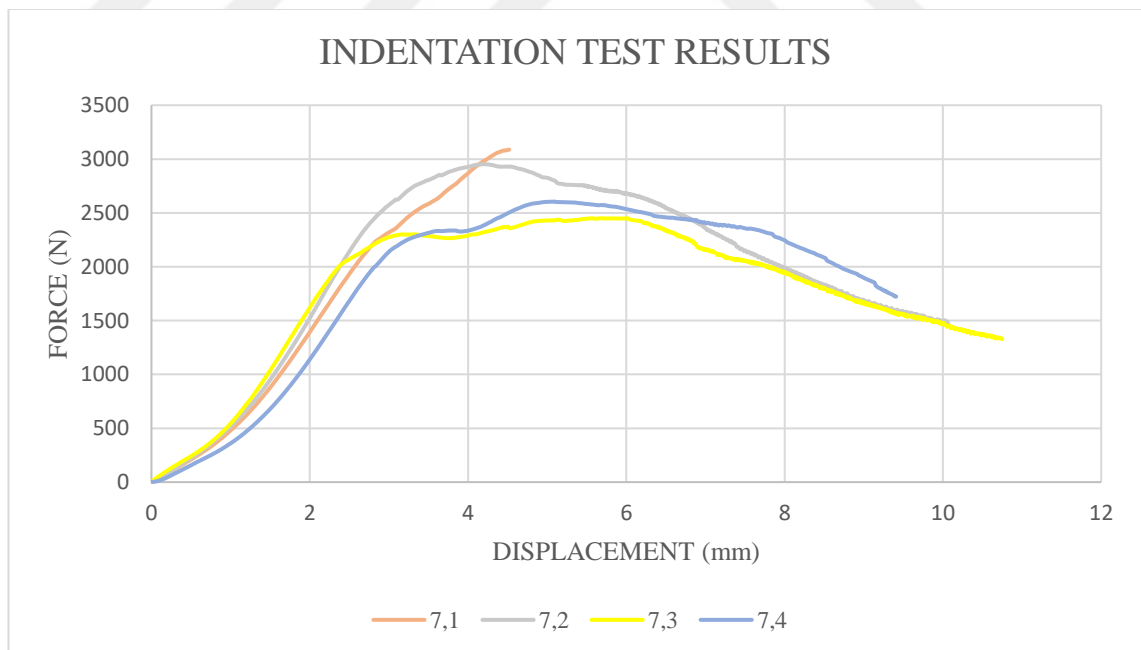
Composite-5 (D3+F) indentation test average curve.



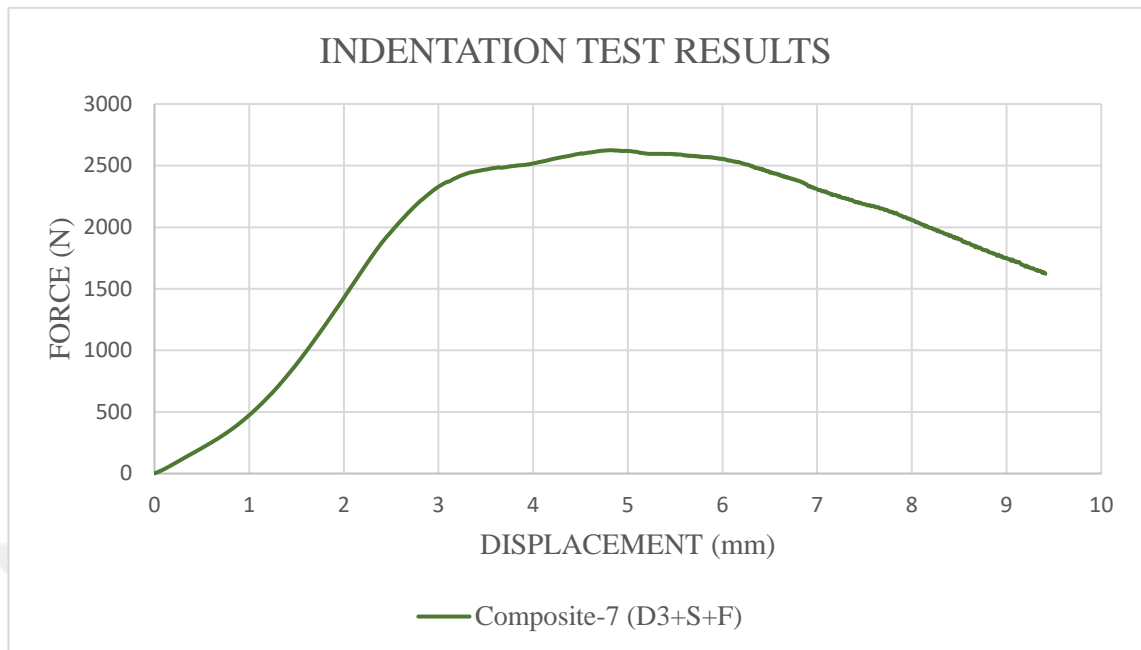
Composite-6 (D3+H) indentation test samples curves.



