DOCTORAL THESIS

Study on Indonesian Albasia Wood Through Compressed Wood Method Under High Temperature and High Pressure to Improve Its Properties for Use as Construction Material

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ABSTRACT

Evaluating the environmental impact of material selection is becoming more important as a way to address sustainability issues. In terms of ecological benefits, utilizing wood as a construction material is one of the most effective methods to reduce carbon dioxide emissions, as wood materials contains 50% carbon during their growth and absorb carbon dioxide from the air. In short, the more wood products are used, the more carbon is stored, thus reducing the effects of global warming. Unfortunately, trees grow slowly, threatening the sustainability of the current wood supply. Therefore, the development of alternative sources of wood is very important, one of which is fast-growing tree species.

Albasia (*Albizia falcataria*), also known as sengon wood, is a fast-growing tree species commonly found in Indonesian forests and plantations. Besides having many advantages, such as a short harvest period (4-7 years) and simple site requirements for its growth, the development of albasia is also in line with the Indonesian government's goal to become the world's largest supplier of lightwood, through the potential of albasia in the ILCF (Indonesian Lightwood Cooperation Forum) in 2018. However, the low density, hardness, and strength of albasia wood limit its commercial use. Therefore, it is essential to improve the density and properties of wood, as denser wood is frequently preferred for commercial use, particularly in construction. To enhance the value of fast-growing wood with low properties, increasing its density in a procedure known as wood modification technology, is advantageous. This study aims to comprehend and investigate the possibility that soft, low-density wood, such as albasia wood, can be transformed into a stronger and more useful wood through compressed wood method under high temperature and high pressure.

Chapter 1, introduction, consists of background, problem statement, research objectives, scopes and limitations, structure of research and research framework. The advantages of wood as a sustainable construction material, the trend and potential of Indonesian albasia wood, and wood modification technology are presented as the background of this research. This topic leads to the development of ideas by looking at the trend and potential of abundant and fast-growing Indonesian Albasia wood as a construction material. This part of the research aims to investigate the potential of

sustainable Indonesian albasia wood to become a more valuable construction material by improving its physical and mechanical properties through the application of wood modification technology.

Chapter 2, literature review, aims to conduct a literature review in identifying an overview of Indonesian albasia wood, wood as a material, wood modification technology, as well as an overview of previously conducted wood modifications on the physical and mechanical properties of Albasia wood as a preliminary basis for research and finding research gaps.

Chapter 3, research methodology, shows the way of data collection, data analysis, and the target of results. There are two types of distinct data: primary and secondary. In this study, qualitative data from ethnographic studies on the role of albasia wood as a building material in Indonesia and quantitative data from wood modification design experiments are used as primary data. Secondary data, meanwhile, includes literature studies, wood standards, and data from government agencies. This chapter also describes the approach to analysis in qualitative and quantitative research. The research framework is provided in order to comprehend the entire procedure.

Chapter 4, an in-depth investigation of the use of Indonesian albasia wood as a construction material. This section focuses on a preliminary study used as an understanding of Indonesian Albasia wood as a construction material. This study aims to identify the perceived use of Indonesian albasia wood in construction from the perspective of Indonesian construction workers. This research used a qualitative method with an ethnographic approach to obtain a comprehensive picture of construction workers' perceptions of Indonesian albasia wood. The results showed that: 1) The understanding of Albasia wood is derived from the legacy of basic skills training, including the introduction of wood species and grades, woodworking tools, tree planting, felling and cutting wood techniques, and their application in building construction; 2) For rural communities, Albasia wood has been identified as a locally sourced material that is readily accessible from Protected Forest (HL), Convertible Production Forest (HPK), and Non-Forest Areas (APL); 3) In terms of terminology, Albasia wood and carpentry tools are referred to by regional names, where the names differ from one region to another; and 4) In terms of application, although it is a low-value wood, Albasia wood can be utilized as a truss and a bottom truss in simple houses for rural communities in West Java, Indonesia.

Chapter 5, the influence of high-temperature and -pressure treatment on physical properties of Indonesian albasia wood, this study's objective was to determine the influence of densification on the physical properties of Indonesian albasia wood at high temperature and high pressure. The albasia board was subjected to various temperatures (100 °C, 120 °C, 140 °C, sandwich 140 °C). The process of densification influences the material's density properties, colour changes, thickness, compression ratio, equilibrium moisture content, and anatomic properties. This procedure increases the density to 0.62 kg/L, an increase of approximately 112.78% over untreated wood. The increase in wood density results in the decomposition of its chemical components, particularly hemicellulose, which darkens the wood's color and stabilizes its moisture equilibrium. Therefore, thermal compression modification under high temperature and high pressure is a highly effective method for improving the physical properties of fast-growing wood species such as albasia.

Chapter 6, optimization of voronoi densification process to enhance the physical and mechanical properties of Indonesian albasia wood. A study was conducted to evaluate the effect of thermal densification integrated with Voronoi-inspired patterns in Indonesian albasia wood on its physical and mechanical properties. The results of this study found that: 1) Wooden slats with a millimeter structure resembling the Voronoi pattern could become a new architectural trend; 2) The treatment increased the density of albasia wood by 211.54%; 3) The EMC stability of the albasia Voronoi composite was more stable than that of the control board as a result of its higher density and hemicellulose degradation; 4) Morphological analysis revealed that the interfacial bond of the Albasia Voronoi composite was significantly superior to that of the control; 5) The Albasia Voronoi composite treatment procedure increased the longitudinal compressive strength of the wood by 100.88%. It also increased the tangential compressive strength by 883.12%; 6) The Albasia Voronoi composite treatment procedure increased the longitudinal bending strength of the wood by 144.05%. It also increased the tangential compressive strength by 859.36%; 7) The tensile strength and elongation at break of albasia Voronoi composite were about 10 and 2 times higher than the control wood.; and 8) In its utilization as a construction material, albasia Voronoi composite may have the potential to be used as columns (tangential direction) and beams (longitudinal direction).

Chapter 7, a comparative study of voronoi wood densification process on Indonesian albasia and Japanese cedar wood. This study focused on the comparison of Voronoi densification treatment between Indonesian albasia and Japanese Cedar which are abundant and fast-growing wood species native to their respective countries. The purpose of this study is to evaluate the effect of thermal densification integrated with the architectural trend of the Voronoi structure on the physical and mechanical properties of albasia and Japanese cedar wood. Evaluations were conducted on the surface appearance, density, compressive and bending strengths of wood. The treatment increased the density of albasia wood by 211.54%, the longitudinal compressive strength by 100.88%, the tangential compressive strength by 883.12%, bending strength by 144.05%. In addition, the procedure enhanced the density, longitudinal compressive strength, tangential strength, and bending strength of Japanese cedar wood by 102.22%, 58.54%, 98.17%, and 59.12% respectively. As anticipated, the Voronoi densification treatment method is extremely promising for improving the physical and mechanical properties of wood and enables the use of fast-growing, low-density wood in structural applications.

Chapter 8, conclusion and recommendation. Finally, the last chapter concludes all the results of the research and provides recommendation for the future. Based on the results there are four key findings: 1) Albasia plays an important role in the construction industry for construction workers in Indonesia although its application is still very limited; 2) Wood modification experiments under high temperature and high pressure in this study can improve the density (increased about 112.78%) and anatomical properties of wood; 3) Besides being a new trend in wood architecture, Voronoi wood densification can improve wood density (211.54), longitudinal (100.88% increase) and tangential (883.12% increase) compressive strength, longitudinal (144.05%) and tangential (859.36% increase) bending strength, tensile strength (10 times higher), more stable EMC, and better morphology; 4) The effects of the Voronoi wood densification treatment on increasing wood density, longitudinal compressive strength, tangential compressive strength, and bending strength were significantly greater in Indonesian albasia wood than in Japanese cedar wood.

In this study, I argue that the development potential of the abundant and rapidly-growing albasia wood in Indonesia makes it a promising local resource for the construction industry. In the future, it will contribute significantly not only to the field of architecture but also to the environment, as the use of albasia wood will reduce reliance on slow-growing hardwood species sourced from natural forests.

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NOMENCLATURE

Abbreviation	**Definition**
APL	Non-Forest Areas (*Areal Penggunaan Lain*)
APKINDO	The Indonesian Wood Panel Association
BPS	Central Bureau of Statistics (*Badan Pusat Statistik*)
BS	British Standard
DIY	Do It Yourself
DM	Digital Microscope
EMC	Equilibrium Moisture Content
FA	Furfuyl Alcohol
FEM	Finite Element Model
FGD	Focus Group Discussion
HK	Conservation Forest (*Hutan Konservasi*)
HL	Protected Forest (*Hutan Lindung*)
HP	Permanent Production Forest (*Hutan Produksi*)
HPK	Convertible Production Forest (*Hutan Produksi Konversi*)
HPT	Limited Production Forest (*Hutan Produksi Tetap*)
ILCF	Indonesian Lightwood Cooperation Forum
JAS	Japan Agriculture Standard
JIS	Japanese Industrial Standard
LVL	Laminated Veneer Lumber (LVL)
MC	Moisture Content
MEG	Monoethylene Glycol
OPEC	Organisation of the Petroleum Exporting Countries
PAKUBA	Construction Worker Community (*Paguyuban Kuli Bangunan*)
SBY	Susilo Bambang Yudhoyono
SEALPA	South-East Asia Lumber Producers' Association
SEM	Scanning Electron Microscopy
SVLK	Indonesian Timber Legality Verification
WPC	Wood Plastic Composite
WPG	Weight Percent Gain
WWII	World War II

CHAPTER 1
INTRODUCTION

CHAPTER 1: INTRODUCTION

This chapter consists of the research background, explanation about the motivation that leads to the research interest. It also contains the research question, research scope, and research aims and objectives. Then the last part of this chapter explains the research framework and thesis structure.

1.1. Background

1.1.1. Wood as a sustainable construction material

Evaluating the environmental impact of material selections is becoming more important as means of addressing sustainability concerns. In terms of ecological benefits, using wood as a building material is one of the most effective ways to reduce carbon dioxide emissions (Bergman et al., 2014) as wood material contains 50 percent carbon throughout its growth, thereby absorbing carbon dioxide from the air (Laturi et al., 2008). Several studies have demonstrated that wood can reduce carbon emissions through carbon sequestration (Tonn & Marland, 2007; Zeng, 2008; Zeng & Hausmann, 2022), carbon offsetting (van Kooten et al., 2015; van Kooten & Johnston, 2016), energy efficiency (Fellin et al., 2016; Quesada-Pineda et al., 2016), low embodied energy (Asdrubali et al., 2023; Bejo, 2017; Lupíšek et al., 2015), and substitution for fossil fuels (Howard et al., 2021; Knauf et al., 2016; Sathre & O'Connor, 2010). In brief, the more wood products utilized, the more carbon is stored, thus mitigating the effects of global warming.

Moreover, wood is renewable and requires less energy to produce than non-renewable materials for construction such as concrete and steel (Dagbro, 2016). According to Sathre and Gustavsson (Sathre & Gustavsson, 2009), wood products are typically manufactured with less energy than nonrenewable materials. The life cycle analysis of material production, which includes the procurement of raw materials, transportation, and processing, reveals that wood products require less energy than functionally equivalent quantities of metals, concrete, or bricks.

Wood is not a novel building material; in fact, it is among the oldest (Wimmers, 2017). Since many thousands of years ago, timber has been used to construct homes on nearly every continent and in virtually every culture (Aryapratama & Pauliuk, 2019). Wood is a promising construction material due to its physical properties: light weight with a high strength-to-weight ratio, excellent performance in seismic zones, low environmental impact as described earlier, and easy application for prefabricated buildings.

Timber and engineered wood products typically have a higher strength-to-weight ratio than steel, and the structural weight of a timber building is typically considerably less than that of a comparable concrete building. Theoretically, these unique characteristics make timber competitive with other building materials.

Wood as a construction material is very efficient for structures or parts of structures, where most of the load to be resisted is the structure's own weight (roofs, certain bridges, and gravity load-bearing systems in tall buildings, for example) (van de Lindt et al., 2008). A further advantage relates to seismic forces, as the force imposed on a structure by swaying is highly dependent on its mass, and lighter structures (such as wood) experience less impact (van de Lindt et al., 2008).

Regarding its mechanical properties, wood may be particularly advantageous in certain structural forms, such as shell structures, which are advantageous for long-span roofs because they transmit loads solely in compression and shear in the shell's plane. This shape has been used to construct very large structures without the infrastructure required for the production of large curved engineered wood products, such as glulam. In seismic zones, timber is an attractive alternative to steel and concrete due to its flexibility, ductility, and lighter weight (Pan et al., 2021). Lastly, wood is an excellent choice for prefabrication, and the production of wood panels can be optimised in terms of precision and efficiency, saving both time and money.

1.1.2. The Trends and Potential of Indonesian Albasia Wood

Wood is generally regarded as a sustainable construction material. Sustainable timber originates from sustainably managed forests (S. Li et al., 2018). In terms of its use, wood from natural forests usually has good properties in terms of strength and durability. Unfortunately, trees grow slowly, disrupting the sustainability of the existing wood availability. As a result, developing alternative wood sources is critical, one of which is fast-growing tree species (Adi et al., 2014). Due to the plentiful availability of fast-growing tree species, they have been extensively utilized in plantations and community forests, making the sustainability of wood is more promising for the environment.

Indonesian timber has tremendous potential to be used as construction material. In Indonesia's construction industry, the use of eco-friendly and indigenous materials is still uncommon. If correctly developed, numerous local materials have potential. Albasia (Albizia falcataria), also known as sengon, is a type of fast-growing wood native to Indonesia that can be grown in industrial plantations and community forests.

Albasia wood is a type of plant that is widely cultivated by the community because it has fast-growing properties that can be harvested in a short time, relatively easy management, uncomplicated growing requirements, versatile wood, helps fertilise the soil, and enhances soil quality (Atmosuseno BS, 1998).

Apart from numerous advantages such as a short harvest period (4-7 years) and simple location requirements for growth the (Darmawan et al., 2013; Hartati et al., 2010; U. J. Siregar et al., 2007a) development of *Albizia falcataria* is also consistent with the Indonesian government's goal of becoming the world's largest supplier of lightwood. At the Indonesia Lightwood Cooperation Forum (ILCF) convened in October 2018, the Director General of National Export Development of the Ministry of Trade, Arlinda, stated the launch of a program to plant 1 billion Albasia trees annually. This program is expected to contribute Indonesia to become the world's largest light timber supplier. Sumardji Sarsono, chairman of the Indonesia Lightwood Association (ILWA), revealed that albasia trees have tremendous potential at the same occasion. This wood can also be used for non-structural, lightweight packaging materials. Considering that the use of construction wood has been restricted to timbers already familiar to the people of Indonesia, such as teak, rosewood, meranti, and others. These materials are costly and challenging to acquire.

Not only the domestic market, the albasia wood market also plays an important role in the Japanese market. Japanese manufacturers and consumers value the expertise and attention to detail employed in the production of Indonesian wood products. China and Europe have become Japan's most important wood suppliers in recent years, followed by Canada, Vietnam, the Philippines, and Indonesia (see Figure 1. 1). For many years, Indonesia and Japan have maintained robust trade relations in the wood industry. This trade partnership facilitates the flow of sustainable and high-quality Indonesian wood into the Japanese market, meeting the demand for sustainable and high-quality wood products.

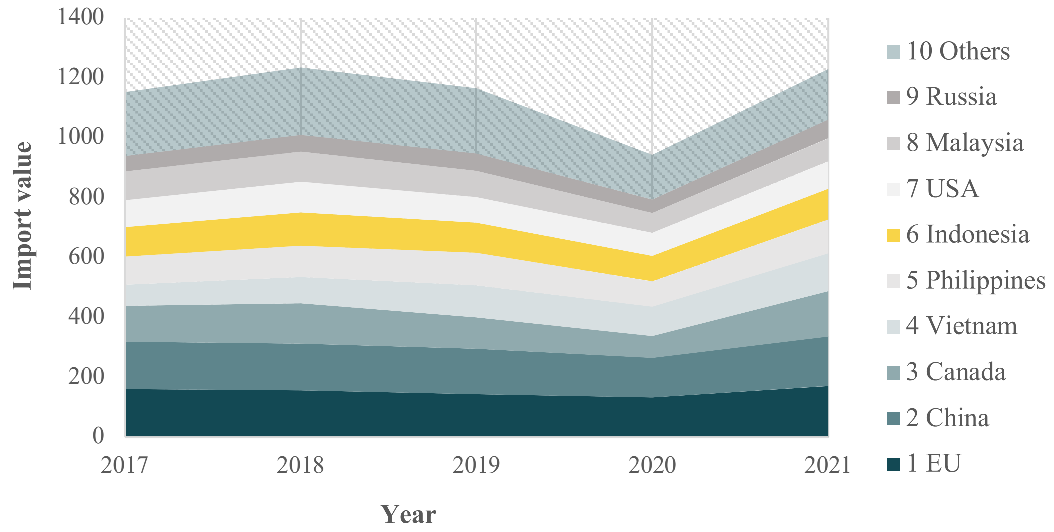


Figure 1. 1. Japan's wood import value

Source: (Japan Forestry Agency, 2022)

Based on the HS two-digit categorization, the primary material of processed wood products produced by albasia is classified as HS 4412 for exports. Figure 1. 2 shows a diagram of Indonesia's export destinations in 2020 for board, plywood, veneer panels and similar laminated wood included in the HS 4412 classification of albacia wood. Japan is the leading export destination for the HS 4412 category, accounting for 27% of exports, followed by the United States (24%), Korea (14.6%), Saudi Arabia (4.98%), and other countries.

Fast-growing wood species have been widely used for plantations and community forests so that the sustainability of wood is more promising for the environment. However, timber from plantation forests, including Albasia, is typically classified as a fast-growing species with inferior density, hardness, strength, and durability compared to timber from natural forests, thereby limiting its commercial use (Kojima et al., 2009).

Therefore, increasing the density and properties of the wood is critical, as denser wood is frequently preferred for commercial use, particularly in construction (Boonstra & Blomberg, 2007; Laine et al., 2016; Pelİt et al., 2017).

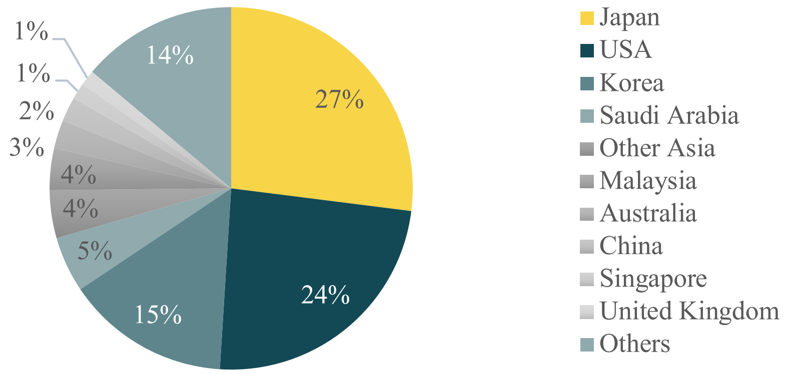


Figure 1. 2 Market share of Indonesian HS 4412 export destination countries, 2020.

Source: (The Central Bureau of Statistics of Indonesia, 2022)

1.1.3. Wood Modification Tecnhology

To increase the value of fast-growing wood with poor properties, increasing the added value of this sustainable material is becoming a market strategy, particularly through the use of environmentally friendly treatments with minimal environmental impact, i.e. the modification of wood.

Hill (C. Hill, 2006)provides a widely accepted definition of wood modification: "Wood modification involves the action of chemical, biological, or physical agents on the material, resulting in the increase of undesirable properties over the lifetime of the modified wood." Notably, the above does not inherently preclude the use of hazardous chemicals in the production of modified wood, provided that no hazardous residues remain after the wood modification process has been completed.

Currently, the timber modification industry is undergoing rapid growth, which is in part driven by environmental considerations (Jones et al., 2019). Four main types of processes can be used to modify wood: (1) chemical treatment, (2) thermo-hydro (TH) and thermo-hydro mechanical (THM) treatment, (3) treatment based on biological processes, and (4) physical treatment using electromagnetic radiation or plasma (Sandberg et al., 2017a).

The increasing use of fast-growing, low-density species from plantation forests, as well as the need to discover new applications for these softwood forests (Jones & Sandberg, 2020a), led to the development of numerous techniques for enhancing the physical and mechanical properties of wood. During the 20th century, a great deal of research and some commercialization were conducted in Europe and the United States on wood modification (F. F. P. Kollmann et al., 1975; Morsing & Hoffmeyer, 1998; Sandberg et al., 2013).

One of the well-known methods for wood modification is thermal compression under high temperature and high pressure (Kutnar & Šernek, 2007; Seborg & Stamm, 1941). The thermal compression method, under high temperature and high pressure treatment, consists of two distinct phases: softening and compression of the wood, followed by a post-treatment phase that minimizes irreversible thickness swelling when the modified wood comes into contact with moist or wet environments. Compared to other wood densification methods, the advantages of this method include the absence of chemicals and the ability to improve the properties of wood, regardless of its species (Bayani et al., 2019; Dwianto et al., 1999; Kocaefe et al., 2015).

1.2. Problem Statement

As a means of addressing sustainability issues, it is becoming increasingly essential to evaluate the environmental impact of material choices. Using wood as a construction material is one of the most effective ways to reduce carbon dioxide emissions (Bergman et al., 2014), as wood materials contain 50% carbon during their growth and absorb carbon dioxide from the environment (Bergman et al., 2014). In brief, the greater the use of timber products, the more carbon is stored, reducing the effects of global warming. Unfortunately, trees develop slowly, risking the long-term availability of wood (Ramage et al., 2017). Therefore, the development of alternative timber sources, such as fast-growing tree species, is crucial.

Albasia (*Albizia falcataria*), also known as sengon wood, is a common tree species in Indonesian forests and plantations. Apart from numerous benefits, such as a short harvest period (4-7 years) and simple location requirements for growth (Hartati et al., 2010; U. J. Siregar et al., 2007a), the development of *Albasia* is also consistent with the Indonesian government's goal of becoming the world's largest supplier of lightwood, as demonstrated by the potential of Albasia at the ILCF (Indonesian Lightwood Cooperation Forum) in 2018. However, its limited density, hardness, and strength limit its commercial application. Therefore, increasing the density and properties of the wood is essential, as denser wood is commonly preferred for commercial applications, especially in construction (Blomberg et al., 2005a; Darmawan et al., 2013; Nandika et al., 2014; Pelİt et al., 2017; Subyakto et al., 1995). In order to increase the value of fast-growing wood with poor properties, it is preferable to increase its density through a process known as wood modification (C. Hill, 2006; C. Hill et al., 2021; Homan & Jorissen, 2004; Sandberg et al., 2017a).

Developing the potential of fast-growing wood as a material for construction is one of the greatest challenges wood technology faces. The development of the potential of low-density wood as a material for construction has been greatly aided by relevant research, but the development of the potential of very fast-growing wood with low density, particularly Indonesian albasia wood, in accordance with the objectives of the Indonesian government has not received as much attention. As a guide for the study, the following five research questions were developed:

1. How is the role of albasia wood as a construction material in Indonesia?
2. How does the modification of wood under high temperature and high pressure treatment influence the physical properties of albasia wood?
3. How does the affect of Voronoi densification on the physical and mechanical properties of albasia wood.
4. How does Voronoi densification impact Indonesian albasia and Japanese cedar wood in comparison?

1.3. Research Objectives

1. To understand the role of albasia wood as a construction material in Indonesia.

2. To determine the influence of high temperature and high pressure treatment on the physical properties of albasia wood.
3. To comprehend the effect of Voronoi densification on the physical and mechanical properties of albasia wood.
4. To compare the impact of Voronoi densification on Indonesian albasia and Japanese cedar wood.

1.4. Scopes and Limitations

1. The investigation focused on construction workers as informats in terms of their experience and expertise in Albasia wood.
2. The scope of the study was limited to to evaluating the effect of wood modification on physical properties, including density, moisture content, and morphology, and mechanical properties, including compressive strength, bending strength, and tensile.
3. The existing Voronoi form does not rely on computer graphics and computational geometry, but rather a combination of wooden slats that resemble Voronoi cell polygons.
4. Due to the ban on importing logs from Indonesia, the Albasia wood used in this study is in the form of boards and beams that are still considered to be indigenous wood.

1.5. Structure of Research

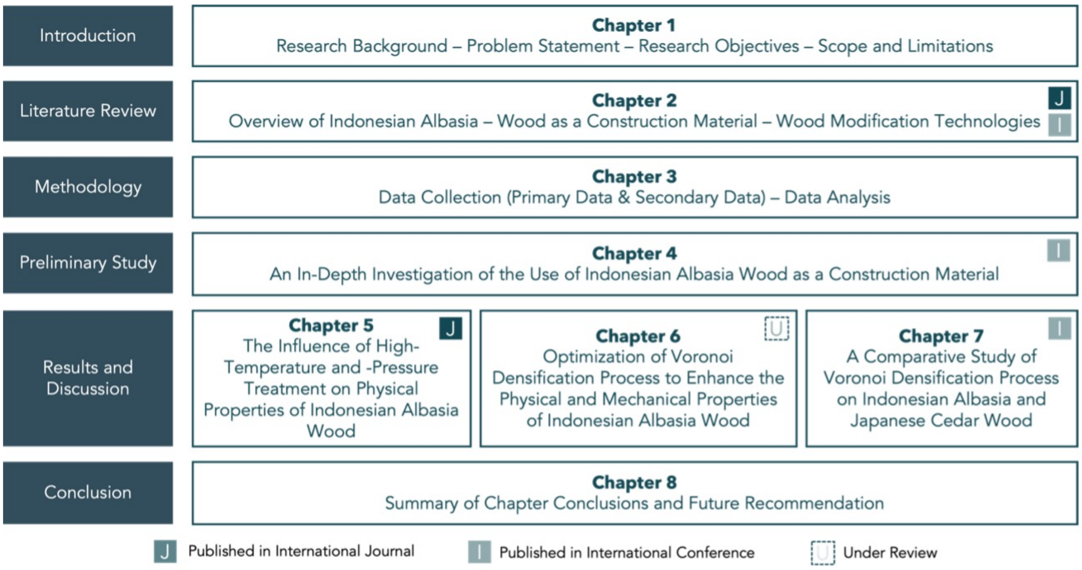


Figure 1. 3 Research Framework

This dissertation is devided into eight chapters (Figure 1. 3). Each chapter represents each stage of the research. The structure of this dissertation consists of the following sections:

Chapter 1, introduction, presents wood as a sustainable construction material, followed by the current issue of the trend and potential Indonesia's fast-growing Albasia wood. In this chapter, wood modification technology as a means of enhancing low-value wood as presented the background of this study. In addition, this topic leads gradually to the study of developing the potential of Indonesian Albasia wood to be used as construction material. This subchapter also describes the research objectives, scope and limitations, as well as the research structure and research framework.

Chapter 2, a literature review to identify Indonesian Albasia wood, general knowledge of wood as a construction material, and an overview of wood modification technologies. The analysis framework is integrated and fulfilled by the study of Chapter 4, Chapter 5, Chapter 6, Chapter 7, Chapter 8, respectively.

Chapter 3, research methodologies, demonstrating the data collection and data analysis. There are two distinct types of data: primary and secondary. Mixed method data is used as primary data in this research, qualitative data taken from ethnographic studies on the role of Albasia wood as a building material in Indonesia and quantitative data taken from wood modification design experiments. Meanwhile, secondary data includes literature studies, wood standards, and government agency data. This chapter is also explains the step of analysis approach in terms of qualitative and quantitative research. The research framework is provided for understanding the whole process.

Chapter 4, an in-depth investigation of the use of albasia wood as a construction material by construction workers in Indonesia. This section focuses on the qualitative data from the ethnographic study on the role of Albasia wood as a construction material in Indonesia through the construction worker informants in the case study. The findings in this study contribute to the understanding of Albasia wood in construction field.

Chapter 5, the influence of high-temperature and -pressure treatment on physical properties of *Albasia* board. This section focuses on the modification of wood by high temperature and high pressure (100°C, 120°C, 140°C, sandwich 140°C). The study contributes to a better understanding of the effect of treatment on the physical properties of wood, including color change, thickness, compression ratio, EMC, and anatomical properties of Albasia wood.

Chapter 6, integrating the Voronoi densification process to improve the quality of Indonesian Albasia wood. This section focuses on Voronoi wood densification of Indonesian Albasia wood. The findings in this study contribute to a greater understanding of the effect of treatments on the physical and mechanical properties of *Albasia*, including density, EMC, anatomical properties, compressive strength, bending strength, and tensile strength of wood.

Chapter *7*, a comparative study of Voronoi wood densification on indonesian albasia and Japanese Cedar wood. This section focuses on comparing the effect of Voronoi wood densification on Indonesian Albasia wood and Japanese cedar wood. The study contributes to a depper understanding of the effect of treatments on the physical and mechanical properties of Indonesian Albasia and Japanese cedar wood.

Chapter 8, conclusion and recommendation. The final section summarizes the key findings and provides recommendations for future research.

CHAPTER 2
LITERATURE REVIEW

CHAPTER 2: LITERATURE REVIEW

This chapter contains the descriptions that consist of theories, definitions, and the information related to the research, including several contexts such as the Indonesian wood industry history as a building material in Indonesia and basic science and characteristics of Albasia wood.

2.1. Overview of Albasia (*Albizia falcataria)*

Albasia, also referred to as sengon or *Albizia falcataria* (see Table 2. 1), is one of the most important pioneers of versatile wood in Indonesia (Hidayat, 2002). This species was selected as one of the types of industrial timber plantations in Indonesia due to its rapid growth, adaptability to different types of soil, excellent silvicultural characteristics, and acceptable wood quality for the panel and carpentry wood industries. Albasia plays an important role in both traditional and commercial agricultural systems in a number of Indonesian regions.

Table 2. 1 Albasia Taxonomy

Botanist Name	*Albizia Falcataria*
Kingdom	Plantae
Family	Fabaceae
Subfamily	Caesalpinioideae
Genus	Albizia
Synonym	*Adenanthera falcata* Linn., *Adenanthera falcataria* Linn., *Albizia falcata* (L.) Backer, *Albizia falcata* sensu Backer, *Albizia falcataria* (L.) Fosberg, *Albizia moluccana* Miq., *Falcataria moluccana* (Miq.)

Source: (Abdurrohim et al., 2004)

Albasia, like other fast-growing tree species, is anticipated to become an increasingly important species for the timber industry in the future, particularly as the availability of lumber from natural forests decreases. In recent years, the number of large and small Albasia plants in Indonesia has increased significantly. Starting from Sumatera, Java, Bali, Flores, and Maluku island, the distribution area of Albasia is quite extensive

(Handayani & Muhammad, 2015).According to a report by the Indonesia Ministry of Forestry and the National Statistics Agency (2004), the provinces with the largest Albasia plant area are West Java and Central Java, with the total number of trees cultivated in these two provinces accounting for more than 60 percent of the total number of Albasia trees planted by Indonesian communities.

2.1.1. Taxonomy

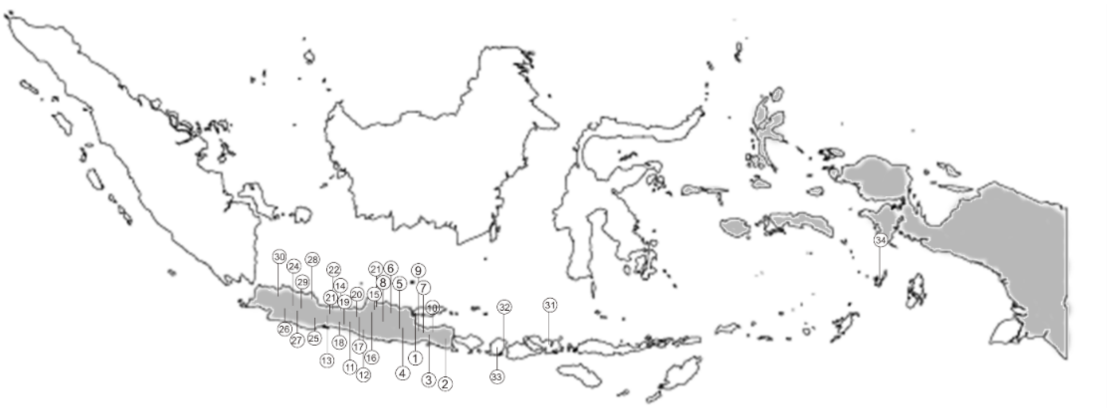
Albasia trees are typically fairly tall, with a maximum height of 40 meters and a free branch height of 20 meters (Figure 2. 1). With a full canopy, the diameter of mature trees can reach 100 cm or greater. When growing in the open air, Albasia tends to have a dome- or umbrella-shaped canopy.

Albasia trees do not typically have buttresses, although small trees can occasionally be found in the field. The bark's surface is white, gray, or bluish-green, smooth, and occasionally slightly grooved with elongated lenticel lines. The leaves of Albasia are double-pinnate and range in length from 23 to 30 centimeters. The saplings are small, numerous, and paired, with 15 to 20 pairs on each axis (stem), oval in shape (6 to 12 mm long and 3 to 5 mm wide), and short at the tip. The upper leaf surface is green and hazy, whereas the lower leaf surface is paler and covered in fine hairs (Soerianegara, I. and Lemmens, 1993).

Figure 2. 1 Growth performance of 13 years (left) and 2 years (right) Albasia wood

Albasia flowers are arranged in panicles that are 12 mm long, yellowish-white, slightly hairy, and shaped like a bell or a channel. The flowers are bisexual and comprise both male and female flowers. The Albasia fruit is a pod measuring 10-13 cm in length and 2 cm in width. It is flat, thin, and lacks a bulky head. Each pod includes 15 to 20 seeds. Albasia seeds are flat, oval, wingless, 6 mm long, green when young, and yellow to blackish brown when mature, quite hard and waxy (Hartati et al., 2010).

2.1.2. Regional distribution



PROVINCE	DISTRICT
EAST JAVA	① Bangkalan ② Banyuwangi ③ Bondowoso ④ Blitar ⑤ Jombang ⑥ Lamongan ⑦ Lumajang ⑧ Madiun ⑨ Pasuruan ⑩ Probolinggo
YOGYAKARTA	⑪ Kulonprogo ⑫ Gunung Kidul
CENTRAL JAVA	⑬ Banyumas ⑭ Batang ⑮ Blora ⑯ Grobogan ⑰ Klaten ⑱ Kebumen ⑲ Kulonprogo ⑳ Magelang ㉑ Pemalang ㉒ Pati ㉓ Tegal
WEST JAVA	㉔ Bandung ㉕ Ciamis ㉖ Cianjur ㉗ Garut ㉘ Indramayu ㉙ Sumedang
BANTEN	㉚ Tangerang
WEST NUSA TENGGARA	㉛ Bima ㉜ West Lombok ㉝ Central Lombok
MALUKU	㉞ Southeast West Maluku

Figure 2. 2 Albasia wood natural distribution in Indonesia (shaded area represents origin planting range in Indonesia)

Source: Research Documentation, 2020

Albasia can grow in a variety of soil types, including dry soils, moist soils, and even soils containing salt and acid, so long as there is adequate drainage. Albasia trees can grow from the coast to an altitude of 1,600 meters above sea level, with an optimal height between 0 and 800 meters above sea level. In tropical regions, these trees are commonly planted. This species is believed to thrive at an altitude between 250 and 400 meters above sea level, in hot, humid climates with an average temperature between 26 and 30 degrees Celsius, particularly on the island of Java. Moreover, Albasia trees can grow and adapt in monsoon and humid climates with annual precipitation between 200 and 2,700 millimeters (Z. Siregar et al., 2008).

Albasia grows and spreads in Papua, specifically in Sorong, Manokwari, Kebar, Biak, Serui, Nabire, and Wamena, and in the Maluku islands, including Halmahera, Buru, Bacan, Banda, Mangille, Seram, Taliabu, Sasan, and Obi. Then, in 1871, Albasia grew and spread rapidly across the island of Java. Albasia was initially planted in the Bogor Botanical Gardens with seeds from the island of Banda, and it is believed that from these seeds Albasia spread across the entire island of Java (Heyne, 1987). This tree is now one of the most popular business trees in Java. About 80% of communal forests in Java are dominated by Albasia species. Figure 2. 2 depicts the regions in Indonesia that are suitable for Albasia. The shaded area represents the potential planting range in Indonesia.

2.1.3. Ecology

In the island of Java, Alamsyah (E. M. Alamsyah et al., 2007) report that Albasia can grow in all soil types except grumps. Albasia grows rapidly in yellow-red latosol, andosol, alluvial, and podzolic soil. In marginal soils, fertilizer may be required to accelerate initial growth; however, the ability of Albasia to bind nitrogen will increase over time, resulting in accelerated growth.

Albasia is a type of pioneer plant that grows in primary forests, secondary lowlands instruct forests and mountain forests, grasslands, and along the roadside close to the coast. Albasia coexists with Agathis labillardieri, Celtis spp., Diospyros spp., Pterocarpus indicus, Terminalia spp., and Toona sureni in its natural habitat in Papua.

In its natural habitat, annual precipitation ranges from 2,000 to 2,700 millimeters, occasionally reaching 4,000 millimeters, and the dry season lasts for more than four months (Soerianegara, I. and Lemmens, 1993). The rapid evaporation of Albasia necessitates a humid environment; optimal growth requires between 2,000 and 5,000 millimeters of precipitation annually. Rainfall less than 2,000 millimeters per year will result in dry growth conditions, while rainfall greater than 3,500 millimeters per year will result in extremely high humidity, which, if accompanied by very low light intensity, may promote mold growth (Charomaini, M. dan Suhaendi, 1997). The optimal temperature for Albasia growth is between 22 and 29 degrees Celsius, with a maximum of 30 to 34 degrees Celsius and a minimum of 20 to 24 degrees Celsius (Soerianegara, I. and Lemmens, 1993). The required minimum number of rainy days during the dry month is 15. In arid regions, Albasia growth may be slow and stem borer attacks will become more likely.

In its natural habitat, Albasia grows at elevations of up to 1,600 meters above sea level, and sometimes as high as 3,300 meters (Soerianegara, I. and Lemmens, 1993). The results of planting trials conducted by the Kupang Agricultural Polytechnic Academy (East Nusatenggara Island, Indonesia) indicate that Albasia can survive in locations with low height and rocky soils. However, growth is comparatively modest. In Manokwari, Papua, Albasia can grow at an elevation of 55 meters above sea level (Charomaini, M. dan Suhaendi, 1997).

2.1.4. Characteristics

In general, Albasia wood is mild, soft to somewhat soft. Albasia is distinguished by its solitary porous and radial multiples, diffuse parenchyma, and pale wood. In Table 2. 2, the chemical composition of albasia wood is displayed.

Table 2. 2 Chemical content of Albasia wood

Chemical content	Quality (%)
Cellulose	49,40
Holocellulose	73,99
Hemicellulose	24,59
Lignin	26,8
Ash	0,60
Silica	0,20

Source:Martawijaya

The wood on the terrace is white to pale light brown or pale yellow to reddish-brown. In young trees, the color difference between terrace wood and sapwood is not so distinct (pale), but in older wood, the difference is quite distinct (Soerianegara, I. and Lemmens, 1993). The density of wood at a moisture content of 12-15% is between 230 and 500 kg/m3 (Table 2. 3).

Table 2. 3 Wood density

Wood density (kg/m^3)			Moisture	References
Low	Medium	High	(%)	
240	330	490	15	(Martawijaya et al., 2005; Soerianegara, I. and Lemmens, 1993)
230	300	500	12	(Soerianegara, I. and Lemmens, 1993)

The wood fibers are either straight or intertwined, and the texture is coarse but uniform. Albasia wood is not suitable for outdoor use, as it is highly susceptible to insect and fungal attacks. The results of wood testing in Indonesia indicate that Albasia wood can remain undamaged on the ground surface for between 0.5 and 2.1 years on average. In tropical climates, however, preserved wood can last up to 15 years (Soerianegara, I. and Lemmens, 1993).

2.1.5. Uses

Albasia wood can be used for a variety of purposes, including lightweight construction materials (such as ceilings, panels, interiors, furniture, and cabinets), lightweight packaging materials (such as packages, boxes, cigarette and cigarette boxes, musical instruments, toys, etc.), and lightweight construction materials (such as ceilings, panels, interiors, furniture, and cabinets). Albasia wood can also be used as a raw material for triplex and plywood, and it is ideally suited for particleboard and block board. Albasia wood is also commonly used for rayon and pulp materials in the manufacture of paper and furniture (Soerianegara, I. and Lemmens, 1993).

Albasia, a type of nitrogen binder, is also utilized in reforestation and afforestation to improve soil fertility (Heyne, 1987). Leaves and branches that fall to the ground will increase the soil's nitrogen content, organic matter, and mineral content (Orwa et al., 2009). Albasia is typically intercropped with corn, cassava, and fruits (Charomaini, M. dan Suhaendi, 1997). Additionally, Albasia is frequently planted in the backyard to provide fuel (charcoal), and its leaves are utilized to feed chickens and goats. In Ambon (Maluku island), the bark of the Albasia tree is used to tan nets and is occasionally substituted for soap (Soerianegara, I. and Lemmens, 1993). Along roadways, Albasia is also planted as a windbreak, firebreak, and ornamental tree.

2.1.6. Growth

2.1.6.1. Growth rate

Albasia is capable of rapid growth, especially in young stands. Albasia trees could reach a height of 7 meters in one year, 16 meters in three years, and 33 meters in nine years. Kurinobu et al. reported that Albasia trees growing in 3- to 5-year-old stands in the Perhutani area of Kediri (East Java Province, Indonesia) have an average diameter of 11.3 to 18.7 centimeters (maximum diameter of 25.8 centimeters) and an average height of 11.7 to 20.5 meters (maximum height of 23.5 meters) (Kurinobu et al., 2007).

In the Albasia community plantations in Ciamis (West Java Province, Indonesia), the average diameter ranges from 3.4 to 16.7 cm, with a maximum diameter of 36.0 cm for stands up to 3 years of age, according to H. et al. The average height of trees in this forest stands between 3.9 and 19.6 meters, with a maximum height of 27.0 meters. For 5-10 year old trees growing in the same location, the average diameter ranges from 8.7 to 40.1, and the average height ranges from 9.9 to 27.9 meters. Twelve-year-old stands are characterized by trees with a diameter of 24.6-74 cm and a height of 15.3-36.2 m. This variation in diameter and height may be attributable to differences in growing conditions, such as site quality, elevation, slope, and applied silvicultural treatment.

Sumarna predicted the growth of Albasia based on 134 sample plots constructed in Kediri (East Java province, Indonesia) and Bogor (West Java province, Indonesia) at various locations (Sumarna, 1961). They note that up to the age of 5 years, the average growth (increase) height of each year in medium-quality growth sites is approximately 4 m, and then decreases with age. At ages 8-9, the average growth in height is between 1 and 1.5 meters, whereas at age 10, the average growth in height is only about 1 meter.

Diameter growth follows a similar pattern, but the average annual increase in diameter fluctuates up to 6 years of age between 4-5 cm. The average increment diameter is still approximately 3 to 4 centimeters at 8 to 9 years of age, and thereafter it decreases gradually.

2.1.6.2. Productivity

Soerianegara and Lemmens (Soerianegara, I. and Lemmens, 1993) report that an average annual volume increase between 10–25 and 30–40 m^3/ha can be accomplished in 8–12 years of rotation. Bhat et al. (1998) reported that Albasia could achieve an average annual volume increase of 50 m^3/ha under optimal growing conditions.

At excellent quality growing sites in Indonesia, it is reported that Albasia plants can attain a maximum annual volume increment of 67 m^3/ha at the age of 6 years, with a total production volume of 403 m3/ha until the end of rotation (Sumarna, 1961).

In 7-8 years, the average annual volume on medium-quality growing sites can reach 50 m^3/ha (stand density of 185 trees/ha at eight years old and 150 trees/ha at seven years old), with the total volume produced reaching 350-400 m^3/ha including thinning results. On low-quality sites, the total production volume in eight years is approximately 313 m^3/ha, and the maximum average production volume of 40 m^3/ha/year may not be reached within twelve years (Sumarna, 1961) (see Table 2. 4).

Table 2. 4 Productivity of Albasia wood

Growing site (quality)	The average annual volume (m^3/ha)	Rotation period (years)	Total production volume until the end of rotation (m^3/ha)	References
Good	67	6	403	(Sumarna,1961)
Medium	50	7-8	350-400	(Krisnawati, et.al, 2011)
Low	40	8	313	(Sumarna, 1961)

2.2. Overview of wood as a construction material

Wood is a complex building material due to its natural origin. The characteristics of wood are highly variable and sensitive to environmental and loading conditions. In this chapter, the properties of wood are discussed.

2.2.1. Basic properties of wood

Typically, tree species are divided into two categories: softwoods and hardwoods. Generally, softwood species retain their needle-like leaves throughout the year.

Hardwood species, on the other hand, are wood species with broad leaves that drop off during the winter.

Due to the arrangement of its fibers and the orientation of the microfibrils in the cell walls, direction has a significant impact on the properties of wood. Particularly, wood is orthotropic because three orthogonal symmetries can be identified. The longitudinal (L) direction, or grain-parallel direction, is parallel to the axis of the tree trunk. The radial (R) direction is parallel to the radius of the tree's cross-section, whereas the tangential (T) direction is perpendicular to the growth rings (Figure 2. 3).

Radial and tangential directions are known as perpendicular to grain directions. In the three directions, the wood's strength, elasticity modulus, and other characteristics such as shrinking and swelling vary. Significantly greater load carrying capacity exists in the grain-parallel direction than in the grain-perpendicular direction.Additionally, the dimensional stability or resistance to deformation under fluctuating moisture content is enhanced.

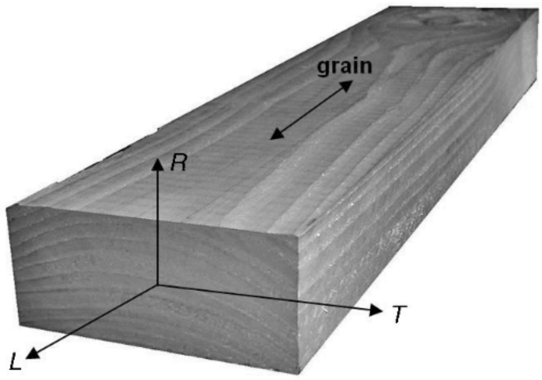


Figure 2. 3 Orthotropic directions for wood properties

Source: (Harte, 2009)

2.2.2. Physical properties of wood

2.2.2.1. Density

The density of wood or specific gravity is primarily determined by the amount of wood per unit volume and its moisture content. The greater the percentage of wood, the greater the density and the superior the mechanical properties(B. J. Zobel, 1995) .

Density averages for softwoods and hardwoods range between 400 and 650 kg/m^3 and 500 and 1200 kg/m^3, respectively (Harte, 2009). Denser wood shrinks and swells more in response to changes in moisture content than less dense wood.

2.2.2.2. Moisture

Wood is a hygroscopic material in that it exchanges moisture with its environment and its properties are highly dependent on its moisture content. The moisture content of wood is the ratio of the mass of water that can be extracted from wood to the mass of dry wood. The moisture content of a growing tree is highly variable and can reach 200%. This moisture exists as free water in cell cavities or lumens and as bound water in cell walls. When wood is harvested and processed, the green wood dries to a moisture content that is in equilibrium with the surrounding relative humidity and temperature. This quantity is referred to as the equilibriummoisture content (EMC).

At a standard indoor climate of 208 °C and 65% relative humidity, the equilibrium moisture content of softwoods is approximately 13%. This is the standard reference moisture content at which wood is tested and international codes and standards generally specify design values.The moisture content of wood can be determined using ovendrying or moisture meters. These meters are calibrated for specific species and operate on the principle that the moisture content influences the electrical resistance.

2.2.3. Mechanical properties of wood

2.2.3.1. Parallel-to-grain properties (Longitudinal compressive strength)

The direction parallel to the grain (longitudinal direction of compressive strength) is the wood's structurally strongest and stiffest. In general, the tensile strength of softwoods at 12% moisture content ranges between 70 and 140 MPa. Typically, the compressive strength ranges between 30 and 60 MPa (Harte, 2009). In general, these values are greater for hardwoods. These values are for samples of clear, straight-grained timber. Knots and other strength-reducing characteristics (commonly referred to as defects) can reduce the strength of structural timber by as much as a factor of 10. The mode of failure is load-dependent, with failure under tension being brittle and failure under compression being ductile. In general, the modulus of elasticity in tension and compression is assumed to be identical. At a moisture content of 12%, typical values for softwoods and hardwoods range between 7 and 14 GPa.

2.2.3.2. Perpendicular-to-grain properties (Radial and Tangential compressive strength)

Perpendicular-to-grain properties (radial and longitudinal direction of compressive strength) are considerably less than their parallel-to-grain properties. The radial and tangential tensile strengths can be as low as 5 to 8 percent and 3 to 5 percent, respectively, of the values in the grain direction (Harte, 2009). Due to these low strength values, it is recommended to design wood structures so that tensile stresses perpendicular to the grain do not occur or are minimized. At junctions, in tapered or curved members, and in notched beams, tension perpendicular to grain stresses can develop. The perpendicular to particle values of compressive strength are approximately 10 to 20 percent of the parallel values. Compressive failure causes the cells to flatten and the cell walls to contact, resulting in a densification of the wood and an increase in its compressive resistance. Nonetheless, this is accompanied by significant deformations, which can occur even at relatively modest load levels.

2.2.3.3. Bending strength

The modulus of rupture is the most commonly used strength characteristic of wood. It is calculated based on an elastic stress distribution and is defined as the bending stress in the bending section at failure load. This value is lower for clean or defect-free wood than the fiber parallel tensile strength. In contrast, structural timber typically contains a large number of strength-reducing characteristics or "defects." According to research, the size effect is crucial for flexural members because the larger the member, the more likely it is to have large defects that reduce its strength. Three types of failure characterize shear strength: fibre parallel shear, fibre perpendicular shear, and rolling shear.