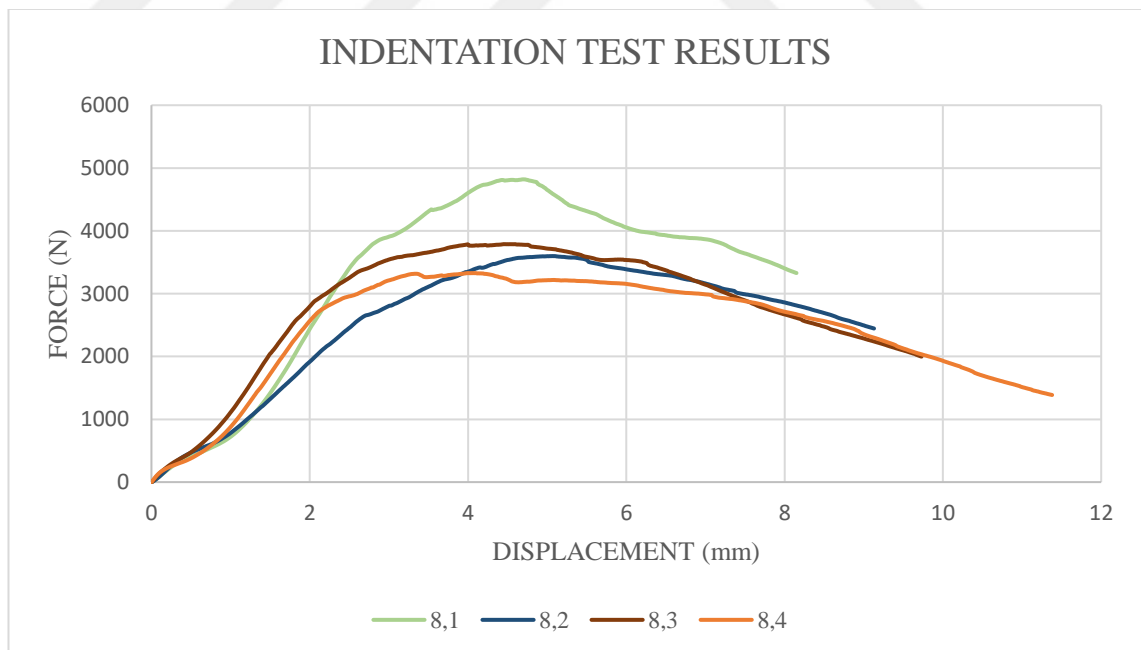
Composite-6 (D3+H) indentation test average curve.



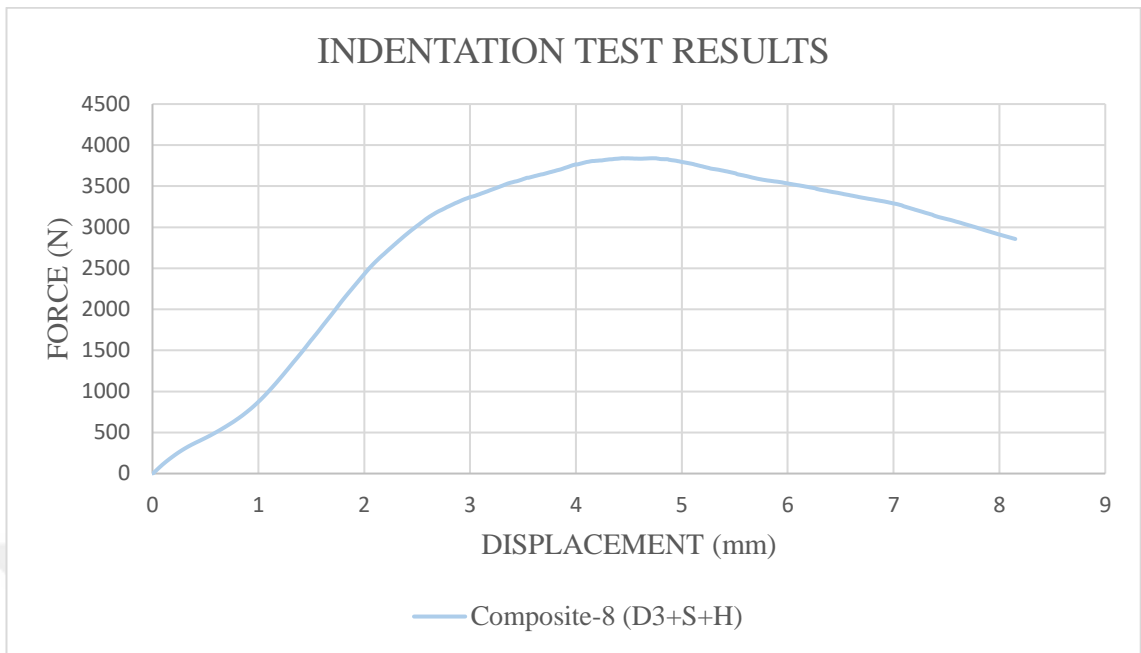
Composite-7 (D3+S+F) indentation test samples curves.