2.3. Overview of wood modification technologies

2.3.1. Introduction

2.3.1.1. Background

Wood has been used by humans for centuries, primarily for fuel, housing, weapons, tools, and furnishings. As a material, wood is considered an ideal building material since it is easy to work with, renewable, widely available, and sustainable. Unfortunately, wood has significant disadvantages compared to synthetic materials derived from non-renewable resources in terms of low dimensional stability, poor mechanical qualities, and low resistance to decay caused by bio-degrading agents. These are generally regarded as undesirable characteristics for various wood applications, especially in the building industry. To achieve these objectives, wood modification was developed as a method to improve and produce new properties in the wood (C. Hill, 2006).

Heat treatment under high temperature and high pressure is one of the processes used to modify wood properties. High temperature and high pressure treatment aim to preserve wood naturally and enhance its dimensional stability, durability, and color, regardless of the wood species. All modifications are accomplished by the high temperature and high pressure treatment process instead, without the addition of any chemicals. Thus, this method has been seen as a more ecologically beneficial method of preserving wood (Manninen et al., 2002). When wood is modified, several physical and mechanical changes occur in the structural properties of wood. There are many parameters in wood modification under high temperature and high pressure treatment that affect the wood properties. These parameters interact each other, such as treatment period, temperature, and media used (Ozsahin & Murat, 2018).

2.3.1.2. Purpose of the research

As a result of the points mentioned above, it is important to understand the optimal conditions for modifying wood to achieve the desired wood qualities. However, this procedure may be somewhat complicated depending on the wood species. The purpose of this study is to carry out a comprehensive review of the published literature on the properties of wood modified under high temperature and high pressure treatment, as well as potential applications in construction and building materials.

2.3.2. Wood Modification Classification

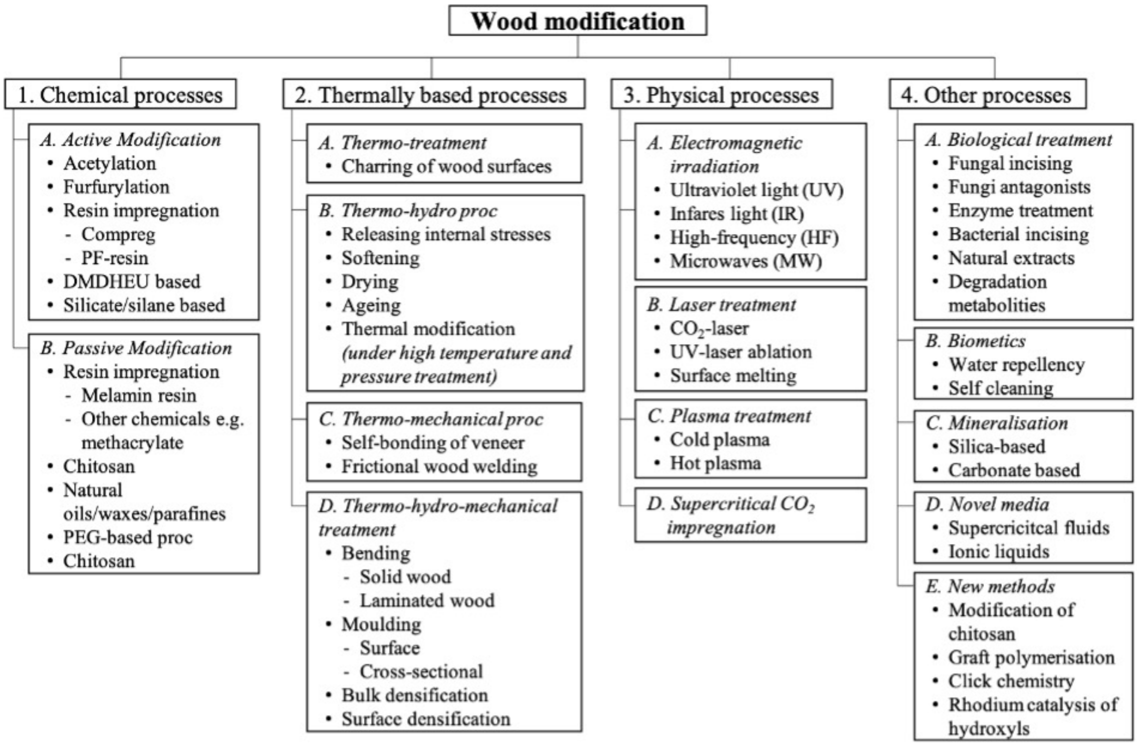


Figure 2. 4 A brief overview of wood modification processes classification

Source: (modified from Jones et al. (Jones & Sandberg, 2020a))

Environmental concerns regarding the use of wood treated with certain classes of preservatives are contributing to the current rapid development of the wood modification industry. Wood modification is a term that refers to the process of enhancing the physical, mechanical, or aesthetic qualities of wood to create a new material that does not pose a more significant environmental hazard than unmodified wood when disposed of at the end of its product cycle. Several relatively new technologies, such as thermal modification, acetylation, furfurylation, and various impregnation processes, have been introduced successfully to the market and demonstrate the potential of these contemporary technologies.

Figure 2. 4 provides a summary of what comprises wood modification. There are four main types of processes applied in modifying wood. These wood modifications

comprise various advanced techniques currently used in the wood preservation industry or different development phases.

2.3.3. Wood Modification under high temperature and high pressure treatment

Among the several wood modification procedures that have been developed, wood modification by thermal treatment at high temperature and high pressure is a thermal-based method. High temperature and high pressure treatment of wood has been identified as a potentially beneficial technique for improving the dimensional stability and deterioration resistance of wood.

The improvements in properties obtained from the high temperature and high pressure treatment depend mainly on the procedure conditions, wood species, and especially the intensity of the treatment (temperature and duration). This treatment significantly affects wood properties in some literature, including its humidity and dimensional stability, resistance to fungus and insects, mechanical properties, and aesthetic qualities like color, odor, gluability, and coating performance.

The modified wood produced by high temperature and high pressure treatment is useful for various applications, particularly in architecture, where the wood is exposed to changes in weather and moisture above ground for both external and interior uses. However, their low properties and strength should be considered in the use of structures, and further research is needed. It is crucial to integrate high temperature and high pressure treatment parameters and optimize strength and processing to reduce the environmental effects.

2.3.4. Effect of wood modification under high temperature and high pressure

The modified wood properties are dependent entirely on the treatment parameters utilized, and it is critical to consider this when comparing the different treatment procedures. The influence of high temperature and high pressure treatment on modified wood's physical and mechanical properties is summarized as follows. Additionally, a short review of some current researches is presented, emphasizing certain treatment variables.

2.3.4.1. Color changes

Among the mechanical properties of the wood used as a construction material, color is also an important property in wood species. In terms of aesthetic considerations, wood color is essential for wood applications, and it can sometimes determine its market value (Huang et al., 2012). Nevertheless, the wood may change color during processing and treatment, but the direction of this change differs between wood species. Natural wood that has not been treated is considered susceptible to environmental degradation due to weathering factors such as solar radiation, visible light, moisture (dew, rain, snow, and humidity), temperature, and oxygen (Feist et al., 1990). Numerous studies on the color changes that occur in untreated commercial wood during weathering have been conducted (Burmester, 1975; Calonego et al., 2012; Cao et al., 2012). When untreated wood is exposed to the weather, its color changes dramatically. In general, direct exposure to sunlight causes the darkness of untreated wood. After a period of weathering, it becomes more yellow or orange, then being darker and eventually lighter with a predominant grey color (Burmester, 1973; de Cademartori et al., 2014).

In color change wood treated studies, Bourgios et al. (Bourgois et al., 1991) revealed that when the wood is thermally processed, the decrease in lightness and increase in color difference are caused by a reduction in hemicellulose content especially pentosan. Additionally, Morita and Yamazumi (Morita & T, 1987) observed that as treatment pressure and time increased, the color difference with steaming increased. Mitsui et al. (Mitsui, 2004) examined the effect of heat treatment on the color of light-irradiated wood. It was discovered that heat treatment significantly increased the lightness in light-irradiated timber compared to unirradiated wood. This is aligned with untreated natural wood that has endured the color mentioned above changes. Even Bekhta and Niemz (Bekhta & Niemz, 2003) explained that high temperature treatment has a significant effect on wood's dimensional stability and mechanical properties, in addition to color change. Moreover, the color parameter, especially the total color difference, can estimate quantitively and predict the wood strength.

2.3.4.2. Mass loss

Mass loss of wood is a critical characteristic of the high temperature and high pressure treatment. Moreover, it is often referred to as a quality indicator of the treatment. However, some of the data that have been collected from the literature are difficult to be compared because of the different wood species and initial moisture content, different treatment processes, and treatment conditions of either the time or temperature setting.

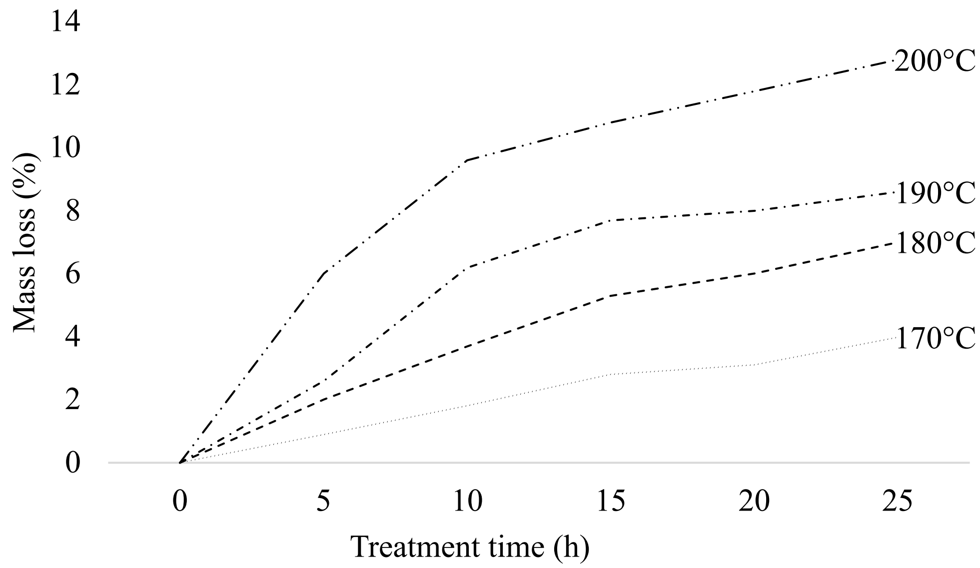


Figure 2. 5 The relationship between the mass loss of wood and the treatment time for the different temperature settings

Source: (B. M. Esteves et al., 2008)

As reported by Tenorio and Moya (Tenorio & Moya, 2013), the final mass loss in wood modification and the high temperature and high pressure treatment depend on the wood species and treatment conditions, such as the heating equipment used and the intensity of the treatment in terms of both temperature and duration. Also, Esteves et al. (B. M. Esteves et al., 2008) reported that the amount of mass loss increased with treatment time and temperature, and the same amount of mass loss could be achieved at various temperatures depending on the treatment time. For instance, a mass loss of 3% in

Pinewood could be achieved in 17 hours at 170 ºC, in 9 hours at 180 ºC, in 5 hours at 190 ºC, and only in 3 hours at 200 ºC (see Figure 2. 5).

Similar findings were obtained by Zaman et al. (Zaman et al., 2000), that the treated scots pine and silver birch at temperatures ranging from 200 ºC to 230 ºC for 4 and 8 hours, and it is found that mass losses for pine ranged from 5.7% (4 hours) to 7.0% (8 hours) at 205 ºC, and between 11.1% (4 hours) and 15.2% at 230 ºC, meanwhile, the results of birch varied from 6.4% (4 hours) and 10.2% (8 hours) at 200 ºC, and 13.5% (4 hours) and 15.2% (8 hours) at 220 ºC. Then Taghiyari et al. (Taghiyari et al., 2020) also found that heat treatment on pine wood with relatively light temperatures, 145 ºC, 165 ºC, and 185 ºC, indicates that the high mass loss is observed at the highest temperature at 185 ºC.

2.3.4.3. Equilibrium moisture content (EMC)

The main effect of high temperature and high pressure treatment is a decrease in the equilibrium of moisture content. Variations in relative humidity (RH) cause changes in the moisture content of wood (MC). When exposed to constant RH, the wood gradually reaches a stable equilibrium moisture content (EMC) (Altgen et al., 2016). Equilibrium moisture content (EMC) is characterized as the moisture content at which the wood is neither gaining nor losing moisture; it has reached equilibrium (W. Simpson & A, 1999). For a long time, it has been commonly recognized that MC has an impact not only on the dimensions but also on the physical and mechanical properties of wood (Hernández et al., 2014).

Because numerous variables affect the increase in equilibrium moisture content, it is not easy to compare most published findings. Tiemann (Tiemann, 1920) carried out the first experiments that formed the basis and reported that drying at high temperatures can lower the equilibrium moisture content of the wood, as a result of which the wood swells and eventually shrinks. Then, the minimum temperature required to perform wood modification treatment, according to several studies, is 100 ºC, where water absorption will decrease if the set temperature is above 100 ºC (D'Jakonov & Konepleva, 1967; F. Kollmann & Schneider, 1963; Nikolov & Encev, 1967).

2.3.4.4. Dimensional stability

Owing to the decrease in the equilibrium moisture content of wood caused by high temperature and high-pressure handling, the dimensional stability of the wood increases. Wood modification process with high pressure and high temperature treatment often aims to improve the dimensional stability of wood. Dimension stability is a critical wood property because it affects how a finished wood product moves and distorts during operation (Sargent, 2019).

Table 2. 5 The impact of high temperature and high pressure on wood's dimensional stability

Wood type	Method	Max Temperature (°C)	Max Duration (h)	Dimensional stability		Reference
				ASE (%)	EMC (%)	
Uludag fir wood	Steam	210	12	-(44~57)	-	(Aydemir et al., 2011)
Chinese fir wood	Steam	230	5	-72	-	(Cao et al., 2012)
Pine	Steam	210	12	-57	-46	(B. Esteves et al., 2007)
Eucalypt	Steam	210	12	-90	-61	(B. Esteves et al., 2007)
Pinus nigra	Steam	225	3	-66	-	(Bilgin Guller, 2012)
Gympie messmate	Steam	240	4	-68	-64	(de Cademartori et al., 2014)
Oak	Steam	220	2/4	-(35/43)	-(56/60)	(Jiang et al., 2014)
Silver oak	Vacuum	210~240	1~8	-(12~42)	-	(Srinivas & Pandey, 2012)
Rubberwood	Vacuum	210~240	1~8	-(20~38)	-	(Srinivas & Pandey, 2012)

Burmester (Burmester, 1973) conducted one of the first experiments to report this development, stating that it was possible to minimize the deformation of wood at the optimum pressure and temperature. Then, two years later, Burmester (Burmester, 1975) concludes that high temperature treatment of wood results in a significant decrease in the hemicellulose content, thus improving the wood's dimensional stability.

In addition to reducing EMC in wood modification studies, the dimensional stability of wood is also usually assessed by the anti-swelling efficiency (ASE). ASE is the rate at which the amount of treated and untreated wood decreases (control), where the swelling is calculated between the dry state and the relative humidity (Rowell, 2006).

Recent literature has also been reviewed regarding the effects of high temperature and high pressure on dimensional stability in wood. The effect of treatment in the current research on several types of wood is summarized in Table 2. 5 using a variety of variables, including the type of gas medium used (vacuum or steam), the maximum temperature, the duration of the maximum temperature, and the decrease in equilibrium humidity following treatment. The classification of gas media either between steam or vacuum used in high temperature and high pressure treatment is based on the field of study that the author is also involved in. Steam and vacuum gas media are simple media due to the absence of other chemical liquids. The maximum temperature was chosen to reflect the effects of dimensional stability. According to the explanation above, ASE and EMC are often used as a basis for determining dimensional stabilization.

2.3.4.5. Anatomical changes

Wood is treated under high temperature and high pressure to improve its properties, effectively shrinking the cell lumen volume. In the treatment process, the morphology of wood changes significantly, but the effects depend on the wood species and the process conditions. The mild thermal treatment (115 °C) had no effect on the size or distribution of the cell wall micropores; higher temperatures were required to increase the size and expand the microporosity distribution (C. Hill, 2006). This increase in cell wall microporosity is assumed to result from component removal during the high steam heating process.

Gao et al. (Gao et al., 2016) reported that poplar veneers exposed to high temperatures and pressure exhibit improved wood morphology. Figure 2. 6 demonstrates that untreated wood cracks were not smooth; instead, fiber pulling occurred more often, resulting in large holes in the cracked surface. However, when the wood is transformed by steam exposure at a high temperature of 170 ºC and a pressure of 0.8 MPa for 15 minutes, the interfacial bonding is better than the untreated wood. On cracked surfaces, tensile phenomena are barely visible, yet tensile fracture phenomena sometimes occur. The phenomenon of pulling fractures increased the number of holes, with smaller holes and a rougher surface.

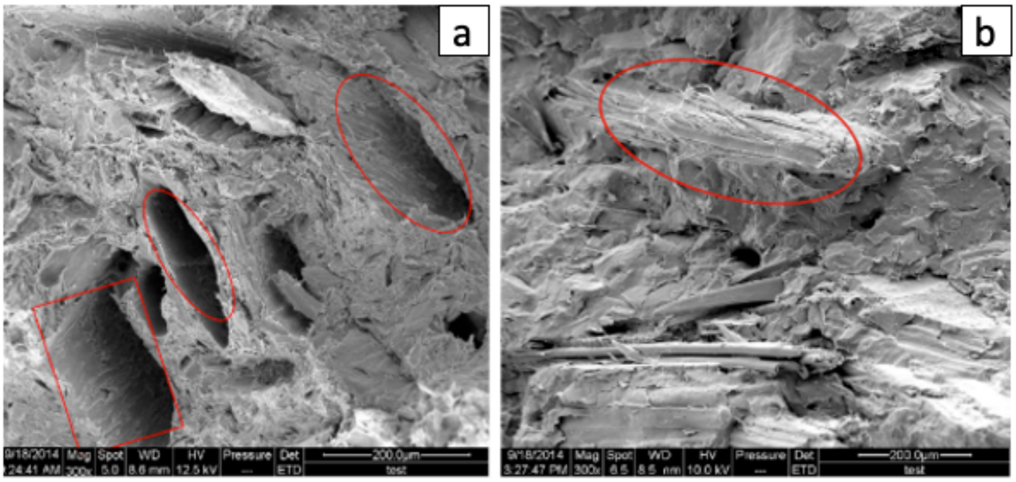


Figure 2. 6 SEM micrographs results of untreated (a) and treated wood (b)

Source: (Gao et al., 2016)

2.3.4.6. Crystallinity changes

Wood is a complicated composite material composed primarily of cellulose, hemicellulose, and lignin. Cellulose is the crystalline component of wood, while hemicellulose and lignin have an amorphous structure. Hemicelluloses and lignin's primary mechanical role is to substantiate the cellulose fibrils (Wikberg & Maunu, 2004). The crystallinity of cellulose, measured as the crystallinity index (CrI), is often estimated by analytical techniques such as X-ray diffraction (XRD), Fourier transform infrared (FT-IR), carbon-13 NMR, and near-infrared (NIR) spectroscopy (Lionetto et al., 2012). The degree of crystallinity has a noticeable effect and acts as a framework that supports the whole wood structure on the thermal stability, mechanical strength, hardness, density, and hygroscopicity of wood.

Numerous investigations have shown that high temperatures and pressure enhance the degree of crystallinity in wood. The increase in crystallinity happens early in the modification process, when the mass loss is low due to molecular rearrangement rather than failure of the amorphous component. In an analysis of the effect of the treatment on crystallinity, it was discovered that steaming for 10 minutes at temperatures ranging from 120 °C to 220 °C increased crystallinity, while heating in air at the same temperatures for 20 hours decreased crystallinity (Dwianto et al., 1996). Yildiz S (Yildiz & Gümüşkaya, 2007) also added that the crystallinity of cellulose in spruce and beechwood samples increased by thermal modification, where the increase was not only related to a high temperature between 150 °C, 180 °C, and 200 °C but also to treatment time (6-10 hours).

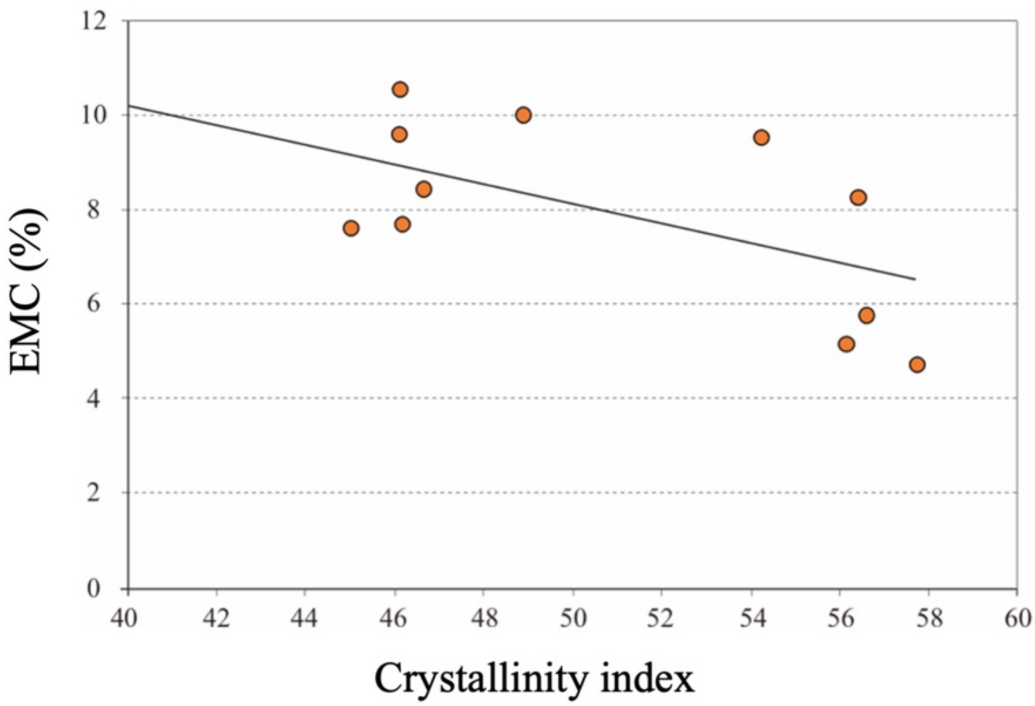


Figure 2. 7 Correlation between crystallinity index and EMC

Source: (Tarmian & Mastouri, 2019)

Changed wood crystallinity led to improvements in wood's moisture removal performance (Tarmian & Mastouri, 2019). As shown in Figure 2. 7, there is a significant negative correlation between the crystallinity and EMC of treated wood samples; the higher the percentage index of wood crystallinity, the less EMC is present in the wood.

2.3.4.7. Mechanical properties

One of the primary disadvantages of high temperature and high pressure treatment is the loss of mechanical strength, making it unsuitable for most structural applications. In some literature, many authors have found that the mechanical strength of wood has a significant decrease in a temperature setting of 180-210 °C and a reasonably long setting time, as listed in Table 2. 6. For example, it is noticeable that Eucalyptus camaldulensis wood modified for 10 hours at 180 °C resulted in a 19% loss in compressive strength (Unsal & Ayrilmis, 2005).

Table 2. 6 Significant reduction in mechanical strength from 180 to 210°C temperature

Wood Type	Temp. (°C)	Duration (H)	Mechanical properties			Reference
			Comp. strength	MOE	MOR	
Eucalyptus camaldulensis	180	10	-19			(Unsal & Ayrilmis, 2005)
Eucalyptus globulus	190, 210	12	-35	15	50	(B. Esteves et al., 2007)
Eucalyptus grandis	200		-5.6	5.5	33.9	(Calonego et al., 2012)

Meanwhile, treated *Eucalyptus globulus* wood (B. Esteves et al., 2007) at 190 °C and 210 °C demonstrated 15% and 50% reductions in modulus of elasticity and modulus of rupture under static bending, respectively, and reduced compressive strength of -35%. Modifying *Eucalyptus grandis* specimens at 200°C resulted in a 3.9 and 5.5% reduction in the MOE parallel to the grain, respectively (Calonego et al., 2012). Furthermore, there is a 5.6% decrease in compressive strength parallel to the grain. Due to the above consequence, the maximum temperature of the high temperature and high pressure treatment should ideally be set below 180 °C, as some authors have observed a considerable decrease in mechanical strength from 180 °C to 210 °C or when applied for an extended time.

2.3.4.8. Durability

Wood is a material that is highly susceptible to deformation and decay, especially in environments with regular high-low moisture variations. Due to high moisture content levels, such as in outdoor applications, soft rot fungus may attack the three major chemical components of wood (lignin, hemicellulose, and cellulose) (Woodrow & Grace, 2008). To avoid fungal deterioration, another significant advantage of high temperature and high pressure procedures is that the durability of wood can be increased.

According to some studies, wood modification reduces the hygroscopicity of the wood, thereby minimizing the harmful consequences of exposure to water and steam and providing improved defense against wood-destroying fungi. Due to the degradation of hemicelluloses, thermal treatment at high temperature and pressurized treatment decreases the hygroscopic properties of wood and avoids water reabsorption, thus increasing the resistance of wood to biological attack (Kocaefe et al., 2007)2007). Therefore, especially for wood with the most unstable hemicelluloses, increasing the durability of high temperature modified wood should be the key to avoid degradation of wood components at extreme temperatures.

To investigate the impact of wood durability, Li et al. 2017 (Li et al., 2017) modified Poplar wood at temperatures ranging from 170 ℃ to 210 ℃ for a set period of 3 hours. Following that, the moisture adsorption behavior and durability to soft rot were studied. After 32 weeks of exposure to the soft rot fungus in a soil block experiment, control wood demonstrated the largest weight reduction compared to modified wood (see Figure 2. 8). The findings indicate that as the treatment temperature increases, the mass loss in the wood decreases, implying that the durability improves. Similarly, Lee et al. (Lee et al., 2013) also state that the durability of larch and tulipwood pellets increases with increasing pelletizing time and temperature. The mass loss is directly related to the intensity of heat treatment at high temperature and pressurized, which is the most important parameter for evaluating the final mechanical properties of wood durability (M. Elaieb et al., 2016).

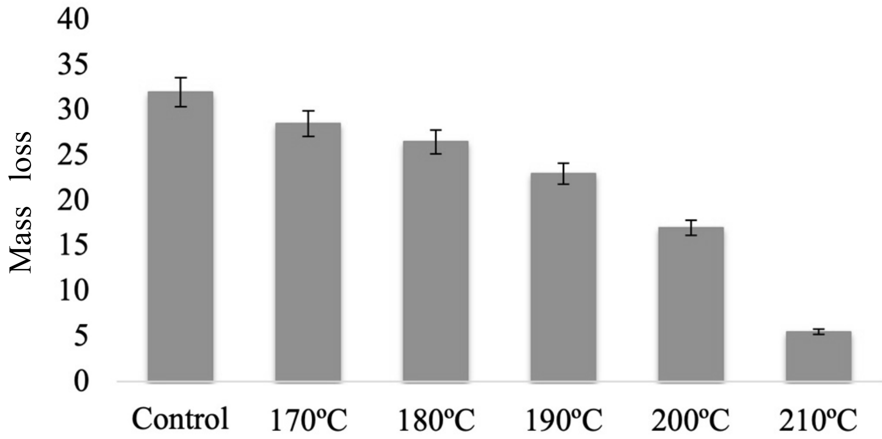


Figure 2. 8 Correlation of mass loss in modified and modified poplar wood caused by soft-rot fungi

Source: (Li et al., 2017)

2.3.5. Conclusions

Wood modification at various high temperature and high pressure conditions has been widely studied and utilized to enhance wood's mechanical and physical properties. At the very least, the parameters obtained in some of the present studies are being refined to achieve optimal results. Therefore, based on the literature review, it can be concluded that:

1. Wood modified under high temperature and high pressure is much darker than the unmodified wood, but the discoloration is not permanent when exposed to direct sunshine on the outside.
2. As an indicator of treatment quality, mass loss increased with treatment time and temperature. Which of these quantities is achievable at different temperatures, depending on the duration of the treatment.
3. High temperatures above 100 °C can reduce the wood's equilibrium moisture content; thus, the wood swells and eventually shrinks.
4. The decrease in the equilibrium moisture content of the wood caused by the high temperature and high pressure treatment also affects the dimensional stability of the wood, where ASE and EMC are often utilized as a basis for dimensional stability determination.

5. The high temperature and high pressure treatment significantly reduced the luminal volume of the cells in the wood, which implies that the increased microporosity of the cell walls is a result of component removal during the high steam heating procedure.
6. Changes in wood crystallinity led to an increase in wood moisture removal performance, the higher the wood crystallinity percentage index, the less EMC in the wood.
7. The mechanical strength of the wood decreased significantly when the temperature was adjusted to 180-210 °C or higher and a reasonably long setting time.
8. As a material susceptible to deformation and deterioration, high temperature and high pressure treatment of wood can increase its durability. In addition, the mass loss in the wood reduced when the treatment temperature rises, suggesting that durability was growing.

2.4. Potential of wood modification technologies on the physical and mechanical properties of Indonesian albasia wood

2.4.1. Introduction

2.4.1.1. Background

In 2013, the Indonesian forest product industry consumed more than 64 million m^3 of wood. However, less than 24 million m^3 of natural forest logs were harvested in the same year (Forestry, 2014). Consequently, there is a gap between supply and demand, and wood businesses are compelled to seek alternative sources of raw materials to fulfill the rising need. One source consists of community-owned and -managed forests. Community forests are primarily composed of fast-growing plants that often have short harvesting cycles (less than ten years).

Albasia is a fast-growing wood species cultivated extensively in Indonesian forests and community plantations. In 2019, the wood industry was supplied with 57.9 million m^3 of logs, more than 85% of which came from forest plantations. Indonesia produced 5.4

million m^3 albasia logs, representing 9.3% of the total national log production (BPS, 2019).

However, the rapid growth of albasia results in low density, poor hardness and strength, and perhaps a large amount of juvenile wood with numerous knots, which has inferior physical and mechanical qualities to mature wood (Julian et al., 2019; Zhang et al., 2004). Therefore, it is essential to increase the density and characteristics of the wood, as denser wood is frequently selected for commercial applications (Blomberg et al., 2005b; Laine et al., 2016; Pelİt et al., 2017). Wood modification is a promising strategy for improving the characteristics of fast-growing species (Candelier et al., 2015; Ratnasingam & Ioras, 2012).

This review focuses on how wood modification has been and could be utilized to advance our fundamental understanding of the impact on the physical and mechanical properties of albasia wood. First, we briefly describe the current state of knowledge regarding the essential characteristics of albasia wood and wood modification technologies. Second, we demonstrate how wood modification can be used to enhance the physical and mechanical properties of albasia. Finally, the objective is to compile a comprehensive compilation of all literature concerning the impacts and various modification procedures on the physical and mechanical properties of *Albasia*.

2.4.1.2. Purpose of the study

We discuss a focused selection of literature intending to inspire future research in the critical field of albasia wood modification research to advance the state-of-the-art of albasia potential. With a greater understanding of the effects of wood modification technologies, it will be feasible to create and refine wood modification procedures to improve the physical and mechanical properties of *Albasia*.

2.4.2. Materials and methods

In this study, we have organized a narrative or semi-systematic review (Wong et al., 2013). The pertinent literature has been analyzed in two sequential steps: (i) i identification of literature from selected databases using a set of criteria, and (ii) mapping the content of the selected literature using a series of particular queries. These procedures are detailed below.

2.4.2.1. Identifying literature

The literature was searched using Google Scholar, ScienceDirect, and ResearchGate portals between April and June 2022. Some terms (in English and Bahasa Indonesia; italics added) were mixed during the literature search, including Acetylation, Albizia falcataria, albasia, densification, furfurylation, impregnation, physical properties, plantation, mechanical properties, sengon, thermal modification, wood modification. The articles included were written in English and Indonesian (Bahasa Indonesia). The study review consisted of a total of 23 selected literature on modified Indonesian Albasia wood, which were then classified based on the type of treatment used and properties achieved in each study.

2.4.2.2. Mapping of contents

The following questions were utilized to map the contents of the selected studies:

- What wood modification technologies have been implemented to albasia wood?
- How is the treatment applied to modified albasia wood?
- How are wood properties achieved and the challenges from different types of treatment on modified albasia?
- What is the future of wood modification technologies on albasia?

2.4.3. Outline and Current Situation

2.4.3.1. Albizia falcataria

Albasia or Sengon (*Albizia falcataria*) is a type of fast-growing tree that is extensively planted in community forests in Indonesia. The origin of the species is in Indonesia, Papua New Guinea, the Solomon Islands, and Australia (Soerianegara, I. and Lemmens, 1993). As a result of the tree's fast growth, the wood has poor density, strength, and durability, and a large proportion of it is juvenile wood. The wood has a density of 0.3-0.5 g/cm^3 and a hardness of 112-122 kg/cm^2, while the trees include up to 100% juvenile wood (Kojima et al., 2009). Albasia has durability and strength classes of IV-V (Martawijaya et al., 2005). Albasia is now utilized in Indonesia for pulpwood, lightweight building, and wood composite. However, its application is limited to original, unaltered wood widely distributed in the wood industry sector.

2.4.3.2. Wood modification technologies

The emergence of wood modification technologies is a response to the need to enhance the performance, durability, and sustainability of wood products. Traditional wood materials have limitations such as decay susceptibility, dimensional instability, and insect and fungus susceptibility. To overcome these obstacles and broaden the range of wood's applications, researchers and industry experts have developed a number of wood modification technologies.

The origins of wood modification technologies can be traced back to the middle of the 20th century, when scientists began experimenting with chemical treatments to improve wood properties. Initially, the emphasis was placed on preserving wood with chemical preservatives. These treatments involved impregnating wood with poisonous chemicals to prevent rot and insect infestation. Concerns regarding the environmental impact and health risks of traditional preservatives prompted the investigation of alternative wood modification strategies.

Wood modification has been defined by Hill (C. Hill, 2006) as a procedure that “requires the effect of physical, biological, or a chemical agent on the wood species, resulting in the desired property enhancement during the life span of the modified wood”. This is commonly regarded as a different technique from the conventional biocide-based wood preservation treatments (Eaton & Hale, 1993). The wood modification sector is undergoing significant development, driven partly by environmental concerns.

Four primary types can be constructed as wood modification (see Figure 2. 4). These wood modifications consist of many advanced procedures now utilized in the wood preservation industry or various stages of development. Several systems are well developed and commercially available, including thermal modification — the method of modifying hygroscopicity by the application of elevated temperatures (160 °C to approximately 230 °C) in an anaerobic environment, steam, or vacuum (B. M. Esteves

& Pereira, 2009a; Lekounougou & Kocaefe, 2014); Acetylation — the esterification of wood with acetic anhydride (R. M. Rowell, 2014).

Table 2. 7 Estimated overall global production of modified wood

Treatment	**Estimated Volumes (m³)**				
	Europe	**China**	**N America**	**Oceania/ Japan**	**Other**
Thermally modified wood	695,000	250,000	140,000	15,000	10,000
Densified wood	2,000	<1,000	-	<1,000	-
Acetylation	120,000	-	-	-	-
Furfurylation	450,000	-	-	-	-
Other methods	35,000	290,000*	-	5,000	TBD*
(*) Figures combine furfurylation processes other than Kebony® and NobelWood®, DMDHEU, and other resin treatments. ( ) Empty fields indicate that no data are available or that the authors of the cited work are unaware of this type of modified wood in this region.					

Source: (Jones & Sandberg, 2020b).

Based on data from Jones and Sandberg, Table 2. 7 summarizes the main wood modification and annual expected commercial volumes worldwide. Thermal modification accounts for a global production volume of 1,608,000 m^3 per year. According to the consumer demand, licensing of technology, and the relative simplicity of producing thermally treated wood utilizing stand-alone treatment chambers, a rise in production is expected in the future years.

2.4.4. Results and Discussion

Table 2. 8 Commonly achieved properties of modified Albasia from various wood modification technologies.

Process	Type	Treatment	Reference	Achieved Properties									
				Density	Mass Loss	Color Changes	Change in	Moisture	Morphology	Dimensional	Hardness	Compressive	MOR & MOE
Thermally based	Hydro	Thermal Modification	(Muthmainnah, 2017)	✓	✓	✓	✓	✓					
			(Karlinasari, Yoresta, et al., 2018)			✓		✓			✓		
			(Karlinasari, Lestari, et al., 2018)	✓				✓		✓			
			(Iskandar et al., 2018)	✓			✓	✓			✓		✓
			(Iskandar et al., 2019a)	✓						✓	✓	✓	
			(Julian et al., 2022)	✓	✓	✓	✓	✓	✓				
			(Iskandar et al., 2021)	✓			✓	✓			✓	✓	
		Drying	(Adzkia et al., 2020)	✓				✓					
	Mechanical	Bonded	(Karliati et al., 2019)	✓				✓	✓				
Chemical	Active Modification	Acetylation	(Asdar, 1999)	✓				✓					✓
			(Y. S. Hadi et al., 1994)	✓	✓								✓
		Impregnation	(Sumardi et al., 2020)	✓	✓	✓	✓		✓	✓		✓	✓
		Furfurylation	(Y. S. Hadi et al., 2005)		✓								
			(Y. S. Hadi et al., 2020)		✓								
			(Y. S. Hadi, Mulyosari,	✓	✓	✓		✓					

			et al., 2021)										
			(Y. S. Hadi, Nawawi, et al., 2021)	✓	✓	✓		✓					
			(Y. S. Hadi et al., 2022)	✓	✓	✓		✓			✓	✓	✓
			(Sabrina et al., 2021)		✓	✓		✓					
	Passive Modification	Impregnation	(Nandika et al., 2015a)	✓			✓	✓	✓	✓	✓		✓
			(Budiman et al., 2020)	✓				✓			✓		✓
			(Rahayu et al., 2020)	✓	✓				✓	✓			
			(Nurhanifah et al., 2020)		✓			✓					
			(Rahayu et al., 2021)	✓	✓				✓	✓		✓	
Empty fields indicate that no benefit is claimed according to the references, to the best of the authors' knowledge													

Source: Research Documentation, 2022.

2.4.4.1. Acetylation

Table 2. 9 Summary of selected studies of Albasia acetylation.

Sample	**Acetylation method**	**Reference**
Medium-density fiberboard (MDP)	Acetic anhydride, subsequently heated at 120°C for 2 hours	(Asdar, 1999)
Flakeboards	Acetic anhydride, subsequently heated at 120°C for 24 hours	(Y. S. Hadi et al., 1994)

Source: Research Documentation, 2021.

One of the best ways to improve the technical properties of less durable wood species is acetylation, which has been the subject of extensive research (C. Hill, 2006; R. M. Rowell & Dickerson, 2014). Additional research and commercialization have been conducted on the acetylation reaction, and these efforts are still ongoing.

The simplified reaction of *Albasia* wood components with acetic anhydride is shown in Figure 2. 9. The acetylation of wood is a chemical alteration in which an external pressure forces an electrophilic reagent (often acetic anhydride) to migrate through the wood pits, and react with accessible nucleophilic hydroxyl groups, then diffuse and react deeper into the cell wall (R. M. Rowell, 1983). Therefore, the thickening of the cell wall and the removal of hydrophilic hydroxyl groups decreases the wood's ability to absorb moisture and enhance its resistance to swelling and decay (C. Hill, 2006; C. A. S. Hill & Jones, 1996). A more detailed description of the acetylation modification of *Albasia* is shown in Table 2. 9, along with the type of sample and acetylation method.

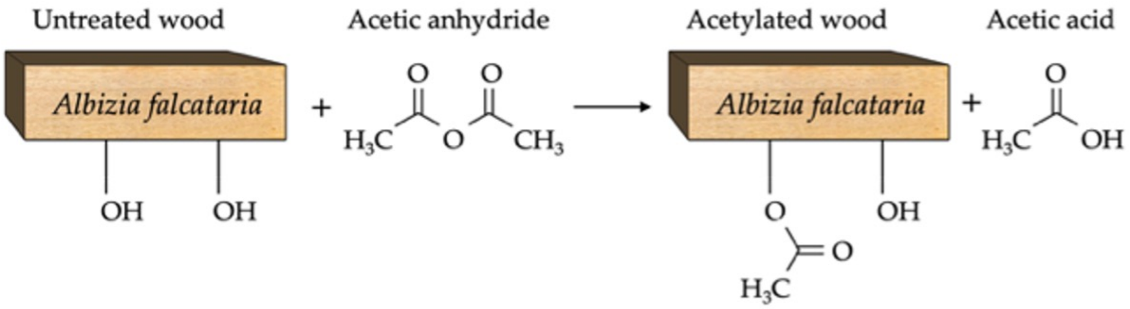


Figure 2. 9 Schematic view of the acetylation of Albasia.

Source: Research Documentation, 2021.

According to the albasia acetylation study, older albasiatrees and acetylation conferred more excellent resistance to fungal infection (Y. S. Hadi et al., 1994). The higher the level of acetylating agent (acetic anhydride), the lower the moisture content and swelling of the wood (Asdar, 1999). Moreover, albasia with a higher WPG (weight percent gain) resulted in increased density, modulus of rupture, modulus of elasticity, and internal bonding; however, this overall score was lower than the control.

2.4.4.2. Furfurylation

Another chemical modification technique that enhances the resistance of wood is furfurylation which has been widely explored and demonstrated to produce high-performing sustainable wood material (B. Esteves et al., 2011). Furfurylation is a wood modification process that involves impregnating wood with a combination of furfuryl alcohol (FA) and catalysts and then heating the wood to produce polymerization (Sandberg et al., 2017b). FA can be made by hydrogenating agricultural and timber byproducts containing pentosans (Baysal et al., 2004).

The furfurylation aims to enhance resistance to biological degradation and dimensional stability by applying a non-toxic, furfuryl alcohol-based polymer using a proprietary formula (Sandberg et al., 2017b). In terms of ecotoxicity, physical and mechanical qualities, dimensional stability, and product durability, the furfurylation of wood has been deemed a good process (Lande et al., 2004). The method offers several benefits and is safe for the environment, with a good potential for furfurylation, providing excellent and environmentally friendly material (Dong et al., 2014; Gérardin, 2016).

Table 2. 10 Summary of selected studies of albasia furfurylation.

Sample	Furfurylation method	Reference
Wood stakes	Vacuum-pressure impregnation (30-L capacity), 92, 48, and 15% FA, vacuum (45 min), pressure 12 bars (2 h), wrapped in aluminum foil, and heated 103 °C (16 h & 8 h)	(Y. S. Hadi et al., 2005)
Flat sawn lumber	FA + tartaric acid (20:1, v/v), streamed into the tank during vacuum release, and pressure at 10 kg·cm−2 (30 min)	(Y. S. Hadi et al., 2020)
Flat sawn timber	FA + 5% tartaric acid (5%), vacuum 600 mmHg (30 min), pressure 10 kg·cm−2 (30 min), wrapped in alumunium foil, and heated 100 °C (24 h)	(Y. S. Hadi, Mulyosari, et al., 2021)
Flat sawn timber	Tartaric acid + FA (1:20; v/v), pressure 9.81 bars (30 min), wrapped with aluminum (30 min), and heated 100 °C (24 h)	(Y. S. Hadi, Nawawi, et al., 2021)
Flat sawn timber	Tartaric acid + FA (5:100 by weight), vacuum 600 mmHg (30 min), immersion in FA, pressure 10 kg/cm^2 (30 min), wrapped with aluminum foil, and heated 100 °C (24 h)	(Y. S. Hadi et al., 2022)
Flat sawn timber	FA + tartaric acid 5% (b/v), oven-dried 60±2°C (48 h), pressure at 5 atm (30 min), wrapped with aluminum foil (30 min), and heated 100 °C (24 h)	(Sabrina et al., 2021)

Source: Research Documentation, 2021.

Table 2. 10 provides an overview of furfurylation treatments for selected albasia wood. Based on subterranean termite field tests conducted in Bogor, Indonesia (Y. S. Hadi et al., 2005), discovered that furfurylated wooden stakes (*Pinus sylvestris*, *Agathis dammara*, and *Albizia falcataria*) experienced a 40% increase in personal weight

(WPG) and their condition remained good after a one-year test period in the field, during which termites did not appear to be able to eat the stakes.

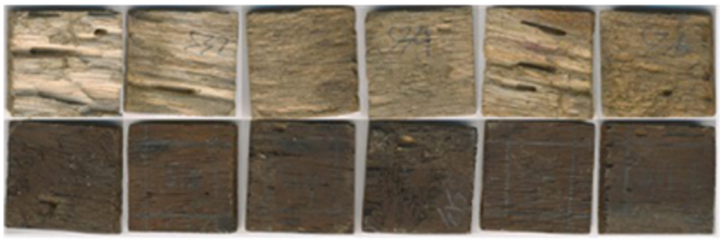


Figure 2. 10 Control and furfurylated wood samples.

Source: Research Documentation, 2021.

In Figure 2. 10 (Y. S. Hadi, Mulyosari, et al., 2021), furfurylation increases the resistance of wood to subterranean termites, as shown by a lower amount of termite damage, a higher wood resistance class (from class IV to class I according to Indonesian standards), and a substantially lower percentage of weight loss (control wood lost 17.30 % of weight loss, while furfuryated wood lost 1.92 %).

2.4.4.3. Thermal modification

Thermal modification of wood has a long history, dating back to the 1920s (B. M. Esteves & Pereira, 2009a), and since the 1990s, Europe has developed new technologies for producing these types of products, resulting in increased industrial production and commercialization of many wood species (Sandberg et al., 2017c).

It has been thoroughly studied that wood that has been thermally modified will typically experience beneficial changes in properties such as decreased equilibrium moisture content, increaed dimensional stability (Srinivas & Pandey, 2012; Uribe & Ayala, 2015), and enhanced durability (B. M. Esteves & Pereira, 2009a). In addition, thermal modification can reduce hygroscopicity (Bal & Bektaş, 2013) and cause hydrophobic alteration of wood (Wang & Piao, 2011). Hydrophobicity is associated with surface qualities and influences wood's coating, absorbency, adhesion, and finishing properties (B. M. Esteves & Pereira, 2009b; Hubbe et al., 2015). A summary of recent thermal modification studies into *Albasia* species is given in Table 2. 10.

Table 2. 11 Summary of selected examples of thermal modification of albasia wood.

Sample	Temperature (°C)	Duration	Others	Reference
Board	170	3 min	Hot oil	(Muthmainnah, 2017)
Board	120, 150, 180	2 h, 6 h	-	(Karlinasari, Yoresta, et al., 2018)
Lumber	120, 150, 180	2 h, 6 h	-	(Karlinasari, Lestari, et al., 2018)
Board	100	45 min	Pressure	(Iskandar et al., 2018)
Board	100	45 min	Pressure	(Iskandar et al., 2019b)
Board	100, 120, 140	30 min	Vacuum Pressure	(Julian et al., 2022)
Board	100	45 min	Pressure	(Iskandar et al., 2021)
Board	165	2 h, 6 h	Drying	(Adzkia et al., 2020)

Source: Research Documentation, 2021.

Among the physical properties of wood, color is crucial for wood applications because it determines its aesthetic market value (Huang et al., 2012b). The high demand for albasia wood supplied by the Indonesian processing industry is due to the wood's bright colors and rough texture (Nemoto, 2002a). In addition, the wood's original color may change during processing and thermal modification. The thermally modified *Albasia* was darker than its control. As the density of the wood grows, its chemical components, specifically hemicellulose, decompose, darkening its color (Julian et al., 2022).

In general, the temperature and time of exposure to the modified thermally treatment performed on *Albasia* caused color changes in all studies. Nevertheless, based on the thermal treatment set, the interaction of pre-treatment factors, temperature, and time of heat treatment had no significant effect on the color and hardness changes of the wood (Adzkia et al., 2020; Julian et al., 2022; Karlinasari, Yoresta, et al., 2018).

Scanning Electron Microscopy (SEM) analysis revealed that the treatment increased wood morphology (Julian et al., 2022). Comparing the control without treatment to the thermal modification and subsequent compaction, the cavity's microscopic structure changes are visible (Muthmainnah, 2017). This alteration in cell shape does not reduce the strength of the wood; in fact, it increases its strength. This is because the cell structure becomes denser, and the lignin remains undamaged, which results in an increase the strength of the wood, a decrease in its moisture content, and enhancement of its dimensional stability.

2.4.4.4. Impregnation

One way to overcome the low physical and mechanical properties of fast-growing wood is to modify it by impregnating it with impregnation material, which modifies the properties of the wood by intervening at the level of the cell wall (C. Hill, 2006).

The method of impregnation includes treating wood with a monomer solution, which diffuses through the cell wall, followed by polymerization. The bulking of the cell wall by the impregnant is the primary cause of property enhancements. A summary of impregnation modification of albasia is shown in Table 2. 12.

Table 2. 12 Summary of selected examples of impregnation modification of Albasia.

Sample	Impregnation	Compregnation	Reference
Tangential board	Chitosan solution 0.5% under 100 °C, 120 °C, 140 °C	Compressed to be 1.5 cm thickness under 150 °C, 170 °C, 190 °C	(Nandika et al., 2015a)
Tangential board	Polystyrene under vacuum 600 mmHg (30 min)	Immersion in monomer styrene pressure at 10kg/cm^2 (30, 60, 90 min)	(Budiman et al., 2020)
Small wooden block	Mono-ethylene glycol (MEG) and nano-SiO2	Pressure 10 and 400 Pa, under a low vacuum mode	(Rahayu et al., 2020)
Glulam	Polystyrene, made into 2 layers using isocyanate adhesives	Cold pressing with specific pressure of 10 kg/cm2.	(Nurhanifah et al., 2020)
Small wooden block	MEG and nano-silica originated from betung bamboo leaves	0.5 bar of vacuum (60 min), 2.5 bar of pressure (120 min)	(Rahayu et al., 2021)

Chemical compounds containing formaldehyde, such as PF, MF, and UF, have typically been utilized as wood impregnation materials (Deka & Saikia, 2000; Fukuta et al., 2011; Gabrielli & Kamke, 2010). Due to the potential health concerns posed by formaldehyde emissions generated by the usage of these items, their use must be restricted. Therefore, alternative chemical substances that are less harmful to the environment are required. The use of chitosan as a preservative and to improve the dimensional stability of wood has increased during the past decade (Arinana et al., 2009; Guo et al., 2006). According to studies conducted on this species of timber, many physical and mechanical properties of *Albizia falcataria* wood can be enhanced by impregnation with chitosan (Nandika et al., 2015a)(Usman et al., 2007).