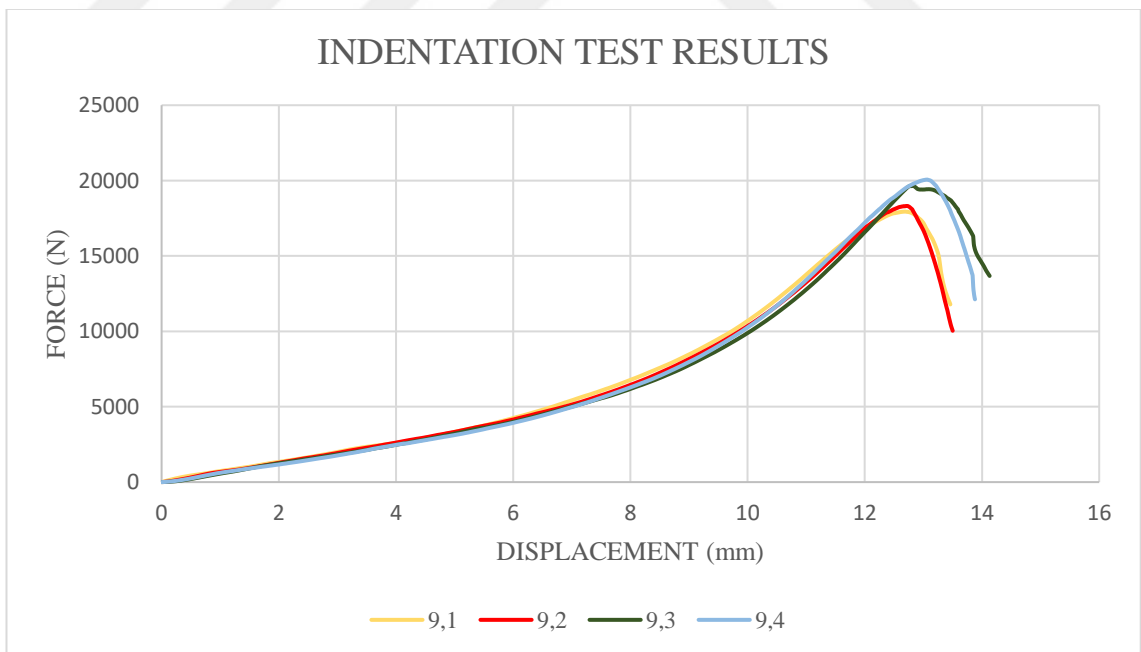
Composite-7 (D3+S+F) indentation test average curve.



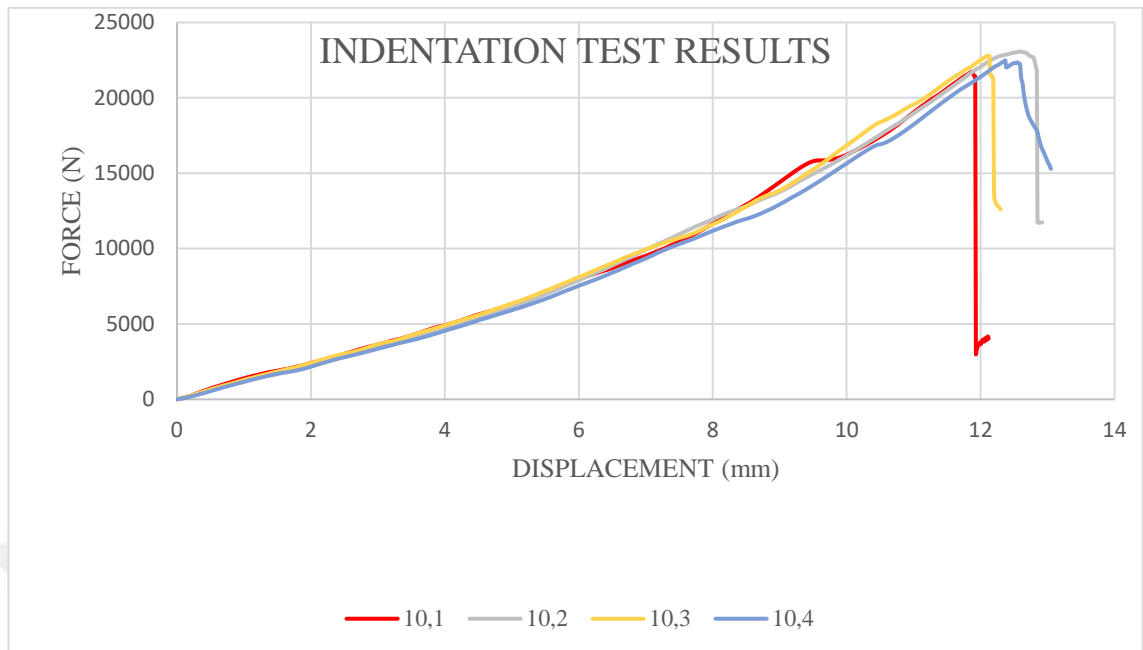
Composite-8 (D3+S+H) indentation test samples curves.