Monoethylene Glycol (MEG) and Silica (nano-SiO2) materials are other environmentally friendly alternatives for the impregnation process. Silica is a chemical that has several applications in a variety of industries, notably as a polymer in wood impregnation. According to research (Dirna et al., 2020), silica can be acquired from commercial marketplaces or derived from natural substances such as bamboo leaf ash. MEG is fully soluble in water, colorless, odoerless, liquid, and volatile, and it has a molecular weight of 62.07 g/mol. The impregnation of sengon wood with MEG and nano-SiO2 also significantly affects dimensional stability and density (Rahayu et al., 2020, 2021) Furthermore, it can be concluded that low-density species, such as *Albasia*, do seem to be typically easier to impregnate (Budiman et al., 2020).

2.4.5. Conclusions

1) Numerous technologies are used in the modification of *Albasia*, an indigenous Indonesian wood, according to recent studies. The modification processes include acetylation, furfurylation, thermal modification, and impregnation treatments.
2) The acetylation process involves the migration and reaction of acetic anhydride through the wood pores of *Albasia*. Another chemical technique, furfurylation, involves impregnation of wood with a combination of FA and a catalyst and then heating the wood for polymerization. In addition, thermal modification required heating with varying heat settings and durations. Furthermore, the impregnation

procedure involves the diffusion of a monomer solution into the cell wall, which is then followed by polymerization.

3) Based on the study of acetylation of *Albasia*, the moisture content and swelling of the wood decrease as the level of acetylating material (acetic anhydride) rises. Meanwhile, furfurylation of *Albasia* boosted the wood's resistance to subterranean termites and its class according to Indonesian standard. On the other hand, thermal modification, which is the most used method for modifying *Albasia* wood since it is environmentally friendly, currently shows an increase in the density of wood, thereby darkening its color. Finally, the modification of wood by impregnation and compregnation improves the dimensional stability of the wood by non-hazardous, alternative chemicals such as chitosan, MEG, and silica.
4) Even though the results of wood modification on *Albasia* have not yet achieved market acceptance in the wood industry, but current research shows that it has potential to improve the physical and mechanical properties of *Albasia* wood in the future.

CHAPTER 3
RESEARCH METHODOLOGY

CHAPTER 3: RESEARCH METHODOLOGY

This section describes the research methodology used for this study. It includes both data collection and analysis.

3.1. Data Collection

The data collection of this research includes primary data and secondary data. Primary data was obtained from qualitative and quantitative methods; ethnographic, observational, and experimental studies. Meanwhile, secondary data was obtained from urban policies, standards, and literature studies.

3.1.1. Primary data

Mixed-method data is used as the primary source for this study. This research incorporates both quantitative and qualitative data. Creswell defines mixed research as a research strategy that incorporates qualitative and quantitative research(Creswell, 2007). According to Sugiyono (2011: 404), a combined research approach (mixed methods) is a research approach that combines or integrates quantitative research and qualitative research to be used together in research activities in order to obtain more comprehensive, valid, trustworthy, and objective data. Initially, the emergence of a mixed methods research approach sought only to incorporate qualitative and quantitative data (Croswell & Shin, 2012).

3.1.1.1. Ethnography study

Due to the lack of references on Albasia wood in relation to the new objectives of the Indonesian government stated in the background of this study, the preliminary study was very beneficial in this research to investigate the understanding of Albasia wood in Indonesia.

In the preliminary study, ethnographic studies provided the primary data for this research. The ethnographic research conducted was beneficial for determining how the Indonesian people perceive Indonesian Albasia wood. Construction workers were selected to represent the community because they interact with Indonesian Albasia wood the most. Ethnography is a combination of empirical and theoretical methods that seeks to obtain an in-depth description and analysis of a culture through intensive field research (Oswald & Dainty, 2020; Pink et al., 2010). An ethnographer examines the particulars of local culture and relates them to larger social processes. Ethnographic cultural studies emphasize qualitative research on values and meanings within the context of 'whole ways of life,' i.e. culture, lifeworld, and identity issues.

According to Spradley (James Spradley, 1979), ethnography is the process of describing a culture. Therefore, ethnographic research entails learning about the world of individuals who have acquired different ways to see, hear, speak, think, and act. Therefore, ethnography does not merely study individuals; rather, it learns from them. The outcome of exhaustive ethnographic research is a detailed descriptive narrative accompanied by interpretations that interpret all aspects of life and illustrate its complexity.

We analyzed the in-depth interviews, which were initially grouped based on the skill areas of construction workers, to determine which perspectives these informants had on each sphere of their work. In addition, we selected the primary informant based on research flow considerations. This ethnographic method enabled us to establish a dynamic relationship between the actual world and the topic, Albasia wood as a material among construction workers as research informants. Due to the fact that this was a qualitative study, a representative sample of professionals engaged in building construction, namely the primary informants, was chosen.

Figure 3. 1 The location of selected ethnography case study.

The first step in controlling the object of study in qualitative data collection using an ethnographic approach is determining the location of the research. In this study, the author selected Sudalarang Village in Indonesia as a case study to examine the results of an investigation into the use of albasia wood as a local material. The location of Sudalarang Village is Sukawening, Garut Regency, West Java, Indonesia (see Figure 3. 1). The distance from Sudalarang Village to the centre of the Garut Regency is 21 km, and to the centre of the Sukawening District is 3 kilometres. Sudalarang Village is situated on a 375,415 m^2 plot at an elevation of 700 m above sea level. The total area of the village of Sudalarang is 56,845 m^2.

Sudalarang Village is an extensive representation of an architectural vocational village where the majority of the population has vocational expertise (Widaningsih et al., 2018). The primary focus is to examine how these informants utilised albasia wood as a potential building material, highlighting their knowledge and experience in their home region and outside of work. The interviewees for this study were accountable for and directly involved with carpentry work skills. The data was collected either at their residence or on the construction site. The method of in-depth interviews involved observation, the author's participation in witnessing the informant's work culture, the creation of field notes, and the recording of data. During the interview description and data collection, we stated that all professionals were male to safeguard their identities, with the exception of the primary informant, who would be investigated in greater depth.We organised the investigation as a thorough perusal of the entire research material, and then analysed the most significant content of the selected results as the pertinent issues.

Table 3. 1 Population-based on type of work of selected ethnography case study

No	Type of Work	Male	Female	Total
1	Farmers	116	32	148
2	Construction workers	331	302	633
3	Traders	12	70	82
4	Breeders	58	-	82
5	Civil servants	22	24	46
6	The National Police	3	-	3
7	Indonesian national army	2	-	2
8	General employees	15	14	29
	Total Population	559	442	1001

Source: Research documentation, 2020.

3.1.1.2. Experimental study

In the next primary data collection, this research used the experimental data. According to Hadi (1985), experimental research is research conducted to find out the consequences arising from a treatment given intentionally by researchers. Experimental research, in principle, can be defined as a systematic method for building relationships that contain causal-effect relationships (Creswell, 2012). Furthermore, the experimental is a research method used to look for the effect of specific treatments on others under controlled conditions (Sugiyono, 2011). Based on the definitions of some of these experts, it can be understood that experimental research is research conducted to determine the effect of giving a treatment or treatment to research subjects.

Experimental method study plays a crucial role in the field of wood modification because they enable researchers to investigate and evaluate the effects of different treatments and parameters on wood properties. These techniques provide valuable information and insights regarding the performance and behaviour of modified wood. It is important to note that the experimental methods employed can vary depending on the objectives, equipment, and resources of the research. In order to gain a complete understanding of the effects of wood modification, researchers may also combine multiple methodologies. In order to increase the value of fast-growing wood such as Indonesian Albasia wood which has low properties, this research applies wood modification technology experiments with thermal compression method under high temperature and high pressure.

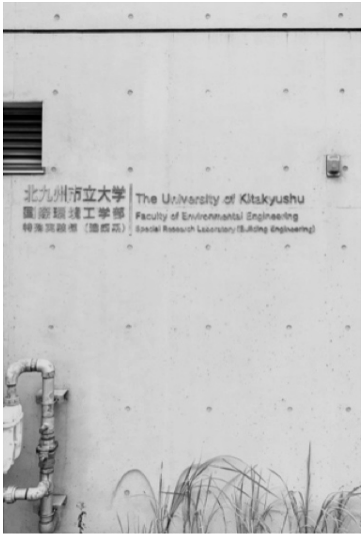


Figure 3. 2 Experimental Building, Special Research Laboratory (Building Engineering), Faculty of Environmental Engineering, The University of Kitakyushu, Hibikino, Kitakyushu, Fukuoka, Japan

Source: Research Documentation, 2023

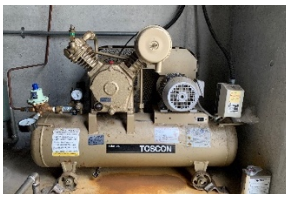
As shown in the Table 3. 2, the experiment in this study was conducted in the high-temperature and -pressure apparatus HTP-50/130 (HISAKA Company, Osaka, Japan) at the Experimental Building, Special Research Laboratory (Building Engineering), Faculty of Environmental Engineering, The University of Kitakyushu, Hibikino, Kitakyushu, Fukuoka, Japan (see Figure 3. 2).

Table 3. 2 Specification of the high-temperature and -pressure apparatus.

Name of the device	Max. temperature	Max. working pressure
HTP-50/130 type manufactured by HISAKA CORPORATION	175°C	1.18 MPa

As described above, the experiments conducted in this study were conducted in a high-temperature and -pressure apparatus. The system consisted a processing tank and a boiler setting machine. The structure of this compressor combines a processing tank with a steam blower autoclave and a pressure device. The press is comprised of two hydraulic cylinders arranged side-by-side along the longitudinal axis of the cylinder processing tank and the top press board placed on the sample. By pressing the hydraulic cylinder through the upper-pressure plate, the sample is compressed. Using the mechanism described above, it is possible to consolidate wood samples in a processing tank containing high-pressure, high-temperature steam. The experiment consists of a sample and a convex upper press plate, a carry-in table for transporting into and out of the tank, and a carriage on a concave lower press plate. The existing system in this research is described in Table 3. 3.

Table 3. 3 High-temperature and -pressure apparatus

No	Apparatus	Function
1	 Figure 3. 3 Processing tank	High-quality pressure vessels can withstand high temperatures, pressure, and vacuum. Processing tank components: 1) Press cradle 2) Press-hold components 3) A steam blow-out pipe and other components are attached. The processing tank will receive the mould apparatus during the experiment.
2	 Figure 3. 4 Heating device	A cylinder valve is used to regulate the temperature within the processing tank by introducing steam generated by the boiler. The power saver button controls the heating device before and after the experiment. 1) The heating device's heating element should be encased to prevent us or metallic conductors from touching the electric current wire. 2) Repair or replace a heating device if its heating element is exposed.
3	 Figure 3. 5 Vacuum	Vacuum devices keep the processing chamber vacuumed. The inlet of a vacuum pump is connected to one or both valve covers. It draws air from the engine to reduce air pressure from combustion gases entering the pan through the piston rings.

4

Figure 3. 6 Press device

The press device is compressed by a hydraulic unit. The following structures are located within the processing tank:

1) press the upper and lower frame
2) hydraulic cylinder (+ press shaft)
3) hydraulic pump unit
4) a stroke sensor. Total load capacity of the hydraulic cylinders (2) is 400kN (48MPa hydraulic pressure).

5

Figure 3. 7 Pressure gauge

It measures fluid density. Without pressure gauges, fluid power systems are unreliable. The use of gauges ensures that the hydraulic system for the processing tank is not compromised by any leaks or pressure changes that could affect its operation.

6

Figure 3. 8 Vacuum gauge

Using a vacuum gauge, gas pressure can be monitored directly or indirectly. Frequently, the output of a vacuum gauge is used to control various aspects of PVD processing, such as when to "crossover" from rough roughing to high vacuum pumping and when to initiate thermal evaporation in the processing tank.

7

Figure 3. 9 Mold device

The mold device contains a sample of wood that will be processed during the experiment.

1) Mold for square timber: It is composed of a mold, a holding plate, and a vice.
2) Inner tank for impregnation: It is composed of an inner tank, a drain valve, and a drain hose.
3) Rhombic mold: It is composed of square mold + upper and lower molds and front and rear partition plates.

In this experiment, we used the mold for square timber and rhombic mold device.

8

Figure 3. 10 Loading

It includes a removable loading and unloading device. There are both horizontal and vertical ways to move the device. Within this apparatus, mold devices can be loaded and removed vertically (via a hydraulic lifting mechanism).

9	 Figure 3. 11 Hydraulic	Vertical loading and unloading of the device. This device's remote contains three buttons for configuring its settings.
10	 Figure 3. 12 Air pressurizing	A vicon provides both operating air and compressed air.

Source: Research Documentation, 2023

3.1.2. Secondary data

Secondary data involves the use of data collected by other researchers; it can also be defined as the reanalysis of previously collected and analysed data (Martins et al., 2018). Secondary data are collected from a variety of data sources. The sources used depend on the focus of the research. In this research, secondary data was gathered from government data, wood standards, and study literature.

3.1.2.1. Literature review

A literature review is a survey of scholarly articles from international journals and conferences, books, and other sources pertinent to a specific problem, research area, or theory, and provides a description, summary, and evaluation of these works. The purpose of the literature review is to provide an overview of the sources the author consulted while conducting research for this study and to demonstrate how the author's research fits into areas of study that other scholars have already investigated.

The literature review conducted for this study examines information published over time on albasia wood and the field of wood modification. In general, the relevant literature was analyzed in two sequential steps: (i) identification of literature from databases selected based on a set of criteria, and (ii) content mapping of the selected literature using a particular set of questions.

Between October 2020 and May 2023, literature was identified using search engine portals such as Google Scholar, ScienceDirect, and ResearchGate. During the search for literature related to this study, some terms in English, Indonesian, and Japanese were mixed up. In the meantime, the content mapping was derived from the mapping of research questions.

3.1.2.2. Wood standards

The wood standards utilized in this investigation include terminology, standard practices, specifications, and methods for testing wood. Existing standards in the wood standard serve as guidelines for determining albasia wood specifications and test methods for testing its physical and mechanical properties, which are then used to collect and analyze primary data.

These wood standards are extremely useful for guiding the author in the selection, testing, and final application of wood testing procedures to ensure that the quality of the research can be safely and satisfactorily accepted.

3.1.2.2.1. Japanese Standard

An experiment conducted in Japan provides the primary data for this study. The standards used in the selection of wood products, measurement of wood in experiments, and testing refer to Japanese standards. In general, engineered wood products entering Japan must be certified to either the Japanese Agricultural Standard (JAS) or the Japanese Industrial Standard (JIS). The Japanese government supervises these schemes and approves certification bodies for each.

3.1.2.2.2. Indonesian Standard

The current Indonesian material and design standard on timber does not include timber strength and stiffness tests but provides a timber strength classification. The Indonesian standard in this study refers to the Center for Research and Development of Forest Products (P3HH) under the Indonesian Ministry of Environment and Forestry. The Indonesian standard used to compare Albasia wood before and after treatment in this study refers to the standard written at the Indonesian Forest Products Research and Development Center.

3.1.2.3. Government agencies

Data derived from government agencies that conduct regular surveys and publish results regarding population demographics and commodity use are also considered secondary data. Typically, government agency data publication schedules are published annually or biannually. In this study, secondary government data is derived from the most recent data published by government agencies in Japan and Indonesia.

3.2. Data Analysis

As stated previously, the primary data collection in this study employs mixed-method data, so the data analysis is comprised of both qualitative and quantitative analysis.

3.2.1. Qualitative analysis

Qualitative data in this research derived from primary data in the form of ethnographic study results and secondary data in the form of literature studies.

3.2.1.1. Analysis of ethnographic study data

The data analysis includes the interpretation of the ethnographic study results from research informants in order to obtain a comprehensive description of the perception of Indonesian Albasia wood. The data results can serve as a guide for the author to discuss issues in all phases of the wood interpreting, including the source of Albasia wood, the planting of Albasia wood trees, how Albasia wood is harvested, the tools used, and the use of Albasia wood in building construction. The results of the ethnographic study are then presented in the form of descriptions and explanations adapted for content analysis.

The following are some of the steps and considerations involved in the analysis of ethnographic data for this study: Transcribing and documenting the case study data collection. This includes notes from the field, observations, in-depth interviews, audio and video recordings, photographs, and other pertinent artifacts.

1) Transcritpion and documentation: Transcribing and documenting the case study data collection. This includes notes from the field, observations, in-depth interviews, audio and video recordings, photographs, and other pertinent artifacts.
2) Immersion and Familiarisation: Dig deeper into the case study's transcription and review to gain a comprehensive understanding of its context and content.
3) Categorization and Theme Development: After gathering the data, classify it. The author searches the data for recurring patterns, connections, and relationships.
4) Interpretation and Analysis: Analysing each category's data. This study's categories pertain to the informants (construction workers), the origin of Albasia wood, as well as its introduction, usage, and application. The author used a theoretical lens to guide the identification of interpretations.
5) Triangulation: Triangulation is the process of comparing and contrasting various data sources to validate and enrich the findings. This entails comparing interviews with observations and analysing various perspectives within the community. Triangulation ensures the reliability and validity of data.
6) Reflexivity and Member Checking: Throughout the analysis, the author reflects critically on biases, assumptions, and positions. To share the author's findings with research informants in order to validate the interpretation of the research results, member checks were conducted.
7) Reporting: Finally, writing up the findings in a comprehensive manner. Provide a detailed explanation of the author's methodology, including the data collection and analysis procedures.

3.2.1.1. Analysis of literature review

The data analysis process for this literature review included identifying numerical data extracted from each research result that answered the research questions, organizing the data thematically, synthesizing, analyzing, and presenting the data descriptively.

3.2.2. Quantitative analysis

Quantitative data in this research comes from primary data in the form of experimental studies and secondary data.

3.2.2.1. Measurement of physical properties

3.2.2.1.1. Specific gravity

Wood density, also known as wood specific gravity, is by far the most significant property of wood, influencing nearly all products (B. Zobel, 2004). Density and specific gravity of wood measure the same thing – the amount of solid wood in a given volume of wood – but are expressed differently. Wood density is typically used in the industrial sector, whereas specific gravity is more common in the scientific community. They are easily distinguishable from one another.

The specific gravity of albasia wood before and after treatment refers to the Japanese Industrial Standard (JIS) Z 2101: 2009 (Japanese Standards Association, 2009) was determined using the following equation:

$$\rho_w = \frac{m_w}{v_w}$$

where ρ_w represents the specific gravity; m_w represents the mass; and v_w represents the volume, at moisture content *w*. The mass of the wood sample was determined using a digital scale with an accuracy of 0.01 g (A&D: FZ-5000i), as shown in Figure 3. 13. The volume of the wood was measured using a caliper with an accuracy of 0.01 mm (Mitutoyo: ABSOLUTE Digimatic Scale Units-572 Series 0-8in/0–200 mm), with a 0.01 mm accuracy, as it can be seen in Figure 3. 14.

Figure 3. 13 a caliper with an accuracy of 0.01 mm (Mitutoyo: ABSOLUTE Digimatic Scale Units-572 Series 0-8in/0–200 mm)

Source: Research Documentation, 2023

Figure 3. 14 Digital scale with an accuracy of 0.01 g (A&D: FZ-5000i)

Source: Research Documentation, 2023

The specific gravity set-recovery (SR-D) was calculated using equation:

$$\text{SR-D } (\%) = \frac{\text{Ds-Da}}{\text{Do-Da}} \times 100$$

Ds = recovery specific gravity after equilibrium moisture content was re-reached (kg/L)

Da = actual specific gravity after high-temperature and -pressure (kg/L)

Do = original specific gravity before high-temperature and -pressure (kg/L)

And the specific gravity change (DC) was determined according to the following equation:

$$\text{DC } (\%) = \frac{\text{Ds-Do}}{\text{Do}} \times 100$$

3.2.2.1.2. Equilibrium Moisture Content (EMC)

It is widely acknowledged that EMC is a physical property of wood that affects both the dimensions and mechanical quality of wood (Hernández et al., 2014). Wood reaches equilibrium moisture content (EMC) in relation to its surrounding relative humidity. EMC is defined as the moisture content at which wood neither gains nor loses moisture (J. E. Reeb, 1995). As relative humidity increases, so does the EMC, indicating that more moisture is retained in the wood.

In this study, the wood's moisture content was measured using a wood moisture content meter (Kett: HM-530 20 MHz / range 2-50%), as shown in Figure 3. 15. Due to the high frequency measurement format, this measurement leaves no trace on the surface of the examined substance.

Figure 3. 15 Wood moisture content meter (Kett: HM-530 20 MHz / range 2-50%)

Source: Research Documentation, 2023

3.2.2.1.3. Color changes

Color, one of the physical properties of wood, is crucial for wood applications because it determines its market value for aesthetic reasons (Huang et al., 2012). Regardless, the original color of the wood may change during processing and treatment, although the direction of this change depends on the species of wood.

3.2.2.1.4. Change in thickness

The thickness of wood was measured prior to and after densification. To determine the densification of spring-back rate, wood specimens were exposed to predetermined relative humidity and temperature conditions for a predetermined period of time (Fang et al., 2012). In order to investigate the'spring-back' potential of the samples, the thickness of each sample was measured on four sides using a caliper under normal atmospheric conditions.

Set-recovery for thickness (SR-T) was determined by Equation:

$$\text{SR-T (\%)} = \frac{\text{Ts-Ta}}{\text{To-Ta}} \times 100$$

Ts = thickness recovery after equilibrium moisture content was re-reached (mm)

Ta = board thickness after high-temperature and -pressure (mm)

To = board thickness before high-temperature and -pressure (mm)

As follows, the final parameter thickness change (TC) was used to analyze the thickness change, in the manner specified in Equation (5).

$$\text{TC (\%)} = \frac{\text{Ts-To}}{\text{To}} \times 100$$

3.2.2.1.5. Morphology of wood

Due to the variety of wood species used and the modifications that alter the appearance and structural integrity of wood, identifying the species of wood is frequently a difficult task. Macroscopic examination of the wood's macroscopic anatomical characteristics can be used to identify its species (Timar et al., 2013).

Macroscopic examination of wood was conducted at Experimental Building, Special Research Laboratory (Building Engineering), Faculty of Environmental Engineering, The University of Kitakyushu, Hibikino, Kitakyushu, Fukuoka, Japan. The development of various microscopy techniques has contributed significantly to the study of wood morphology. In this study, the morphology of wood materials was examined using a Digital Microscope and a Scanning Electron Microscope (SEM).

Figure 3. 16 Digital Microscope: VHX-7000 series.

Source: Research Documentation, 2023

Figure 3. 16 depicts the VHX-7000 series digital microscope (Keyence Company, Itasca, USA) utilized in this study. The Digital Microscope was utilized to scan the wood's textures and coloration in greater detail.

In the meantime, the Scanning Electron Microscope (SEM) utilized in this investigation is a JSM-7800F Schottky Field Emission SEM (JEOL Company, Tokyo, Japan). SEM enables the simultaneous observation of larger wood sections at lower magnification and the acquisition of high-resolution images of the three-dimensional wood microstructure. SEM can detect cell wall thinning caused by the loss of cell wall components that can result from wood modification more precisely (see Figure 3. 17).

Figure 3. 17 Scanning Electron Microscopy: FE-SEM JSM-7800F.

Source: Research Documentation, 2023

Digital Microscope and Scanning Electron Microscopy analysis must be performed in a vacuum, necessitating sample drying for morphological observation without causing damage such as wood deformation and collapse. Figure 3. 18 shows the constant temperature oven DKM600 (Yamato Scientific Co., Ltd., Tokyo, Japan) used to dry the wood samples prior to performing morphological tests in this study.

Figure 3. 18 Constant oven DKM600 for drying sample.

Source: Research Documentation, 2023.

3.2.2.2. Measurement of mechanical properties

3.2.2.2.1. Compressive strength test

Compressive strength represents the strength property of wood that is most affected by moisture content and, therefore, must be considered more than other strengths (Aicher & Stapf, 2016).

As shown in Figure 3. 19 , compressive strength testing in this study was conducted using a universal material testing machine UH-2000kNXR (Shimadzu Corporation, Japan) at the Experimental Building, Special Research Laboratory (Building Engineering), Faculty of Environmental Engineering, The University of Kitakyushu, Hibikino, Kitakyushu, Fukuoka, Japan.

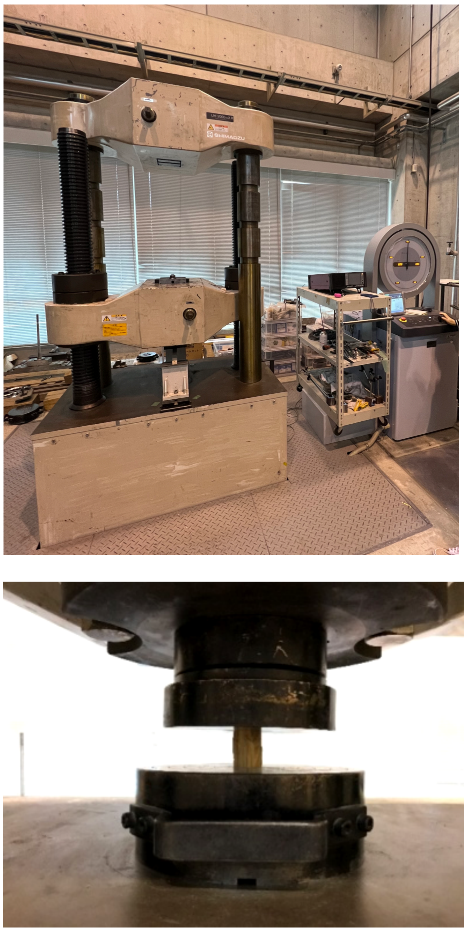


Figure 3. 19 Universal material testing machine UH-2000kNXR for compressive strength test.

Source: Research Documentation, 2023.

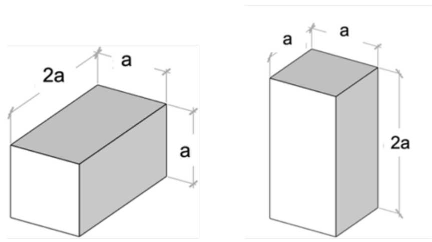
Table 3. 4 Compressive strength test equipment

Equipment	Explanation
Compressive strength test machine	A testing device capable of applying a compressive load to a sample at a constant loading speed or deformation ratio and measuring the maximum load to within 1%.
Uniform loading jig	To apply a compressive load to the sample so that a uniform load is applied to both sides of the sample

	edge, a jig consisting of two opposing steel plates with a ball seat or other crafted apparatus is utilized.
Digital calipers	With an accuracy of 0.01 mm, the dimensions can be measured.
TML strain gauges	Gauge Type: LFLA-10-11 Gauge Factor: 2.10

Source: Research Documentation, 2023.

The compressive strength was determined by applying an increasing compressive load parallel to the specimen fibers until failure, then measuring the fracture load. During the test, the specimen's shrinkage is also measured, and the longitudinal compressive proportional limit stress is determined. The compressive strength of selected wood samples was evaluated in accordance with Japanese Industrial Standard (JIS) Z 2101: 2009.



(a) (b)

Figure 3. 20 The dimension of a wood sample for the compressive strength

The preparation of a wood sample for the compressive strength test as shown in fFigure 3. 20 is as follows:

(a) Longitudinal direction
The sample shall have a square cross section with a side length (a) and a length along the fiber rectangular parallelepiped which is twice the length (a) of one side. When preparing the specimen, the longitudinal direction should be parallel to the fiber direction, and both end faces should be perpendicular and parallel to the longitudinal direction.

(b) Tangential direction
The sample shall have a square cross section with a side length (a) and a length along the fiber rectangular parallelepiped which is twice the length (a) of one side.

This study measured the longitudinal and tangential compressive strength of wood in order to gain a better understanding of its compressive strength properties. The procedure for testing compressive strength is as follows:

1. To determine the sectional area of the sample, the longitudinal or tangential cross-sectional dimension of the sample was measured with a digital caliper at the sample's center and then calculated.
2. Using a uniformly loaded jig, apply a compressive load to the sample. The test was conducted using a compression tester with a constant loading speed, so that the sample fractured within one to two minutes of loading initiation, or compressive load at deformation speed. Determine the load at failure as the maximum load (Pmax).

The compressive strength is computed using equation in conformance with the preceding specifications:

$$\sigma_c = \frac{P}{A}$$

$$\varepsilon_c = \frac{\Delta l}{l}$$

σ_c = Compressive strength (MPa)

P = Maximum load (N)

A = Cross sectional area of sample (mm^2)

l = Target point distance (mm)

Δl =Shrinkage corresponding to ΔP (mm)

When shrinkage is measured, the proportional stress of compression and the Young's modulus of compression of the wood are calculated by the following formula.

$$\sigma_{cp} = \frac{P_p}{A}$$

$$E_c = \frac{\Delta P l}{\Delta l A}$$

σ_{cp} = Compressive proportional limit stress (MPa)

E_c = Compressive Young's modulus (N/mm^2)

P_p = Proportional limit load (N)

A = Cross sectional area of sample (mm^2)

ΔP = Difference between the upper and lower load limits in the proportional limit region (N)

3.2.2.2.2. Bending strength test

The bending strength is defined as the bending section at failure load when elastic stress distribution is assumed. Wood bending strength tests are conducted by situating a length of material on a span and bending the material to failure along the span. To determine the maximal bending strength in this study, wood specimens were subjected to three-point static bending strength tests in accordance with Japanese Industrial Standard (JIS) Z2101-94: 1994.

As shown in Figure 3. 21, longitudinal bending strength test in this study was conducted using a universal material testing machine UH-2000kNXR (Shimadzu Corporation, Japan) at the Experimental Building, Special Research Laboratory (Building Engineering), Faculty of Environmental Engineering, The University of Kitakyushu, Hibikino, Kitakyushu, Fukuoka, Japan.

Figure 3. 21 Universal material testing machine UH-2000kNXR for bending strength test.

Source: Research Documentation, 2023.

Table 3. 5 Compressive strength test equipment

Equipment	Explanation
Bending strength test machine	A testing device capable of applying a compressive load to a sample at a constant loading speed or deformation ratio and measuring the maximal load to within 1%.

Uniform loading jig	Create a centralized loading method that samples the bending force between the fulcrum steel plate and the load point. The fulcrum is a jig with a steel plate whose length is twice the side length and whose breadth is 1.5 times the side length; the loading point should be a steel cylinder with a 30 mm radius of curvature. When the load point penetration impacts the form of bending fracture, however, the shape of the load point is designed to prevent any influence.
Digital calipers	With an accuracy of 0.01 mm, the dimensions can be measured.

Source: Research Documentation, 2023.

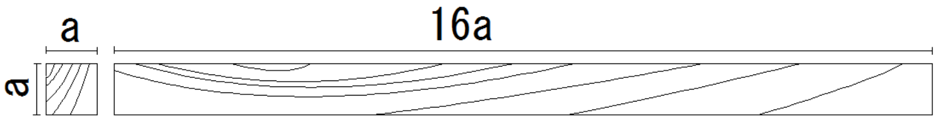


Figure 3. 22 Bending strength test sample

Source: Research Documentation, 2023.

The preparation of a wood sample for the bending strength test as shown in Figure 3. 22 is as follows:

1) The sample has a square cross section with side length a (a).
2) The length along the fiber should be sixteen times the length a (16a). In preparing the sample, the longitudinal direction is parallel to the fiber direction. Both end surfaces are made vertical and parallel to the longitudinal direction.

The procedure for the bending strength test is as follows:

1) Using digital calipers, measure the longitudinal center cross-sectional dimensions of the bending strength test sample in the longitudinal direction.
2) The distance between the fulcrum and the side length (a) is 12 to 16 times the side length. During the test, deflection measurements are taken; when calculating the apparent Young's modulus, the distance between the fulcrums must be 14 times the side length. The load surface is assumed to be a straight surface (gray), but it is taken from the tree surface when it is a flat or chasing surface (normal). In the test, using a bending testing machine, a steel fulcrum plate, and a load point, a constant loading speed is applied so that the sample breaks within one to two minutes of the beginning of bending load loading, or within one to two minutes of bending load loading at the deformation speed. Determine the fracture load and use it as the maximum load (Pmax).

These calculations were carried out according to equation,

$$\sigma_b = \frac{Pl}{4Z}$$

σ_b = bending strength of the wood (MPa)

P = maximum load (N)

l = distance between fulcrums (mm)

Z = Section modulus (mm)

If the declection is measured, the proportional bending limit stress (σ_{bp}) of the wood and the approximate Young's modulus in bending (E_b) are calculated by the following formula:

$$\sigma_{bp} = \frac{P_p l}{4Z}$$

$$E_b = \frac{\Delta P l^3}{48 I \Delta y}$$

σ_{bp} = bending proportional limit stress (MPa)

E_b = Apparent Young's modulus im bending (N/mm^2)

P_p = proportional limit load (N)

l = distance between fulcrums (mm)

Z = section modulus (mm)

I = Moment of inertia (mm)

ΔP = Difference between upper and lower limit load in proportional limit region (N)

Δy = Mid-span deflection corresponding to ΔP (mm)

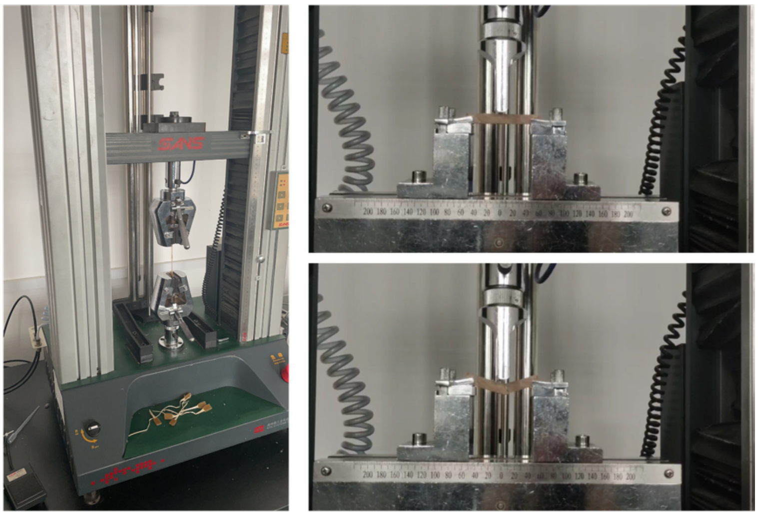


Figure 3. 23 Universal material testing machine CMT6104 for bending strength test.

Source: Research Documentation, 2023.

On the other hand, in the tangential direction wood bending test, the three-point bending test was conducted. The test was conducted using a universal material testing machine CMT6104 (MTS Corporation, China) in School of Chemical and Materials Engineering, Zheijang A&F University, Hangzhou, China (see Figure 3. 23).

3.2.2.2.3. Tensile test

Commonly, the tensile test is used to evaluate the mechanical properties of materials, including wood. It is useful for determining the tensional strength and elasticity of wood samples. A wood sample is subjected to an axial pulling force along its length until it fractures in a tensile test. The test measures the applied force (load) and the sample's subsequent deformation (strain).

Typically, tensile tests are performed using specialised testing machines known as universal testing machines. These machines apply a controlled force to a wood sample while measuring its load and deformation simultaneously. To ensure consistent and reliable results, the test is conducted under controlled conditions, including a specified loading rate. Figure 3. 24 shows the testing machine for the tensile test in this study. Tensile tests were conducted using a strain-controlled tensile testing machine, Instron 5565 A (Instron, America) in School of Chemical and Materials Engineering, Zheijang A&F University, Hangzhou, China.

Figure 3. 24 Strain-controlled testing machine (Instron 5565 A) for tensile test

Source: Instron Company, America (https://www.instron.com/en-gb/)

Wood's mechanical behaviour, such as its tensile strength, elasticity, and ductility, can be better understood through tensile testing. These characteristics are essential to comprehending the performance of wood in structural applications, such as beams, trusses, and load-bearing components. In addition to comparing the properties of various wood species, evaluating the effects of wood modification techniques, and determining the quality of wood products, tensile tests are also used to conduct tensile tests. Wood modification techniques can significantly impact the tensile behavior of wood, and conducting tensile tests on modified wood samples allows researchers and engineers to assess the effects of these modifications.

3.2.2.2.4. Finite Element Model (FEM) Simulation

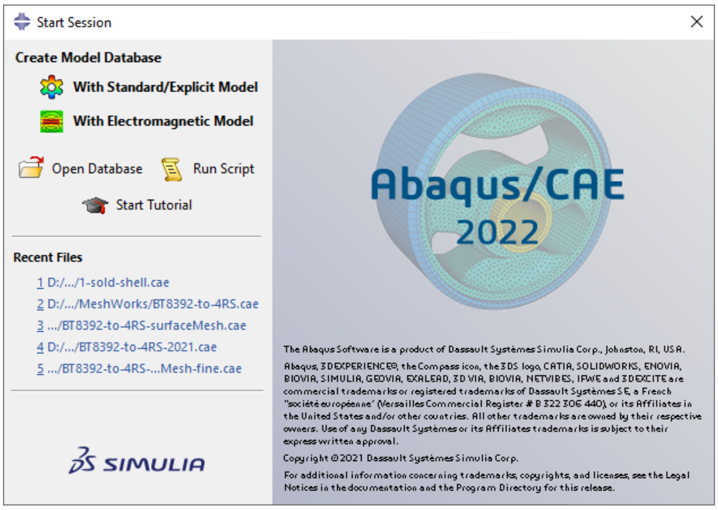


Figure 3. 25 Finite Element Model (FEM) Simulation using Abaqus 2022 software.

Source: Research Documentation, 2023.

Simulation of the Finite Element Model (FEM) is a potent computational technique used to analyse and predict the behaviour of materials and structures, including wood. FEM simulation permits the virtual modelling of complex geometries, material properties, and loading conditions, which provides insight into the mechanical response and performance of wood components. In this study, Finite Element Model (FEM) simulation was done by using Abaqus 2022 software (see Figure 3. 25) to comprehend:

1) Structure analysis
   Analysing the structural behaviour of wood components for specimens using FEM simulation is possible. FEM software can predict stress distributions, deformations, and failure modes under different loading conditions by creating a virtual model of the wood structure. Researchers can use this information to evaluate the structural integrity and performance of wood elements and optimise their designs.
2) Material Characterization
   FEM simulation can aid in the mechanical property characterization of wood. By incorporating experimentally determined material properties, such as modulus of elasticity, strength, density, or tensile for this focus of the study, into the FEM model, simulations can shed light on the behaviour of wood under various loading scenarios. This enables the prediction of wood stress-strain relationships, deformation patterns, and failure mechanisms.
3) Wood modification assessment
   Evaluation of wood modification techniques FEM simulation is useful for evaluating the effects of wood modification techniques. By incorporating the modified material properties into the FEM model, simulations are able to predict the resulting changes in structural behaviour. For instance, if thermal modification is applied to wood, FEM simulation can predict the effects on the material's dimensional stability, moisture content, and mechanical properties.
4) Load capacity and failure prediction
   Prediction of load capacity and failure FEM simulation can assist in predicting the load-carrying capacity and failure modes of wood components. By applying realistic loading scenarios, such as uniform loads or point loads, simulations can determine the maximum load that a wooden structure can withstand prior to failing. This data facilitates design optimisation and ensures that wood components are sized and configured appropriately for their intended applications.
5) Optimization and design improvement
   FEM simulation enables iterative design processes for optimising the performance of wood structures. By simulating various design configurations, materials, and loading conditions, engineers are able to evaluate and compare the performance of alternative design configurations. This iterative approach assists in identifying design enhancements, such as shape optimisation, material selection, and

reinforcement strategies, resulting in more efficient and dependable wood structures.

Simulation based on the finite element method is a cost-effective and efficient method for assessing the mechanical behaviour of wood materials and structures. It offers insights into the response of wood under various loading conditions, aids in the optimisation of designs, and facilitates the development and evaluation of wood modification techniques.

3.2.2.3. Statistical Analysis

Statistical analysis means applying quantitative data to investigate trends, patterns, and associations. The experimental data were then subjected to statistical analysis to determine the relationship between the effects of the examined treatments. As shown in Figure 3. 26, statistical analysis was conducted using SPSS (IBM, United States) software. SPSS (Statistical Package for the Social Sciences), also referred to as IBM SPSS Statistics, is a statistical data analysis software package.

Figure 3. 26 IBM SPSS Statistics software for statistical analyisis

Analysis of variance (ANOVA) is the most effective parametric method for analyzing experimental data. Analysis of Variance (ANOVA) is a statistical test used to compare two or more means. One-way analysis of variance (ANOVA) was used to determine the effect of experimental treatments for each category of experimental results in this study. ANOVA was used to determine whether there was a statistically significant difference between the means of the treatment effects of three or more independent (unrelated) groups.

Using statistical analysis, information was obtained on the characteristics of the experimental samples in both physical properties and mechanical properties of the wood. In one-way analysis of variance, the homogeneity test was employed to determine the significance and mean separation between treatments. The mean values were then compared using Tukey's Honestly Significant Difference (HSD) test. Significant Difference test considers all pairwise comparisons statistically significant at $p<0.05$. The significance level in the test in this study was $p<0.05$.

CHAPTER 4
AN IN-DEPTH INVESTIGATION OF THE USE OF INDONESIAN ALBASIA WOOD AS A CONSTRUCTION MATERIAL

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AN IN-DEPTH INVESTIGATION OF THE USE OF INDONESIAN ALBASIA WOOD AS A CONSTRUCTION MATERIAL

Summary

As a developing country, Indonesia has the advantage of being located in a tropical area so that wood proliferates because the sun shines all year long. Albasia wood (*Albizia Falcataria)* is a fast-growing wood species widely planted and cultivated by the community in Indonesia. The purpose of this study was to identify perceptions of the use of Albasia wood in the construction field from the viewpoint of construction workers. A periodic in-depth interview guide was used to elicit information from the construction workers community called Paguyuban Kuli Bangunan (PAKUBA) in Sudalarang Village, Sukawening, Garut regency, West Java, Indonesia. The construction workers were used as informants in this study in terms of their experience and expertise in recognizing Albasia wood as one of the local materials in Indonesia and its potential as a building material. As regards the main purposes, the authors collect and analyze qualitative data through an ethnographic method. According to the results it was found that: 1) The understanding of Albasia wood is derived from the legacy of basic skills training, including the introduction of wood species and grades, woodworking tools, tree planting, felling and cutting wood techniques, and their application in building construction; 2) For rural communities, Albasia wood has been identified as a locally sourced material that is readily accessible from Protected Forest (HL), Convertible Production Forest (HPK), and Non-Forest Areas (APL); 3) In terms of terminology, Albasia wood and carpentry tools are referred to by regional names, where the names differ from one region to another; and 4) In terms of application, although it is a low-value wood, Albasia wood can be utilized as a truss and a bottom truss in simple houses for rural communities in West Java, Indonesia.

CHAPTER 4: AN IN-DEPTH INVESTIGATION OF THE USE OF INDONESIAN ALBASIA WOOD AS A CONSTRUCTION MATERIAL

4.1. Introduction

4.1.1. Background

To help tackle sustainability problems, evaluating the environmental impact of material choices is increasingly important. The use of wood material in the construction sector is one of the best ways to minimize carbon dioxide emissions in terms of environmental benefits (Bergman et al., 2014) because wood material contains 50% carbon during its development, absorbing carbon dioxide in the air (Li et al., 2018). In short, the more wood products are used, the more carbon is retained, and the global warming impact is also minimized.

Besides, in terms of strength and longevity, the use of hardwood from natural forests typically has constant values. The trees, unfortunately, grow slowly, disrupting the sustainability of the supply of wood. Seeking alternative wood sources is therefore important, and one approach is to use fast-growing wood types. For plantations and community forests, fast-growing wood species have been commonly used in order to make the sustainability of wood more appealing for the ecosystem with its plentiful availability.

Albasia wood (*Albizia Falcataria*) is a fast-growing wood species that is widely planted cultivated by the community in Indonesia. Besides having many advantages such as a short harvest period (4-7 years) and uncomplicated growth location requirements (Hartati et al., 2010), this is also in line with the Indonesian government's plan to become the largest supplier of lightwood in the world through the potential of Albasia wood in ILCF (Indonesian Lightwood Cooperation Forum) 2018. This condition causes its utilization and economic value to be relatively low, so it is necessary to apply technological innovations that can improve the wood quality in question (Julian et al., 2019). This paper is a preliminary study to examine its presence in Indonesia due to the lack of research references to Albasia wood regarding the government's new move.

4.1.2. Purpose of the study

This study identifies perceptions of Albasia wood's use in the construction field from the viewpoint of construction workers as research informants. The construction workers in question are the executors of building construction, which in Indonesia has unique characteristics; they acquire vocational skills through cultural heritage rather than through formal education (Widaningsih et al., 2018). The construction workers were used as informants in this study in terms of their experience and expertise in recognizing Albasia wood as one of Indonesia's local materials and its potential as a building material.

Embarking from the above-mentioned issue, this study has the objective of disseminate knowledge and provide a big-picture view of the perspective of Indonesian construction workers in understanding and using Albasia wood. Such an issue is considered essential to address the characteristics and use of Albasia wood in building construction.

This study's novelty is that it succinctly covers current knowledge and provides important insights about Albasia wood: trees as a resource for village communities, the use of language as communication between construction workers, supporting equipment, the scope of work, and government support actions. Following this investigation, we also highlight directions for future research that will be considered for developing the potential of Albasia wood.

4.2. Literature Review

4.2.1. Ethongraphy in Qualitative Research

Qualitative research is frequently viewed as quantitative research's narrative counterpart. In an effort to answer "why and how" questions about human behavior and events, qualitative research permits an in-depth examination of data frequently accompanied by anecdotes or personal information (Guest et al., 2013).

Humans have a general fascination with the environment around them. Due to technological advancements, we now have greater access than ever before; research can be conducted in a variety of methods. Ethnography is a qualitative research method. To comprehend ethnography thoroughly, one must comprehend what ethnography is all about. Ethnography is profoundly rooted in philosophy and anthropology, as researchers analyze and comprehend cultures and other societal norms to better comprehend humanity (Alotaibi, 2018). It is nearly impossible to comprehend ethnography without recognizing that it is founded in social theories.

In response to the query, "What kind of person would be interested in ethnography?" (Agar, 1996), Agar suggests that the first type of ethnographer is someone who grew up disconnected from society and now seeks a deeper understanding and connection with those around them. Moreover, Agar suggests that the second type of ethnographer was reared in a diverse environment, with an appreciation of cultural differences as the norm fueling their desire to learn more about human behavior. Ethnographers endeavor to discover and comprehend human behavior and experience, but their interpretations and perceptions are influenced by their personal beliefs and prevalent theories. There is a yearning to "discover what lies beneath" underlying everything (W Wiersma, 1986).

4.2.2. Construction workers in Indonesia

Indonesia is one of the largest markets for construction services, with a value of 267 billion USD. In Asia, Indonesia ranks fourth after China (1.78 trillion USD), Japan (742 billion USD), and India (427 billion USD) (Kementrian Pekerjaan Umum dan Perumahan Rakyat, 2015). According to the most recent data (BPS, 2019), the labor market in the construction sector in 2013 reached 6,349.387 people (6.35%) and increased by 7,280,086 (6.35%) in 2014. It indicates a 0.70 percent increase, or approximately 930,000 additional construction employees, in the construction industry within one year.

According to Law No. 13 of 2003 on employment, Law No. 2 of 2017 on construction services, and ministerial regulations and regulation of the Construction Services Development Agency (LPJK), the construction worker in question is the executor of the construction of buildings (architecture), who is referred to as a *tukang* (skilled worker).

They are average people laboring in the sun and construction material dust in an energy-intensive industry (Eaves et al., 2016). They are the lowest level of construction workers directly involved with technical field labor (Bada Haryadi, 2010). They may not receive public attention, but it is their rough hands that construct everything from simple houses to luxurious buildings, shopping centers, hotels, and city parks, among other urban structures. They travel from various parts of the village in groups with fellow villagers, relatives, or friends, carrying carpentry tools and a few essentials for survival in the city.

Badan Pusat Statistik (2014) reports that only 4% of the 7,280,086 construction workers are experts, 20% are skilled workers, and the remaining 76% are unskilled laborers. Consequently, it is not remarkable that they are typically not registered as workers in formally protected sectors (Rothenberg et al., 2016). They gradually acquire construction abilities on the job. As in other industries, the career levels in the construction industry are hierarchical, ranging from kenék/ladén (construction laborers) to specialized and skilled employees such as bricklayers, carpenters, and painters (Rothenberg et al., 2016; Samuel & Badaruddin, 2015). This skill specialization is developed on the job using self-designed training models.

These established characteristics illustrate the cultural background from which these construction employees originate. This study identifies the cultural and social aspect of a community that merits attention as an andragogic and lifelong education issue. Survival of the people will depend on how they acquire life skills in their daily lives in order to face global challenges (Aleandri & Refrigeri, 2013; Höghielm, 2010; Sălcudean et al., 2014).

4.3. Methods

4.3.1. Research methods

Regarding the main purposes, we decided to take a qualitative approach (Creswell, 2014) to analyze the knowledge and perspectives of the research informants. An ethnographic method was obtained to collect the data (James Spradley, 1979). We undertook an analysis of the in-depth interviews, which were initially grouped based on construction workers' skill areas, to identify which looks these informants had on each field of their work. Furthermore, we chose the main informant based on the research flow considerations.

This ethnographic approach allowed us to establish a dynamic relationship between the real world and the subject, Albasia wood as a material among construction workers as research informants. As this was a qualitative study, a sample of professionals involved in building construction was selected, namely the main informants who were sufficiently representative of the studied area.

Figure 4. 1 For data collection, in-depth interviews are conducted with research informants.

Source: Research Documentation, 2018.

This study was conducted in one location in Indonesia. Sudalarang Village is a comprehensive example of an architectural vocational village where most of the population has vocational expertise (D.P.Mulyana et al., 2017). The key emphasis is to see how Albasia wood was used by these informants as a prospective building material, emphasizing the knowledge and experience in their practice in the area where they live and outside work practices.

The research informants who were interviewed were responsible for and were directly involved in carpentry work skills. Data collection was carried out either at their residence or at the construction site (see Figure 4. 1). The in-depth interview approach was an exploration that involved observation, the author's participation in experiencing the informant's work culture, creating field notes, and recording data. During the interview description and data collection, we stated that all professionals were male as a further means of identity protection except for the main informant who would be delved deeper for investigation. We organized the investigation as a comprehensive reading of the entire research material, and then the most significant content of the selected results was analyzed as the relevant issues.

Figure 4. 2 The use of albasia wood for construction in practical work.

Source: Research Documentation, 2018.

4.3.2. Data collection

4.3.2.1. Case study

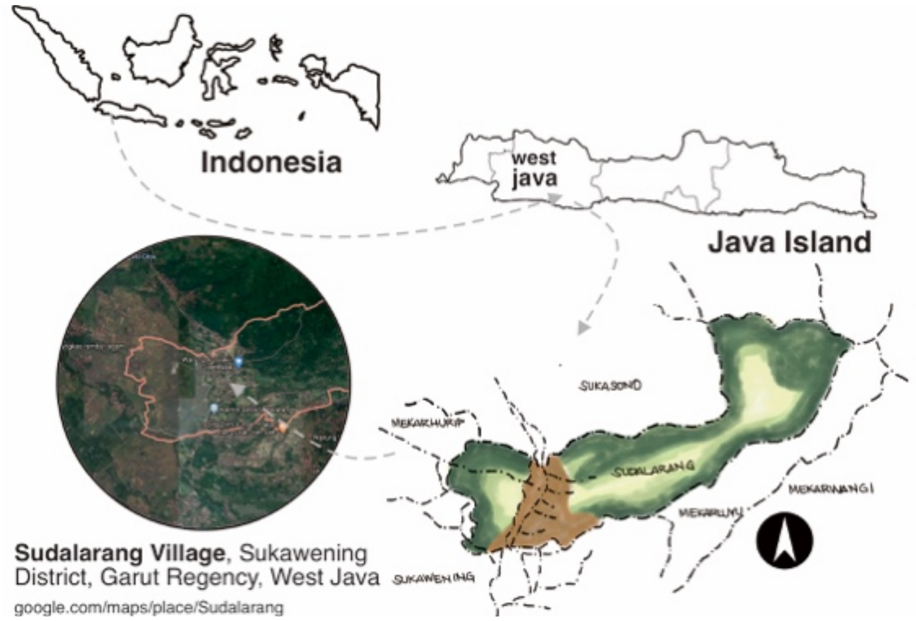


Figure 4. 3 Study area in Sudalarang Village, Sukawening District, Garut Regency, West Java Province, Indonesia.

Source: Research Documentation, 2021.

Determining the research location in collecting qualitative data through an ethnographic approach is the first step to control the object of study. The authors have selected one case study in Indonesia, Sudalarang Village, as a representative to observe and map the research results. Located in Sukawening District, Garut Regency, West Java, Indonesia (Figure 4. 3), this village stands on an area of 375,415 m^2. The total area of the settlement of Sudalarang village is 56,845 m^2. It consists of 3 urban villages, 10 RW (hamlets), and 33 RT (neighborhoods). The village is bordered by Sukasono Village (North), Mekarluyu Village (East and North), and Mekarhurip Village (West).

In Indonesia, especially in Java, construction workers are agricultural sector workers who have transformed into construction workers (Soemardi et al., 2011). Figure 4. 3 illustrates that the land status in Sudalarang Village is surrounded by the agricultural sector and forest areas. This makes construction workers come from agricultural sector workers where they will leave the fields after the harvest and work as construction workers while waiting for the next planting season. This means that construction workers know very well how the agricultural sector in general in preserving agricultural and forestry products.

4.3.2.2. Research participants

The data collection was carried out through observation, in-depth interviews, FGD, and document analysis. Research informants were a construction worker community called *Paguyuban Kuli Bangunan* (PAKUBA) in the case study. This study is a follow-up study of PAKUBA community who has been involved from three generations of construction workers in the previous survey. The selection of informants is under the requirements of ethnographic and was then selected through preliminary data collection and FGD to map their expertise according to the research topic. Three informants were then chosen to be the primary data collection informants through in-depth interviews.

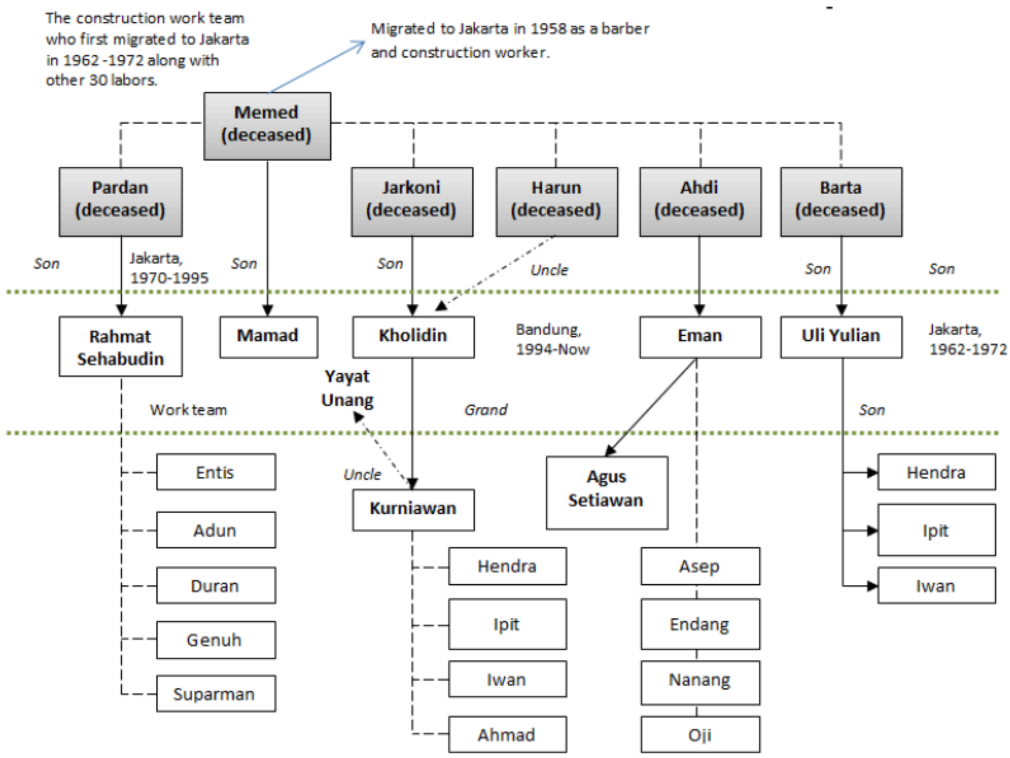
4.3.3. Data analysis

Ethnographic research is comprised of in-depth analysis derived from specific ethnographic data (Julian Murchison, 2010). Analysis is conducted through coding, in which events, interview notes, profound moments, and other field experiences were identified(Johnny Saldana, 2009); interpretation of themes, which was supported by triangulations between concepts and theories, among informants, and other sources; and ethnographic writing, which is conducted inductively from data collection, data categorization, and abstraction of interpretations.

4.4. Results and Discussion

The following analysis seeks to describe and explain the research findings. Given the qualitative study sourced from key informants, we cannot generalize the answers. Still, we can certainly see that these responses revealed many insights into their experience with Albasia wood.

4.4.1. Construction workers of Sudalarang Village



Note:

Direct descendant (father-son): the passing down of basic vocational skills
Work team, horizontal kinship: siblings, relatives, and neighbours
The first-generation work team who passed down vocational skills
Research informant

Figure 4. 4 A 3-generation network of construction workers in Sudalarang Village

Source: (Widaningsih et al., 2018)

Based on the data obtained, 79 construction workers are reported to be active members of the construction worker community. According to Widaningsih (2018) what happens in Indonesia is that construction workers acquire vocational skills through inheritance from previous generations. The results of the mapping of construction workers are illustrated in Figure 4. 4 as a 3-generation network of construction workers in Sudalarang which explains the inheritance of work skills across three generations. The data of construction workers who are not included in the three-generation network are migrants.

Sociologically, Sudalarang villagers have a strong emotional attachment to their village, which ensures that they will remain villagers and work together to develop their hometown, Sudalarang Village. There are villagers who work in the city because they are involved in various construction projects, but they almost certainly remit their earnings to the village to improve its socioeconomic conditions.

Figure 4. 5 explains that construction workers are classified according to the type of work they are focused on, including bricklayer (TT: Tukang Tembok), carpenter (TK: Tukang Kayu), blacksmith (TB: Tukang Batu), painter (TC: Tukang Cat), electrician (TL: Tukang Listrik), the executor (P: Pelaksana), and labor (B: Buruh Bangunan).

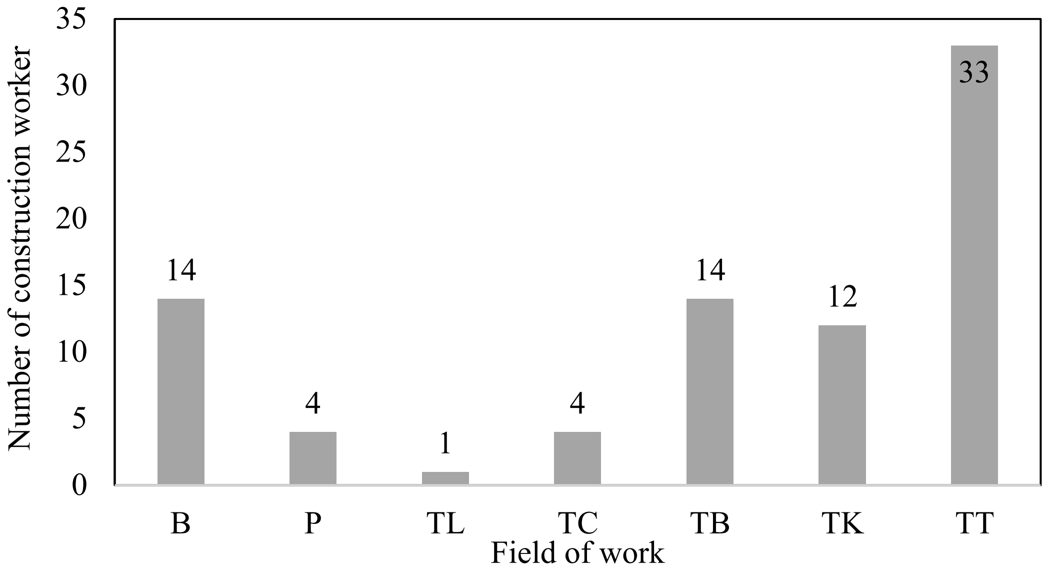


Figure 4. 5 Construction worker’s field of work

Source: Research Documentation, 2021.

Figure 4. 5 indicates that there are 12 carpenters in the construction worker community of Sudalarang. From this data, three carpenters were selected as the main informants. The selection of key informants was based on their background, track record of working in construction, and their position in representing the existing generation network. Data collection on the main informants was conducted in accordance with ethnographic research procedures through periodic in-depth interviews.

From this data, three carpenters were selected as the main informants. The selection of key informants was based on their background, track record of working in construction, and position as representatives of the existing generational network. Data collection on the main informants was conducted in accordance with ethnographic research procedures through regular in-depth interviews.

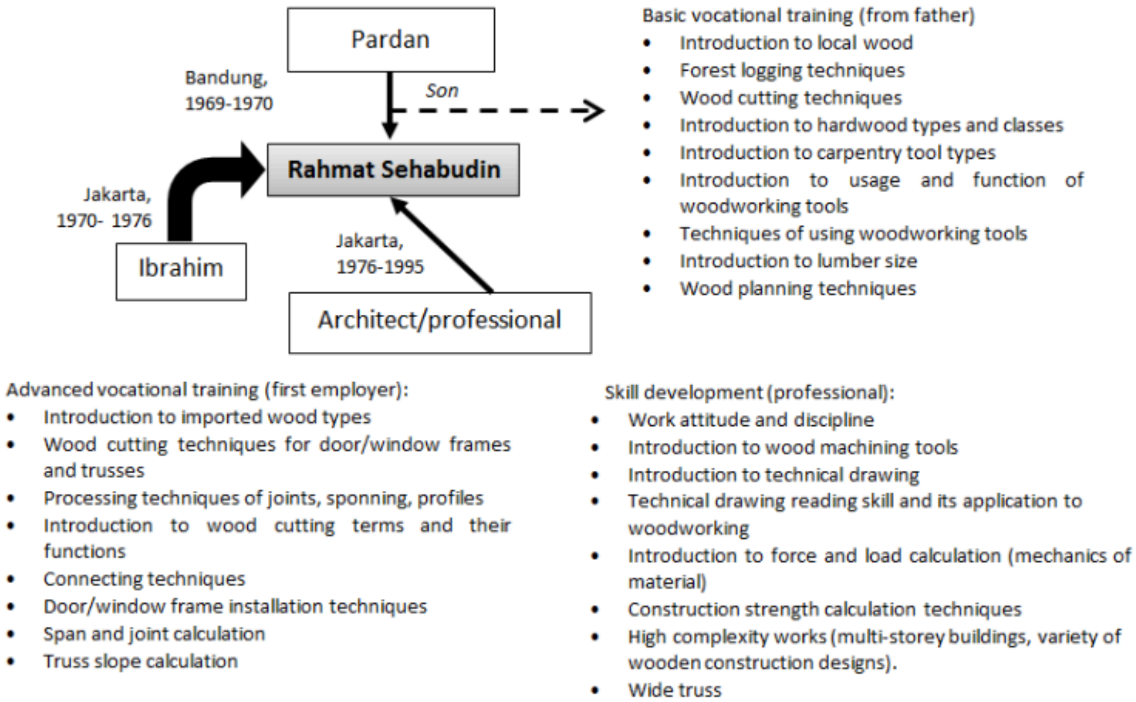


Figure 4. 6 An example of a pattern of vocational skill inheritance that starts with the introduction of woodworking skills

Source: (Widaningsih et al., 2018)

The classification of construction workers derived from current data is a requirement of contemporary labor. As stated previously, the work skills of Indonesian construction workers have been inherited from previous generations. Figure 4. 6 illustrates an example of the pattern of vocational skill inheritance that began with the introduction of woodworking skills.

The inheritance of vocational skills starts from basic vocational training originating from the first generation which includes introduction to local timber, logging techniques from the forest, wood cutting techniques, introduction to hardwood types and grades, introduction to types of woodworking tools, introduction to the use and function of woodworking tools, techniques for using woodworking tools, introduction to wood sizing, and wood planning techniques. Located in a rural area surrounded by community forests where the average tree is planted with Albasia plants, from here we will explore the understanding of construction workers in Sudalarang regarding Albasia wood.

4.4.2. Albasia wood availability

The Indonesian Ministry of Environment and Forestry divides the Forest Zone into five functional categories with different legal status, including Conservation Forests (HK: *Kawasan Hutan Konservasi*), Protection Forest (HL: *Kawasan Hutan Lindung*), Permanent Production Forest (HP: *Hutan Produksi Tetap*), Limited Production Forest (HPT: *Kawasan Hutan Produksi*), Conservation Forest (HK: *Kawasan Hutan Konservasi*), Convertible Production Forest (HPK: *Hutan Produksi Konversi*), while the rest are Non-Forest Areas (APL: *Areal Penggunaan Lain*).

According to the village topography, Sudalarang Village residents are traditional rural communities who live in mountainous valleys and rice fields. The existing housing forms were made very simple, with constructions known to originate from their ancestors. The materials for making houses generally use the types of wood in the natural environment as raw materials to manufacture house components.

Figure 4. 7 shows the typical house in the case study. With its simple form, the materials required were mostly obtained from local wood, where the wood comes from around the village.

Table 4. 1 Albasia wood sources classification

PAKUBA	Forest Zone		
Hutan Lindung	Protection Forest	(Kawasan Hutan Lindung)	[HL]
Hutan Lokal	Convertible Production Forest	(Kawasan Hutan Produksi)	[HPK]
Independent Community Plantation	Non-Forest Area	(Areal Penggunaan Lain)	[APL]

Source: Research Documentation, 2021.

Table 4. 1 indicates that the Albasia wood sources classification based on the forest zone. The first source, Hutan Lindung (Protection Forest: HL) is dedicated to conserving important forest ecosystem functions which allow it to be harvested but not for commercial purposes. Management is regulated by the Local Government (refers to the Garut Regency Government). Several types of wood in the case study include Albasia (Albazia Falcataria), Puspa (Schima wallichii spp.), Rasamala (Altingia excelsa Noronha), Saninten/Kihiur (Castanopsis agrentea A. DC.), and Cangcaratan (Lithocarpus sundaicus Bl.).

Then the second source is Hutan Lokal (Convertible Production Forest: HPK) which is intentionally preserved for production purpose but the function of the forest can be converted into non-forest uses such as agriculture, plantations, or settlements. The licensor is regulated by the Village Head Office (refers to the Sudalarang Village Office). The types of wood produced were Albasia (Albazia Falcataria), Surian (Toona sureni Merr.), Tisuk (Hibiscus macrophyllus Roxb.), And Salam (Syzygium polyanthum).

Known as an easy-to-grow plant, the growing requirements for albasia were not complicated. So this makes it possible for villagers to grow Albasia wood independently as a third source (Non-Forest Area: APL). Through this interpretation, we get an illustration of how the informants went directly to cultivate trees, cut wood, manufacture wood products, and there was learning by doing approach in working as a carpenter in understanding Albasia wood.

Figure 4. 7 The typical house in the case study.

Source: Research Documentation, 2021.

4.4.3. Overview on understanding carpentry terms

Due to many cultures in Indonesia, there are considerable cultural differences between regions and others. It is not difficult to get a representation of just how linguistically diverse Indonesia is. Indonesia has 726 languages as the second most diverse country, after Papua New Guinea, which has 823 local languages (A. Alamsyah, 2018). Likewise, the issue of belief in understanding the term naming something occurs from one area to another.

"The ability to understand Sundanese language verbally becomes a means of communication that makes it easier for fellow construction workers and not infrequently to the architect during building design and construction"

The data in this stage are Sundanese speech (the informant's regional language) in the form of a house-making carpentry term spoken by the informant. In Widaningsih 2018, through Sundanese culture, the language of "loma" becomes an important way for anyone to make it easier for informants to communicate with a cultural approach.

4.4.3.1. Albasia wood terminology

Table 4. 2 Albasia wood terminology

Local language	Regional speakers	Spoken name	Reference
Javanese	Central Java; East Java	Sengon laut	(Krisnawati et al., 2011)
Sundanese	West Java; Banten; parts of western Central Java; southern Lampung	Jeungjing; Jeunjing	Research documentation, 2020
Madurese	Madura; Sapudi	Jing laut	(Atmosuseno BS, 1998)
Minangkabau	West Sumatra, Riau, Jambi; Bengkulu; North Sumatra; Aceh	Sengon	(Nemoto, 2002b)

Source: Research Documentation, 2021.

As a wood that is easy to grow in all corners of Indonesia, the Albasia wood, authors found interesting findings because the term Albasia wood is different in each region in Indonesia. The carpentry terminology was based on the results of identification and the common language, according to the massive population levels in each regional representative in Indonesia were shown in Table 4. 2.

Sundanese language is the second-largest local language used in Indonesia, where 12% in the country. Despite it's called Sengon or Albasia by the Indonesian language in general, informants called it Jeungjing or Jeunjing as their communication term.

4.4.3.2. Carpenter tools terminology

In addition to term used for naming wood, an interesting fact was found that carpentry tools also play a supporting role. As a village community, the awareness of Albasia wood by the informants is helped by the carpentry tools they use.

Figure 4. 8 Carpenter tools made by informant

Source: Research Documentation, 2018.

Before getting to know technology, traditional people were accustomed to making woodworking tools with their own hands. Figure 4. 8 shows the woodworking tools recorded in this study that inherited from generation to generation.

Figure 4. 9 Data collection through FGD

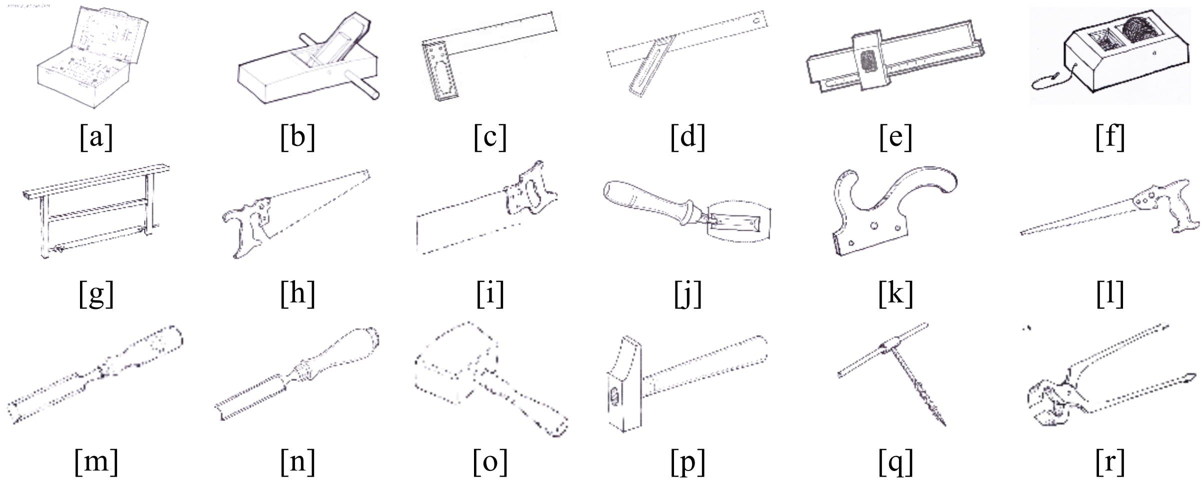
Source: Research Documentation, 2018.

Then Table 4. 3 shows the carpenter tools terminology and illustrations to make it clearer. With limited materials and knowledge, the informants made wooden tools by themselves with an essential function that could be achieved to facilitate their woodwork.

Table 4. 3 Carpentry tools terminology

National	Wooden Utensil PAKUBA	English	Function	
kotak alat	*peti parabot*	carpenter toolbox	Protects and stores woodworking tools	[a]
ketam	*sugu*	planner	Wood smoothing and grading	[b]
penggaris siku	*pasekon*	L-square angle	Control the wood clum perpendicular 90°	[c]
siku serong	*pasekon serong*	45° angle ruler	Controls 45° tilting angle	[d]
perusut	*perusut*	wood tracer	Mark a line parallel to longitudinal plate	[e]
meteran	*meteran*	gauge	Wood measurements	[f]
gergaji belah	*ragaji angklung*	split saw	Splitting in the required shape and size	[g]
gegaji potong	*ragaji potong*	chainsaw	Cut the fibers in a perpendicular direction	[h]
gergaji punggung	*ragaji punggung*	backsaw	Cut thin wood	[i]
gergaji vinir	*ragaji vinir*	veneer saw	Woodwork that requires precise precision	[j]
gergaji gurat	*ragaji gurat*	streak saw	Cut the wood in narrow places	[k]
gergaji kompas	*ragaji tusuk*	keyhole saw	Cut the middle corner	[l]
pahat tusuk	*tatah*	skew chisel	Clean wood surfaces	[m]
pahat lengkung	*tatah lengkung*	curved chisel	Carve wood with curved shapes	[n]
palu kayu	*palu kayu*	wooden hammer	Sculpting, assembling and setting	[o]
palu besi	*palu tukang awi*	hammer	Nailing and adjusting the planner	[p]
penggerek	*bor*	wood drill	Make a round hole	[q]

kakak tua	*gegep*	pincers	Pull out the nails	[r]



Source: Research Documentation, 2021.

4.4.4. Applications in the construction field

This section aims to describe the current use of Albasia wood in the construction field. This data was fulfilled through a focus group discussion step, then evidenced by mapping and documenting wooden buildings in a case study.

Building construction consists of parts that support one another. Each part of the building construction has its characteristics because it was made for a specific purpose. The raw material for making the building part also varies according to its initial designation.

FGD has been performed to identify the knowledge and skills of construction workers in making simple home projects. Construction workers are required to describe parts of building construction and materials used. The results can be identified about the habit of using Albasia wood in making simple houses in the case study.

As shown in Figure 4. 7, we can identify that although Albasia wood is weak and has a very low density, this wood also has the potential to be used as construction material even though there are only a few parts in making simple houses in Indonesia.

However, in its use as an albasia wood construction material must meet the technical requirements first. If albasia wood is to be used as a building material, then the strength and durability of the wood must be taken into account, because the general goal of building owners and planners is to build safe and robust residential buildings.(W Wiersma, 1986)

Table 4. 4 The scope of work

Types of Woodwork			Types of wood
National	PAKUBA	English	
Bubung; Nok	*Bubungan*	Roof ridge	Clat tile
Gording	*Gording*	Purlin	Meranti
Usuk; Kaso	*Usuk*	Rafter	Meranti; Borneo; Kamper
Klos/Tupai-tupai	*Beam support*	Gandel	Meranti; Borneo; Kamper
Kaki kuda-kuda	*Seprit*	Bottom truss	Albasia
Kuda-kuda	*Adeg*	Truss	Albasia
Balok tembok	*Pamikul*	Wall beam	Meranti; Borneo; Kamper
Balok Tarik	*Pangeret*	Tie beam	Meranti; Borneo; Kamper
Siku-siku	*Sisiku*	Arris	Meranti; Borneo; Kamper
Tiang	*Tihang*	Post	Jati
Lantai Bambu	*Palupuh*	Bamboo floor	Bamboo
Balok bawah	*Gagalur*	Sloof	Meranti; Borneo; Kamper

Source: Research Documentation, 2021.

4.5. Conclusion

Despite all the expectations of the government that wants to make Indonesia as the largest supplier of Albasia wood in the world through its potential, in particular the study has shown that this wood has played a major role in the building construction field. Such a notion was reflected on the results of the investigation from the perspective of construction workers as informants.

1) The understanding of Albasia wood is derived from the legacy of basic skills training, including the introduction of wood species and grades, woodworking

tools, tree planting, felling and cutting wood techniques, and their application in building construction.

2) For rural communities, Albasia wood has been identified as a locally sourced material that is readily accessible from Protected Forest (HL), Convertible Production Forest (HPK), and Non-Forest Area (APL).
3) In terms of terminology, Albasia wood and carpentry tools are referred to by regional names, where the names differ from one region to another.
4) In terms of application, although it is a low-value wood, Albasia wood can be utilized as truss and a bottom truss in simple houses for rural communities in West Java, Indonesia.

CHAPTER 5
THE INFLUENCE OF HIGH-TEMPERATURE AND -PRESSURE TREATMENT ON PHYSICAL PROPERTIES OF INDONESIAN ALBASIA WOOD

CHAPTER 5:
THE INFLUENCE OF HIGH-TEMPERATURE AND -PRESSURE TREATMENT ON PHYSICAL PROPERTIES OF INDONESIAN ALBASIA WOOD

Summary

Albasia (*Albizia falcataria*), known as sengon wood, is a fast-growing tree species commonly found in Indonesian forests and community plantations. However, the low-density, hardness, and strength significantly restrict its commercial application. The purpose of this study was to determine the influence of densification on the physical properties of albasia under high-temperature and -pressure. Different temperatures were applied to the albasia board (100 °C, 120 °C, 140 °C, sandwich 140 °C). The densification process influences the density properties, color changes, thickness, compression ratio, equilibrium moisture content, and anatomical properties of the material. With this procedure, the density can be increased to 0.62 kg/L, a gain of approximately 112.78% over untreated wood. The density of wood increases, resulting in the decomposition of its chemical components, especially hemicellulose, which darkens the wood color and stabilizes equilibrium moisture control. As a result, the thermal compression modification treatment under high-temperature and -pressure is a highly effective method for enhancing the physical properties of fast-growing wood species, such as albasia.

CHAPTER 5: THE INFLUENCE OF HIGH-TEMPERATURE AND -PRESSURE TREATMENT ON PHYSICAL PROPERTIES OF ALBASIA WOOD BOARD

5.1. Introduction

5.1.1. Background

Evaluating the environmental impact of material selections is becoming more important as means of addressing sustainability concerns. In terms of ecological advantages, utilizing wood as a construction material is one of the most effective methods to decrease carbon dioxide emissions (Bergman et al., 2014), since wood material contains 50% carbon throughout its growth, collecting carbon dioxide from the air. In brief, the more wood products utilized, the more carbon is stored, thus mitigating the effects of global warming. Unfortunately, trees grow slowly, disrupting the sustainability of the existing wood availability. As a result, developing alternative wood sources is critical, one of which is fast-growing tree species (Adi et al., 2014). Due to the plentiful availability of fast-growing tree species, they have been extensively utilized in plantations and community forests, making the sustainability of wood is more promising for the environment.

Albasia (*Albizia falcataria*), known as sengon wood, is a fast-growing tree species commonly found in Indonesian forests and community plantations. Apart from numerous advantages, such as a short harvest period (4–7 years) and simple location requirements for growth (Darmawan et al., 2013; Hartati et al., 2010; U. J. Siregar et al., 2007b), the development of albasia is also consistent with the Indonesian government's goal of becoming the world's largest supplier of lightwood, through the potential of albasia in the ILCF (Indonesian Lightwood Cooperation Forum) 2018. Fast-growing wood is an alternative solution for replacing the function of broadleaf plants as a material for floor, furniture, and interior elements (Inoue, 1996), as well as structural components (Tomme et al., 1998). However, the low-density, hardness, and strength of fast-growing wood limit its commercial use . Therefore, increasing the density and properties of the wood is critical, as denser wood is frequently preferred for commercial use, particularly in construction (Blomberg et al., 2005a; Laine et al., 2016; Pelİt et al., 2017).

To enhance the value of fast-growing wood with low properties, increasing its density in a procedure known as wood densification, is advantageous. Densification of wood is a practical modification technique for improving its properties to produce new materials that do not pose a greater environmental risk than non-modified wood when discarded (B. M. Esteves & Pereira, 2009a; Homan & Jorissen, 2004). The first wood densification studies were done in Germany in the 1930s (F. F. P. Kollmann et al., 1975). One well-known method for wood densification is thermal compression under high-temperature and -pressure (Kutnar & Šernek, 2007; Sandberg et al., 2017d; Seborg & Stamm, 1941). The thermal compression method, under high-temperature and -pressure treatment, consists of two distinct phases: wood softening and compression, followed by a post-treatment phase that minimizes irreversible re-thickness swelling when modified wood makes contact with moist or wet environments. In comparison to other methods of wood densification, the benefits of this method include the absence of chemicals and ability to enhance the properties of wood, regardless of species (Bayani et al., 2019; Dwianto et al., 1999; Lekounougou & Kocaefe, 2014).

5.1.2. Purpose of the study

Improving the characteristics of albasia wood in sustainably is one of the most significant challenges facing wood technology. To optimize the process of improving wood properties, it is essential to comprehend how operating parameters affect properties in the wood densification process. Until recently, data on the impact of the wood modification on albasia wood performance were scarce. Furthermore, the purpose of this study was to determine the influence of the thermal compression modification treatment under high-temperature and -pressure on the physical characteristics of albasia wood.

5.2. Literature Review

5.2.1. Wood modification under high-temperature and -pressure

Among the various wood modification techniques that have been established, wood modification by thermal treatment at high temperature and high pressure is a thermal-based method. The treatment of wood through high temperatures and pressures has been identified as a potentially advantageous method for enhancing wood's dimensional stability and resistance to deterioration (C. Hill, 2006; C. Hill et al., 2021).

The improvements in properties resulting from the high temperature and high pressure treatment are primarily dependent on the procedure conditions, the wood species, and most importantly the treatment intensity (temperature and duration). According to some sources, this treatment has a significant impact on the properties of wood, including its humidity and dimensional stability, resistance to fungi and insects, mechanical properties, and aesthetic qualities such as color, odor, and varnish performance (Candan et al., 2013; DeBruijn et al., 2008; Goodrich et al., 2010; Kocaefe et al., 2015; Sikora et al., 2018; Xu et al., 2019).

The modified wood produced by high temperature and high pressure treatment is beneficial for a variety of applications, especially in architecture, where the wood is exposed to weather and moisture changes above ground. However, their low properties and strength should be considered in the use of structures, and further research is needed. It is essential to incorporate high-temperature and high-pressure treatment parameters and to optimize strength and processing in order to reduce environmental impacts.

5.2.2. Physical properties of wood

Wood has a variety of physical properties that make it a versatile and widely used material. It’s important to note that the specific physical properties of wood can vary widely depending on the species, growth conditions, and processing methods. The physical properties of modified wood, particularly those modified by thermal treatment at high temperatures and temperatures, have unquestionably changed. Changes in density, color, timber thickness, compression ratio, EMC, and wood anatomy are some of the physical properties affected by the treatment.

The density of wood will increase under high temperature and high pressure densification processe (B. J. Zobel, 1995; Bilgin Guller, 2012; Feng & Chiang, 2020). In addition, the wood may change color during processing and treatment under thermal modification, but the direction of this change differs between wood species (Burmester, 1975; Calonego et al., 2012; Cao et al., 2012). When wood is densified, the fibers are compressed and rearranged, which causes the material to become denser. This compression causes the overall thickness of the wood to decrease (Z. Gao et al., 2016a; Iskandar et al., 2021; Unsal et al., 2011).

In contrast, the compression ratio in wood densification refers to the ratio of the densified wood's final thickness to its original thickness before the compression procedure. The compression ratio can vary based on the specific densification method and the desired ultimate product properties (Kitamori et al., 2010a; Srivaro et al., 2021). In the meantime, densification can result in a denser wood structure with fewer pores. Consequently, densified wood has a reduced capacity to absorb and release moisture, resulting in a decrease in EMC. This decreased EMC can contribute to the enhanced dimensional stability of densified wood, making it less susceptible to swelling or shrinking as a result of moisture changes (Lenth & Kamke, 2001; W. T. Simpson & Rosen, 1981; Yi et al., 2008). Finally wood fiber compression is one of the most important morphological changes that occurs during densification. The application of extreme pressure and heat causes the wood fibers to deform and become denser. This compaction reduces the number of cell cavities and intercellular spaces in the wood structure mi(Ahmed et al., 2013; Darwis et al., 2017; Reza et al., 2015).

5.3. Materials and methods

The wood boards of albasia wood are obtained from one of the building material supplier industries in Kitakyushu City, Fukuoka Prefecture, Japan. The albasia wood used in this study is certified by Indonesian Timber Legality Verification (SVLK) and bears the Indonesian Legal Wood logo for the Japanese market. Under the SVLK rule, regulated by the Indonesian Ministry of Industry, it is regarded permissible in the chain of harvesting, processing, transporting, and trading as an export-oriented destination (Susilawati et al., 2019a).

5.3.1. Sample Preparation

Samples were taken in accordance with the requirements and methods specified in the Japanese Industrial Standard (JIS) Z 2101: 2009 (Japanese Standards Association, 2009) for testing the mechanical and physical properties of wood. The defect-free boards had the following dimensions: 13.5 × 150 × 910 mm (thickness x width x length) wrapped in plastic from the manufacturer. All specimens were pre-conditioned to a temperature of 20 °C and humidity of 60% before the experiment. The samples were then cut and prepared for treatment with 13.5 × 120 × 910 mm (thickness × width × length).

5.3.2. Experiment Procedures

The experiment was carried out in the high-temperature and -pressure apparatus HTP-50/130 (HISAKA Company, Osaka, Japan) at the Graduate School of Environmental Engineering, The University of Kitakyushu, Kitakyushu, Japan. The system consisted of the processing tank and boiler setting machine. The experimental procedure for the albasia wood board at high-temperature and -pressure is visualized in Figure 5. 1. The procedure begins with setting the mold device, inserting the wood specimen into the mold device, adjusting the upper plate on the mold device, inserting the mold device into the processing tank, selecting, and adjusting the experimental order settings, and, finally, performing the consolidation process of high-temperature and -pressure treatment.

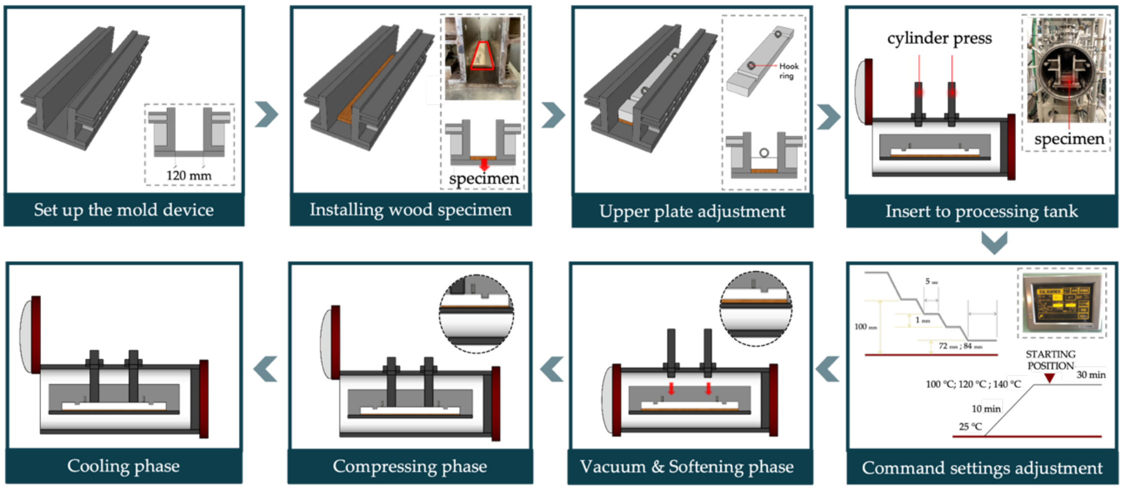


Figure 5. 1 Schematic illustration of the high-temperature and -pressure process.

Source: Research Documentation, 2022.

As seen in Figure 5. 2, the consolidation step of the high-temperature and -pressure treatment on the albasia wood board begins with a five-minute *vacuum phase*, followed by a softening phase, involving heating and temperature holding processes. According to the previous study, the minimum temperature required to perform heat treatment is 100 °C (F. Kollmann & Schneider, 1963).The wooden board specimens were divided into one for control and four categories with varying degrees of high-temperature and -pressure treatment. Six replicated measurements were recorded for each condition. There were four categories used: 100, 120, 140, and a sandwich (treatment formation two samples top as S[1] and bottom as S[2], divided with 3 mm aluminum base) at 140 °C.

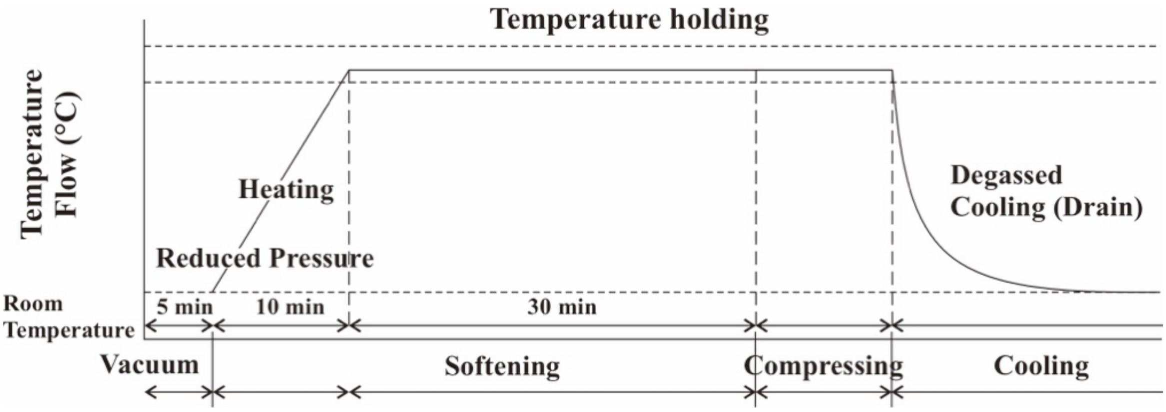


Figure 5. 2 Consolidation process on high-temperature and -pressure treatment.

Source: Research Documentation, 2022.

The heating process takes ten minutes to reach the desired temperature. This process reduces the defects caused by temperature differences between the wood sample and processing environment. Starting at this point, the temperature holding process can take up to 30 min. After softening, the wood was compressed to 50% thick. During the *compressing phase*, the two engine cylinders press against the top steel plate.

The recovery in thick timber is one of the method's main flaws (spring-back). After the experiment, the spring-back phenomenon has been defined as lost compression work (Yuhe & Muehl, 1999). After heating, the temperature difference between the wood and ambient air is high. Thus, to minimize the fault defects in the wood after the modification phase, the *cooling phase* of the wood is carried out in the processing environment until the temperature is equivalent to that of the external environment.

After densification, all specimens were stored for up to 360 H by weighing them periodically until the mass difference was negligible for the test.

5.3.3. Measurement of Physical Properties

5.3.3.1. Density Profile Measurement

The wood density was measured using the following Equation:

$$\rho_w = \frac{m_w}{v_w}$$

where ρ_w denotes the density; m_w denotes the mass; and v_w denotes the volume, all at moisture content w. The mass of the wood specimen was measured using a digital weighing scale, with a readability of 0.01 g (A&D: FZ-5000i). Then, we determined the volume using a caliper (Mitutoyo: ABSOLUTE Digimatic Scale Units-572 Series 0-8in/0–200 mm), with a 0.01 mm accuracy.

Set-recovery for density (SR-D) was determined by Equation:

$$\text{SR-D}\ (\%) = \frac{\text{Ds-Da}}{\text{Do-Da}} \times 100$$

Ds = recovery density after equilibrium moisture content was re-reached (kg/L)

Da = actual density after high-temperature and -pressure (kg/L)

Do = original density before high-temperature and -pressure (kg/L)

And the parameter density change (DC) (Bekhta et al., 2017) was calculated as listed in Equation:

$$\text{DC}\ (\%) = \frac{\text{Ds-Do}}{\text{Do}} \times 100$$

5.3.3.2. Color Changes

Among the physical properties of wood, color is essential for wood applications because it can determine its market value, regarding aesthetic purposes (Huang et al., 2012). Regardless, the original color of the wood may change during processing and after treatment, although the direction of this change varies, according to the wood species.

5.3.3.3. Change in Thickness

Board thickness was determined before and after densification. To assess the densification of spring-back rate, wood specimens were put under predefined relative humidity and temperature conditions for a specified length of time (Fang et al., 2012; Gong et al., 2010; Navi & Girardet, 2000). In investigating the 'spring-back' possibility of the samples, the thickness of each sample was measured with a caliper, under normal atmospheric conditions, on four different sides.

Set-recovery for thickness (SR-T) was determined by Equation:

$$\text{SR-T}\ (\%) = \frac{\text{Ts-Ta}}{\text{To-Ta}} \times 100$$

Ts = thickness recovery after equilibrium moisture content was re-reached (mm)

Ta = board thickness after high-temperature and -pressure (mm)

To = board thickness before high-temperature and -pressure (mm)

As follows, the final parameter thickness change (TC) was used to analyze the thickness change, in the manner specified in Equation.

$$\text{TC}\ (\%) = \frac{\text{Ts-To}}{\text{To}} \times 100$$

5.3.3.4. Compression Ratio

Compression ratio was used to determine treatment efficiency (Gong et al., 2006). The thickness of densified boards was determined prior to and following densification. The level of densification, which also known as the compression ratio (CR), was determined using Equation, whereas *To* denotes the original thickness and *Ta* denotes the final compressed thickness.

$$\text{CR}\ (\%) = \frac{\text{To-Ta}}{\text{To}} \times 100$$

5.3.3.5. Equilibrium Moisture Content

The main consequence of high-temperature and -pressure treatment is reducing moisture content equilibrium. The moisture content (MC) of wood changes as the relative humidity (RH) changes. When subjected to constant RH, the wood progressively acquires a steady equilibrium moisture content (EMC) (Altgen et al., 2016). The moisture level at which the wood is neither accumulating nor losing moisture is known as EMC (W. Simpson & A, 1999). It has been well accepted that EMC is a physical property of wood that affects not only the dimensions of wood but also its mechanical qualities (Hernández et al., 2014).

In this study, the moisture content of the wood was determined using a wood moisture meter (Kett: HM-530 20 MHz/2–50% range) at six points on the sample, measured from top to bottom. These measurements leave no trace on the surface of the material being examined, due to the high-frequency measurement format.

5.3.3.6. Scanning Electron Microscopy (SEM)

Scanning electron microscopy (SEM) was used to investigate the anatomical changes caused by the treatment. As seen in Figure 5. 3, the wood fiber morphology was examined by a JSM-7800F Schottky Field Emission SEM (JEOL Company, Tokyo, Japan). An observation plate was made from fractured 3 × 5 × 5 mm (thickness × width × length) cross-sections of each test sample. Before the anatomical examination, the samples were dried for 24 h at 105 °C in a constant temperature oven DKM600 (Yamato Scientific Co., Ltd., Tokyo, Japan), as shown in Figure 5. 4, to reduce the moisture content by approximately 3–5%. The outer surface of the wood specimens was examined under SEM (100, 500, and 1000 μm magnification) at 15 kV without metal coating.

Figure 5. 3 SEM Investigation equipment: FE-SEM JSM-7800F

Source: Research Documentation, 2022.

Figure 5. 4 Constant oven DKM600.

Source: Research Documentation, 2022.

5.3.3.7. Statistical Analysis

For each category, one-way analysis of variance (ANOVA) was used to determine the influence of high-temperature and -pressure treatment on the mass change, density, thickness, and EMC of albasia wood. Statistical analysis was used to elicit useful information about the characteristics of the sample determined in the experiment. To determine the significance and mean separation of the treatments, a homogeneity test was used (Scheffe, 1959). Average values were compared using Tukey's honestly significant difference (HSD) test; this test considers all pairwise comparisons statically significant at $p < 0.05$ (Fox et al., 1961). The significance level in all tests was $p < 0.05$. All statistical computations and analyses were conducted using SPSS software (Version 28.0, IBM, America).

5.4. Results and Discussion

Normally, during the thermal densification method under high-temperature and -pressure, changes in the wood structure occur based on many treatment circumstances, wood species, and, especially, the treatment intensity (temperature and duration) (Julian & Fukuda, 2021). As a result, the wood specimen was transformed at elevated temperatures (in our study, 100, 120, 140, and a sandwich at 140 °C). These alterations include the removal of hydrophilic OH groups from wood and their replacement with

O-acetyl groups (Poncsák et al., 2006; Popescu et al., 2013), which inhibits water reabsorption and formation of hydrogen bonds between water and wood polymers. After all, hemicellulose is the first component of wood to decay, due to its lower molecular weight and branching structure, which leads to an increase in lignin concentration (Severo et al., 2012; Wikberg & Maunu, 2004; Woodrow & Grace, 2008).

Table 5. 1 ANOVA test results on mass, density, thickness, and EMC.

Dependent Variable	**SS**	**MS**	***F* Ratio**	***p* Value**
Mass (g)	41,106.233 [a]	8221.247	6.371	0.001
Density (kg/L)	0.435 [b]	0.087	3.130	0.026
Thickness (mm)	146.507 [c]	29.301	3.511	0.016
EMC (%)	90.005 [d]	18.001	0.409	0.837

SS, sum of squares; MS, means square; a, R squared = 0.570 (adjusted R squared = 0.481); b, R squared = 0.395 (adjusted R squared = 0.269); c, R squared = 0.422 (adjusted R squared = 0.302); d, R squared = 0.079 (adjusted R squared = −0.113).

Source: Research Documentation, 2022.

The analysis of variance for mass, density, thickness, and EMC value is shown in Table 5. 1, indicating that a significant difference exists, when the computed F value exceeds the F table (F count > F table) or the *p* value is less than 0.05 (*p* value 0.05). The significant variables were then subjected to a further analysis using Tukey's HSD test (Table 5. 2). Significant differences were marked by different lowercase letters, and the significance level was marked in alphabetical order from maximum to minimum.

Table 5. 2 Tukey's HSD test results for main effects.

Category	**Mass (g)**	**Density (kg/L)**	**Thickness (mm)**	**EMC (%)**
100	452.058 [abc]	0.558 [ab]	8.052 [ab]	10.718 [a]
120	391.034 [ab]	0.57 [ab]	7.178 [a]	12.884 [a]
140	441.212 [ab]	0.606 [b]	7.504 [a]	10.1 [a]

140 S[1]	490.298 [c]	0.618 [b]	7.972 [ab]	14.784 [a]
140 S[2]	455.898 [bc]	0.568 [ab]	7.994 [ab]	12.65 [a]
Control	385.304 [a]	0.266 [a]	13.61 [b]	14.432 [a]

Different letters a, b, and c, given next to the mean value, show statistically significant differences between the treatments for each sample categories at $p < 0.05$.

Source: Research Documentation, 2022.