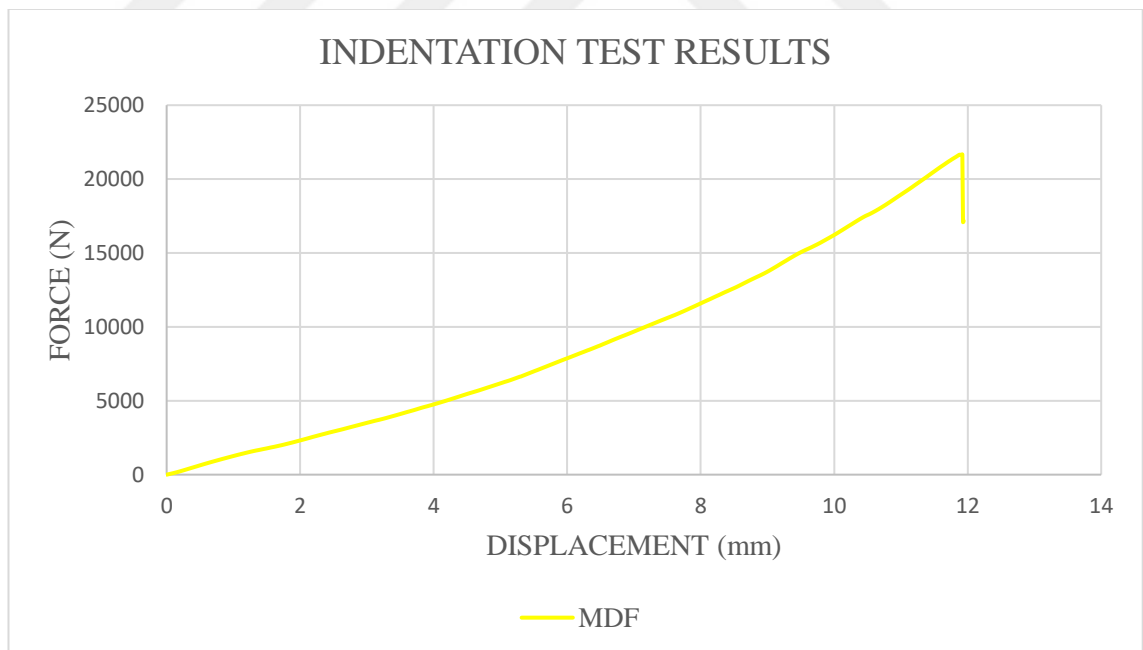
Composite-8 (D3+S+H) indentation test average curve.



Particleboard indentation test samples curves.

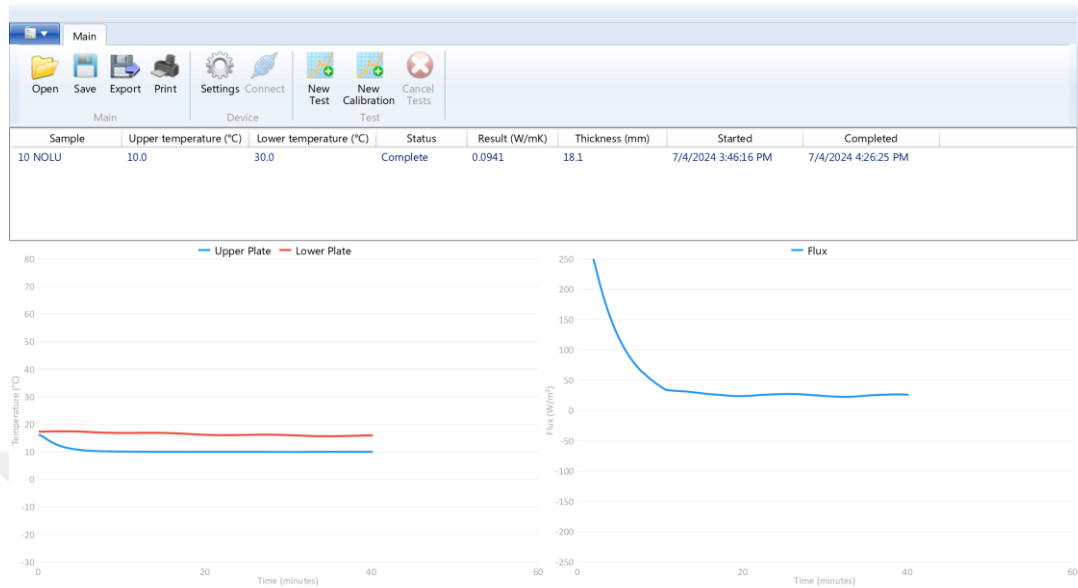


MDF indentation test samples curves.