5.4.1. Effect on the Density Profile

Figure 5. 5 shows the specimen masses measured. The mass of the wood increases rapidly after treatment; after 120 H, it decreases and stabilizes. However, the final mass of the specimen was higher than the original mass. Treatment at high-temperature and -pressure resulted in the greatest increase in wood mass (30% at 100 °C) and smallest increase (7% at 120 °C) immediately following treatment. After 120 H, the highest change in wood mass occurred in the 140 °C S [1] category, while the lowest occurred at 120 °C, at 4 and 2%, respectively. After 240 H, the largest changes occurred in the 140 °C S [1] and S[2] categories, while the smallest changes occurred in the 120 °C, at 7 and 1%. Furthermore, after 360 H, the highest changes occurred at temperatures of 100 and 140 S [1] and S [2], totaling 7%, while the lowest changes occurred at 120 °C and 140 °C, totaling 5%. This result can be confirmed from the mass data shown in Table 5.3, where the highest value is found in the 140 S [1] and S[2] category. The ANOVA showed that there were significant differences ($F = 6.371$; $p < 0.05$) in the percentage change in mass found in treated wood, with respect to the control sample (Table 5. 1). Thermal deterioration of thermally treated wood was determined to be the cause of mass loss (Candelier et al., 2016). Furthermore, Tenorio and Moya (Tenorio & Moya, 2013) investigated mass loss during heat treatment and discovered that it is species- and treatment-intensity dependent.

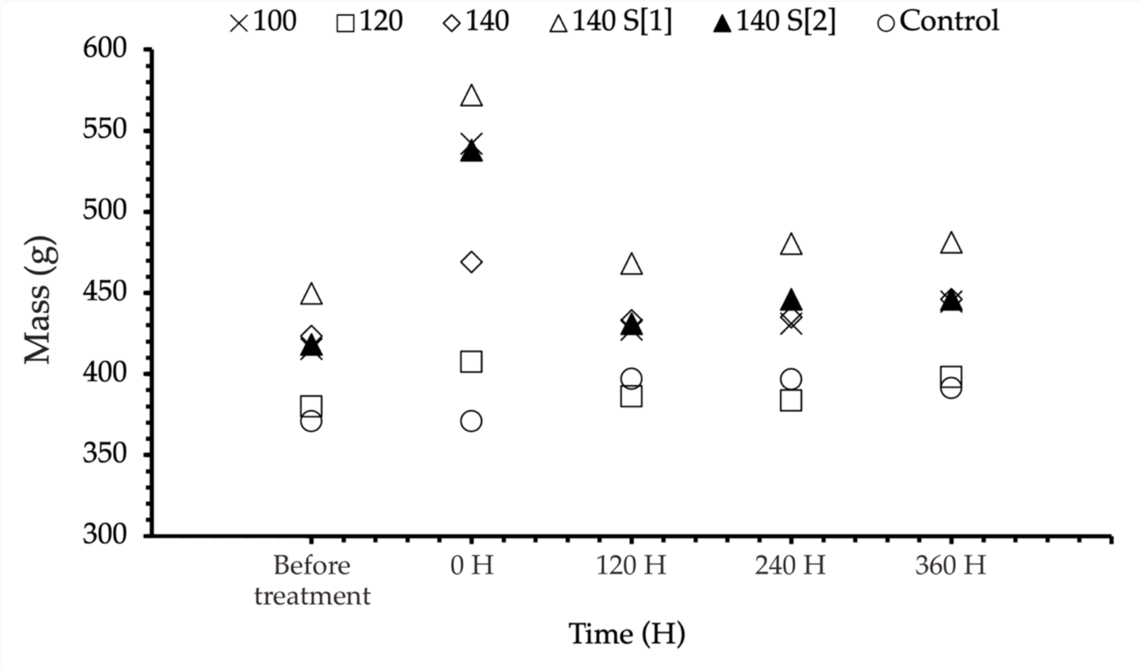


Figure 5. 5 Mass change of specimens.

Source: Research Documentation, 2022.

As shown in Table 5. 5, treated albasia wood (0.62 kg/L) had a higher average density than untreated (0.29 kg/L). The treatment increased the density by an average of 112.78%. The densities of *Albasia* board, after treatment under various temperature conditions, are presented in Figure 5.6. The density increase was accomplished by reducing the volume of the wood, since the compression process was dependent on the viscoelastic nature of the wood (Yu et al., 2017). The densities of the wood samples were significantly enhanced by high-temperature and -pressure treatment at different category levels, with an increase of 100 (at 100 °C), 127 (at 120 °C), 114 (at 140 °C), 109 (at 140 °C S [1]), and 114% (at 140 °C S [2]), compared with the control density. The highest density was achieved with high-temperature and -pressure treatment at 120 °C (0.59 kg/L). This is most likely related to the decomposition of wood chemical components, particularly hemicellulose, due to wood mass loss (Mburu et al., 2008).

Table 5. 3 The density of Albasia before and after densification treatment.

Category	Density (kg/L)			SR-D(%)	DC(%)
	Do	Da	Ds		

100 °C	0.29	0.75	0.58	36.96	100.00
120 °C	0.26	0.84	0.59	43.10	126.92
140 °C	0.29	0.85	0.62	41.07	113.79
140 °C S[1]	0.32	0.78	0.67	23.91	109.38
140 °C S[2]	0.29	0.71	0.62	21.43	113.79
Control	0.26	-	-	-	-

Source: Research Documentation, 2022.

The density profile affects the physical and mechanical properties of the wood and is defined by its thickness. Additionally, moisture content and thickness also have a great effect on the density. Untreated wood had nearly equal density, due to its thickness not being compressed. Immediately after treatment, treated wood gained significant density. However, after 120 H, the density decreased and remained steady. This consistent density correlated with the material used in this experiment (Yu et al., 2017). The selection of defect-free wooden boards contributes to the establishment of consistent density distribution.

As expected, the values for the density profile increased significantly following treatment. The ANOVA demonstrated that, when compared to control board, high-temperature and -pressure treatment had a significant effect ($F = 3.130$; $p < 0.05$) on the density profile Table 5. 1. The control density or initial density has a significant influence on the magnitude of the densified board density (Iskandar et al., 2019c).This is confirmed by the results of Tukey's HSD tests (Table 5.2). The initial density category, 140 S [1], has a high density, which leads in a high final density value. The rise in density as the temperature of the treatment increases may also be related to the softening of solid wood at higher temperatures (Fengel & Wegener, 1989; Welzbacher et al., 2008) and decrease in the volume of the lumen cavity in the wood, as well as a rise in the amount of cell walls per unit volume (Tabarsa & Chui, 1997).

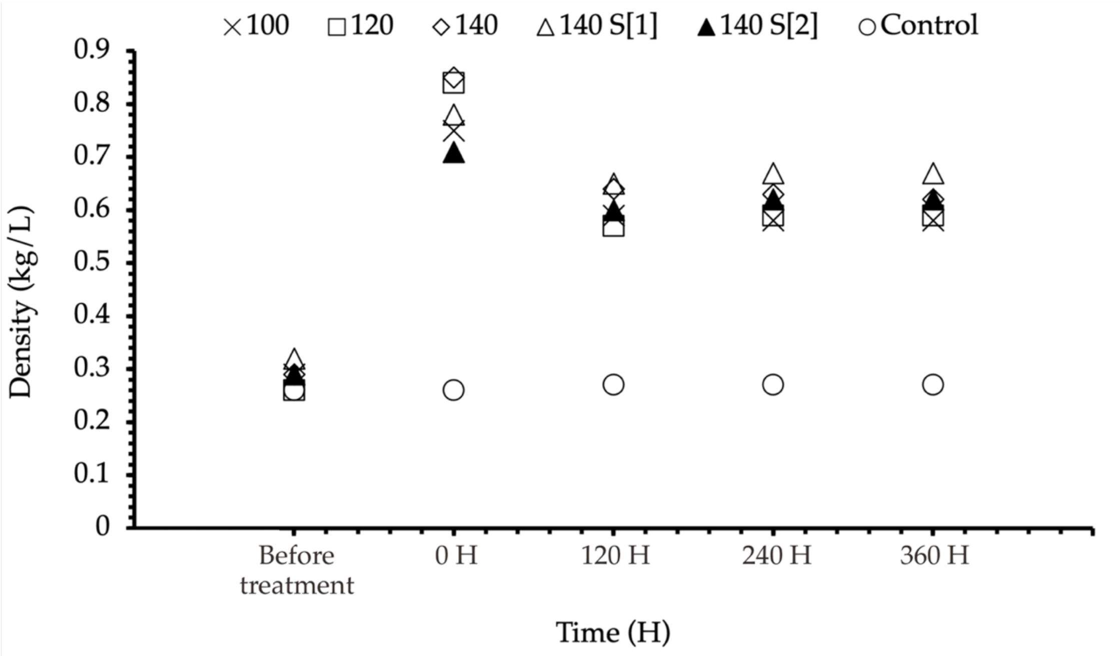


Figure 5. 6 Density profile of specimens.

Source: Research Documentation, 2022.

5.4.2. Color Changes

Wood can change color during and after processing under high-temperatures and -pressure. Albasia wood from Indonesia has gained industrial interest in the global market. This species becomes a value-added product in international trade because of its color. The worldwide demand for albasia wood board by supply from the Indonesian processing industry, specifically the Japanese market, is very high, owing to the light color and rough texture of the wood (Nemoto, 2002a).

In this study, there was a difference in wood color between untreated wood (control) and treated wood (100, 120, 140, and sandwich 140 °C), as shown in Figure 5. 7. Wood may be modified mechanically and physically by high-temperature and high-pressure treatment (Bekhta & Niemz, 2003). Moreover, the color parameter, particularly the overall color difference, can be used to quantify and predict the strength of wood.

The specimens showed that the treated wood had a darker color than the control. In untreated wood, cellulose and hemicellulose do not absorb visible light or contribute to wood discoloration. In color change wood treated studies, when the wood is thermally processed, the decrease in lightness and increase in color difference were attributed to the presence of formation by-products (Kocaefe et al., 2008), caused by a drop in hemicellulose content, particularly pentosan (Bourgois et al., 1991). Polysaccharides and lignin are oxidized to form phenolic chemicals, which may potentially cause color changes (Fengel & Wegener, 1989). Additionally, the color difference generated by steaming increased as the treatment pressure and duration increased (Morita & T, 1987). The deeper color in treated albasia board might be an aesthetic advantage for some applications.

Figure 5. 7 Color differences of albasia wood at different temperatures and pressures.

Source: Research Documentation, 2022.

5.4.3. Change in Thickness

Table 5. 4 The thickness of Albasia before and after densification treatment.

Category	**Thickness (mm)**			**SR-T (%)**	**TC (%)**
	To	**Ta**	**Ts**		
100 °C	13.5	6.53	6.88	5.02	−49.04
120 °C	13.41	4.36	6.02	18.34	−55.11
140 °C	13.23	5.04	6.61	19.17	−50.04
140 °C S[1]	13.24	6.74	6.6	−2.15	−50.15
140 °C S[2]	13.29	6.9	6.59	−4.85	−50.41
Control	13.52	-		-	-

Source: Research Documentation, 2022.

Table 5. 4 summarized the thickness change of the experiment. The effects of high-temperature and -pressure on the thickness of albasia wood are substantial. Previous research established that the specimen thickness decreases when the densification temperature and pressure increase (Bekhta et al., 2017). At the same densification temperature, the higher the densification pressure, the higher the TC. Yet, it should be mentioned that this analysis discovered no discernible difference between 100 and 140 °C. This study reduced the average initial thickness from 13.4 mm to 6.5 mm. Densification of wood, up to 50% of its original thickness, can increase the density up to two times denser (S, 2000). The average density increase of 113% in this study was in the direction of wood densification, up to 51% of its original thickness.

The greater the final density of the treated wood, the more TC is produced. A negative value indicates that the thickness of the albasia wood has been reduced. The 120 °C category exhibited substantial increases in thickness throughout the treatment process, while the 100 °C category exhibited very minor alterations. In terms of the final thickness change parameter, a substantial change in thickness happens at a temperature of 120 °C of 55.11%, while a modest change occurs at a temperature of 100 °C of 49.04%. This result is also explained by the density value of the 120 °C category, which is higher than the lower density value of the 100 °C category (Table 5.3). In addition, the ANOVA results revealed that there were significant differences ($F = 3.511$; $p < 0.05$) in the high-temperature and -pressure treatment of wood thickness (Table 5.1).

Due to the fact that wood is a viscoelastic material, the cell deformations generated by compression may result in internal stresses being stored in the microfibrils and matrix of the wood, which explains why densified wood springs back (Yu et al., 2017). The integrity of the compressed albasia wood thickness over time is also critical for subsequent applications of the wood board. After the cooling phase and storing the board under predefined relative humidity and temperature conditions, the surfaces of the control and treated boards were compared (see Figure 5. 8). The two tangential surfaces of the treated board are not as flat as the surface of the control board. Then, low, medium, and high treatment flatnesses were, thus, markedly more stable, when compared to the sandwich treatment. It is conceivable that the surface of the wood board treated with the sandwich result is not entirely flat following treatment, due to compression employing a steel plate separator. It is essential to further investigate the configuration of the steel separator plates used in the sandwich category in future studies.

Figure 5. 8 Comparison of Albasia boards, both treated and control.

Source: Research Documentation, 2022.

5.4.4. Compression Ratio

Table 5. 5 Correlation between Albasia density and compression ratio.

Category	**Density (kg/L)**		**CR (%)**
	Before	**After**	
100 °C	0.29	0.58	103.63
120 °C	0.26	0.59	104.11
140 °C	0.29	0.62	103.78
140 °C S[1]	0.32	0.67	103.79
140 °C S[2]	0.29	0.62	103.79
Control	0.26	-	-

Source: Research Documentation, 2022.

Table 5. 5 data on albasia wood compression ratio densification. The compression ratio dictates the change in density; a higher compression ratio results in a denser surface layer with a higher wood density (Z. Gao et al., 2016b; Kitamori et al., 2010b). At a compression ratio of 104.11%, the wood density rose by 127% to 0.59 kg/L. When the compression ratio is 104%, the thickness of the layer with the largest densification is roughly uniform in thickness of the layer with the lowest densification. Among the wood specimens investigated, the 120 °C category had the highest compression ratio,

and the 100 °C category had the lowest compression ratio. These findings were consistent with the rise in density following treatment, in that the percentage increase in density was greater in the sample with a high compression ratio. Along with density, the compression ratio determines the decrease in thickness of compressed wood. The observed increase in the compression ratio, as densification increased, was attributable to a reduction in the volume of the lumen's cavity in the wood. The density of densified wood is highly dependent on the compression ratio, densification method, and wood species properties (Rautkari et al., 2013).

5.4.5. Equilibrium Moisture Content

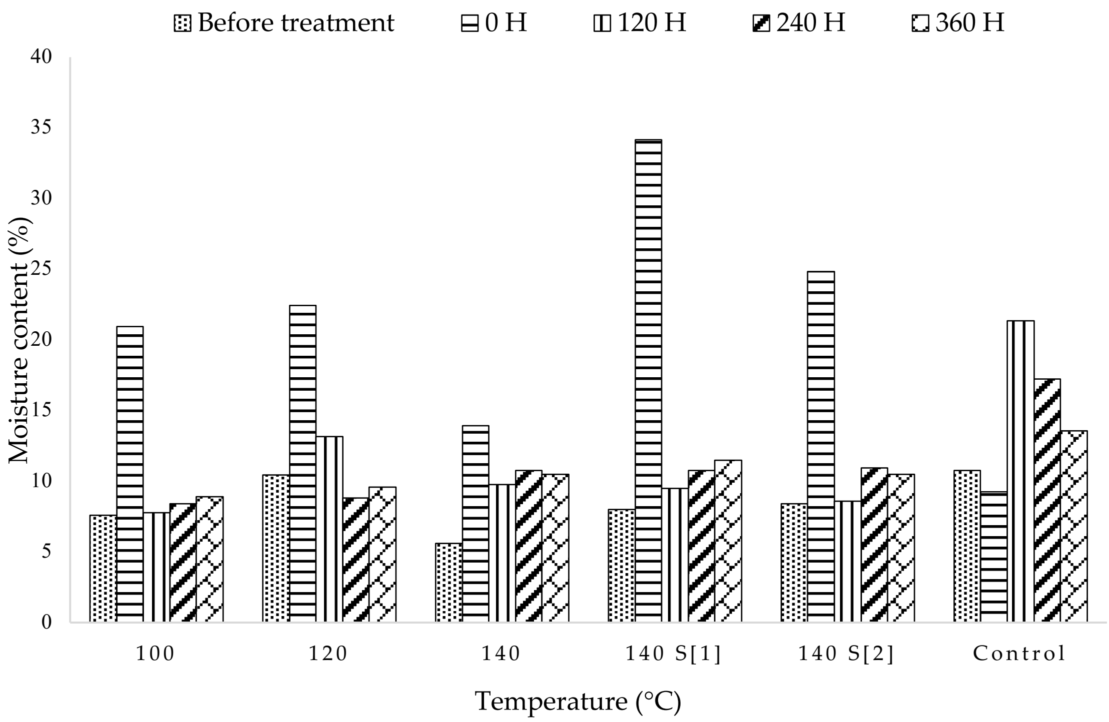


Figure 5. 9 Correlation between equilibrium moisture content and time after treatment.

Source: Research Documentation, 2022.

The equilibrium moisture content (EMC) of the treated and untreated albasia wood board samples of various categories are presented as bar graphs in Figure 5. 9. The results of this study indicated that the densified wood had a more stable EMC than the control. Immediately after treatment, the EMC increased from 8% to 23.25%. The treatment atmosphere is quite humid during the cooling process, resulting in a very moist wood surface when measured. Furthermore, the results decreased from 120 H to 360 H and reached a stable EMC level. In comparison to untreated wood, the yield varies; it does not remain constant.

The rise in temperature, associated with heat treatment, results in a reduction in the EMC of the wood (Akyildiz & Ates, 2008). Meanwhile, the findings of this study, based on ANOVA results, revealed that there was no significant influence of temperature treatment on the EMC of compressed wood ($F = 0.409$, $p > 0.05$) when subjected to elevated temperatures and pressures (Table 5.1). Nandika et al. (Nandika et al., 2015b) also stated that there was no significant difference in the results of temperature control treatment, when using the impregnation method on *sengon* wood. There was no correlation between temperature levels in many categories and EMC. This may be due to damage or disruption of the cellular structure during the treatment process at high-temperature and -pressure, allowing for easier absorption/evaporation of moisture (Yu et al., 2020).

Several studies demonstrate that the minimum temperature required to modify wood is 100 °C, with water absorption decreasing as the temperature increases above 100 °C (D'Jakonov & Konepleva, 1967; Nikolov & Encev, 1967). Compared with control board, the treated wood has a lower EMC after 120 H. The decrease in the EMC of wood results from a decline in the quality of the hemicellulose, induced by high-temperature and -pressure treatment, which impairs the wood's ability to bind OH. The lower the EMC value of wood, which should be significantly less than the fiber saturation limit of between 21 and 32%, the better the wood's physical and mechanical properties (C. Hill, 2006), meaning these mechanical and physical properties will increase as the moisture content decreases (Hartono & Sucipto, 2018).

5.4.6. Scanning Electron Microscopy (SEM)

SEM micrographs of cross-sections from control and treated specimens, at various magnifications, are shown in Figure 5. 10. The fracture surface of the control is not smooth at 500 µm magnification. At 1000 µm magnification, fiber pulling occurs more frequently, resulting in large, regular voids on the control wood surface. When *Albasia* is modified at 140 °C, the polarity of the fibers decreases, resulting in an increase in the interfacial bonds between the fibers in the wood. The interface bonding is superior to that of the control sample. The pulling phenomena are practically invisible on the surface of the modified wood; nevertheless, tensile fractures occur instead. The tensile fractures occur in this modified wood, resulting in increased voids, smaller voids, and a rougher, denser surface than the control wood. The cavity (empty slot) is relatively small and uneven, so the contact between the wood fibers is not apparent.

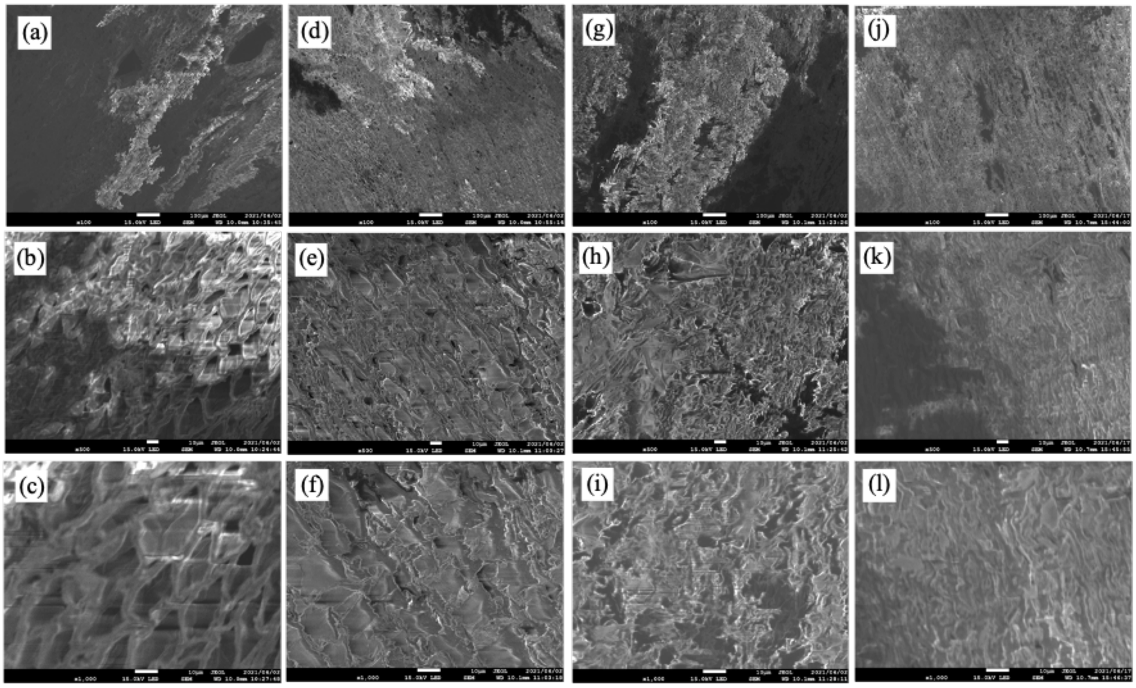


Figure 5. 10 SEM micrographs: control (a) 100 "µm" , (b) 500 "µm" , (c) 1000 "µm" ; 100 °C (d) 100 "µm" , (e) 500 "µm" , (f) 1000 "µm" ; 120 °C (g) 100 "µm" , (h) 500 "µm" , (i) 1000 "µm" ; 140 °C (j) 100 "µm" , (k) 500 "µm" , (l) 1000 "µm."

Source: Research Documentation, 2022.

The morphology of the wood was improved by modifying it with high-temperature and -pressure. Even though the tensile fracture is not entirely controlled, and voids remain on the fractured wood’s changed surface, the interfacial binding is better than that of untreated fiber composites (X. Gao et al., 2016). Consequently, the improved morphological properties under high-temperature and -pressure are compatible with earlier work, regarding the optimized thermal compression morphology (Ahmed et al., 2013; Bao et al., 2016, 2017). This investigation demonstrated that treated *Albasia* showed characteristic enhancement, as indicated by the magnification of 1000 µm.

5.5. Conclusions

The densification method under high-temperature and -pressure in this study affect the physical properties of the albasia wood board. The main findings of this study are as follows:

1) The albasia wood board that has been densified to a density of 0.62 kg/L is denser than the control board that has not been densified to 0.29 kg/L.
2) The treated specimens were darker than the control board. As the density of the wood increases, its chemical components, particularly hemicellulose, decompose, darkening the color of the wood.
3) Board thickness can be modified to 50.95%, nearly twice its pre-treatment thickness. However, upon treatment and storage, the tangential surface of the board is not as flat as the control.
4) The increased density and hemicellulose degradation decreased moisture, with treated specimens exhibiting a more stable EMC than the control board. These mechanical and physical properties increase as the moisture level declines.
5) SEM analysis revealed that the treatment increased wood morphology. Notably, the observations demonstrated an improvement in mechanical properties. Although the interfacial bonding was not perfectly controlled, the results were better than the untreated board.
6) The ANOVA showed that the high-temperature and -pressure treatment had no significant effect on the EMC of compressed wood ($p > 0.05$) but had a significant effect on the mass, density, and thickness changes of the wood ($p < 0.05$), compared to the control board.

Finally, the enhanced performance properties of wood board create new possibilities for its use as a flooring material. The study results provide a guide for advancing wood densification to increase the value of fast-growing wood species, such as albasia wood, throughout the wood industry.

CHAPTER 6
OPTIMIZATION OF VORONOI DENSIFICATION PROCESS TO ENHANCE THE PHYSICAL AND MECHANICAL PROPERTIES OF INDONESIAN ALBASIA WOOD

CHAPTER 6: OPTIMIZATION OF VORONOI DENSIFICATION PROCESS TO ENHANCE THE PHYSICAL AND MECHANICAL PROPERTIES OF INDONESIAN ALBASIA WOOD

Summary

Voronoi diagrams have gained popularity in architecture and design for their aesthetic appeal and potential to create visually striking and unique structures. A study was conducted to evaluate the effect of thermal densification integrated with Voronoi-inspired patterns in Indonesian albasia wood on its physical and mechanical properties. The wood was cut into small sizes weighing 4000g, combined with 700g adhesive and 105g isocyanate, and then compressed at 140°C into a size of 65mm x 65 mm x 800 mm. The effects of the treatments on wood density, EMC, morphology, compressive strength, and bending strength were then evaluated. The study found that 1) Wooden slats with a millimeter structure resembling the Voronoi pattern could become a new architectural trend, not just for Indonesian Albasia wood but for all wood material; 2) The density of the Albasia Voronoi composite is 0.81 kg/L, which is greater than the natural wood density of 0.26 kg/L. The treatment increased the density of albasia wood by 211.54%; 3) The EMC stability of the albasia Voronoi composite was more stable than that of the control board as a result of its higher density and hemicellulose degradation. These mechanical and physical characteristics improve as the level of moisture decreases; 4) Morphological analysis revealed that the cellulose nanofibers of treated wood were very similar to natural wood, but the interfacial bond of the albasia Voronoi composite was significantly superior to that of the control; 5) The albasia Voronoi composite treatment procedure increased the longitudinal compressive strength of the wood by 100.88%. It also increased the tangential compressive strength by 883.12%; 6) The Albasia Voronoi composite treatment procedure increased the bending strength of the wood by 144.05%. It also increased the tangential compressive strength by 859.36%; and 7) The tensile strength and elongation at break of albasia Voronoi composite were about 10 and 2 times higher than the control wood.

CHAPTER 6: INTEGRATING THE VORONOI DENSIFICATION PROCESS TO IMPROVE THE PHYSICAL AND MECHANICAL PROPERTIES OF INDONESIAN ALBASIA WOOD

6.1. Introduction

6.1.1. Background

The density of wood is positively correlated with its strength properties. As a renewable and eco-friendly material, high-density wood is utilised extensively in everyday life (e.g., in the construction, furniture, and flooring industries). However, the supply of this type of wood is insufficient to meet the rising market demand, primarily due to its extremely lengthy growth period (Dong et al., 2016; Julian et al., 2019; Rahayu et al., 2020). Due to their unfavourable mechanical properties and low density, fast-growing plantation forests can be used as a resource to solve this issue, as they have not been effectively exploited in the past.

Albasia (*Albizia falcataria*) is a wood species with a rapid growth rate that is widely planted and cultivated in Indonesia. This wood was chosen for this study because, in addition to its many advantages, such as a short harvest period (4-7 years) and uncomplicated growing site requirements, it aligns with the 2018 Indonesia Lightwood Cooperation Forum (ILCF) plan to develop the potential of Albasia wood. However, its limited density, hardness, and strength restrict its commercial use. Denser wood is commonly preferred for commercial applications, particularly in construction (Blomberg et al., 2005a; Nandika et al., 2014); therefore, increasing the density and properties of the wood is crucial. It is preferable to increase the density of fast-growing wood with poor properties through a process known as wood modification (C. Hill, 2006; Homan & Jorissen, 2004).

In addition to the durability of wood, architects and designers also take advantage of the structural material's aesthetic qualities. Voronoi diagrams have gained popularity in architecture and design for their aesthetic appeal and potential to create visually striking and unique structures (Abbas, 2022; Makiyama et al., 2002; Nowak, 2005; Poupon, 2004). Voronoi defines the self-organizing system of biological structures seen in beehives, dragonfly wings, sea urchin shells, or turtle shells (Nowak, 2005).

6.1.2. Purpose of the study

One of the biggest challenges to achieving sustainability is improving the quality of abundant wood. To optimize the process of improving wood properties, it is crucial to understand how operating parameters impact wood properties. A study was conducted to evaluate the effect of thermal densification integrated with Voronoi-inspired patterns in Indonesian Albasia wood on its physical and mechanical properties. The effects of the treatments on wood density, EMC, morphology, compressive strength, and bending strength were then evaluated.

6.2. Literature Review

6.2.1. Albasia wood

Albasia (*Albizia falcataria*), also known as sengon wood, is a fast-growing tree species that is commonly found in the forests and plantations of Indonesia. In addition to its many advantages, such as a short harvest period (4-7 years) and simple planting sites for tree growth (Chandra et al., 2018; U. J. Siregar et al., 2007a), (Serangan et al., 2015) albasia development efforts are also in line with the Indonesian government's goal to become the world's largest supplier of lightwood, as evidenced by the potential of albasia wood in the ILCF (Indonesian Lightwood Cooperation Forum) in 2018.

More than 85% of the 57.9 million m^3 of logs utilised by the Indonesian timber industry in 2019 originated from plantation forests. Indonesia produced 5,4 million m3 of albasia logs, representing 9.3% of the nation's total log production (BPS, 2019). It is used almost identically to Japanese cedar wood for furniture and wallcovering raw materials.

However, the rapid growth of albasia results in low density, low hardness and strength, and possibly a large quantity of immature wood with numerous knots, which has inferior physical and mechanical properties than mature wood (Zhang et al., 2004). This condition reduces the wood's usefulness and economic value, necessitating the implementation of technological advancements that can enhance its quality.

6.2.2. Voronoi structure

Voronoi is representative of a significant architectural design trend. Voronoi defines the self-organizing system of biological structures seen in beehives, dragonfly wings, sea urchin shells, or turtle shells (see Figure 6. 1) (Nowak, 2005). A Voronoi diagram (Dirichlet tessellation, Voronoi tessellation) is a graph composed of centers (seeds) that are the diagram's edges that create a Voronoi cell (Gawell & Nowak, n.d.).

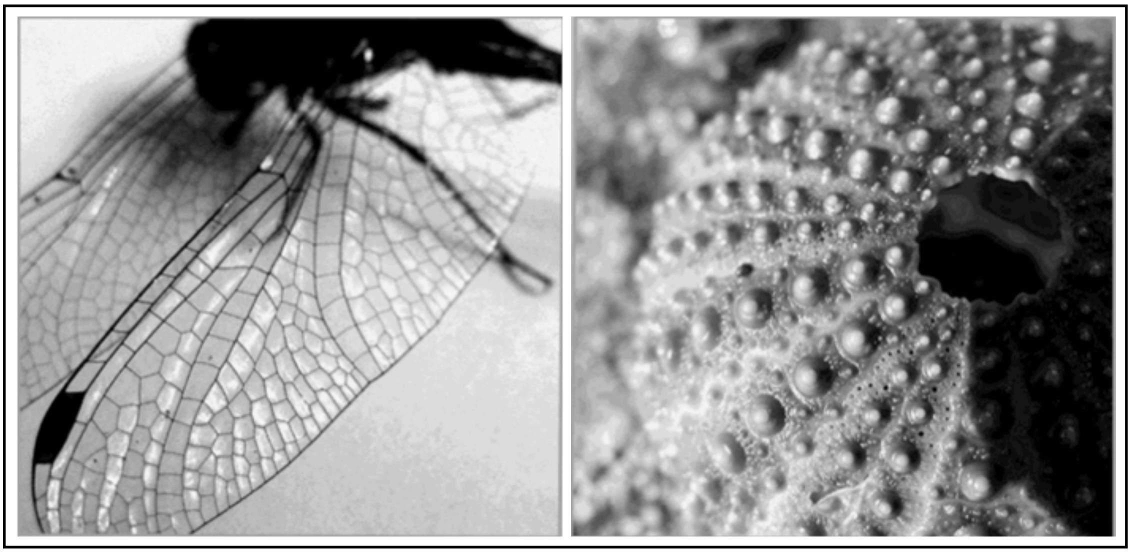


Figure 6. 1 Example of Voronoi found in nature in dragonfly wing and sea urchin shell

Source: (Nowak, 2005)

Regarding the incorporation of computing into the design process, architects and academics have investigated the potential for more complex geometries and more adaptable shapes and structures. Shaping architectural elements and structural forms with Voronoi diagrams is one of the most significant emerging ideas in architectural design that seeks new modes of expression (Friedrich, n.d.). As a three-dimensional space-filling structure that is both modular and non-repeating, Voronoi diagrams are an intriguing design tool since their non-repeatability suggests as a more adaptable parametric quality than conventional modular systems.

The application of Voronoi diagrams as a leading trend in architecture to seek out new expressions can be seen in Figure 6. 2. The Tree-Structure canopy of WestendGate Tower in Frankfurt upon main in 2011 uses Voronoi diagrams in its roof surface discretization. Next is The Water Cube (National Swimming Center), which utilizes a Voronoi diagram-based division system to fill the bubble cell facade that represents the water in the building's swimming pool. Then The Airspace Building in Tokyo was constructed in 2007 with a facade comprised of two separate layers of sheet metal to create a three-dimensional Voronoi diagram.

Figure 6. 2 The application of Voronoi diagrams in Architecture.

(a) (b) (c)

Source: (a) Tree-Structure canopy of WestendGate Tower in Frankfurt upon Main, 2011. (Agkathidis & Brown, n.d.); (b) The Water Cube National Swimming Center, 2008. (Architizer, n.d.); (c) Airspace Building Tokyo, 2007 (faulders-studio, n.d.).

6.3. Materials and methods

6.3.1. Preparation of wood specimens

In this study, Indonesian albasia wood boards were obtained from a building material supply industry in Kitakyushu City, Fukuoka Prefecture, Japan (see Figure 6. 3). Samples were taken in accordance with the requirements and methods specified in the Japanese Industrial Standard (JIS) Z 2101: 2009 (Japanese Standards Association, 2009) for testing mechanical and physical properties of wood. The defect-free boards had the following dimensions: 13.5 × 250 × 910 mm (thickness x width x length) wrapped in plastic from the manufacturer. All specimens were pre-conditioned to a temperature of 20 °C and humidity of 60% before the experiment. To make the smaller pieces of wood to be compressed, the *Albasia wood* board was then cut into 13.5 x 15 x 910 mm (thickness x width x length) using a table saw (Figure 6. 4).

Figure 6. 3 Albasia wood available at building material supply stores in Kitakyushu.

Source: Research Documentation, 2023.

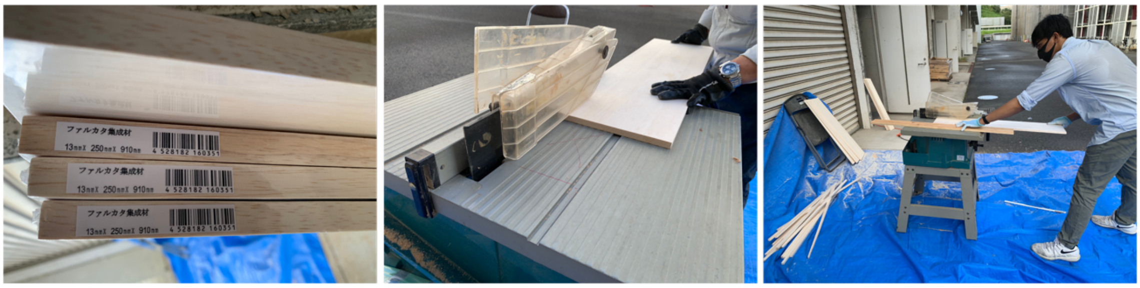


Figure 6. 4 Photographs of the process of cutting Albasia wood into small pieces.

Source: Research Documentation, 2023.

Figure 6. 5 Albasia wood has been cut into small lengths.

Source: Research Documentation, 2023.

The albasia wood in Figure 6. 5 has been cut into small lengths. In this study on the compression of albasia wood with a Voronoi form, the wood was combined with adhesive and isocyanate. As illustrated in Figure 6. 6, the adhesive used was KR-134L and the isocyanate used was AJ-1 (KR Bond, a two-component water-based polymer-isocyanate wood adhesive developed by Kyuo Sangyo.Co.Ltd., Japan).

Figure 6. 6 Adhesive and Isocyanate (Cross linker) used in the experiment.

Source: Research Documentation, 2023.

The adhesive KR-134L is a quick-drying type that can enhance water resistance, heat resistance, and cold resistance. This product must be combined with cross-linking agent AJ-1. Both adhesive and cross-linker products conform to the Japanese Agricultural Forestry Standard (JAS) for structural laminated timber.

6.3.2. Experiment Procedures

Table 6. 1 Manufacturing conditions.

Sample	Temperature (°C)	Softening time (min)	Cooling time (h)	Adhesive (g)	Isocyanate (g)	Weight (g)
FS-1	140	30	24	700	105	4000
FS-2	140	30	24	700	105	4000
FS-3	140	30	24	700	105	4000
FS-4	140	30	24	700	105	4000

Source: Research Documentation, 2023.

Experiments were conducted in the high-temperature and -pressure apparatus HTP-50/130 (HISAKA Company, Osaka, Japan) at The University of Kitakyushu's Graduate School of Environmental Engineering in Kitakyushu, Japan. The apparatus included a processing tank and a boiler-setting machine. Table 6. 1 displays the manufacturing conditions for this experiment. The consolidation phases of the densification process for albasia wood wood consist of the preliminary vacuum phase, the softening phase, the final vacuum phase, the gluing phase, the compressing phase, and the cooling phase.

Figure 6. 7 Albasia wood that has been cut lengthwise totaling 4000 g.

Source: Research Documentation, 2023.

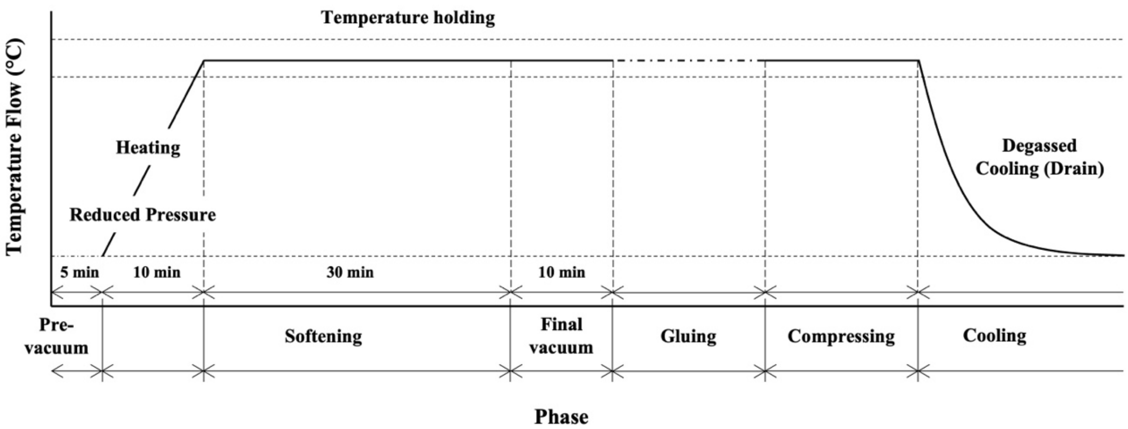


Figure 6. 8 Consolidation process of Albasia Voronoi composite wood.

Source: Research Documentation, 2023.

The first step was to collect and weigh 4000 g of small cut wood (see Figure 6. 7) before placing them in the processing tank. As can be seen in Figure 6. 8, the consolidation of Albasia Voronoi composite starts from the five-minute *preliminary vacuum phase*, followed by a *softening phase* involving heating and maintaining temperatures. According to previous research, the minimum temperature necessary(F. Kollmann & Schneider, 1963)(F. Kollmann & Schneider, 1963), while the optimal temperature is 140℃. Ten minutes are required to attain the desired temperature of 140℃ during the heating process. This procedure minimizes defects resulting from temperature differences between the wood sample and the processing environment. From this point forward, the temperature-maintenance process can take up to 30 minutes. After the softening phase is complete, a 5-minute *final vacuum phase* is administered.

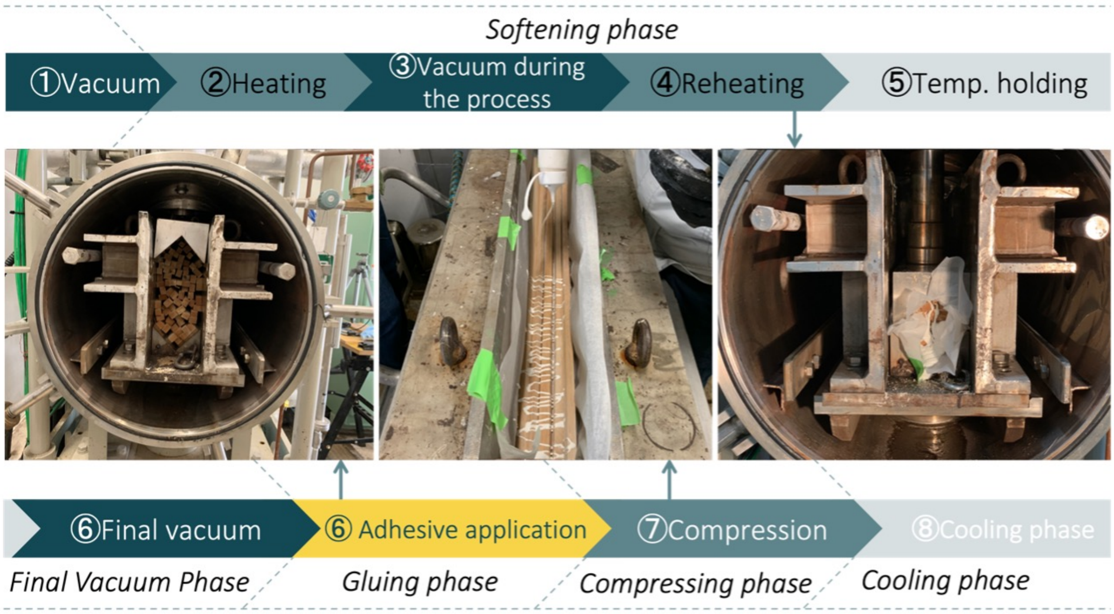


Figure 6. 9 Consolidation illsutration of Albasia Voronoi composite wood.

Source: Research Documentation, 2023.

Immediately following the softening phase, the adhesive and isocyanate are mixed with the softened wood (Figure 6. 9). The wood parts are evenly coated with a mixture of 700 g adhesive and 105 g isocyanate (*gluing phase*) in the mold device. After the combining of the adhesive and isocyanate has been completed, move on to the *compressing phase*. During the compressing phase, two machine cylinders press the mold device's upper steel plate. The spring back phenomenon following treatment has been defined as the lost compression effort (Yuhe & Muehl, 1999). The temperature difference between wood and ambient air becomes significant after heating. In order to minimize fracture defects in the wood after the treatment, the *cooling phase* is carried out in the processing environment until the temperature reaches that of the external environment. An illustration of compressed wooden slats and adhesive can be seen in Figure 6. 10. After the treatment procedure was complete, all specimens were stored for up to 360 hours by periodically weighing them until the mass difference for testing was negligible.

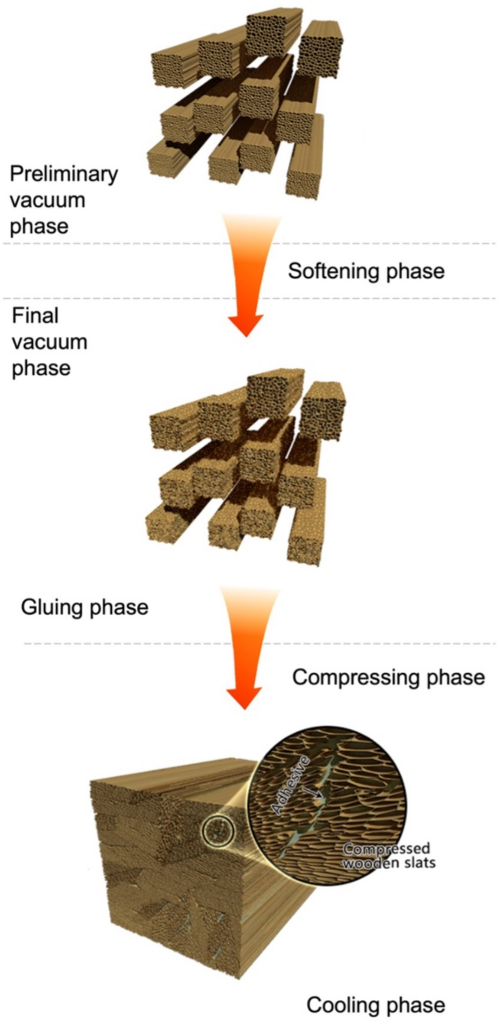


Figure 6. 10 Illustration of Albasia Voronoi Composite treatment.

Source: Research Documentation, 2023.

6.3.3. Preparation for the test

After treating Albasia wood with densification integrated with voronoi form, the wood was stored and periodically measured for 360 H in terms of wood dimensions, wood density, and wood EMC. The wood samples were then prepared for sectioning according to standardized dimensions for various test variables.

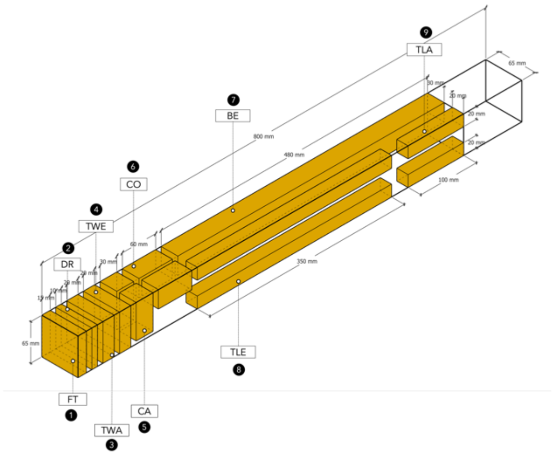


Figure 6. 11 Wood cutting pattern on treated sample.

Source: Research Documentation, 2023.

Table 6. 2 Description of wood cutting on treated samples

No	Code	Test Variable	Dimension (thickness x width x length)	Pcs
1	FT	Fracture tougness test	7.5 mm x 15 mm x 60 mm	4
2	DR	Dry test	60 mm x 60 mm x 10 mm	1
3	TWA	Tensile Width (American Standard) Test	20 mm x 20 mm x 60 mm	2
4	TWE	Tensile Length (European Satndard) Test	20 mm x 20 mm x 60 mm	2
5	CO	Compression test (longitudinal)	30 mm x 30 mm x 60 mm	2

6	CA	Compression test (lateral)	60 mm x 30 mm x 30 mm	2
7	BE	Bending test	30 mm x 30 mm x 480 mm	1
8	TLA	Tensile Length (American Standard) Test	20 mm x 20 mm x 100 mm	2
9	TLE	Tensile Length (European Standard) Test	20 mm x 20 mm x 350 mm	2

Source: Research Documentation, 2023.

Figure Figure 6. 11 illustrates cutting pattern for the treated albasia wood sample. While Table 6. 2 displays the codes, descriptions of the test variables, dimensions, and the amount of wood required to prevent failure in the test.

6.3.4. Determining of Physical Properties

6.3.4.1. Density Profile Measurement

The density of compressed wood refers to the Japanese Industrial Standard (JIS) Z 2101: 2009 (Japanese Standards Association, 2009) was determined using the following equation:

$$\rho_w = \frac{m_w}{v_w}$$

where ρ_w represents the density; m_w represents the mass; and v_w represents the volume, at moisture content w. The mass of the wood sample was determined using a digital scale with an accuracy of 0.01 g (A&D: FZ-5000i). The volume of the wood was measured using a caliper with an accuracy of 0.01 mm (Mitutoyo: ABSOLUTE Digimatic Scale Units-572 Series 0-8in/0–200 mm), with a 0.01 mm accuracy.

The density set-recovery (SR-D) was calculated using Equation (2):

$$\text{SR-D } (\%) = \frac{\text{Ds-Da}}{\text{Do-Da}} \times 100$$

Ds = recovery density after equilibrium moisture content was re-reached (kg/L)

Da = actual density after high-temperature and -pressure (kg/L)

Do = original density before high-temperature and -pressure (kg/L)

And the parameter density change (DC) [26] was determined according to the following Equation (3):

$$DC\ (\%) = \frac{Ds\text{-}Do}{Do} \times 100$$

6.3.4.2. Equilibrium Moisture Content (EMC)

The main consequence of high-temperature and -pressure treatment is reducing moisture content equilibrium. The moisture content (MC) of wood changes as the relative humidity (RH) changes. When subjected to constant RH, the wood progressively acquires a steady equilibrium moisture (EMC) (Altgen et al., 2016). The moisture level at which the wood is neither accumulating nor losing moisture is known as EMC (W. Simpson & A, 1999). It has been well accepted that EMC is a physical property of wood that affects not only the dimensions of wood but also its mechanical qualities (Hernández et al., 2014).

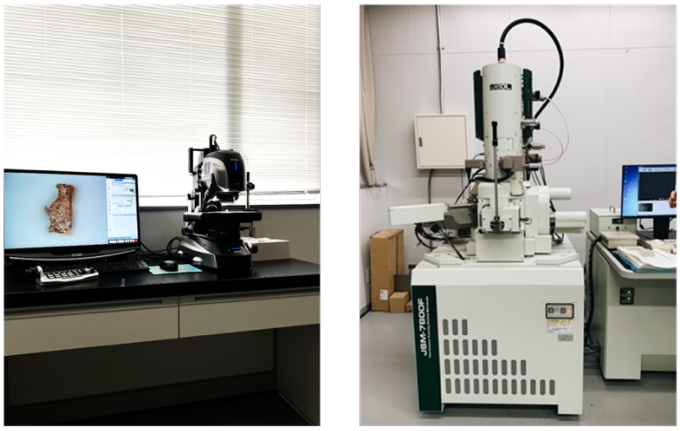
In this study, the moisture content of the wood was determined using a wood moisture meter (Kett: HM-530 20 MHz/2–50% range) at six points on the sample, measured from top to bottom. These measurements leave no trace on the surface of the material being examined, due to the high-frequency measurement format.

6.3.4.3. Morphology

This study utilized Scanning Electron Microscopy (SEM) and Digital Microscope (DM) to examine the anatomical changes caused by the treatment. The morphology of the wood fibers was examined using a Digital Microscope (DM): VHX-7000 series (Keyence Company, Itasca, USA) and a Scanning Electron Microscope (SEM): JSM-7800F Schottky Field Emission SEM (JEOL Company, Tokyo, Japan), as shown in Figure 6. 12.

Observation plates were made from 3 × 5 × 5 mm (thickness × width × length) cross-sections broken off from each test sample. Figure 6. 13 represents how the samples were dried for 24 hours at 105°C in a DKM600 constant temperature oven (Yamato Scientific

Co., Ltd., Tokyo, Japan) to reduce the moisture content by 3-5% prior to anatomical examination.



(a) (b)

Figure 6. 12 (a) Digital Microscope: VHX-7000 series (b) Scanning Electron Microscopy: FE-SEM JSM-7800F

Source: Research Documentation, 2023.

Figure 6. 13 Constant oven DKM600 for drying sample.

Source: Research Documentation, 2023.

6.3.5. Determining of Mechanical Properties

6.3.5.1. Compressive strength test

Selected specimens of Indonesian albasia wood were tested for their compressive strength in accordance with the Japanese Industrial Standard (JIS) Z 2101: 2009 and the British Standard (BS) 373: 1957, respectively (Japanese Standards Association, 2009)(British Standard, 1957). In order to better comprehend the compressive strength properties of wood, longitudinal and tangential compression tests were prepared. Each specimen of control and treated wood, as well as the loading direction of the test specimens, were prepared with comparable dimensions of 60 x 30 x 30 mm (thickness x width x length).

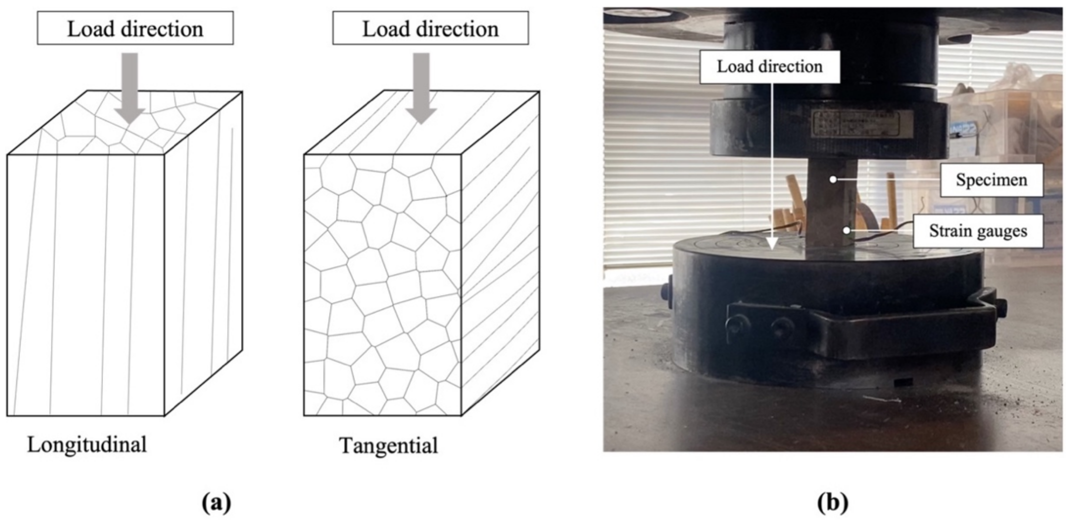


Figure 6. 14 Loading application of compressive strength test.

Source: Research Documentation, 2023.

Figure 6. 14 demonstrates the application of compressive strength test loading. The compressive strength tests were conducted using a universal material testing machine, UH-2000kNXR (Shimadzu Corporation, Japan), with a computer-controlled servo-hydraulic system, 60 Hz operating frequency, and a maximal load capacity of 2000 kN. The measurement was controlled at a load rate of 0.5 MPa/s, and the SFRC axial strain was measured by averaging the signals from two displacement strain gauges (Tokyo Measuring Instruments Lab, type LFLAB-10-11-5LJC-F, gauge length 10 mm) attached to the specimen. The test is terminated when the burden stabilizes during

continuous pressing. All values were adjusted to a 12% moisture content in accordance with each applicable standard's specifications. The compressive strength is computed using equation in conformance with the preceding specifications:

$$\sigma_c = \frac{P}{A}$$

$$\varepsilon_c = \frac{\Delta l}{l}$$

σ_c = Compressive strength (MPa)

P = Maximum load (N)

A = Cross sectional area of sample (mm^2)

l = Target point distance (mm)

Δl =Shrinkage corresponding to ΔP (mm)

When shrinkage is measured, the proportional stress of compression and the Young's modulus of compression of the wood are calculated by the following formula.

$$\sigma_{cp} = \frac{P_p}{A}$$

$$E_c = \frac{\Delta P l}{\Delta l A}$$

σ_{cp} = Compressive proportional limit stress (MPa)

E_c = Compressive Young's modulus (N/mm^2)

P_p = Proportional limit load (N)

A = Cross sectional area of sample (mm^2)

ΔP = Difference between the upper and lower load limits in the proportional limit region (N)

Maximum force measured (Pm) is used to calculate compressive strength. The compressive strength at proportionate limit is the highest stress that a material can withstand while exhibiting no permanent distortion (Rowell et al., 2012). Graphically, it represents the endpoint of the linear range of the stress-strain curve (Báder & Németh, 2019). Using the equation, the compressive strength at the proportionate limit was also computed based on these factors.

6.3.5.2. Bending strength test

Control and compressed specimens were subjected to three-point static bending strength experiments in accordance with the Japanese Industrial Standard (JIS) Z2101-94: 1994 to determine the maximum bending strength.

In the longitudinal direction bending strength test, the three-point bending test was conducted. The test was conducted using a universal material testing machine UH-2000kNXR (Shimadzu Corporation, Japan). Test specimens of compressed wood and control wood were cut to dimensions of 30 mm (height), 30 mm (width), and 480 mm (length).

The loading procedure parameters were determined using the estimated maximal load (P), which was derived from a bending strength test conducted until failure. The distance between lower supports was 420 mm for the three-point static bending strength measurements. The loading point in the center was corrected. The test was carried out at a speed of 0.08 mm/s. The diagram in Figure 6. 15 depicts the configuration for a three-point bending test.

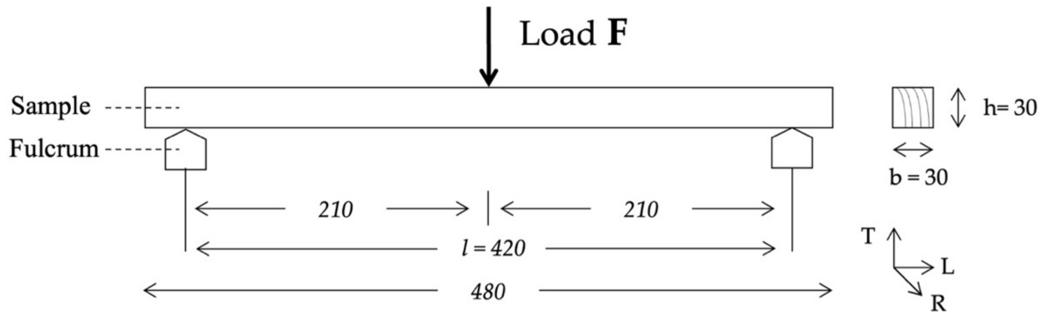


Figure 6. 15 Schematic Illustration for three-point longitudinal bending tests. Dimensions are presented in mm.

The modulus of rupture (MOR) of the samples were calculated after cyclic loading. These calculations were carried out according to equation,

$$\sigma_b = \frac{Pl}{4Z}$$

σ_b = bending strength of the wood (MPa)

P = maximum load (N)

l = distance between fulcrums (mm)

Z = Section modulus (mm)

If the declection is measured, the proportional bending limit stress (σ_{bp}) of the wood and the approximate Young's modulus in bending (E_b) are calculated by the following formula:

$$\sigma_{bp} = \frac{P_p l}{4Z}$$

$$E_b = \frac{\Delta P l^3}{48I \Delta y}$$

σ_{bp} = bending proportional limit stress (MPa)

E_b = Apparent Young's modulus im bending (N/mm^2)

P_p = proportional limit load (N)

l = distance between fulcrums (mm)

Z = section modulus (mm)

I = Moment of inertia (mm)

ΔP = Difference between upper and lower limit load in proportional limit region (N)

Δy = Mid-span deflection corresponding to ΔP (mm)

On the other hand, in the tangential direction wood bending test, the three-point bending test was conducted. The test was conducted using a universal material testing machine CMT6104 (MTS Corporation, China). Test specimens of compressed wood and control wood were cut to dimensions of 8 mm (height), 12 mm (width), and 60 mm (length).

The loading procedure parameters were determined using the estimated maximal load (P), which was derived from a bending strength test conducted until failure. The distance between lower supports was 50 mm for the three-point static bending strength measurements. The loading point in the center was corrected. The diagram in Figure 6. 16 depicts the configuration for a three-point tangential bending test.

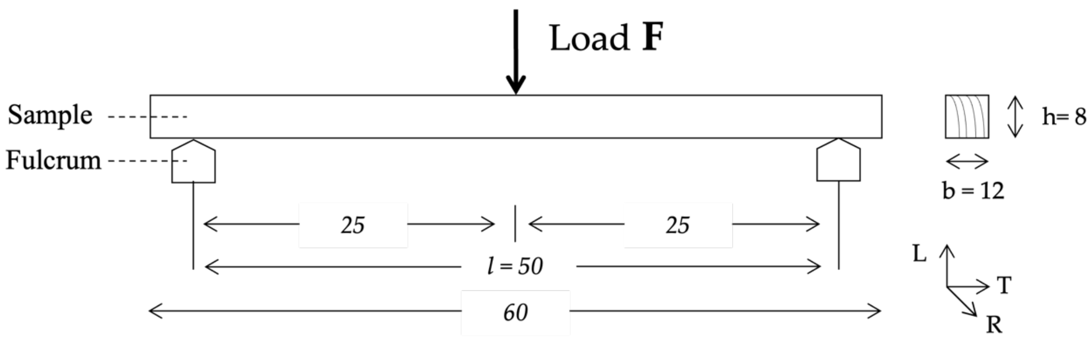


Figure 6. 16 Schematic Illustration for three-point tangential bending tests. Dimensions are presented in mm.

6.3.5.3. Tensile test

6.3.5.3.1. Tensile field test

A tensile test, also known as a tension test, is commonly used to determine the mechanical properties of various materials, including wood. The tensile test provides valuable information regarding the strength, elasticity, and behavior of a material under tension. Figure 6. 17 shows the testing machine for the tensile test in this study. Tensile tests were conducted using a strain-controlled tensile testing machine, Instron 5565 A (Instron, America) in in School of Chemical and Materials Engineering, Zheijang A&F University, Hangzhou, China.

Figure 6. 17 Strain-controlled testing machine (Instron 5565 A) for tensile test

Source: Instron Company, America (https://www.instron.com/en-gb/)

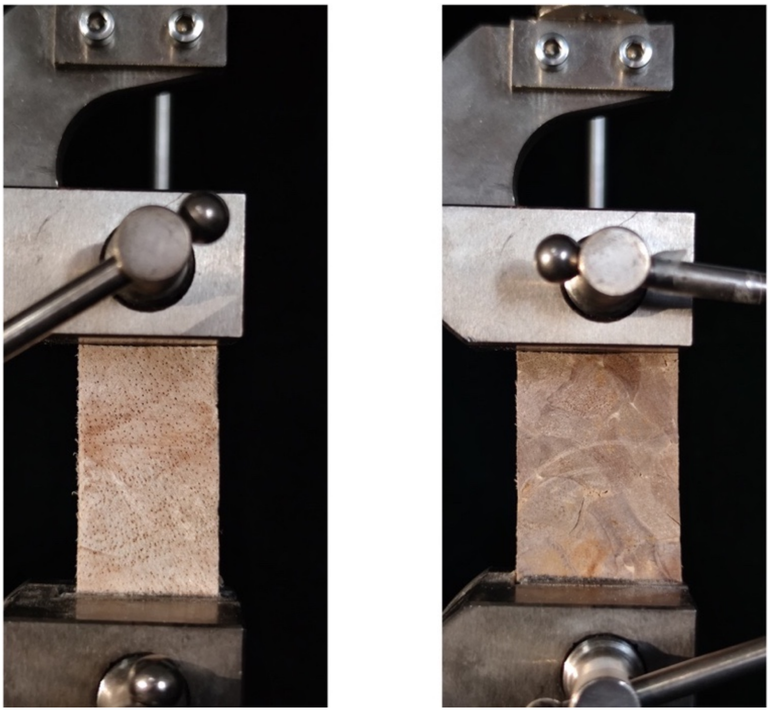


Figure 6. 18 Tensile test on control wood (left) and treated wood (right).

Source: Research Documentation, 2023.

Treated wood (albasia Voronoi composite) and untreated wood were subjected to tensile tests (see Figure 6. 18). In this study, the tensile test consisted of the following procedures:

1. Wood specimens were prepared on both treated and untreated wood in accordance with the Japanese Industrial Standard (JIS) Z 2101: 2009 (Japanese Standards Association, 2009) for testing the mechanical and physical properties of wood. The sample used had a rectangular cross section. Approximately 50,8 millimeters by 25,4 millimeters by 12.7 millimeters was the size of tensile samples.
2. Specimen mounting: the wood specimen is firmly mounted in the testing machine. Ensure that the sample is properly seated and there is no friction that could interfere with the test.
3. Load application: The samples were clamped at both ends and stretched in the direction of the sample length until they fractured at a constant test speed of 5 mm min-1 at room temperature. The specimens of untreated and treated wood were gradually stretched along their longitudinal axis as a result of a progressive tensile load. The load was increased at a controlled rate until failure or fracture occurred in the specimens.
4. Load and Deformation Measurement: During the test, the load (force) applied to the specimen and the deformation (strain) that occurs are continuously measured. These data are used to construct a stress-strain curve that describes the response of the wood to the applied tensile load.
5. Failure Analysis: Upon specimen failure, the nature and location of the failure can be analyzed to determine the failure mode and structural integrity of the wood.

6.3.5.3.2. Finite Element Model (FEM) Simulation

Figure 6. 19 Finite Element Model (FEM Simulation using Abaqus 2022 software.

Source: Research Documentation, 2023.

Finite Element Model (FEM) Simulation, or often called FEM analysis, is a numerical method used to model and analyze the behavior of complex structures or systems. This method involves dividing the structure into small interconnected elements, where each element is analyzed separately. Finite Element Model (FEM) Simulation can be used in the context of wood tensile tests to predict the behavior and response of wood structures when subjected to tensile loads.

A two−dimensional (2D) nonlinear finite element model is developed using the commercial software ABAQUS 2022 Figure 6. 19. In the simulation, a 2D Voronoi structure (60 × 30 μ m2) is adopted, as shown in Figure 6. 20. The BM structure in the FE model contains a randomly staggered arrangement of cells bonded by the thin layer of adhesive which is modeled as a cohesive zone with a bilinear traction−separation and undergoes dry friction after damage. The cells with isotropic bulk modulus Ep=7 GPa, Poisson ratio vp = 0.3 and the failure strength σ_p^m = 60 MPa bear elastic deformation before brittle failure.

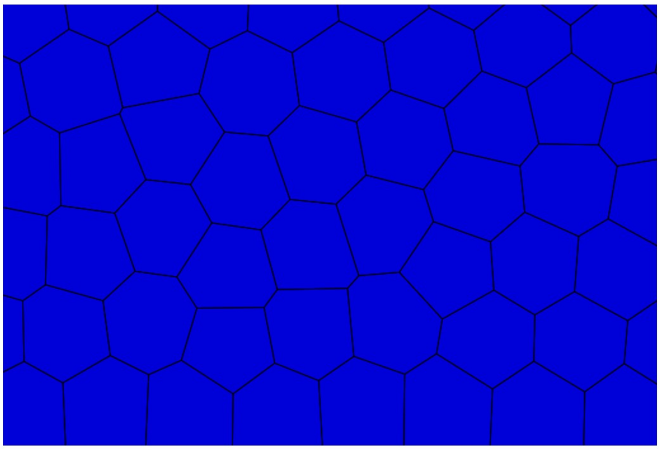


Figure 6. 20 a 2D Voronoi structure (60 × 30 µm2).

Source: Research Documentation, 2023.

6.4. Results and Discussion

6.4.1. Physical properties

Figure 6. 21 displays the results of integrating compressed albasia wood with a mixture of adhesive and isoccyanate. Dimensions of tangential, longitudinal, and radial cross-sections measuring 65 mm x 65 mm x 800 mm.

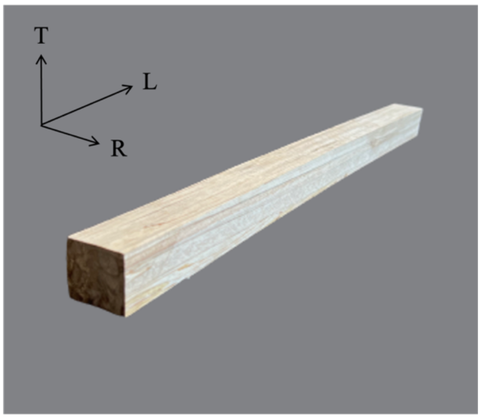


Figure 6. 21 The result of compressed Albasia wood.

At high temperatures and pressures, the color of wood can change during and after the densification process (Bekhta & Niemz, 2003). According to previous research, the color of Albasia wood that has been subjected to a thermal treatment involving high temperature and high pressure can darken as a result.

Figure 6. 22 shows the cross sectional area of compressed Albasia wood integrated with Voronoi shapes, through samples FS-1, FS-2, FS-3, and FS-4 as a starting point. The cross-sectional area of the compressed wood has a Voronoi form with a solidified wood lattice containing glue lines and isocyanate. In wood architecture, the use of surface cross-sections with a Voronoi shape may become a new trend.

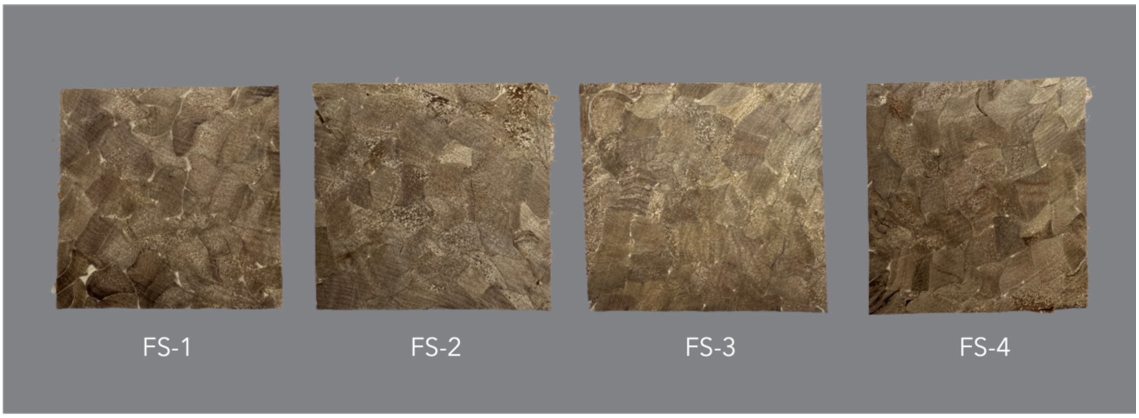


Figure 6. 22 Cross-section of treated Albasia wood

Source: Research Documentation, 2023.

6.4.1.1. Influence on density

According to Table 6. 3, the average density of treated albasia wood (0.81 kg/L) was greater than that of untreated (0.26 kg/L). The treatment resulted in a 211.54% increase in average density. Figure 6. 23 depicts the density of albasia wood boards following Voronoi-integrated densification at 140 °C. Due to the viscoelastic properties of wood, the increase in density was achieved by decreasing the volume of wood during the compression process (Yu et al., 2017). In this study, the density of wood samples densified with isocyanate and adhesive mixtures increased significantly. Almost twice as dense as the previous study, which compressed the wood to 50% of the thickness of the Albasia wood board, were the wood samples (Julian et al., 2022).

Table 6. 3 The density of albasia wood before and after densification treatment.

Sample	**Density (kg/L)**			**SR-D(%)**	**DC(%)**
	Do	**Da**	**Ds**		
FS-1	0.26	0.97	0.82	21.13	30

FS-2	0.26	0.85	0.76	15.25	24
FS-3	0.26	0.9	0.84	9.38	32
FS-4	0.26	0.91	0.82	13.85	30
C-1	0.23				
C-2	0.26				
C-3	0.29				
C-4	0.29				

Source: Research Documentation, 2023.

The thickness of the wood determines the density profile, which influences the physical and mechanical properties of wood. Because it has not been subjected to compression treatment and its thickness has not changed, untreated wood has nearly the same density in periodic measurements conducted for this study. One of the major drawbacks of this method (spring back) is its inability to recover in dense wood. After experimentation, the phenomenon of spring back has been defined as the lost compression work (Yuhe & Muehl, 1999).

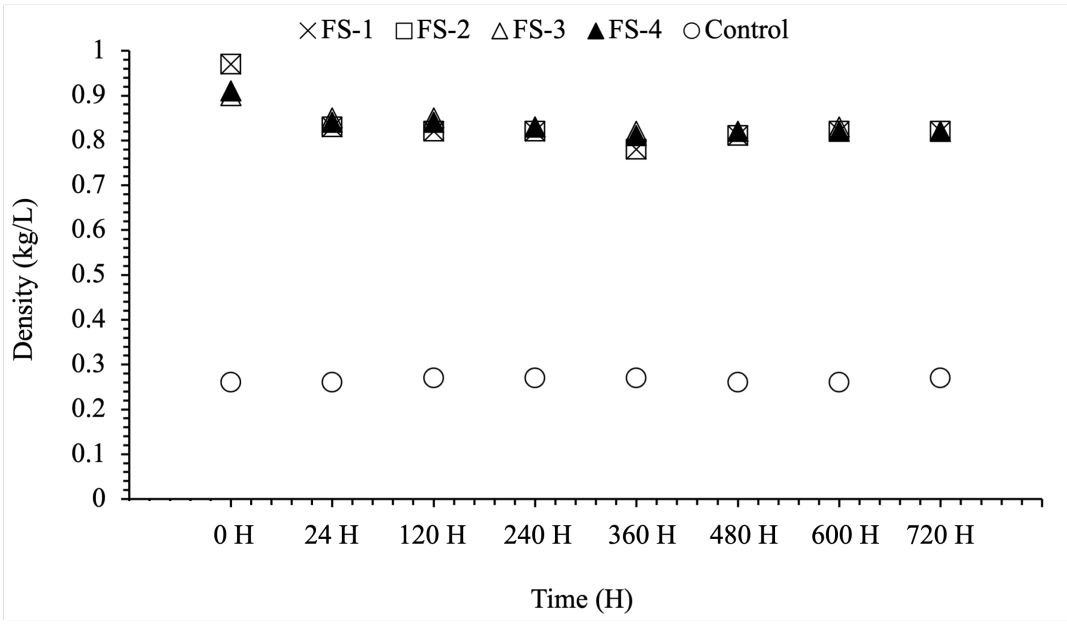


Figure 6. 23 Density profile of specimens.

Source: Research Documentation, 2023.

As depicted in Figure 6. 23, at 0 H immediately following the treatment, the densities of all samples were notably greater than those measured later. After 24 hours of treatment, the densities of all treated samples remained stable until the end of the measurement, which occurred at 720 hours. This can be interpreted to mean that immediately after treatment (0H), the wood experienced thickness recovery (spring back), but thereafter, the density of this wood, which is determined by its thickness, stabilized.

Nandika et al. also discovered that the density of tangential board type albasia wood increased when impregnated with 0.5% chitosan solution at the maximum temperature of 140 °C and then compressed at the highest temperature of 190 °C, resulting in an average wood density of 80.70% (Nandika et al., 2014). Meanwhile, high temperature and high pressure treatment on albasia wood boards with the maximum treatment temperature of 140% revealed an average wood density of 112.78% (Julian et al., 2022), as determined by Julian et al.

Table 6. 4 The Indonesian Timber Strength Class

Wood Strength Class	**Specific gravity (kg/L)**	**Maximum bending strength (kg/cm^2)**	**Maximum Compressive strength (kg/cm^2)**
I	More than 0.90	More than 1100	More than 650
II	0.60 – 0.90	725 – 1100	425 – 650
III	0.40 – 0.60	500 – 725	300 – 425
IV	0.30 – 0.40	360 – 500	215 – 300
V	Less than 0.30	Less than 360	Less than 215

(Pusat Penelitian dan Pengembangan Hasil Hutan (P3HH) et al., n.d.) (refer to The Foundations for the Classification of Dutch East Indies Timber Species 1923 (Den Berger, 1923))

Source: Research Documentation, 2023.

However, because wood density is highly correlated with specific gravity, referring to the Indonesian Timber Strength Class (Table 6. 4), the strength of treated Albasia wood increased to Wood Strength Class II (Specific gravity 0.60 - 0.90 kg/L) compared to untreated Albasia wood, which belongs to Wood Strength Class V (Less than 0.30 kg/L).

6.4.1.2. Equilibrium Moisture Content (EMC)

Figure 6. 24 depicts the Equilibrium Moisture Content (EMC) of densification treated and untreated albasia wood samples. According to the findings of this study, treated wood has a more stable EMC than untreated wood. From 0 to 720 hour, measurements on untreated wood revealed a highly unstable EMC.

Immediately following the treatment of the wood, the cooling process in the processing tank had a moderately humid atmosphere. Figure 6. 24 demonstrates that the EMC value of the wood is higher at 0 H than in subsequent measurements. During the cooling process, the wood is treated in a moderately humid atmosphere, resulting in a very moist surface when measured. This also occurred in the previous study, which utilized the same processing tank despite utilizing different treatment steps.

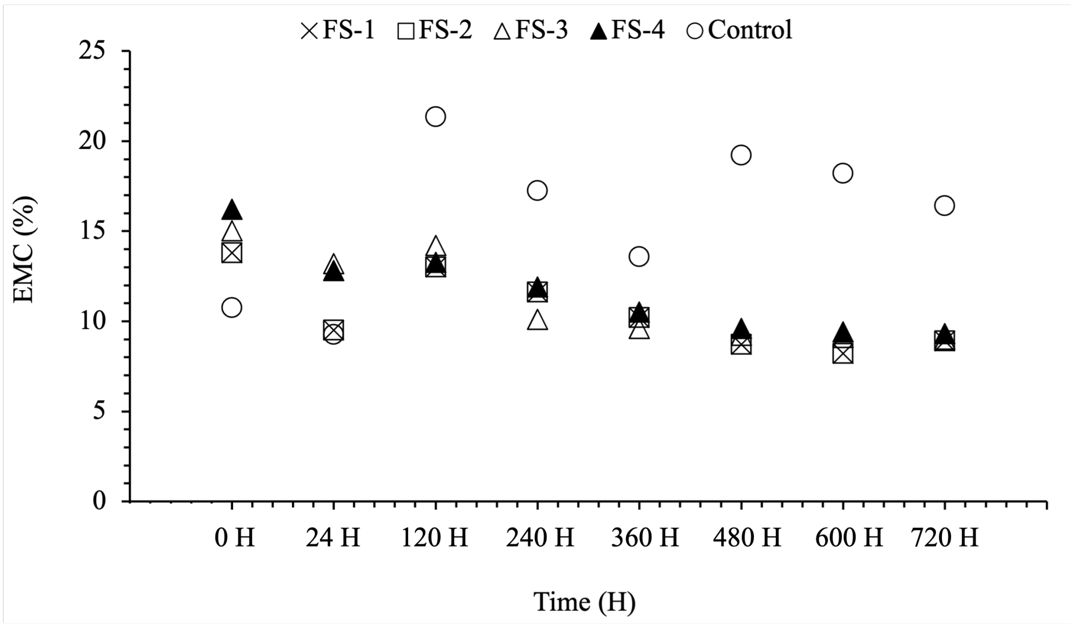


Figure 6. 24 Correlation between equilibrium moisture content and time after treatment.

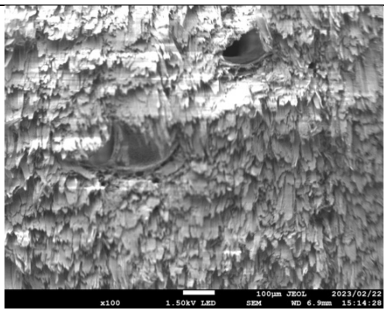
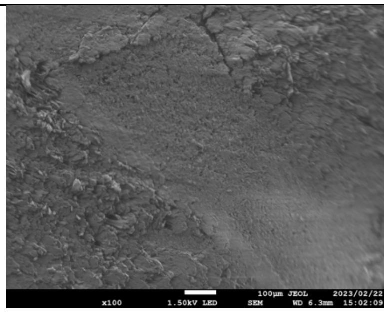
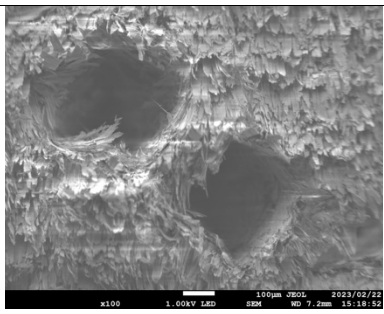
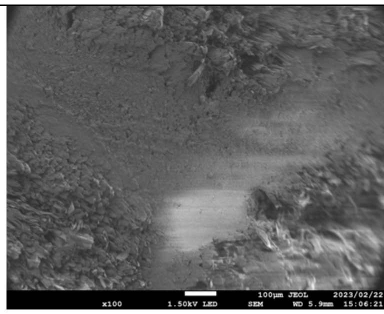
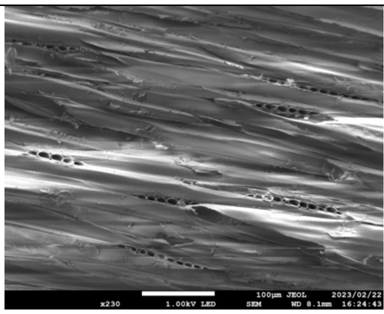
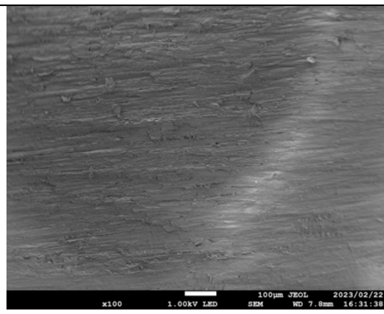
Source: Research Documentation, 2023.

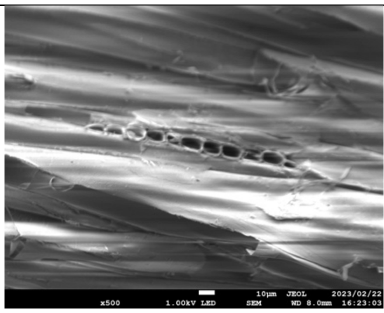
6.4.1.3. Morphology

6.4.1.3.1. Analysis of Scanning Electron Microscopy

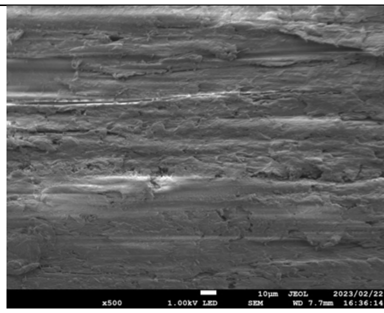
Analyzing the Scanning Electron Microscopy (SEM) results of wood can reveal important information about the microstructure, surface morphology, and cellular characteristics of the wood material. The images below were taken from the SEM images presented in Table 6. 5. As can be seen, SEM provides key information regarding cell structure, pore structure, surface morphology, adhesion and interfaces, as well as defects and abnormalities.

Table 6. 5 SEM photographs between control and treated wood.

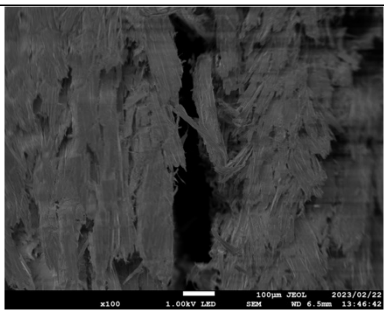
Control wood	**Albasia Voronoi composite**
 (a) Control wood – Top side	 (b) Treated wood – Top side
 (c) Control wood – Top side (detail)	 (d) Treated wood – Top side (detail)
 (e) Control wood – Low side	 (f) Treated wood – Low side



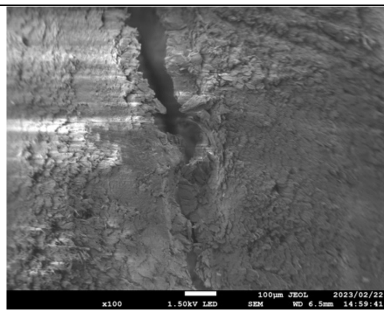
(g) Control wood – Low side (detail)



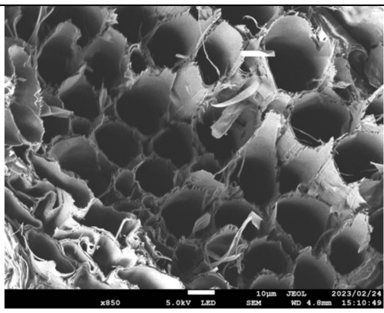
(h) Treated wood – Low side (detail)



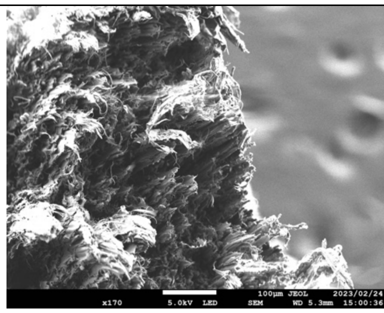
(i) Control wood – Bending



(j) Treated wood – Bending



(k) Control wood – Broken surface



(l) Treated wood – Broken surface

Source: Research Documentation, 2023.

According on the analysis conducted for this study, the following aspects were derived from the SEM analysis:

1) Cell structure

   SEM could reveal the cellular structure of wood, including the arrangement and shape of individual cells. It implies that SEM images could aid in the identification of these cell types and provide information about their shape and distribution in untreated and treated wood.

2) Pore structure

   Wood contains pores or void spaces that are necessary for water transport and gas exchange. The SEM was able to capture the pore structure and distribution of the original wood, including the presence of large vessels (Table 6. 5 (a) and (b)).

3) Surface morphology

   This study's SEM analysis also permits a thorough examination of the surface differences between untreated and treated wood, including the presence of cracks, fissures, and other surface irregularities. The surface morphology may indicate wood decomposition, weathering, or mechanical damage.

4) Adhesion and Interfaces

   Based on the objectives of this study, which consisted of compressing Indonesian albasia wood with a mixture of isocyanate and adhesive, SEM was utilized to examine the interfaces between the wood and the applied substances, as the wood was subjected to adhesive treatments. Thus, adhesion and interfaces could provide us with information regarding the adhesion properties of wood surfaces.

5) Defects and anomalies

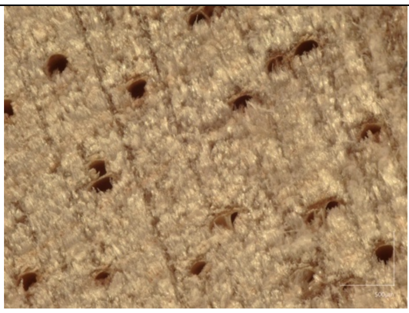
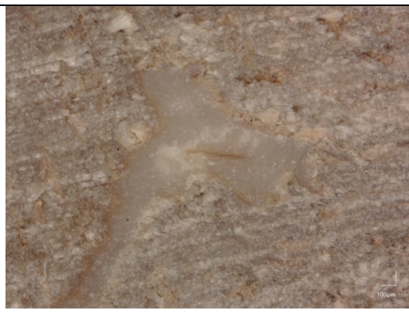
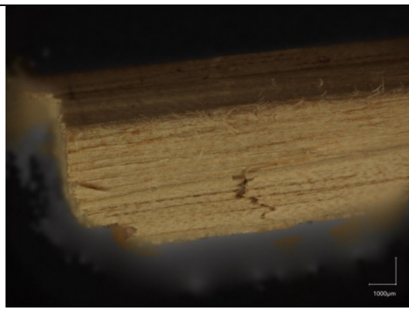
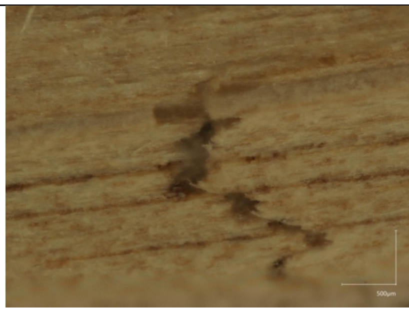
   SEM analysis could assist in identifying defects and anomalies within the wood structure, such as voids or irregular cell formations.

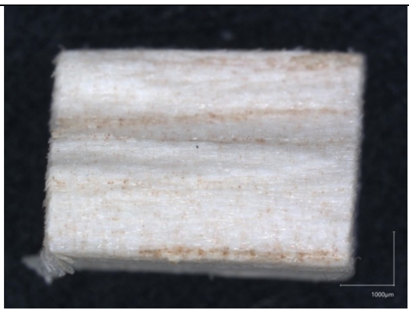
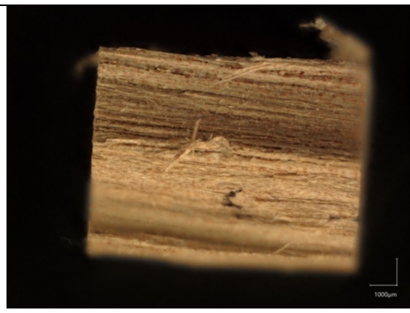
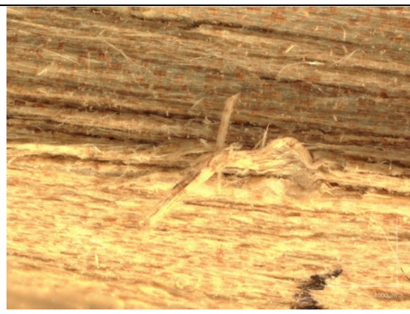
6.4.1.3.2. Analysis of Digital Microscopy

Analyzing the results of digital microscopy of wood requires the examination of high-resolution images captured using digital microscopy techniques. Digital microscopy allows for the visualization of wood surfaces and structures in exquisite detail, providing valuable information about the microstructure and surface characteristics. The images in

Table 6. 6 were captured using a digital microscope.

Table 6. 6 DM photographs between control and treated wood.

Control wood	**Albasia Voronoi composite**
 (a) Control wood – Top side	 (b) Treated wood – Top side
 (c) Control wood - Bending	 (d) Treated wood - Bending
 (e) Control wood – Bending (detail)	 (f) Treated wood – Bending (Detail)

 (g) Control wood – Broken surface	 (h) Treated wood – Broken surface
 (i) Control wood – Broken surface (detail)	 (j) Treated wood – Broken surface (detail)

Source: Research Documentation, 2023.

Based on the analysis conducted for this study, the following aspects were derived from the DM analysis:

1) Surface features

   The digital microscope made it possible to examine the surface characteristics of untreated and treated wood samples. The generated images depict the surface irregularities and texture of wood.

2) Cell structure

   At a higher magnification, the digital microscope revealed the cell structure of both untreated and treated wood. The images in

   Table 6. 6 reveal the size, shape, arrangement, and distribution of the various cell types found in wood, including traikeids, vessels, fibers, and parenchyma cells. Understanding cellular composition and organization contributes to the

characterization of wood properties and behavior, particularly in treated wood, which contains a new cellular structure, adhesive glue.

3) Defect analysis

   In this study, the use of a digital microscope aided in the identification and analysis of wood defects such as knots and cracks. These observations helped evaluate the structural integrity, quality, and suitability of the wood. As shown in

   Table 6. 6, the control wood's surface was characterized by an abundance of pores.

4) Dimensional measurement

   The digital microscope analyzer enables precise measurements of the wood sample's various dimensions and properties. We can observe the cell size, wall thickness, pore diameter, geometrical parameters, and glue ratio in the treated wood. These dimensions can be used for quality control and contribute to the characterization of wood properties.

6.4.1.3.3. Comparative Analysis

The morphology of the SEM micrographs on the cross-section of the untreated albasia specimen (control) is shown in Figure 6. 25, while the treated one is shown in Figure 6. 26. As can be seen in the SEM micrographs, the control specimen's cross section contains distinct empty spaces. Moreover, when the wood was modified in this study, it resulted in improved interfacial bonding between the fibers in the wood.

In Figure 6. 27 which shows more detailed SEM micrographs, the interfacial bond in the treated wood is far superior to the control sample. Although the tensile fracture is not fully controlled, and voids remain on the altered wood surface, the interfacial bonding is better than the untreated fiber composite (X. Gao et al., 2016).

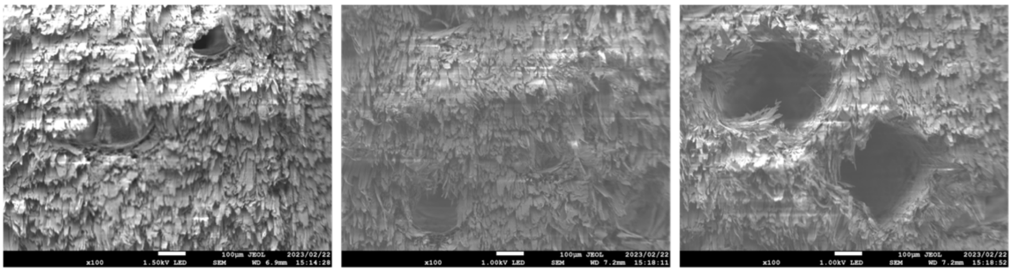


Figure 6. 25 SEM Micrographs of control wood.

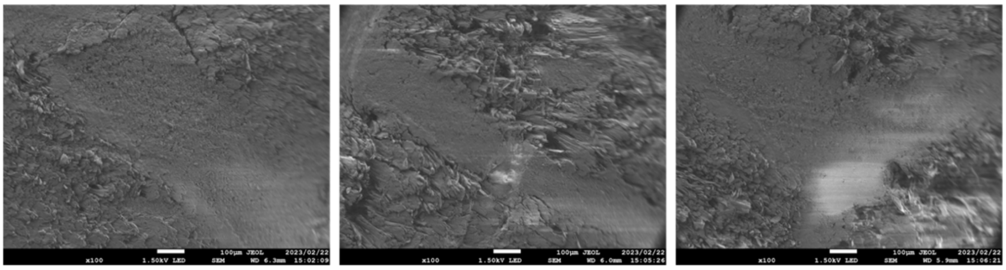


Figure 6. 26 SEM Micrographs of treated wood.

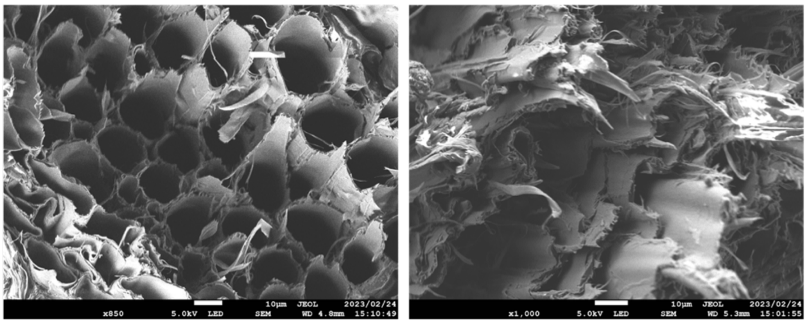


Figure 6. 27 SEM Micrographs of control (left) and treated (right) wood.

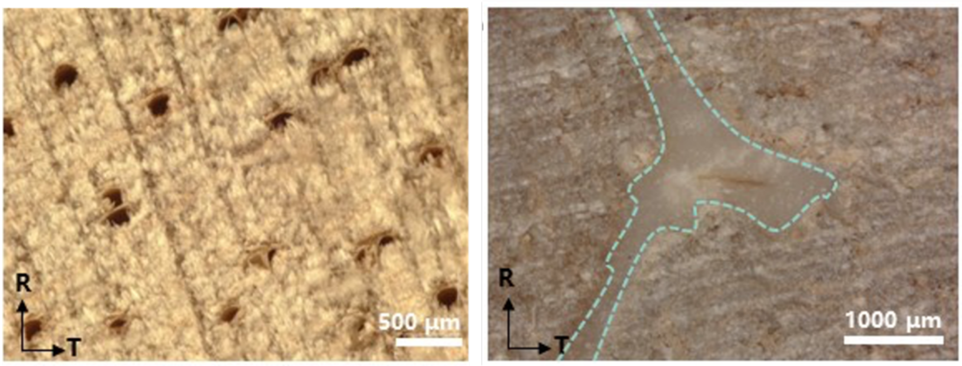


Figure 6. 28 Digital Microscope of control (left) and treated (right) wood.

Finally, it was discovered that digital microscopy produced much clearer images of the wood's color and composition. Similar to the results of SEM micrographs, the untreated wood has empty space cavities in Figure 6. 28, whereas the adhesive and isocyanate mixture lines are clearly visible in the cross section of the treated wood.

6.4.2. Mechanical properties

6.4.2.1. Analysis of compressive strength test

Using a universal testing machine, a monotonically increasing compressive load was applied orthogonally to the cross-section of each treated and untreated albasia wood specimen.

6.4.2.1.1. Analysis of longitudinal compressive strength test

The longitudinal compressive strength test on the control wood is presented in Figure 6. 29. While the longitudinal compressive strength test on the treated wood (albasia Voronoi composite) is presented in Figure 6. 30. In this test, both control and treated wood samples in the longitudinal (parallel to grain) are placed in a universal testing machine with two plates, one fixed and one movable, that exert a compressive force on the sample.

The specimen is positioned vertically between the plates, and the necessary alignment adjustments are made. The compressive load is then applied gradually in the direction of the load, from top to bottom. At a constant rate, the load is increased until the specimen fails or reaches the end point. Using strain gauges, the deformation or displacement of the specimen is simultaneously measured. The test is then repeated until the specimen fails, as indicated by crushing or cracking along the wood fibers. Then, the maximum load that can be resisted before failure is recorded.

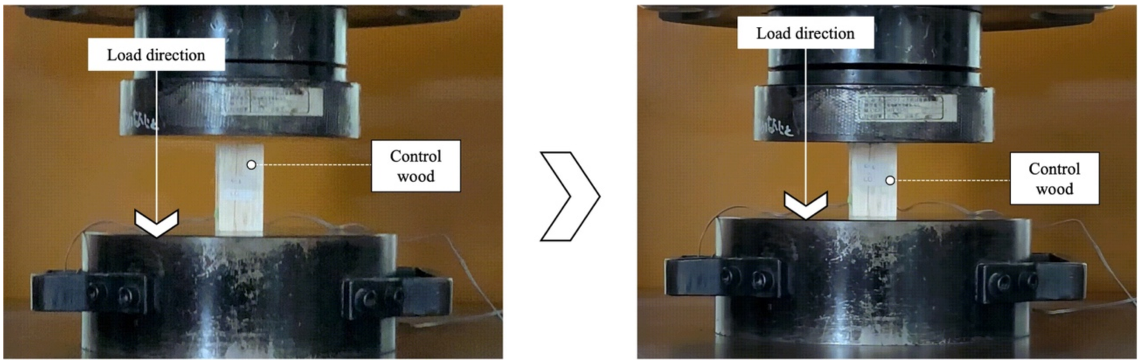


Figure 6. 29 Longitudinal compressive strength test on the control wood

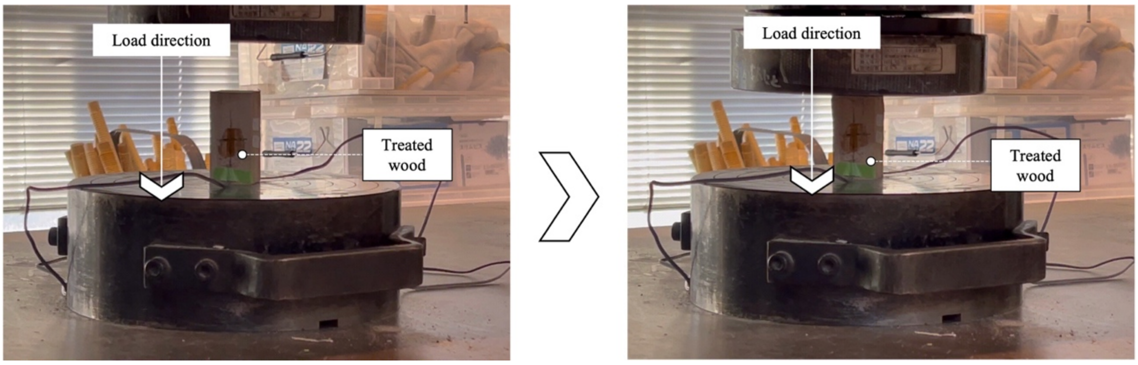


Figure 6. 30 Longitudinal compressive strength test on the treated wood

Source: Research Documentation, 2023.