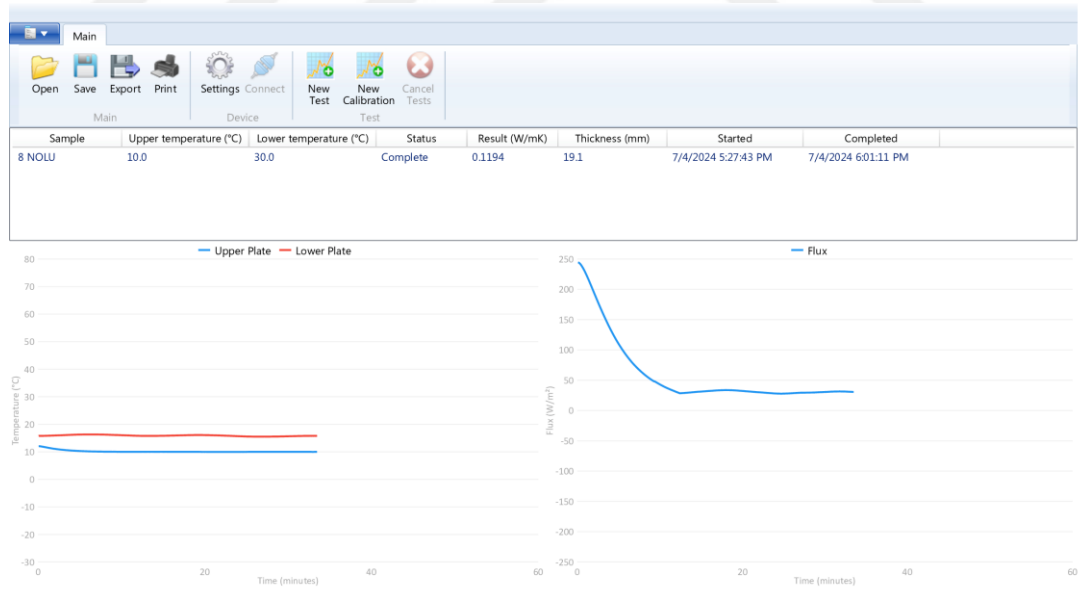


MDF indentation test average curve.

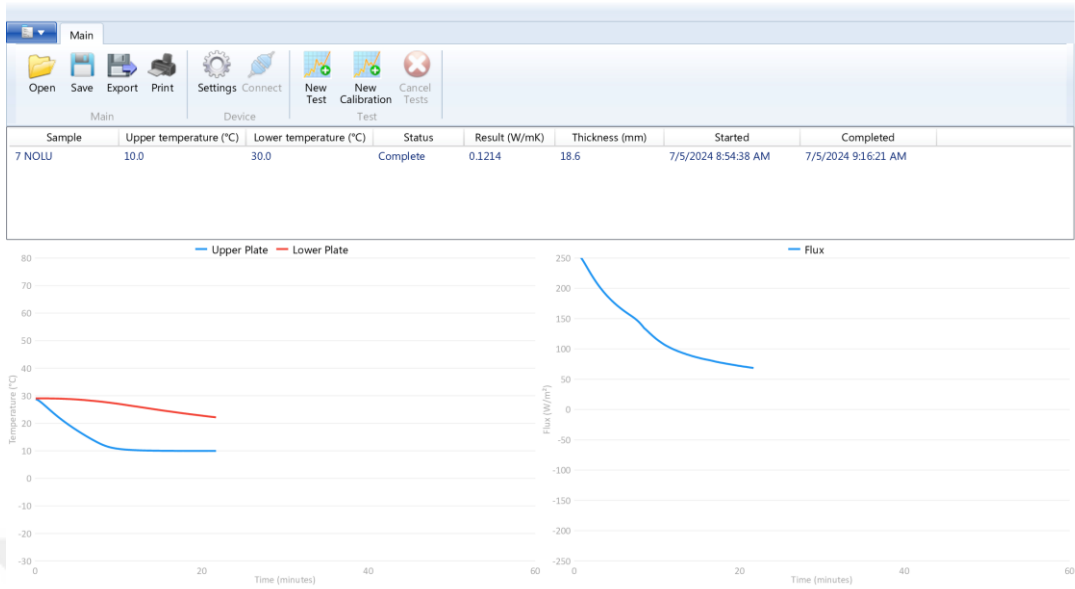
ANNEX 3. Thermal Conductivity Coefficient Results



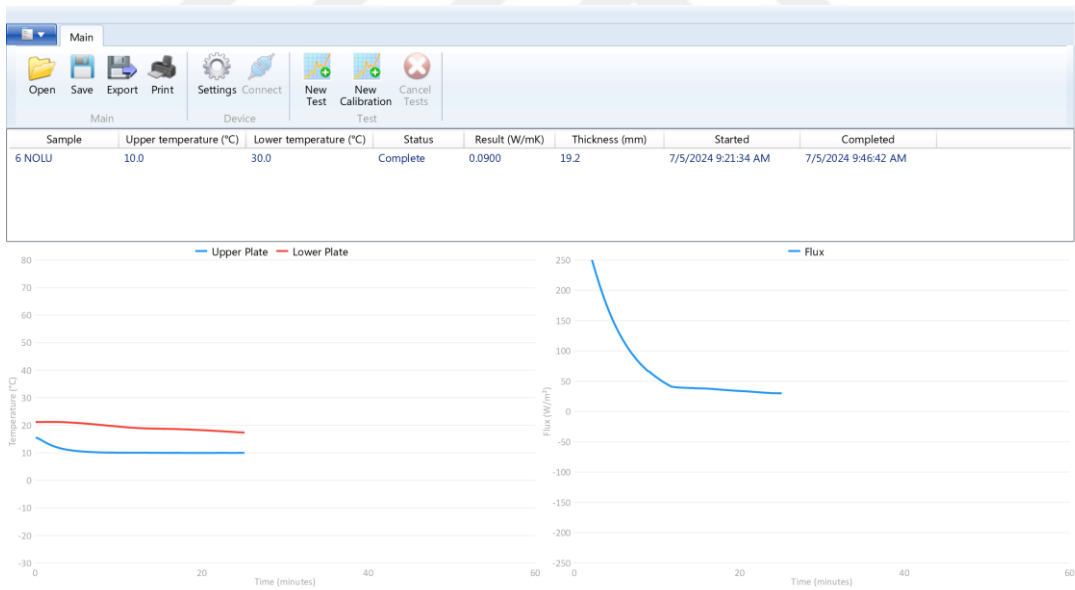
MDF thermal conductivity coefficient results.



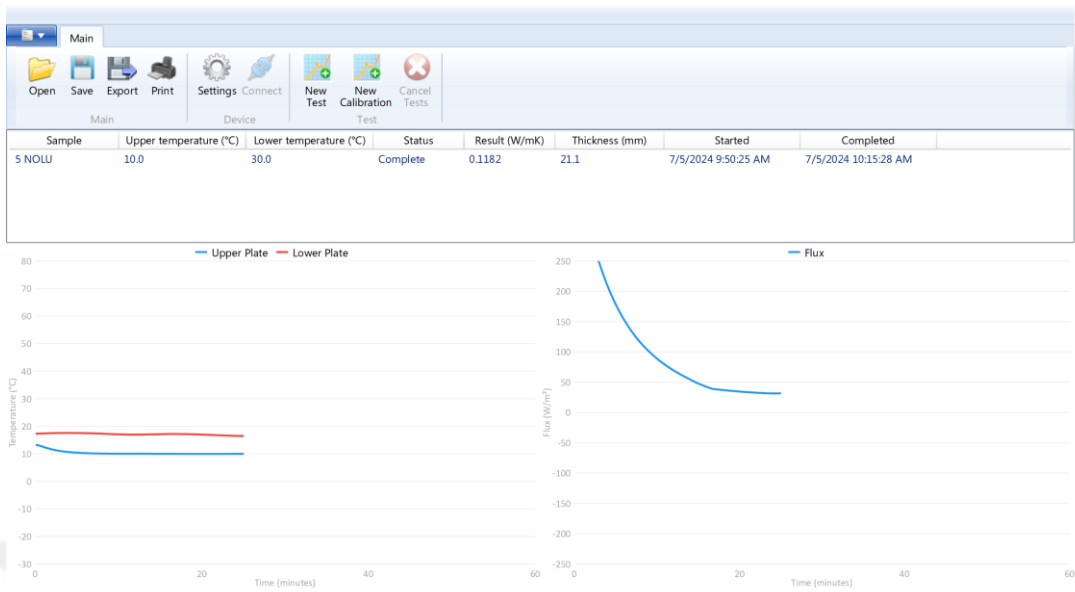
Composite -8 thermal conductivity coefficient results (D3+S+H).



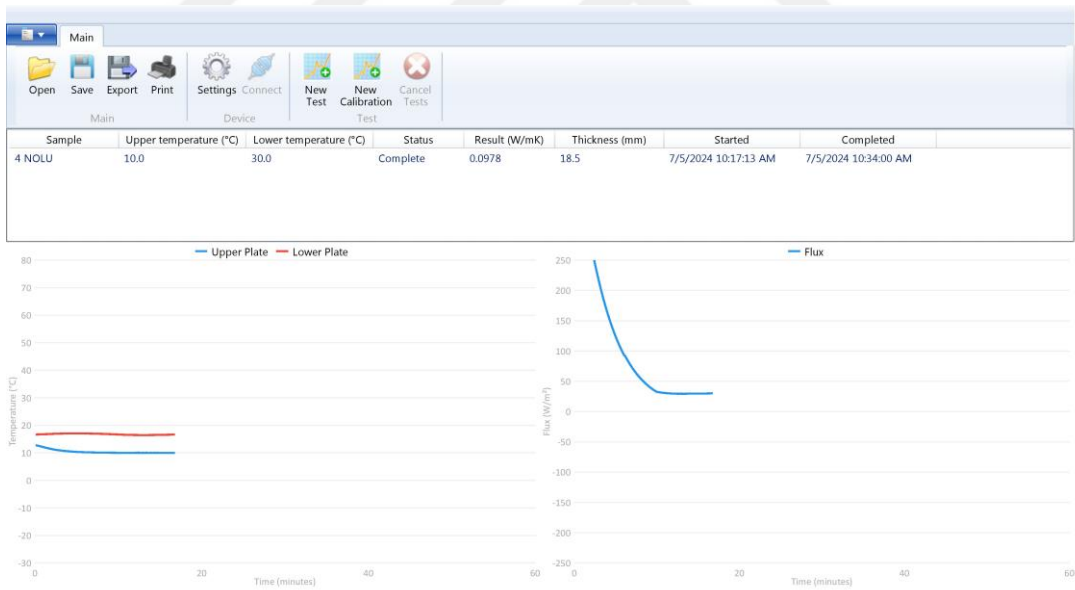
Composite -7 thermal conductivity coefficient results (D3+S+F).