6.4.2.1.1.1. Relationship between stress and strain

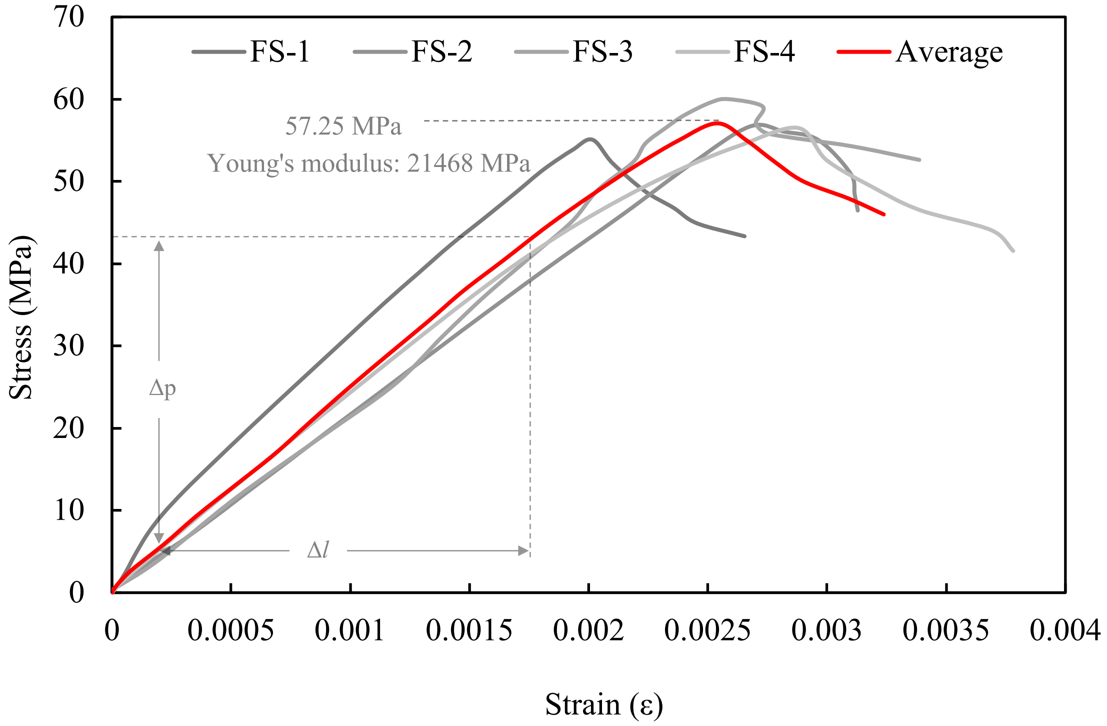


Figure 6. 31 Relationship between stress (MPa) and strain (ε) of treated wood (albasia Voronoi composite) in longitudinal direction compressive strength test.

Source: Research Documentation, 2023.

The graph of the relationship between stress and strain in the compressive strength test parallel to the fiber (longitudinal direction) is shown in Figure 6. 31 for treated wood (albasia Voronoi composite) and control wood in Figure 6. 32. Results showed that the treated wood had an average maximum load of 57.25 MPa and Young's Modulus of 21468 MPa. Meanwhile, results showed that the control wood had an average maximum load of 28.50 MPa and Young's Modulus of 7308 MPa.

In compressive strength tests parallel to the wood grain (longitudinal direction) on the control and treated wood, the comparative relationship between stress and strain can be described using a stress-strain curve as shown in the Figure 6. 33. This curve demonstrates how wood responds to a compressive load.

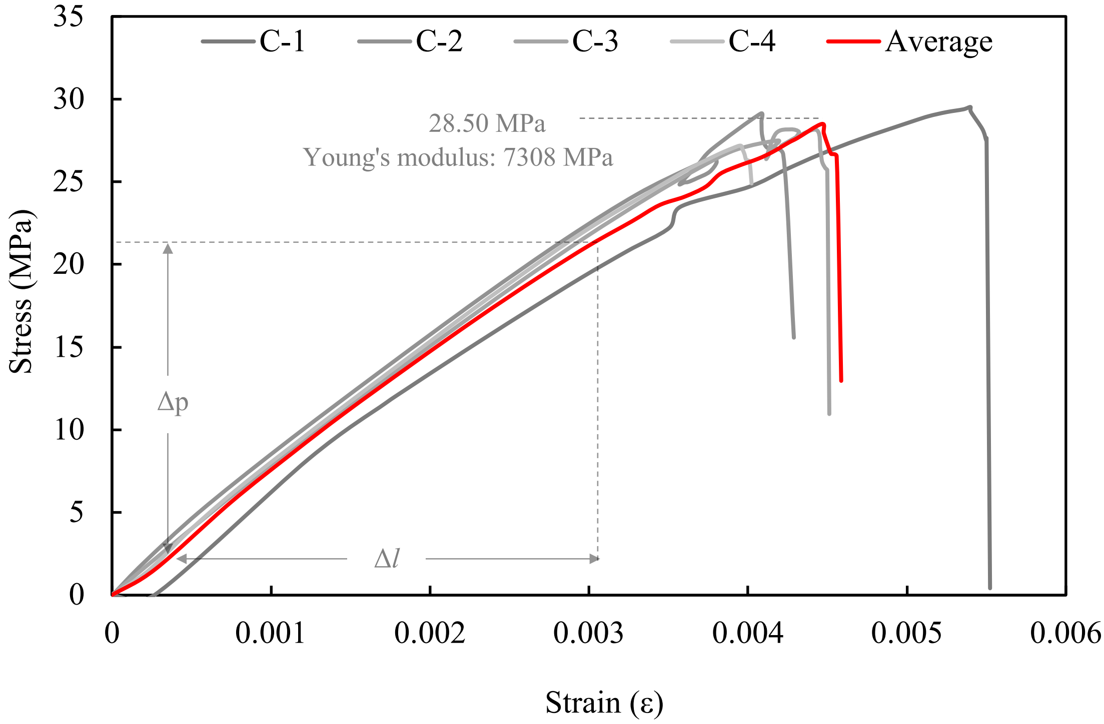


Figure 6. 32 Relationship between stress (MPa) and strain (ε) of control wood in longitudinal direction compressive strength test.

Source: Research Documentation, 2023.

In both treated wood and control wood, initially, when the load is applied to the wood, the strain that occurs in the wood is still relatively small. At this stage, the wood tends to be elastic, which means that the strain is reversible and the wood will return to its original shape once the load is removed. The relationship between stress and strain at this elastic stage is given by Hooke's law. Hooke’s Law states that the strain is proportional to the stress, which states that stress (σ) is proportional to strain (ε), i.e. σ = Eε, where Ec is the modulus of elasticity of the wood of the compressive strength test (Stanciu et al., 2020).

However, as the applied load continues to increase, the strain in the wood will reach a point where the wood begins to undergo "permanent deformation" or "plastic strain" (Stanciu et al., 2020). At this stage, the relationship between stress and strain is no longer linearly proportional. The wood will begin to permanently deform, and the strain that occurs cannot be fully recovered. As shown in the figure, the stress-strain curve at this stage will show a rapid increase in stress as the strain increases. Subsequently, as the load continues to be applied, the wood will reach the point of failure or fracture. At this point, the stress reaches its maximum value and the wood undergoes structural failure, which can be either splitting or cracking.

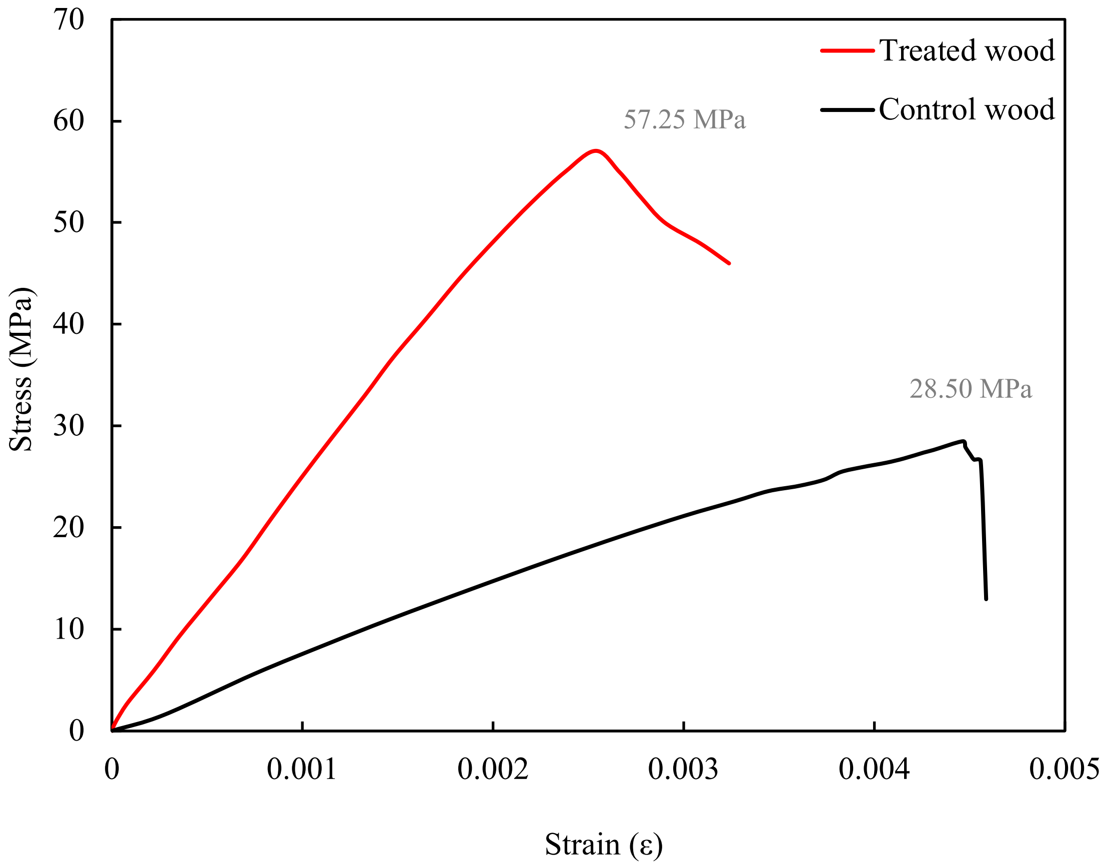
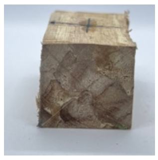


Figure 6. 33 Comparative relationship between stress (MPa) and strain (ε) of treated and control wood in longitudinal direction compressive strength test.

Source: Research Documentation, 2023.

6.4.2.1.1.2. Failure mode

Table 6. 7 Images of treated wood in the longitudinal direction following testing of its compressive strength

	A side	B side	C side	D side	E side	F side
FS-1						
FS-2						
FS-3						
FS-4						

Source: Research Documentation, 2023.

Table 6. 8 Images of control wood in the longitudinal direction following testing of its compressive strength.

	A side	B side	C side	D side	E side	F side
C-1						

C-2						
C-3						
C-4						

Source: Research Documentation, 2023.

Table 6. 7 depicts the results of the longitudinal compressive strength test on treated wood samples, whereas Table 6. 8 depicts the same test on untreated wood samples. Each side of the longitudinal compressive strength sample (from A to F) was photographed to illustrate the mode of failure that occurred on each side following the wood compression test.

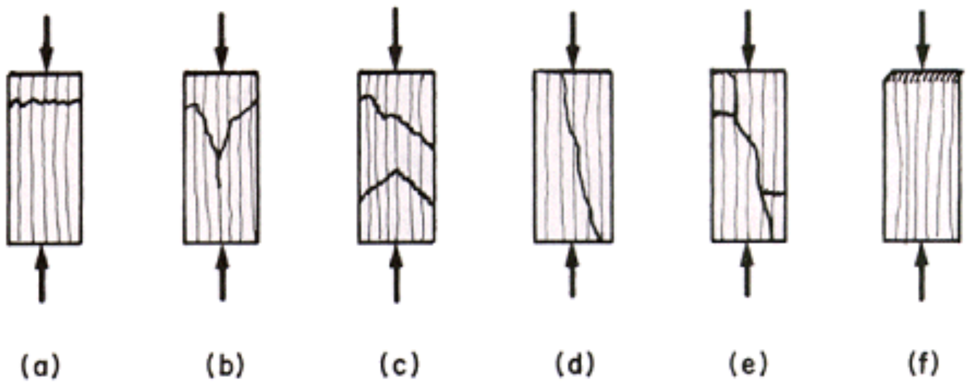


Figure 6. 34 Failure types of wood in compressive strength test parallel to grain (a) crushing, (b) wedge splitting, (c) shearing, (d) splitting, (e) crushing and splitting, (f) brooming or end rolling.

Source: (Jozsef Bodig & Benjamin A. Jayne, 1993).

Figure 6. 34 represents the failure types of wood in compressive strength test parallel to grain (longitudinal direction) (Jozsef Bodig & Benjamin A. Jayne, 1993). Based on failure types, the compressive strength test results in the longitudinal section of both treated and control wood in this study belong to the crushing type failure (see Figure 6. 35).

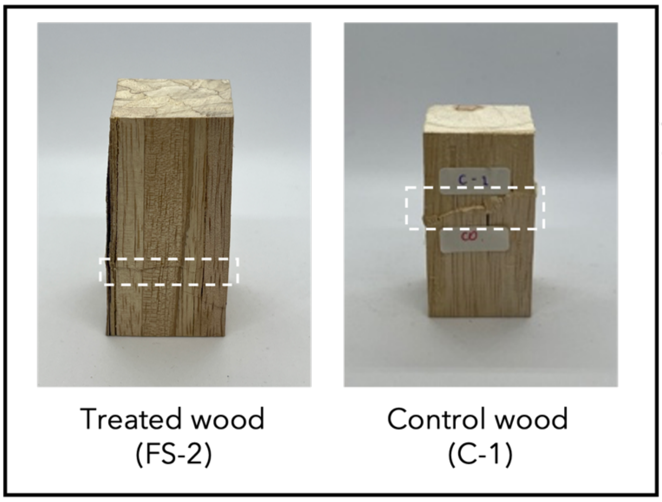


Figure 6. 35 Crushing failure type of wood in compressive strength test parallel to grain (longitudinal direction)

Source: Research Documentation, 2023.

In a compressive strength test, crushing failure type is a common mode of failure. When the wood material is subjected to a compressive load, it experiences forces that push or compress the material, resulting in compression stresses. Crushing failure type can occur if the applied compressive stresses exceed the material's compressive strength. During a compressive strength test, both control and Albasia Voronoi composite were typically loaded in a direction that applies a compressive force along its axis. The specimen undergoes deformation as the load increases, and if the compressive stresses become too high, the material may fail by curshing failure type.

Therefore, crushing failure type is characterized by the collapse or deformation of the material under a compressive load. In the context of control and albasia Voronoi composite, crushing failyre type in can compressive strength test can occur when the wood fibers on the compression side of the specimen are compressed to the point of collapse or deformation. This can result in localized flattening, splitting, or splintering of wood fibers.

6.4.2.1.1.3. Longitudinal compressive strength

Table 6. 9 shows the calculation results for the treated and control albasia wood in the longitudinal compression strength test. Maximum load indicates the maximum force measured to calculate the compressive strength. The compressive strength at the proportional limit which is the highest stress that the treated albasia wood material can withstand shows the highest result is 52.2 kN in FS-3 and the lowest stress result is 46.26 kN in FS-1. Meanwhile, the compressive strength at the proportional limit that the untreated albasia wood material can withstand is the highest at 26.46 kN in C-2 and the lowest at 25.11 kN in C-4.

Table 6. 9 Calculation results of treated and control wood samples in longitudinal compressive strength test

Sample	Density (kg/L)	A (mm^2)	Maximum Load (kN)	Compressive Strength (MPa)	Compressive Proportional limit stress (MPa)	Young's Modulus (MPa)
FS-1	0.82	840	46.26	55.07	40.1	20652
FS-2	0.76	900	51.67	57.41	42.0	21529
FS-3	0.84	870	52.2	60.00	44.4	22500
FS-4	0.82	900	50.86	56.51	41.4	21192
C-1	0.23	857.28	25.3	29.51	22.2	7567
C-2	0.26	908.46	26.46	29.13	25.6	7468
C-3	0.29	893.52	25.18	28.18	24.0	7226
C-4	0.29	923.67	25.11	27.19	23.3	6971

Figure 6. 36 displays the longitudinal compressive strength test results. Results indicated that the longitudinal compressive strength of treated albasia wood reached a maximum of 60 MPa in FS-3 and a lowest value of 55.07 MPa in FS-1. In the meantime, the longitudinal compressive strength of untreated albasia wood (control) reached a maximum of 29,51 MPa at C-1 and a lowest of 27,19 MPa at C-4.

In the longitudinal direction, the average longitudinal compressive strength of treated wood is 57.25 MPa, compared to 28.50 MPa for untreated wood (control). Therefore, the treatment increased the longitudinal compressive strength of albasia wood by 100.88% in comparison to untreated wood.

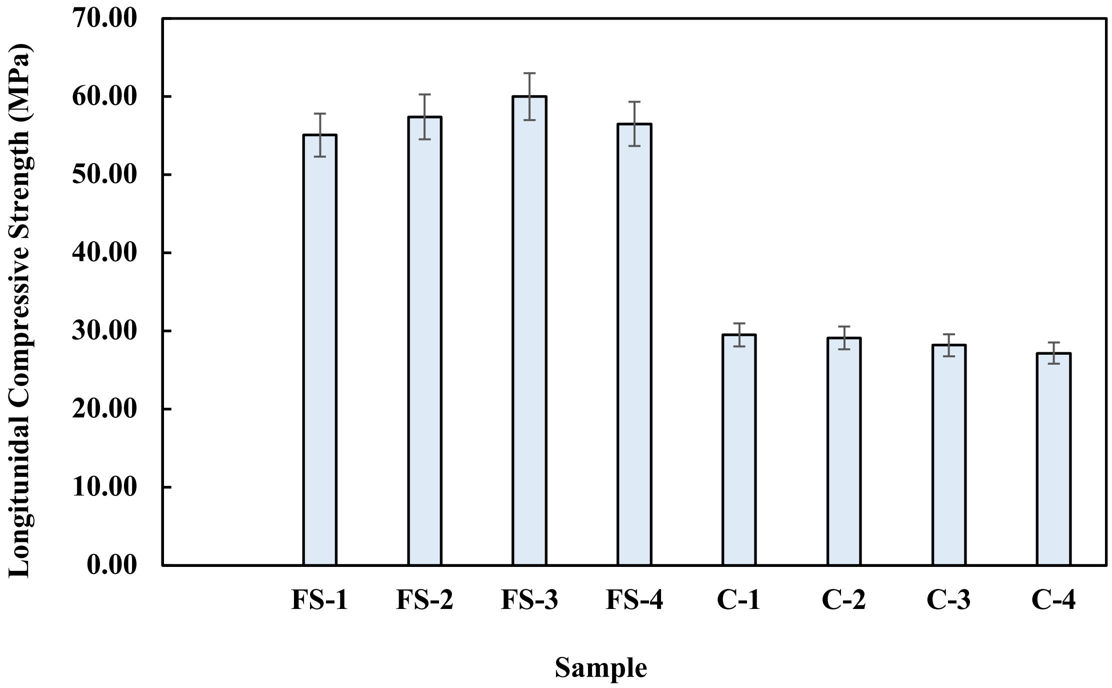


Figure 6. 36 Longitudinal Compressive Strength of treated and control albasia wood.

Source: Research Documentation, 2023.

6.4.2.1.2. Analysis of tangential compressive strength test

The longitudinal compressive strength test on the control wood is presented in Figure 6. 37. While the longitudinal compressive strength test on the treated wood (albasia Voronoi composite) is presented in Figure 6. 38. In this test, both control and treated wood samples in the tangential direction are placed in a universal testing machine with two plates, one fixed and one movable, that exert a compressive force on the sample. The specimen is positioned vertically between the plates, and the necessary alignment adjustments are made. The compressive load is then applied gradually in the direction of the load, from top to bottom. At a constant rate, the load is increased until the specimen fails or reaches the end point. Using strain gauges, the deformation or displacement of the specimen is simultaneously measured. The test is then repeated until the specimen fails, as indicated by crushing or cracking along the wood fibers. Then, the maximum load that can be resisted before failure is recorded.

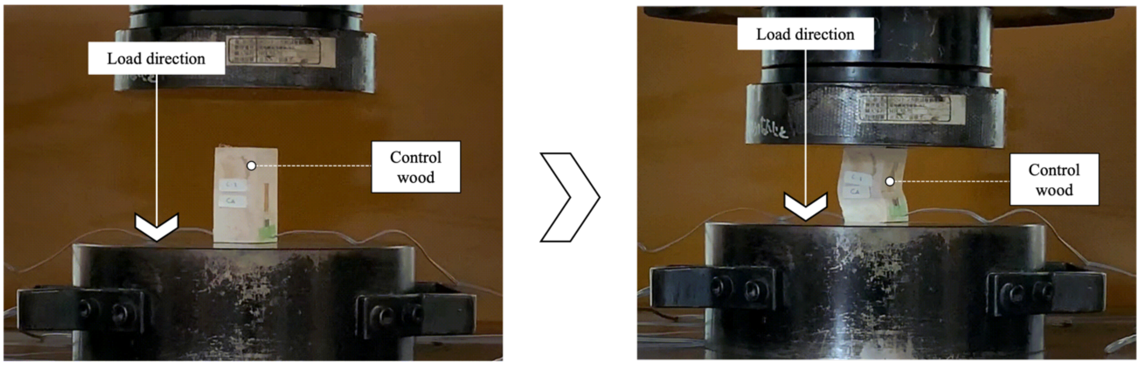


Figure 6. 37 Tangential compressive strength test on the control wood

Source: Research Documentation, 2023.

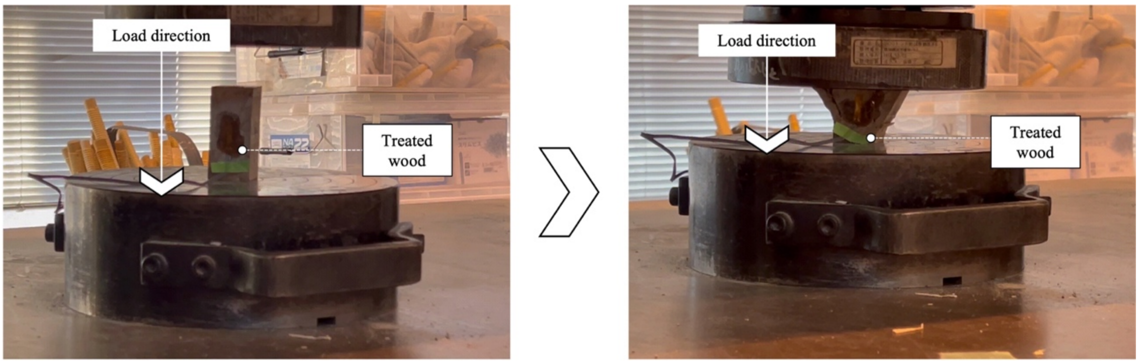


Figure 6. 38 Tangential compressive strength test on the treated wood (albasia Voronoi composite)

Source: Research Documentation, 2023.

6.4.2.1.2.1. Relationship between stress and strain

The curves of the relationship between stress and strain in the compressive strength test tangential direction is shown in Figure 6. 39 for treated wood (albasia Voronoi composite) and control wood in Figure 6. 40. Results showed that the treated wood had an average maximum load of 15.14 MPa and Young's Modulus of 5678 MPa.

Meanwhile, Results showed that the control wood had an average maximum load of 1.54 MPa and Young's Modulus of 395 MPa.

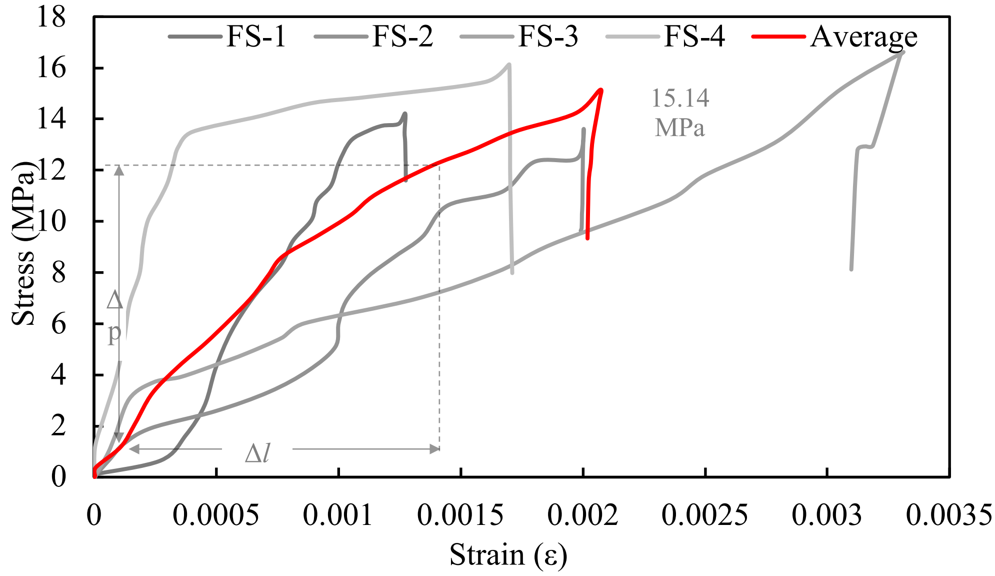


Figure 6. 39 Relationship between stress (MPa) and strain (ε) of of treated wood (albasia Voronoi composite) in tangential direction compressive strength.

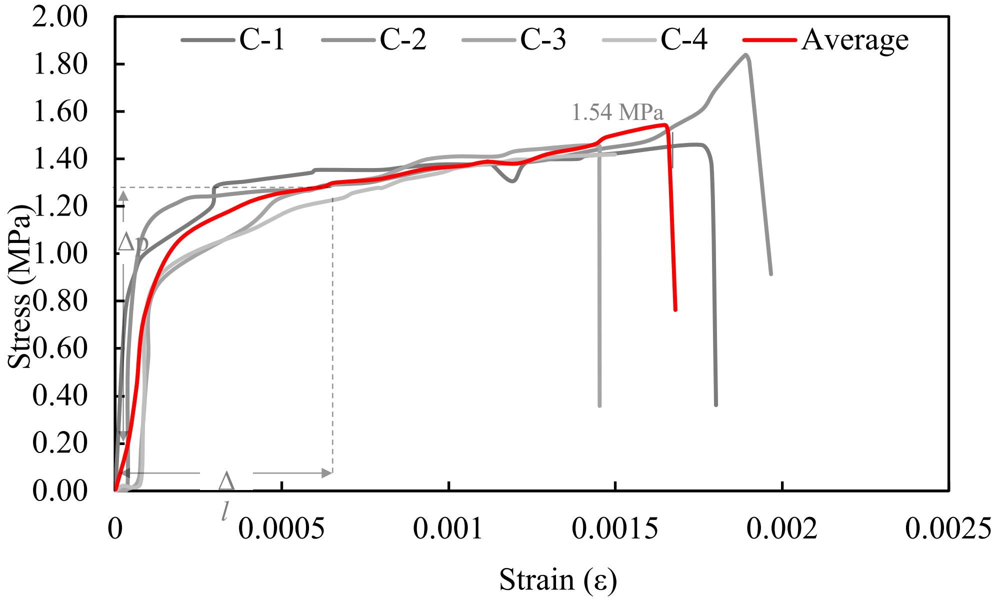


Figure 6. 40 Relationship between stress (MPa) and strain (ε) of control wood in tangential direction compressive strength.

The comparative relationship between stress and strain of treated and control wood in tangential direction can be shown in Figure 6. 41. A phenomenon known as "tangential shrinkage" or "latitudinal shrinkage" occurs in tangential direction wood (M. T. Elaieb et al., 2019; Luis Christoforo et al., 2016; Yamashita et al., 2009). When wood is stressed in the tangential direction, the fibers tend to slide against one another transversely, resulting in a greater strain than in the direction of parallel fibers. This results in a nonlinear relationship between stress and strain in tangential wood.

Typically, the stress-strain curve of tangential direction timber will exhibit a rapid increase in strain with an initial increase in stress. Then, as the load continues to increase, the wood strain will increase and the stress will peak prior to the wood's eventual failure.

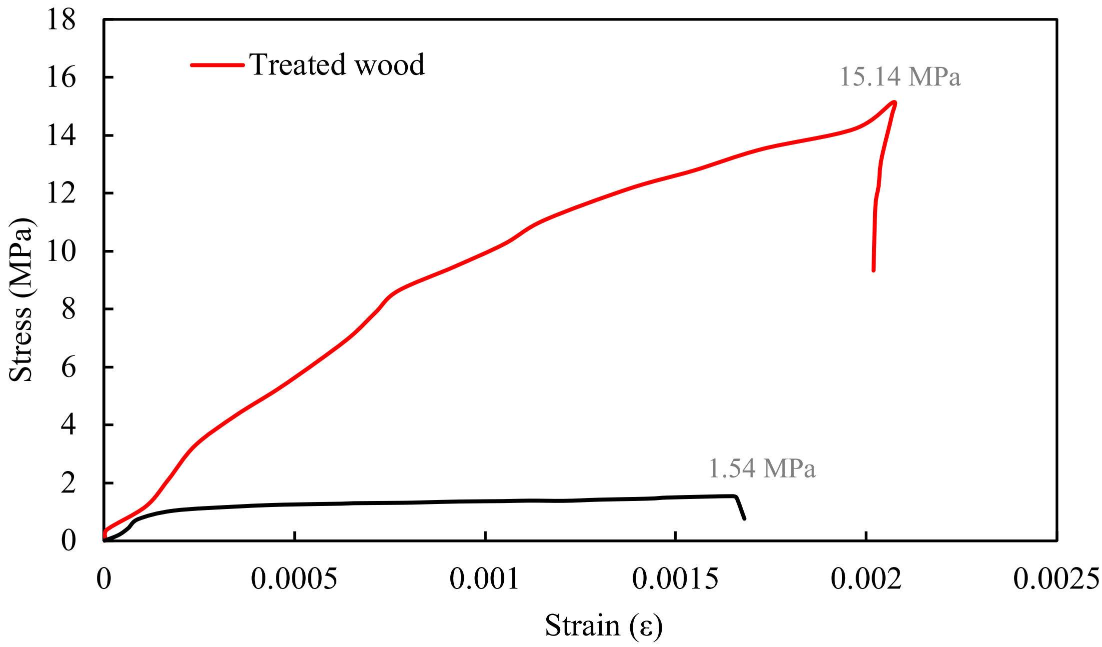


Figure 6. 41 Comparative relationship between stress (MPa) and strain (ε) of treated and control wood in tangential direction compressive strength test.

6.4.2.1.2.2. Failure mode

Table 6. 10 shows the results of the compressive strength test on untreated and tangentially treated wood samples, respectively. Table 6. 11 shows the results of the compressive strength test on untreated and tangentially treated wood samples. Each side

of the tangential compressive strength sample (from A to F) was photographed to illustrate the mode of failure that occurred on each side following the wood compression.

Table 6. 10 Images of treated wood in the tangential direction following testing of its compressive strength

	A side	B side	C side	D side	E side	F side
FS-1						
FS-2						
FS-3						
FS-4						

Source: Research Documentation, 2023.

Table 6. 11 Images of control wood in the tangential direction following testing of its compressive strength.

	A side	B side	C side	D side	E side	F side
C-1						

Source: Research Documentation, 2023.

Based on the failure type referring to the wood failure type by Jozsef Bodig & Benjamin A. Jayne, the compressive strength test results in the tangential direction show that the sample has a *splitting failure type* as shown in Figure 6. 42. In contrast, the FS-2 sample showed a unique failure type named *edge failure type*. Meanwhile, in the control wood sample, the control wood sample also showed a very unique type of failure, namely the *bend failure type* (see Figure 6. 43).

Splitting failure type, also known as shear failure, can occur when the wood specimen splits along the fibers under applied stress. Splitting failure is more likely to occur in species with lower strength properties such as albasia wood or when the compression force is not evenly distributed across the specimen.

In contrast, the type of failure that best represents the compression process of Albasia Voronoi composites is *splitting failure type*, in which stress is transmitted through the edges and vertices. Due to the edges connecting different cells in the Voronoi structure and bearing the stress transfer between the cells, the initial mode of failure is edge fracture. When an excessive load is applied, the edges may crack and eventually fail. Following the failure of the edge, the load will be transferred to the adjacent cell, resulting in cell fracture. Conforming to the typical Voronoi failure process, cell fracture typically begins at the weakest points of the cell wall and eventually spreads throughout the cell, causing irreversible deformation or damage to the structure of the wooden Voronoi composite when it reaches a critical state.

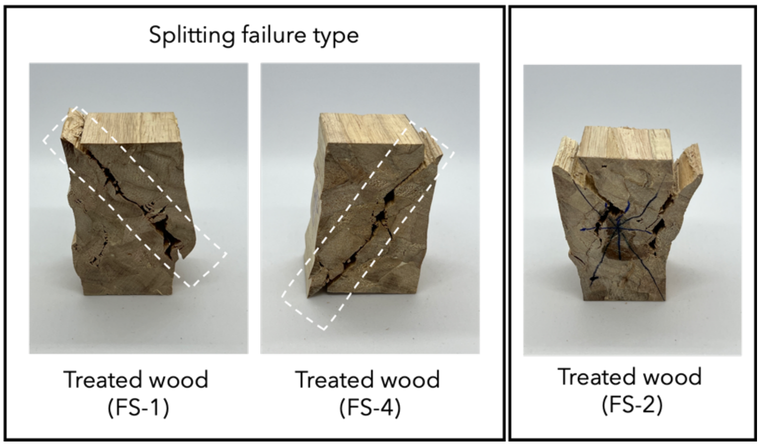


Figure 6. 42 Splitting failure type of wood in compressive strength test tangential direction on treated wood (albasia Voronoi composite)

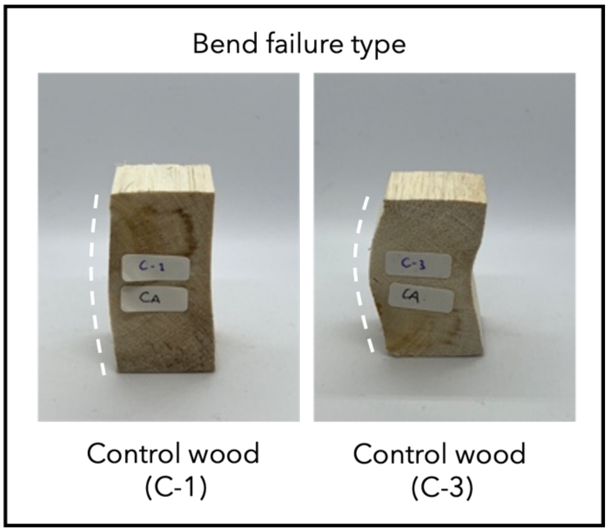


Figure 6. 43 Bend failure type of wood in compressive strength test tangential direction on control wood

Figure 6. 43 demonstrates that during the loading process, natural wood undergoes bending, resulting in stress concentration on one side, which causes deformation and failure. Because the fibers are densely packed, the wooden Voronoi composite and

natural wood are more susceptible to cracking when subjected to compressive stress in the L direction. This is due to the wood's poor deformability.

6.4.2.1.2.3. Tangential compressive strength

Table 6. 12 shows the calculation results for the treated and control albasia wood in the tangential compression strength test. Maximum load indicates the maximum force measured to calculate the tangential compressive strength. The compressive strength at the proportional limit which is the highest stress that the treated albasia wood material can withstand shows the highest result is 14.52 kN in FS-4 and the lowest stress result is 11.94 kN in FS-1. Meanwhile, the compressive strength at the proportional limit that the untreated albasia wood material can withstand is the highest at 1.67 kN in C-2 and the lowest at 1.3 kN in C-3.

Table 6. 12 Calculation results of treated and control wood samples in tangential compressive strength test.

Sample	Density (kg/L)	A (mm^2)	Maximum Load (kN)	Compressive Strength (MPa)	Compressive Proportional Limit Stress (MPa)	Young's Modulus (MPa)
FS-1	0.82	840	11.94	14.21	9.81	5330
FS-2	0.76	900	12.25	13.61	9.64	5104
FS-3	0.84	870	14.45	16.61	11.56	6228
FS-4	0.82	900	14.52	16.13	11.23	6050
C-1	0.23	857.28	1.25	1.46	1.03	373.90
C-2	0.26	908.46	1.67	1.84	1.26	471.35
C-3	0.29	893.52	1.3	1.45	1.01	373.06
C-4	0.29	923.67	1.31	1.42	0.99	363.66

Source: Research Documentation, 2023.

Figure 6. 44 displays the tangential compressive strength test results. Results indicated that the tangential compressive strength of treated albasia wood reached a maximum of 16.61 MPa in FS-3 and a lowest value of 13.61 MPa in FS-1. In the meantime, the longitudinal compressive strength of untreated albasia wood (control) reached a maximum of 1.84 MPa at C-2 and a lowest of 1.42 MPa at C-4.

In the tangential direction, the average tangential compressive strength of treated wood is 15.14 MPa, compared to 1.54 MPa for untreated wood (control). Therefore, the treatment increased the tangential compressive strength of albasia wood by 883.12% in comparison to untreated wood.

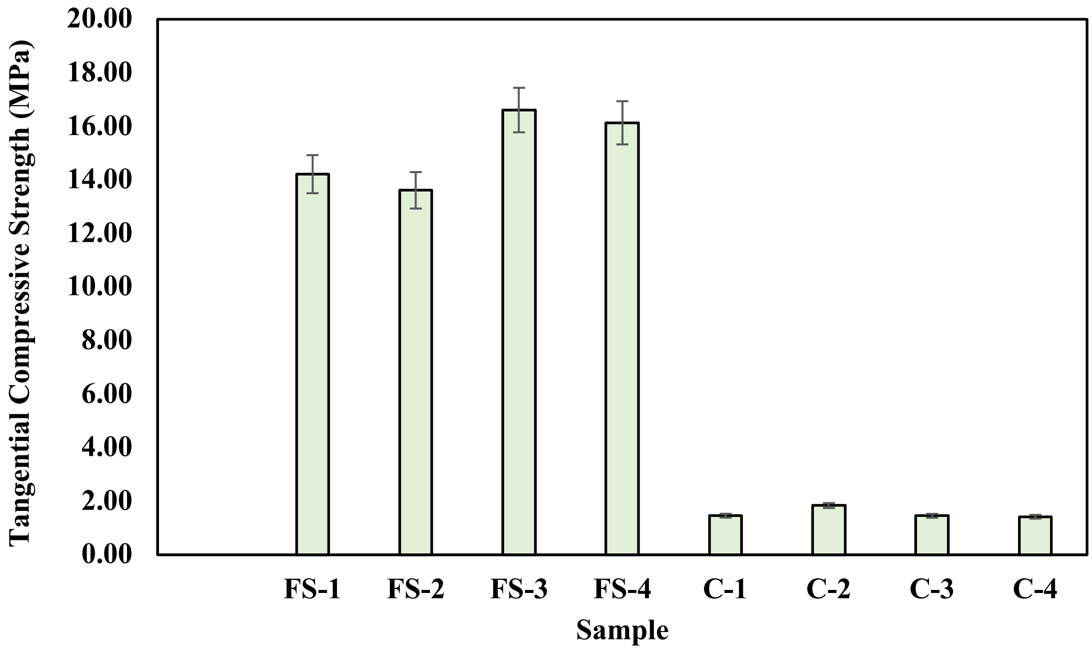


Figure 6. 44 Tangential Compressive Strength of treated and control albasia wood

Source: Research Documentation, 2023.

The albasia composite inherits the structural characteristics of the longitudinal wood fibers of the wood, which determine its high resistance to transverse fracture in the direction perpendicular to longitudinal direction. The cracks perpendicular to the grain are easily propagated along the grain and absorb energy during loading, preventing the cracks from expanding in the transverse direction and forming a new crack perpendicular to the original one. The new crack along the interface absorbs the excess strain energy, preventing the original crack from propagating further and avoiding catastrophic failure. Moreover, the crack parallel to the applied stress does not continue to extend. The tensile failure of natural wood is caused by relative sliding between the open wood layers, followed by the pulling and tearing of the layers along the fracture surface.

The failure of the compacted wood and wooden Voronoi composite is caused by relative sliding between the dense wood cell walls, followed by the pulling and breaking of the cell walls along the fracture surface. At the microscopic level, the dense and intertwined wood cell walls in the compacted wooden Voronoi composite result in a highly aligned arrangement of cellulose nanofibers, greatly increasing the interfacial area between the nanofibers. At the molecular scale, the relative sliding of the dense wood cell walls involves the formation, breaking, and recombination of a large number of hydrogen bonds that are repeatedly present in the cellulose molecular chains containing abundant hydroxyl groups. As a result, the mechanical properties of the longitudinal direction of the wooden Voronoi composite have been greatly improved compared to natural wood.

6.4.2.1.3. Comparative analysis of compressive strength

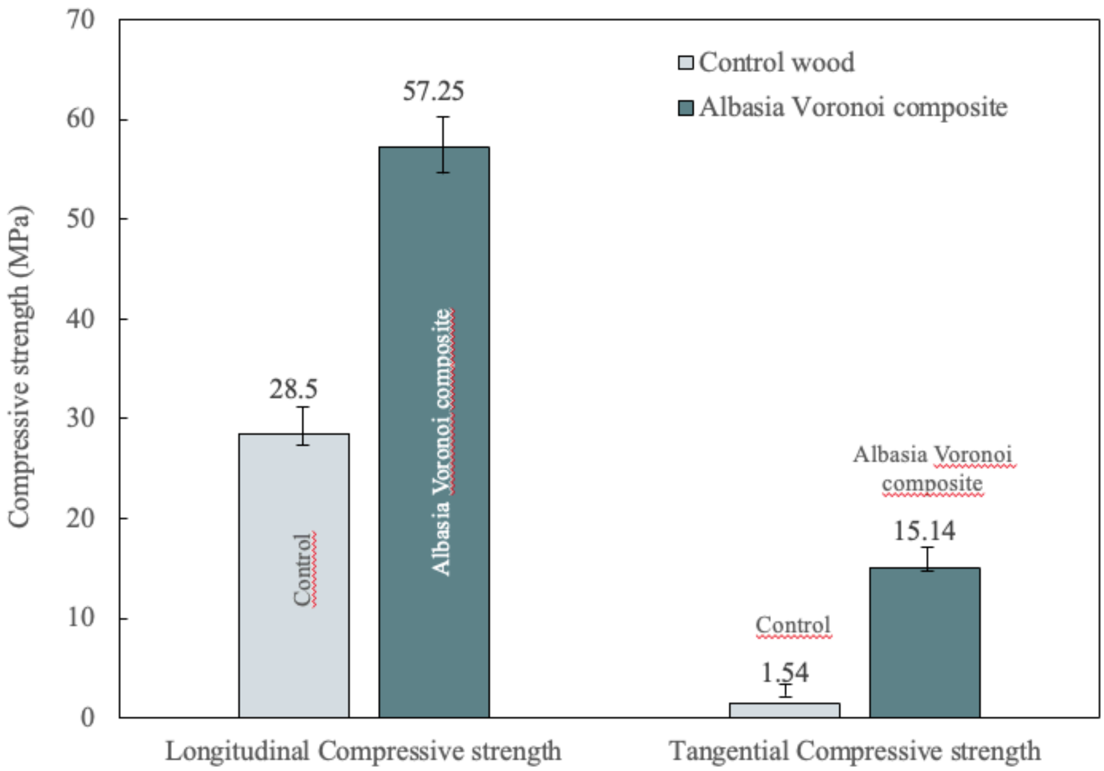


Figure 6. 45 Comparative analysis of compressive strength.

Source: Research Documentation, 2023.

Comparative analysis of compressive strength can be seen in Figure 6. 45. Based on the results obtained in this study, the average longitudinal compressive strength of treated wood is 57.25 MPa, compared to 28.50 MPa for the control. As a result, the treatment increased 100.88% compared to the control.

Meanwhile, the average tangential compressive strength of treated wood is 15.14 Mpa, compared to 1.54 Mpa for the control. Therefore, the treatment increased 883.12% compared to the control.

6.4.2.2. Analysis of bending strength test

6.4.2.2.1. Analysis of longitudinal bending strength test

The three-point bending strength test on the control wood is presented in Figure 6. 46. While the three-point bending strength test on treated wood is presented in Figure 6. 47. In this test, the wood sample is subjected to a bending load (fulcrum) applied at two points at the bottom of the sample, while the sample is supported at one point in the middle (breaking force). A force is applied vertically at the center point of the sample using a load device (breaking force). Then the maximum load or peak force experienced by both the control and treated wood before failure is the main parameter measured during the test which indicates the bending strength of the wood.

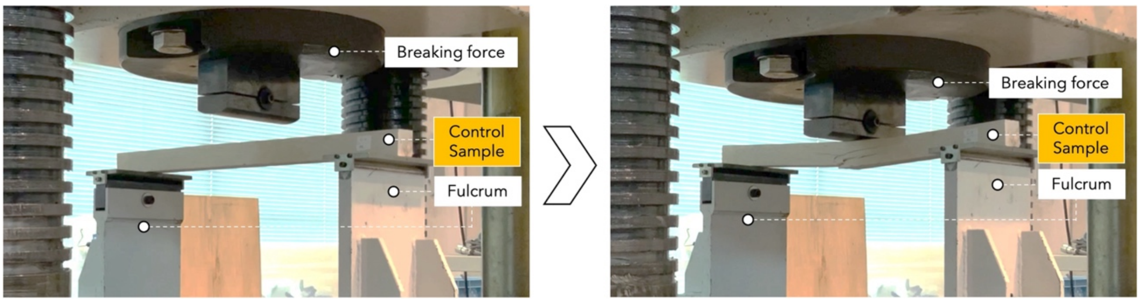


Figure 6. 46 Longitudinal bending strength test on control wood.

Source: Research Documentation, 2023.

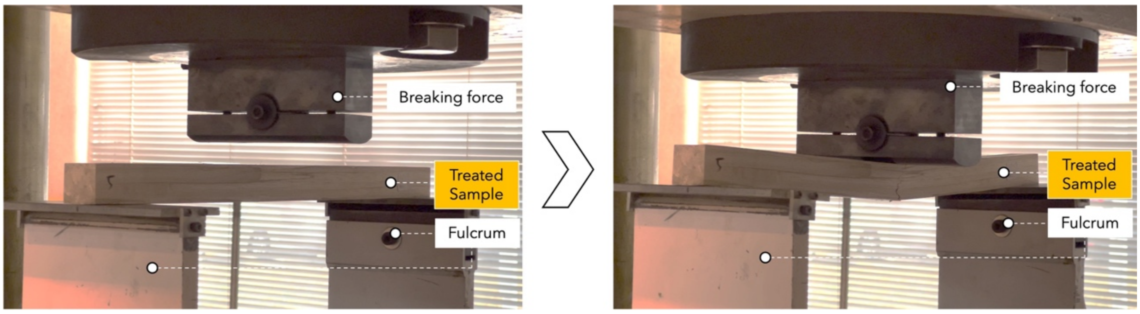


Figure 6. 47 Longitudinal bending strength test on treated wood.

Source: Research Documentation, 2023.

6.4.2.2.1.1. Failure mode

The appearance of each sample, both control wood (Table 6. 13) and treated wood (Table 6. 14) after the three-point bending strength test are shown. In the bending strength test on treated wood, each category has 2 test samples (BE-1 and BE-2) which are then averaged.

Table 6. 13 Appearance of control samples after bending strength test

Sample	Appearance after bending strength test
C-1	
C-2	
C3	
C-4	

Table 6. 14 Appearance of treated samples after bending strength test

Sample	Appearance after bending strength test
FS-1 (BE-1)	
FS-1 (BE-2)	
FS-2 (BE-1)	
FS-2 (BE-2)	
FS-3 (BE-1)	
FS-2 (BE-2)	
FS-4 (BE-1)	
FS-4 (BE-2)	

Source: Research Documentation, 2023.

Figure 6. 48 presents the failure types of clear wood in bending with span parallel to grain (Jozsef Bodig & Benjamin A. Jayne, 1993). According to the existing failure types, the longitudinal bending strength test results for both treated and control wood in this study are simple tension failure types. Simple tension failure occurs when wood breaks or cracks due to tensile stress induced by bending loads. When wood is bent, the outer fibers of the specimen are subjected to tensile stress, while the inner fibers are stressed.

If the tensile stress exceeds the tensile strength of the wood, simple tension failure can occur.

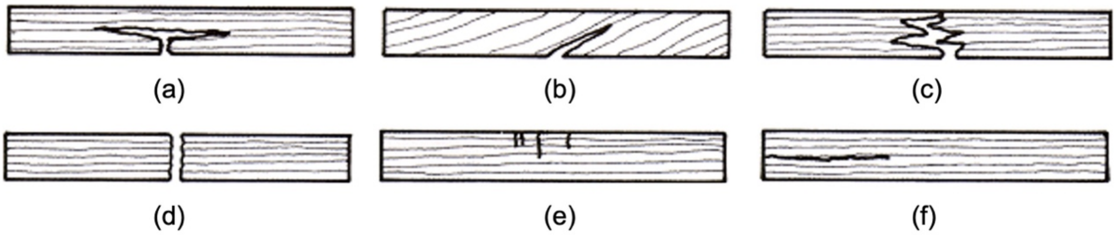


Figure 6. 48 Failure types of clear wood in bending with span parallel to grain: (a) simple tension, (b) cross-grain tension, (c) splintering tension, (d) brash tension, (e) compression, (f) horizontal shear.

Source: (Jozsef Bodig & Benjamin A. Jayne, 1993)

During the wood bending test, the control wood and albasia Voronoi composite wood were subjected to increasing bending loads until they reached their maximum capacity. If the tensile stress in the outer fibers is too high, it can exceed the tensile strength of the wood, leading to a simple tension failure. This failure, as depicted in Table 6. 13 and Table 6. 14, is characterized by splitting or cracking that typically begins at the surface. When simple tension failure occurs in a wood bending test, it indicates that the wood is unable to withstand the tensile stress induced by the bending load. This failure can be influenced by a variety of factors, including wood composition, microstructure and mechanical properties.