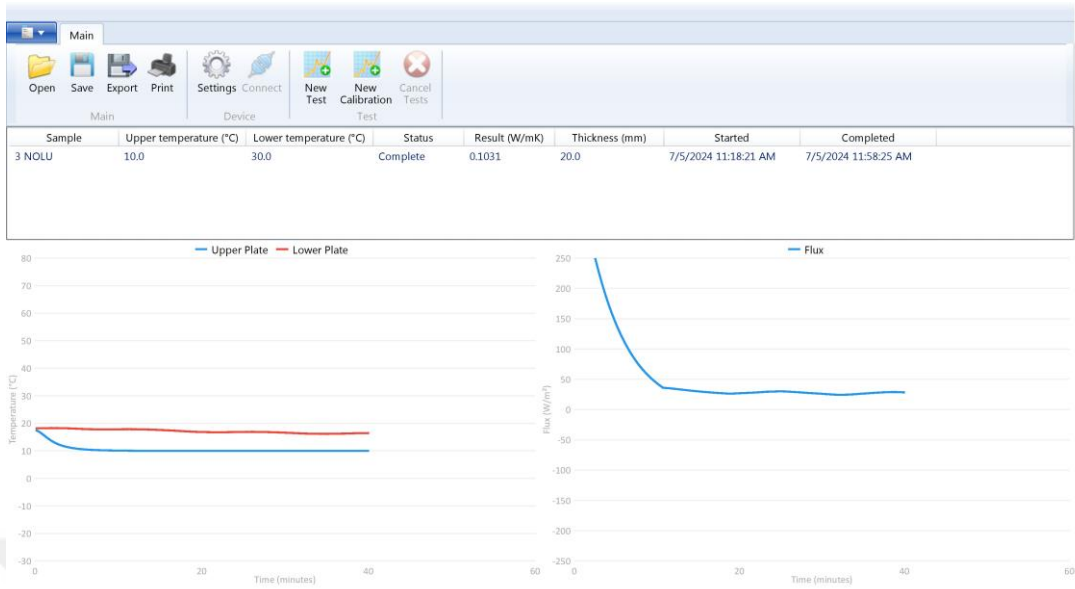
Composite -6 thermal conductivity coefficient results (D3+H).



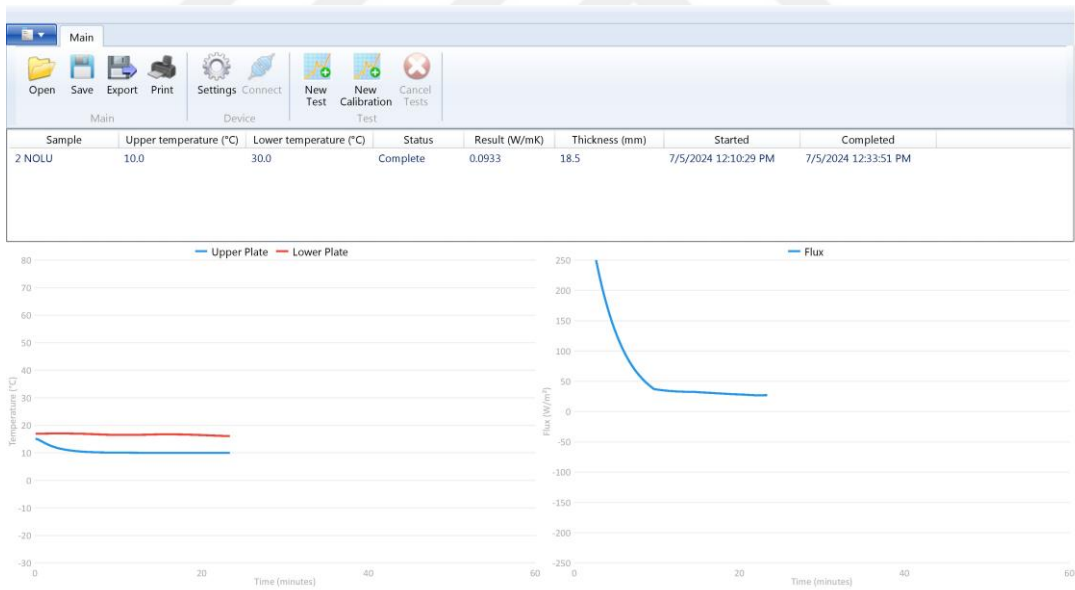
Composite -5 thermal conductivity coefficient results (D3+F).



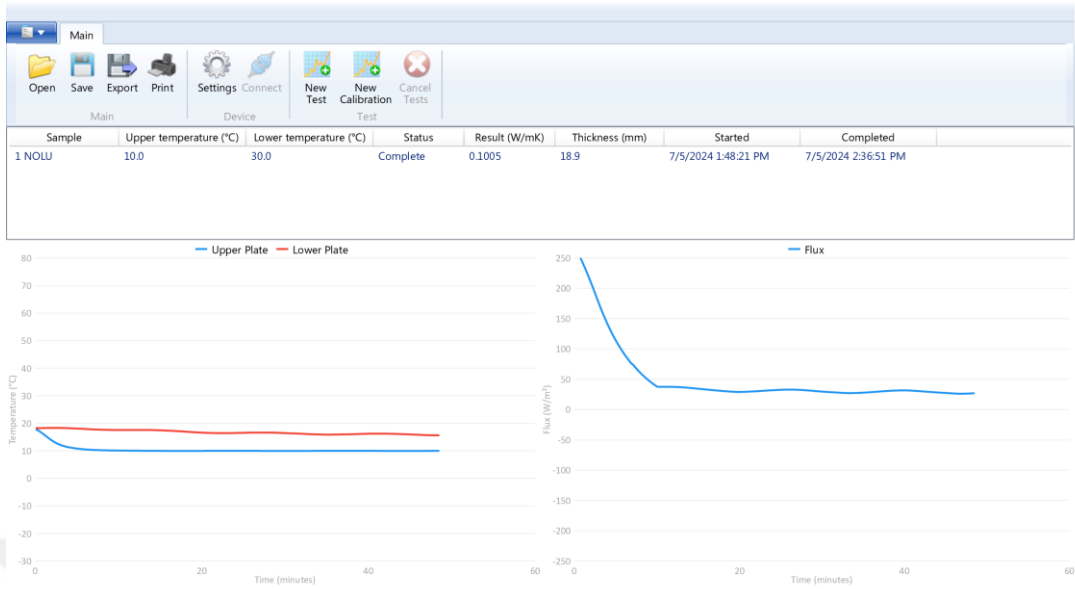
Composite -4 thermal conductivity coefficient results (PU+H).



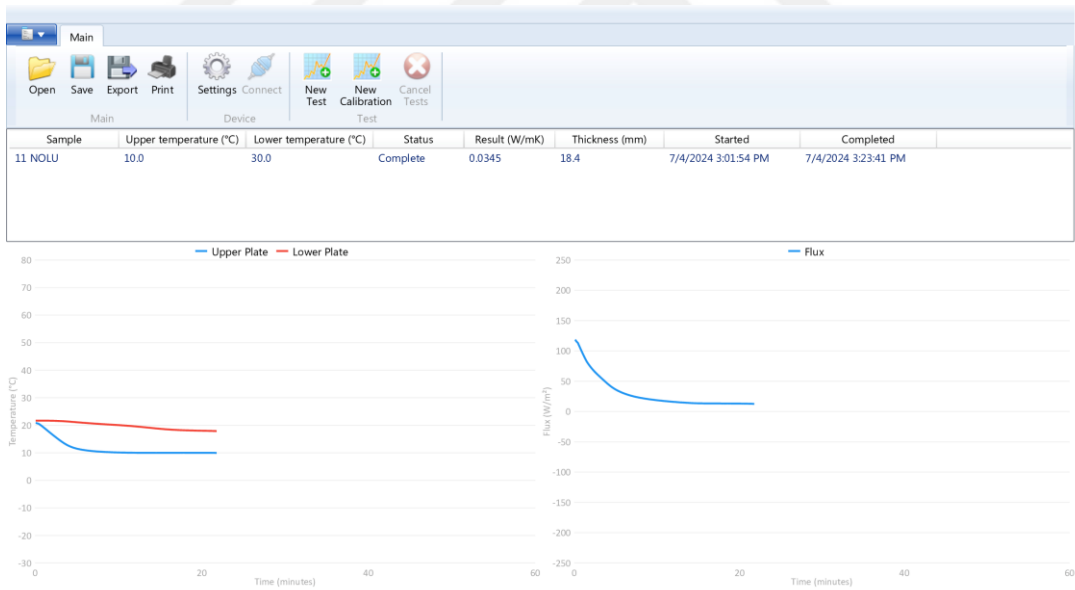
Composite -3 thermal conductivity coefficient results (PU+F).



Composite -2 thermal conductivity coefficient results (D4+H).



Composite -1 thermal conductivity coefficient results (D4+F).



EPS thermal conductivity coefficient results.

RESUME

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BSc	Anadolu University, Faculty of Business Administration, Business Administration	2024
BSc	Süleyman Demirel University, Mechanical Engineering	2014
High school	Kayseri High School, Kayseri	2005

WORK EXPERIENCES

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2017- Present	Bellona Mobilya San. Tic. A.Ş.	International Purchasing Specialist

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PUBLICATIONS

1. Gumustekin, A., Ozden S., Nair F., 2024. The Production of Bamboo Based Natural Composite Materials and Comparison of Their Material Properties with Particleboard MDF Boards, *International Conference on Engineering, Natural Sciences, and Technological Developments, Balıkesir, Türkiye*, 19-21 July 2024, pp. 352-357.