6.4.2.2.1.2. Bending strength

Then the calculation results for the bending strength test of treated and untreated Albasia wood are displayed in Table 6. 15. Maximum load represents the maximum force measured to determine the maximum limit of wood's bending strength. FS-1 had the greatest maximum load for treated wood at 4.75 kN, while FS-4 had the least at 3.42 kN. In contrast, the maximum load on untreated wood was highest in C-2 at 2.06 kN and lowest in C-3 at 1.45 kN.

Table 6. 15 Calculation results of treated and control wood samples in bending strength.

Sample	Density (kg/L)	A (mm^2)	Maximum Load (kN)	Bending Strength (MPa)	Bending Proportional Limit Stress (MPa)	Young's Modulus (Mpa)
FS-1	0.82	14832	4.75	102.75	71.89	8091
FS-2	0.76	14544	3.86	87.42	62.21	6705
FS-3	0.84	15024	4.66	91.03	63.76	7836
FS-4	0.82	14112	3.42	79.30	55.45	6122
C-1	0.23	14850	1.51	32.05	22.48	2569
C-2	0.26	14541	2.06	44.88	31.49	3579
C-3	0.29	14688	1.45	32.73	22.86	2494
C-4	0.29	15024	1.72	37.96	26.48	2892

Source: Research Documentation, 2023.

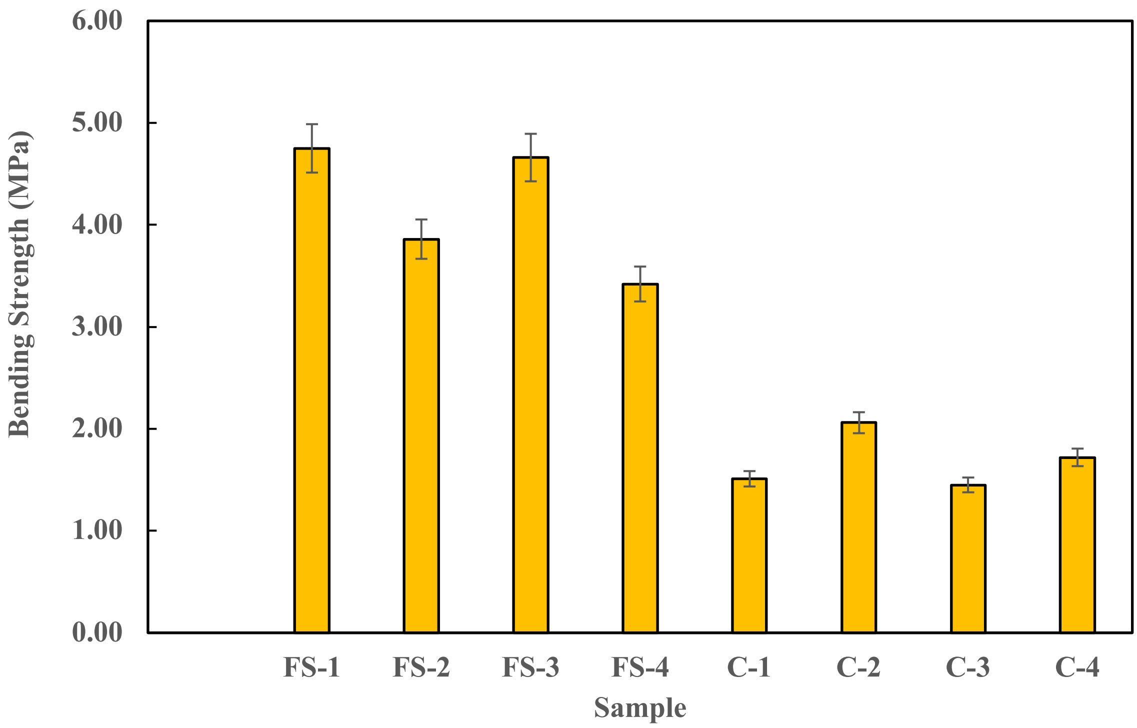


Figure 6. 49 Bending Strength of treated and control albasia wood.

Source: Research Documentation, 2023.

Figure 6. 49 illustrates the findings of bending strength testing. The results indicated that the bending strength of treated albasia wood was highest in FS-1 at 102.75 MPa and lowest in FS-4 at 79.03 MPa. The results indicated that the bending strength of untreated albasia wood (control) reached a maximum of 44.88 MPa at C-2 and a minimum of 32.05 MPa at C-1. The average bending strength of treated wood is 90.12 MPa, while the average bending strength of untreated wood (control) is 36.91 MPa. In comparison to untreated wood, the treatment procedure increased the bending strength of albasia wood by 244.21%.

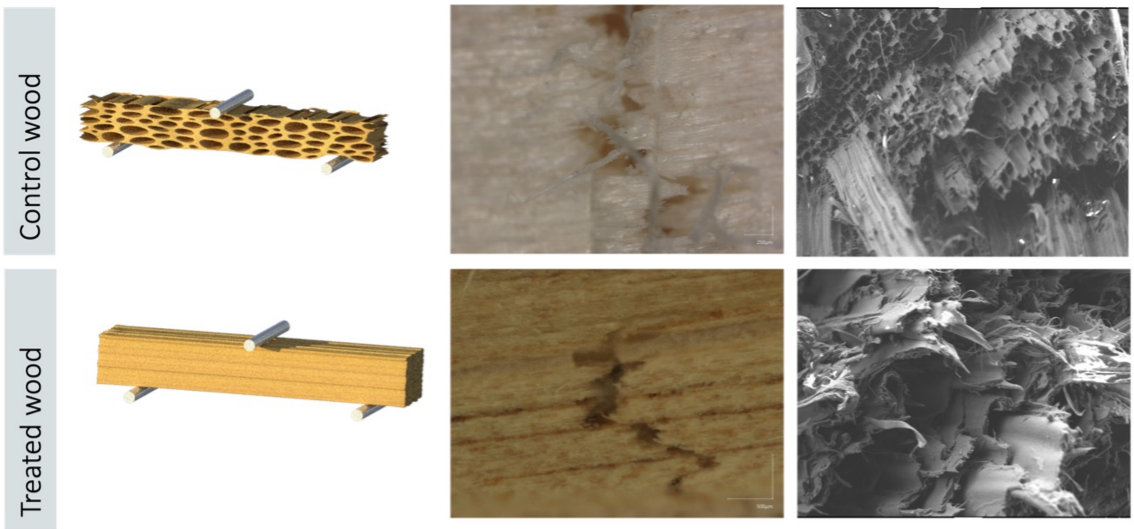


Figure 6. 50 Observation of the microscopic scale on bending strength test.

Source: Research Documentation, 2023.

As can be seen in Figure 6. 50, observations at the microscopic scale indicated that, under normal conditions, control wood is susceptible to fracture when subjected to R-direction stress due to weak inter-fiber bonding, which results in elongation failure.

Treated wood possesses greater resistance to R-direction stress, preventing the crack from widening in the transverse direction and forming a new crack perpendicular to the original crack.

6.4.2.2.2. Analysis of tangential bending strength test

Tangential bending test is a type of mechanical test used to evaluate the strength and flexural properties of wood when subjected to a load in the tangential direction, which is parallel to the wood fibers. This test helps in understanding the behavior of wood when it is bent or subjected to bending loads along its grain direction.

The three-point bending strength test on the treated and control wood is presented in Figure 6. 51. In this test, the wood sample is subjected to a bending load (fulcrum) applied at two points at the bottom of the sample, while the sample is supported at one point in the middle (breaking force). A force is applied vertically at the center point of the sample using a load device (breaking force). Then the maximum load or peak force experienced by both the control and treated wood before failure is the main parameter measured during the test which indicates the bending strength of the wood.

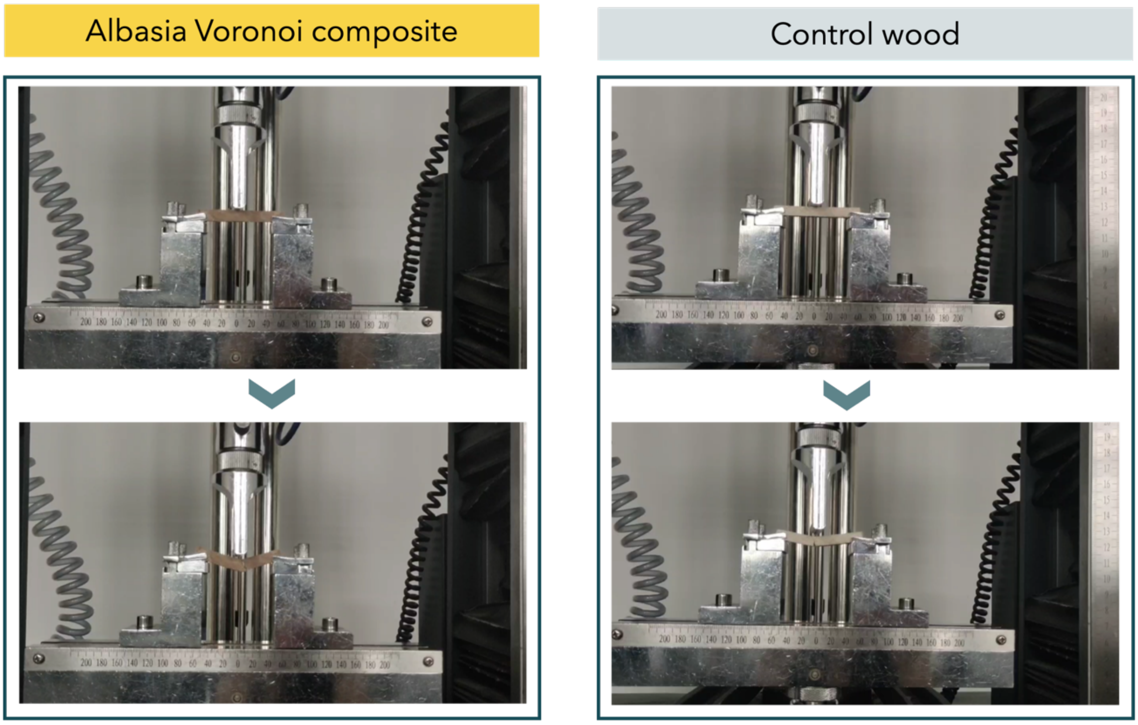


Figure 6. 51 Tangential bending strength on control and treated wood.

Source: Research Documentation, 2023.

6.4.2.2.2.1. Relationship between stress and strain

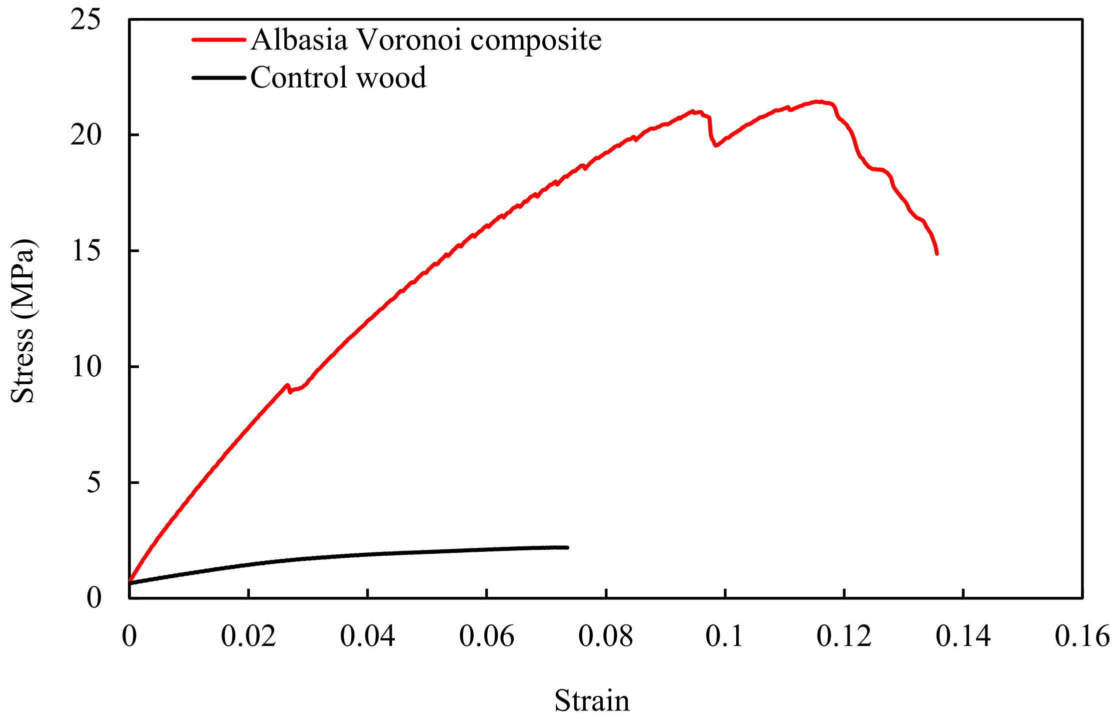


Figure 6. 52 Comparative relationship between stress (MPa) and strain (ε).

Source: Research Documentation, 2023.

The curves of the relationship between stress and strain in the tangential bending strength test is shown in Figure 6. 52. Results showed that the treated wood had an average maximum load of 21.01 MPa, compared to 2.19 MPa for the control.

The relationship between stress and strain in wood bending strength tests is represented by the stress-strain curve shown in the figure. When the load is applied, the wood will experience strain and form a stress-strain curve in treated wood and control wood. This curve shows how the stress in the wood changes along with the strain as the wood bends.

6.4.2.2.2.2. Failure mode

According to the existing failure types, the tangential bending strength test results for both treated and control wood in this study are simple tension failure types. Simple tension failure occurs when wood breaks or cracks due to tensile stress induced by bending loads. When wood is bent, the outer fibers of the specimen are subjected to tensile stress, while the inner fibers are stressed. If the tensile stress exceeds the tensile strength of the wood, simple tension failure can occur.

6.4.2.2.3. Comparative analysis of bending strength

Comparative analysis of bending strength can be seen in Figure 6. 53. Based on the results obtained in this study, the average longitudinal bending strength of treated wood is 90.12 MPa, compared to 36.91 MPa for the control. As a result, the treatment increased 144.05% compared to the control. Meanwhile, the average tangential bending strength of treated wood is 21.01 MPa, compared to 2.19 MPa for the control. Therefore, the treatment increased 859.36% compared to the control.

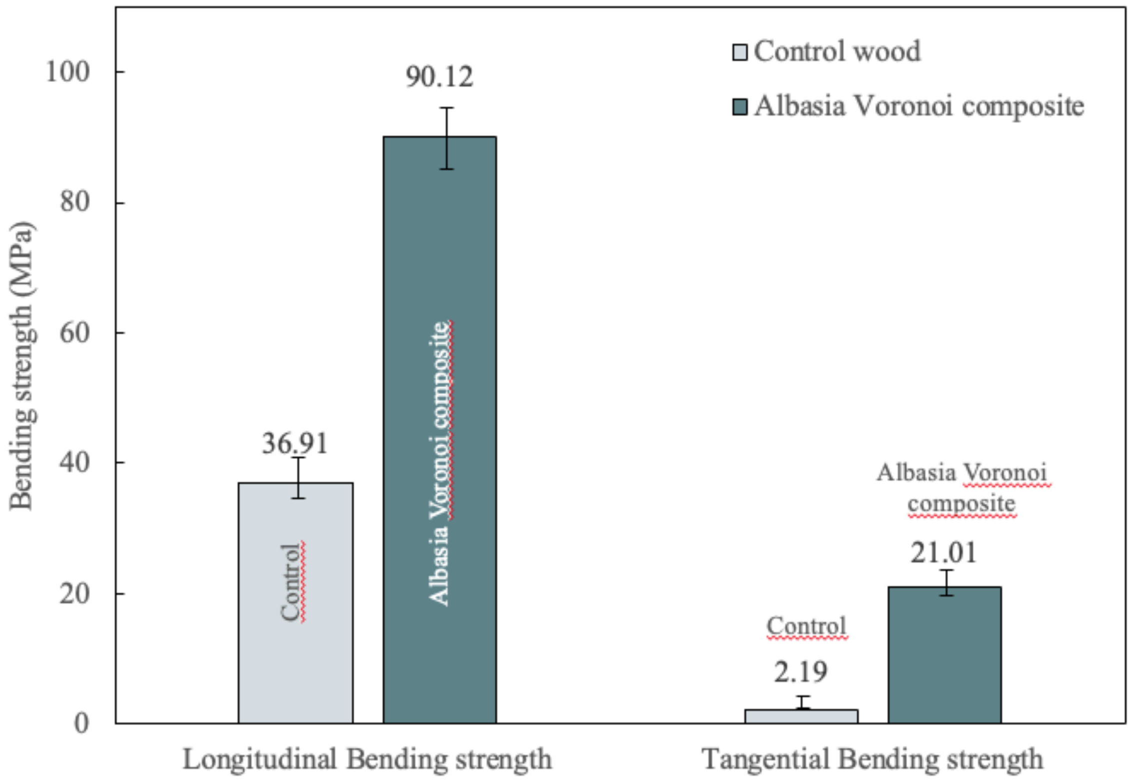


Figure 6. 53 Comparative analysis of bending strength.

Source: Research Documentation, 2023.

6.4.2.3. Analysis of tensile test

6.4.2.3.1. Relationship between tensile strength and strain

In wood tensile tests, there is a relationship between strength and strain that is described by the wood's stress-strain curve. To further corroborate the effect of albacia Voronoi composite treatment in this study, Figure 6. 54 presents the relationship curves between tensile stress and strain of control and treated wood (albacia Voronoi composite).

The results show that the treated and control woods have an average maximum tensile strength of 19.8 MPa and 2.8 MPa, respectively. Both curves elucidate a linear deformation behaviour preceding tensile failure.

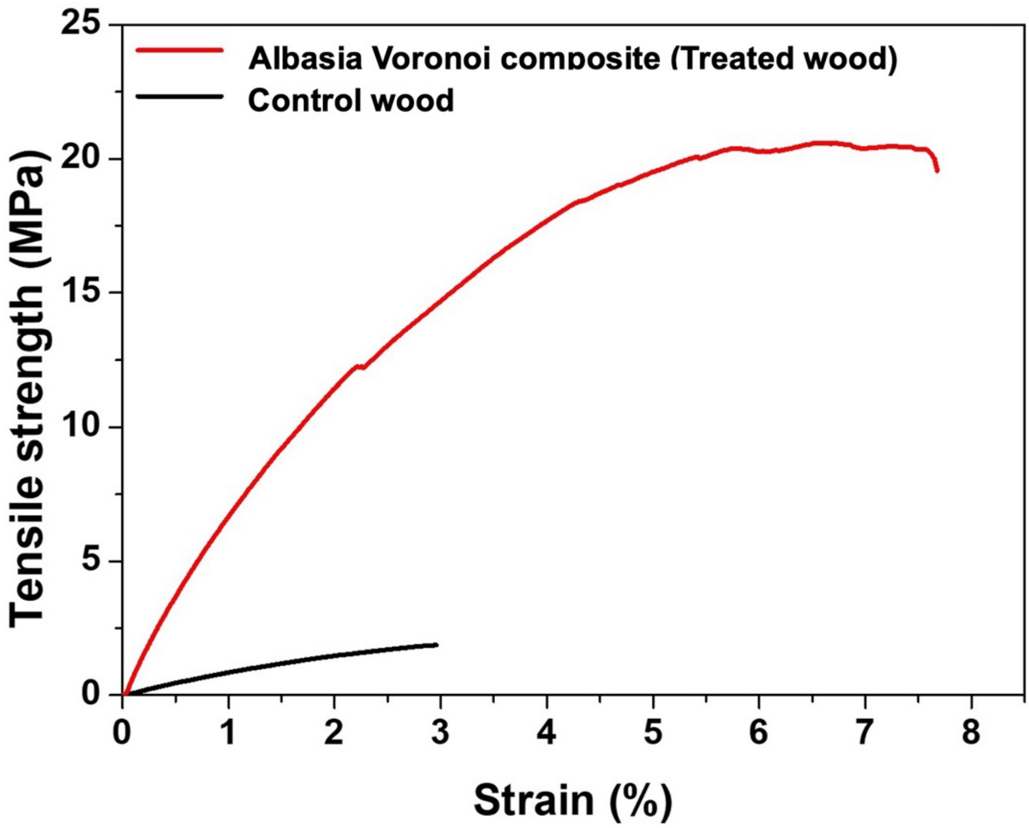


Figure 6. 54 Relationship curves between tensile stress and strain of control and treated wood (albasia Voronoi composite).

Source: Research Documentation, 2023.

This curve illustrates the response of wood to an applied tensile force. At the beginning of the tensile test, when the tensile load is applied to the wood, the strains that occur in the wood are still relatively small and linear, while the resulting stresses increase proportionally. This is referred to as the elastic regime. The relationship between stress (σ) and strain (ε) in the elastic regime is given by Hooke's Law, which can be written as:

$$\sigma = E * \varepsilon$$

Where E is the wood's modulus of elasticity. In the elastic regime, once the tensile load is removed, the wood will return to its original shape, and the relationship between stress and strain is reversible. However, as the tensile load is increased, the wood will undergo increasingly significant deformation. The wood's strain will increase more rapidly as the stress reaches its maximum level. At this point, the wood's ultimate tensile strength (UTS) is reached. After the wood reaches UTS, it begins to undergo plastic deformation, where permanent deformation occurs even after the tensile load is removed. The highest point on the stress-strain curve represents UTS, and the strain that occurs at UTS is known as the ultimate strain. After the wood reaches UTS, the stress will decrease as the strain continues to increase. Eventually, the wood will fail or break.

6.4.2.3.2. The tensile strength and elongation

Wood's behavior under tension is best characterized by its tensile strength and elongation, which are crucial mechanical properties. These characteristics provide insight into the material's tensile strength and its deformability prior to failure. The tensile strength of a material is the maximum force it can withstand before breaking under tension. It represents the maximum force or load that a wood specimen can withstand per unit of cross-sectional area prior to failure. Meanwhile, Elongation, also known as strain or deformation, is the measurement of how much a material stretches or deforms under tension. It quantifies the change in length relative to the initial length of the material. Wood's elongation can be expressed as a percentage of its initial length. It provides information about the material's ductility or stretchability prior to failure.

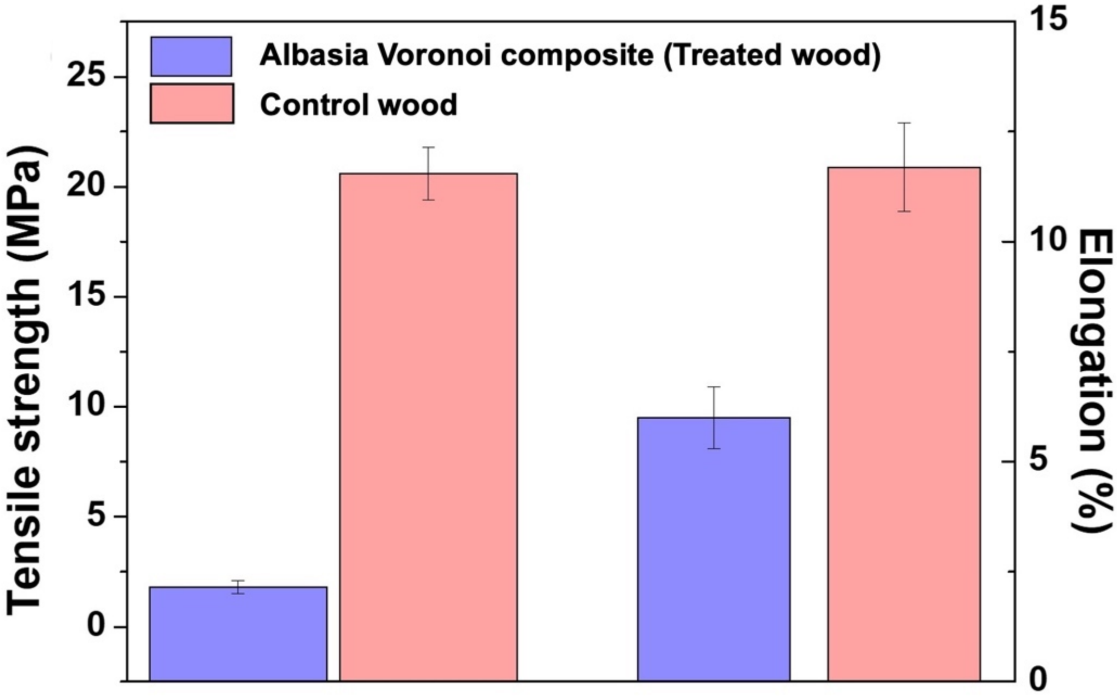


Figure 6. 55 The tensile strength (Mpa) and elongation (%) between treated wood and control wood along tangential direction.

Source: Research Documentation, 2023.

As it can be seen, Figure 6. 55 shows the tensile strength (MPa) and elongation (%) between treated wood and control wood along tangential direction. The tensile strength and elongation at break in the tangential direction of the Albasia voronoi composite were about 10 and 2 times higher than the control wood, respectively. It is important to note that tensile strength and elongation are related but distinct properties. Tensile strength represents the maximum load capacity of wood, while elongation measures the extent to which the material can stretch before breaking.

6.4.2.3.3. Fracture pattern

Figure 6. 56 Tensile test on control wood

Source: Research Documentation, 2023.

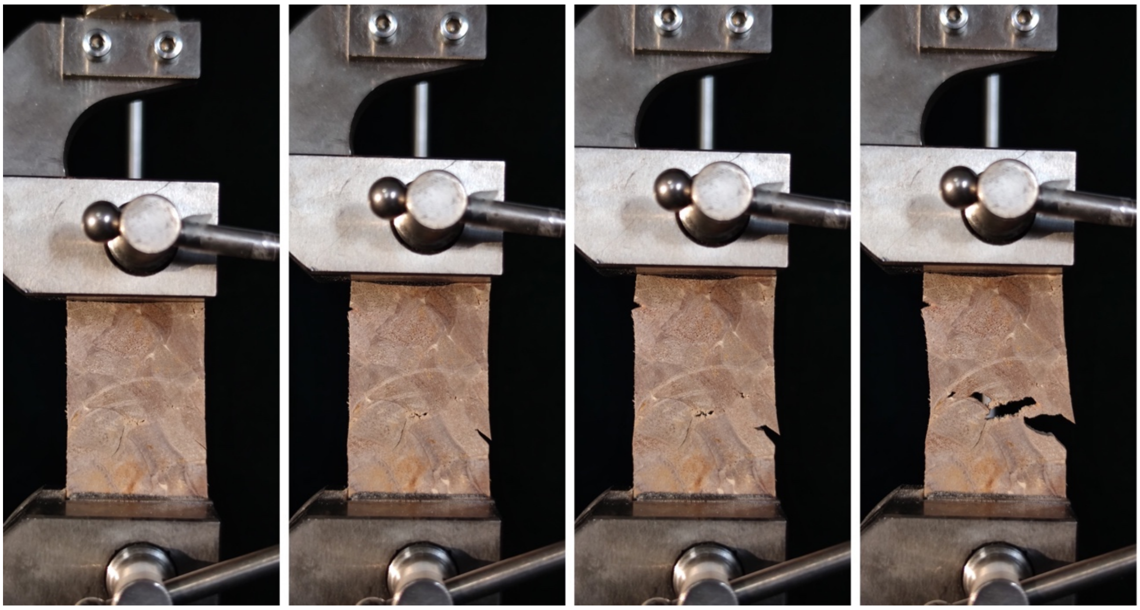


Figure 6. 57 Tensile test on treated wood.

Source: Research Documentation, 2023.

The fracture pattern or mode of failure during a tensile test on wood can provide valuable information about the material's behavior under tension. The fracture pattern can provide insight into the wood specimen's structural integrity, strength, and other mechanical properties. Notably, the fracture pattern observed during a wood tensile test can be affected by a number of factors, including the wood species, moisture content, density, grain orientation, and the presence of defects or structural abnormalities in the wood. Analyzing the fracture pattern can provide insight into the wood's quality and structural performance, as well as its failure mechanisms. As it can be seen, the images captured in the tensile test on the control (Figure 6. 56) and treated wood (Figure 6. 57)

These images were taken at key points on the previous stress-strain curves, with the subsequent failure mechanism described as follows:

In accordance with previous examinations of the relationship between tensile strength and strain, the control wood cracked faster during tensile testing due to shorter strains than the albacia Voronoi composite. Due to its stronger wood, the composite Voronoi albacia was able to withstand a greater strain.

The pull from the tensile testing machine causes a longitudinal crack to form in the center of the control wood when viewed from the perspective of crack shape. In contrast, the cracks in composite Voronoi albacia differ from those in the control wood. The cracks originate from the first longitudinally oriented wood cell. The greater the tension generated by the tensile machine, the more the crack propagates and spreads to weaker wood cell regions. The fracture line indicates that the fracture did not originate and propagate to the glue line between the voronoi of the wood. This suggests that the glue mixture utilized in this study possesses a strong quality.

6.4.2.3.4. Analysis of Finite Element Model (FEM) Simulation

An Abaqus model of the Voronoi architecture, established to analyze the stress distribution in the wooden Voronoi composites during tensile processes (Figure 6. 58). This model encapsulates a multitude of Voronoi units, emulating the real composite structure. We applied appropriate material properties, boundary conditions, and delineated the tensile loading trajectory. During the simulation, we observed the deformation and failure behaviour of the Voronoi architecture under tension.

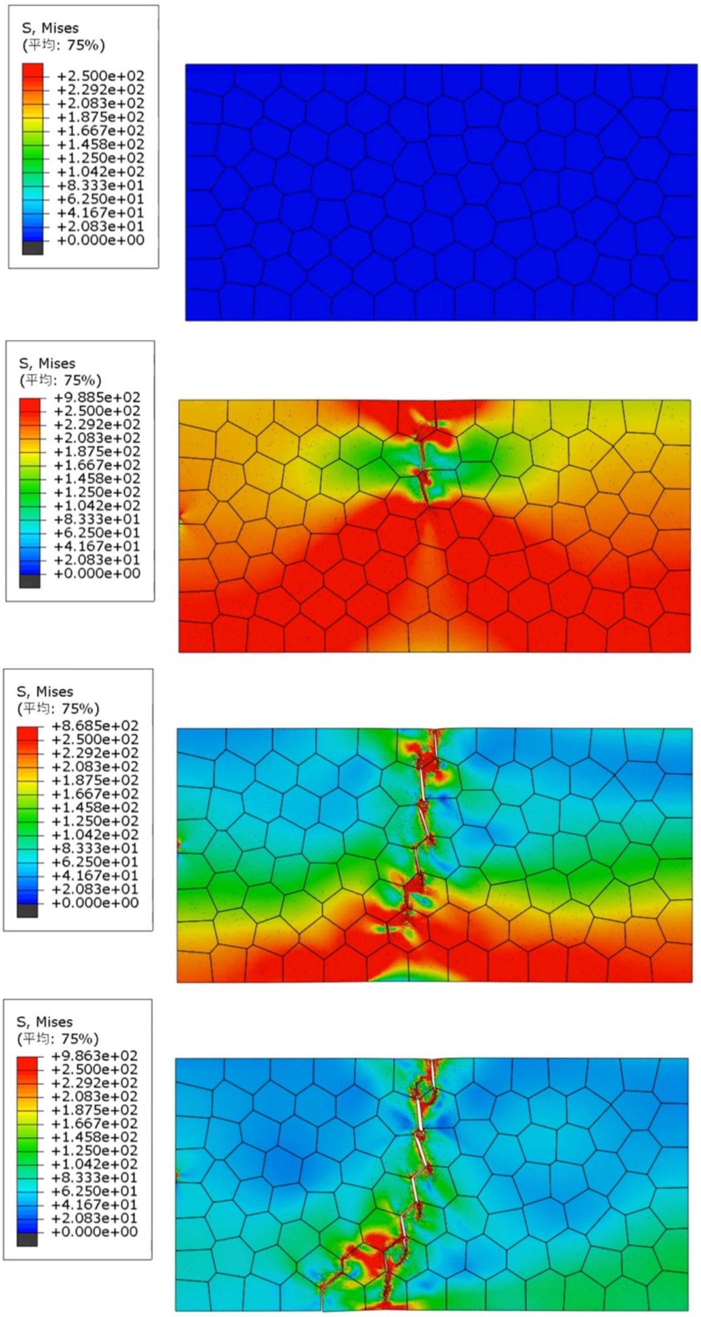


Figure 6. 58 Finite Element Model (FEM) Simulation on treated wood

Source: Research Documentation, 2023.

In the initial phase, the structure exhibited elastic deformation under load, with all Voronoi units uniformly withstanding tension. However, as tension escalated, some Voronoi units began to manifest plastic deformation, usually situated at the structural weak points, such as areas adjacent to the boundary or regions with relatively weak material properties.

Under further tension, plastic deformation gradually proliferated to more Voronoi units, at which point the overall strength of the structure began to plummet significantly. In some particularly weak Voronoi units, fractures even occurred. These fractures initially manifested in individual units, then swiftly extended to adjacent units, giving rise to a fracture zone. During this process, the structure's load-bearing capacity sharply declined until it ultimately succumbed to complete failure.

Moreover, we noticed that different Voronoi units might exhibit distinct failure modes. For instance, some units primarily exhibited longitudinal fractures during the tensile process, while others might display transverse fractures.

6.4.2.3.5. Comparative analysis of tensile test

A comparative study between the tensile test results and the finite element model simulation was conducted. As it can be seen in Figure 6. 59, the results showed that the wood samples in the field tensile test with Instron 5565 A tensile testing machine and the finite element model simulation with Abaqus 2022 had different crack patterns in the Albasia Voronoi composite.

The field results with the tensile testing machine concluded that the wood cracks originated from the first wood cell in the longitudinal direction and then spread to weaker areas of the wood cell. Where the crack line shows that the crack did not originate and propagated to the glue line between the wood voronoi. This indicates that the glue mixture used in this study is of strong quality.

Meanwhile, the results of the Finite Element Simulation show that the cracks are on the voronoi lines. In other words, the FEM simulation can be used as an example to determine that if the glue used in this study is inadequate then cracks will form and propagate along the Voronoi lines.

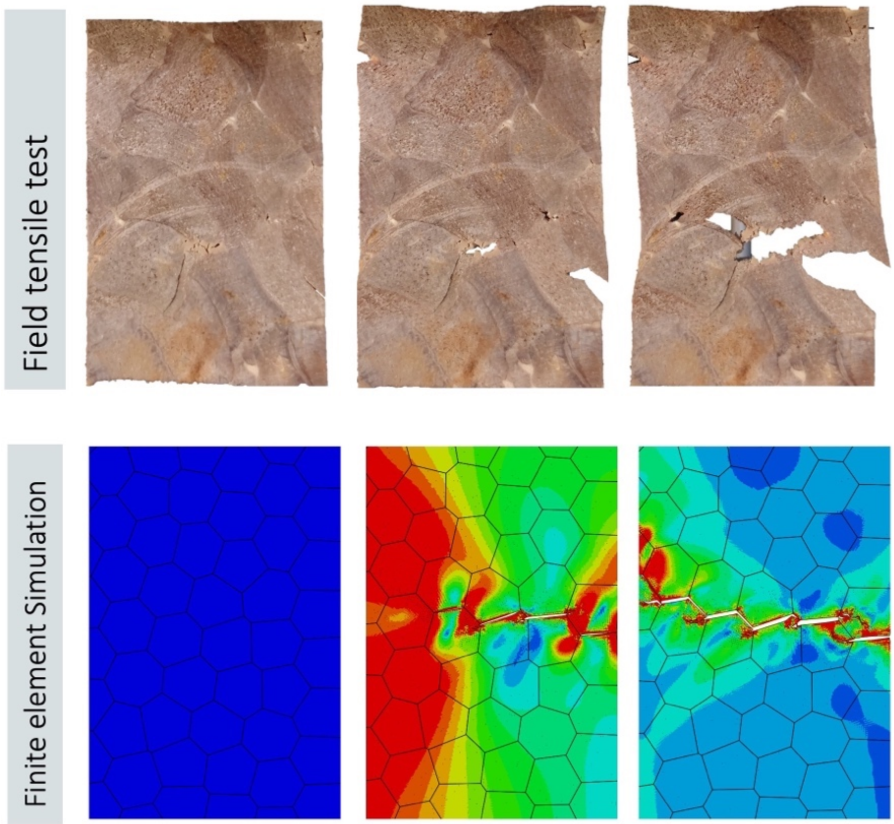


Figure 6. 59 Comparative study between field tensile test and FEM simulation

Source: Research Documentation, 2023.

6.5. Conclusions

In this study, the densification method integrating the Voronoi structure affects the physical and mechanical properties of Indonesian Albasia wood. The following are the conclusions of this study:

1. Wooden slats with a millimeter structure resembling the Voronoi pattern may become a new architectural trend, not only for Indonesian Albasia wood but also for wood materials.
2. The density of the Albasia Voronoi composite is 0.81 kg/L, which is greater than the natural wood density of 0.26 kg/L. The treatment increased the density of Albasia wood by 211.54%.

3. The EMC stability of the Albasia Voronoi composite was more stable than that of the control board as a result of its higher density and hemicellulose degradation. These mechanical and physical characteristics improve as the level of moisture decreases.
4. Morphological analysis revealed that the cellulose nanofibers of treated wood were very similar to natural wood, but the interfacial bond of the Albasia Voronoi composite was significantly superior to that of the control.
5. The Albasia Voronoi composite treatment procedure increased the longitudinal compressive strength of the wood by 100.88%. It also increased the tangential compressive strength by 883.12%.
6. The Albasia Voronoi composite treatment procedure increased the longitudinal bending strength of the wood by 144.05%. It also increased the tangential compressive strength by 859.36%.
7. The tensile strength and elongation at break of Albasia Voronoi composite were about 10 and 2 times higher than the control wood.
8. In its utilization as a construction material, albasia Voronoi composite may have the potential to be used as columns (tangential direction) and beams (longitudinal direction).

CHAPTER 7
A COMPARATIVE STUDY OF VORONOI WOOD DENSIFICATION PROCESS ON INDONESIAN ALBASIA AND JAPANESE CEDAR WOOD

CHAPTER 7:
A COMPARATIVE STUDY OF VORONOI WOOD DENSIFICATION PROCESS ON INDONESIAN ALBASIA AND JAPANESE CEDAR WOOD

Summary

Indonesian albasia (*Albizia falcataria*) and Japanese Cedar (*Cryptomeria japonica*) are abundant, fast-growing wood species native to their respective countries. However, low density, hardness, and strength limit their applications. A study was conducted to evaluate the effect of thermal densification integrated with architectural trend Voronoi structure on the physical and mechanical properties of albasia and Japanese cedar wood. Wood surface appearance, density, compressive and bending strengths were evaluated. The treatment resulted in an increase of 311.54% in density, 200.86% in longitudinal compressive strength, 981.72% in tangential compressive strength, and 244.21% in bending strength in albasia wood. While the procedure also increased the density, longitudinal compressive strength, tangential strength, and bending strength of Japanese cedar wood by 203.35%, 158.56%, and 198.1%, respectively. As expected, the Voronoi densification treatment method is extremely promising for enhancing the physical and mechanical properties of wood and enables the use of fast-growing, low-density timber in structural applications.

CHAPTER 7: A COMPARATIVE STUDY OF VORONOI WOOD DENSIFICATION ON INDONESIAN ALBASIA AND JAPANESE CEDAR WOOD

7.1. Introduction

7.1.1. Background

Wood, a renewable and eco-friendly material with high density, is extensively used in everyday life, particularly in the construction industry. However, the supply of high-density wood is insufficient to satisfy the rising market demand, primarily due to its lengthy growth period and limited availability. Due to the unfavorable mechanical properties associated with its low density, wood from fast-growing crops or wood that is abundantly available can therefore be utilized as a resource.

Indonesia and Japan have an economic relationship involving the import and export of timber (Julian et al., n.d.). Japan has become one of the most significant importers of Indonesian wood products (Simanjuntak & Nurmalina, 2017) because the demand for wood in Japan has increased dramatically, necessitating Japan's importation of Indonesian wood products to satisfy the demands of the wood market industry. Albasia wood is a fast-growing tree species that is abundant in Indonesia (Hartati et al., 2010) and is quite popular among Japanese people as a result of exports to satisfy Japan's timber requirement (Tomita, 2001). In Japan, Japanese Cedar is one of the most abundant softwoods (Ogura et al., 2014), accounting for 43% of the country's plantation area.

Both Indonesian albasia and Japanese cedar are abundant woods in their respective nations. Due to their inferior timber quality, softwood and low-density fast-growing timber species are only appropriate for lightweight construction materials. (Husain et al., 2017). Consequently, it is crucial to increase the density and characteristics of wood, as denser wood is frequently preferred for commercial applications (Zhang et al., 2004). Wood modification is a promising method for enhancing the qualities of softwood and rapidly growing species (Laine et al., 2016) (Pelİt et al., 2017).

One of the value-added wood modification technologies that researchers have examined extensively over the past few decades is the densification process of the wood. Densification is particularly advantageous for softwood and fast-growing wood species. Densification enables low-density wood to serve as a substitute for harder wood species, as low-density wood species can be transformed into high-value performance products through densification (Kutnar & Šernek, 2007). Also, wood species that already have a high density can be further modified through densification (Blomberg et al., 2005a). The objective of the densification procedure is to increase the density of wood by compressing wood samples between metal surfaces heated to the appropriate temperature, time, and pressure. There are a variety of densification methods available in the literature (Boonstra & Blomberg, 2007), including thermal compression (Ang et al., 2018; Z. Gao et al., 2016b; Julian & Fukuda, 2021).vThe two primary phases of thermal compression are wood softening and wood compression. This method incorporates a post-treatment phase that reduces irreversible thickness swelling caused by exposure of densified wood to moist or wet conditions (Yu et al., 2020).

In addition to the strength of wood, architects and designers take advantage of its structural system's aesthetic qualities (Huang et al., 2012). *Voronoi diagrams*, also known as Voronoi tessellations, appear to be a significant trend in contemporary architectural design. A Voronoi diagram is a graph composed of nuclei (seeds) whose edges form a Voronoi cell inspired by nature (Makiyama et al., 2002). In addition to the mechanical characteristics of wood, its market value can also be determined by its physical properties for aesthetic purposes.

7.1.2. Purpose of the study

Improving the quality of abundant wood is one of the greatest challenges to achieving sustainability. To optimize the process of enhancing wood properties, it is essential to comprehend how operating parameters influence wood properties. In addition, the purpose of this study was to examine the influence of densification treatment integrated with voronoi structure on the density and mechanical properties of abundant wood, specifically albasia and Japanese cedar. Density, hardness, and bending were utilized to evaluate the treatment's efficacy.

7.2. Literature Review

7.2.1. Trends of Indonesian albasia wood products in domestic and Japanese market

7.2.1.1. Introduction

7.2.1.1.1. Background

The wood sector is an essential commodity for Indonesia's forest products since it delivers major economic benefits, mainly through export activities. Japan has emerged as one of the most important importers of Indonesian timber products (Simanjuntak & Nurmalina, 2017).

In general, the need for wood in Japan has expanded substantially (Tomita, 2001). Japan needs to import wood products from Indonesia to satisfy the demand of the wood industry and market. Then albasia is a fast-growing type species developed through industrial and community forest plantations in Indonesia and potentially developed as shade trees for industrial crops, i.e., coffee and cocoa. Albasia is also a popular product among Japanese people and has been marketed in various Japanese shops and online marketplaces.

Several scientific names have been assigned to albasia wood (including *Albizia falcata* (L.) Backer, *Albizia moluccana* Miq., *Falcataria moluccana* (Miq.), *Paraserianthes falcataria* (L.) I.C.Nielsen). In Indonesia, *Albizia falcataria* is known as *sengon* or *albasia*, also has numerous local names such as *jeungjing*;*jeunjing* (Sundanese), *sengon laut* (Javanese), *jing laut* (Madura), *tedehu pute* (Sulawesi), *sika* (Maluku), and *bae;wahogon* (Papua) (Atmosuseno BS, 1998; Julian et al., 2019). *Albizia falcataria* is known by several local names in other countries, namely *kayu machis* (Malaysia), *puah* (Brunei Darussalam), *batai* (America, France, Germany, Italy, Canada), and *farukata* (Japan) (A. Q. Hadi & Napitupulu, 2011).

7.2.1.1.2. Purpose of the study

The purpose of this study is to obtain an overview of trends in the Indonesian timber sector, namely albasia wood, in both the domestic and foreign markets, particularly the Japanese market.

This study is expected to provide an overview of the sustainable timber industry's expansion in Indonesia, which has the potential to improve its contribution to the national economy.

7.2.1.2. Methods

The investigation begins by examining the history of the wood trade and the timber flow from the Indonesian timber industry to the Japanese market. Then, this study employs a qualitative methodology that consists of a structured literature review and observations.

In various years, timber time series data for albasia were obtained from the Ministry of Forestry, Indonesian Central Bureau of Forestry Statistics. Then the observation of the albasia wood trade in the Japanese market was carried out in the building material supply industry in Kitakyushu City, Fukuoka, Japan.

7.2.1.3. Overview of the timber trade

7.2.1.3.1. Trends in Japanese-Southeast Asia timber trade

Japan has long been one of the world's major consumers and importers of wood products, owing to insufficient domestic timber supply to meet rising demand (Owari, n.d.; Owari & Sawanobori, 2007). Domestic wood sector has contributed a lesser portion and is degraded due to the competitiveness of imported products, high harvesting and processing costs, and labor shortages. North America, Russia, and Southeast Asian countries have traditionally been Japan’s principal wood suppliers. Table 7. 1 presents an overview of the Japanese Southeast Asian timber trade (Samejima, 2020).

Table 7. 1 The Japanese-Southeast Asian timber trade.

Year	Occurence
1935	Tropical wood from Southeast Asia was popular in Japan before WWII.

1945	After WWII, Japan exempted foreign timber imports from earning foreign exchange.
1950	The Philippines is Japan's leading log exporter.
1970	Exporters shifted to Sabah, Indonesia (primarily Kalimantan), then Sarawak.
1973	Three major timber producers (Philippines, Sabah, Indonesia) established SEALPA by OPEC to control wood prices.
1985	Indonesia, Sabah, and Sarawak banned timber exports in 1985, ending SEALPA.

WWII: World War II; SEALPA: South-East Asia Lumber Producers' Association; OPEC: Organisation of the Petroleum Exporting Countries.

Source: Research Documentation, 2022.

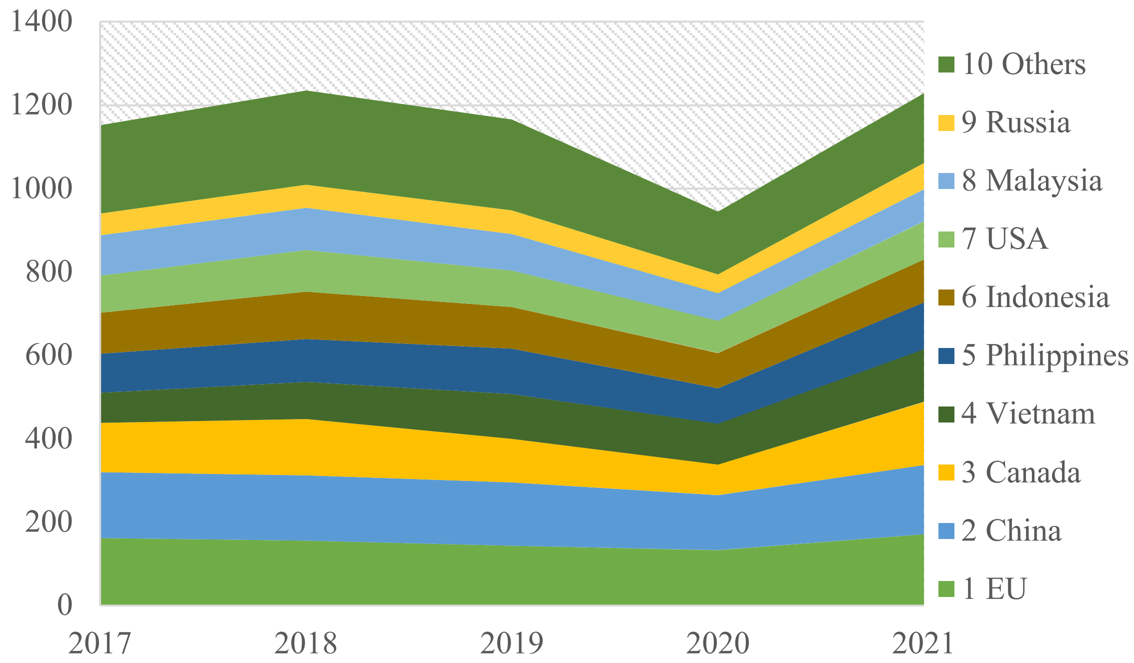


Figure 7. 1 Japan's wood import value

Source: Japan Forestry Agency, 2021 (Japan Forestry Agency, 2022).

Currently, the supply structure is fast shifting, as imports of logs from North America and Russia have fallen (Yoshimoto & Yukutake, 2013), and major Southeast Asian producers have restricted log exports (Table 7. 1). The export limits were intended to promote the development of the plywood sector, which had been developed in the 1980s (Dauvergne, 1997), forcing Japan to move from importing logs to plywood.

The number of Japan’s wood import value between the years of 2017 and 2021 is shown in Figure 7. 1. In recent years China and Europe have become key wood suppliers for Japan, followed by Canada, Vietnam, the Philippines, and Indonesia. Simultaneously, both conventional and new suppliers are rapidly substituting logs with value-added processed products, such as plywood. The overall trend of wood product imports has led to a further downturn in the domestic wood industry, creating more chances for foreign producers, particularly those in Southeast Asia.

7.2.1.3.2. Trends of timber trade from Indonesia to Japan

Indonesia has the potential to become the world's most significant exporter of forest products, as it ranks among the top ten countries with the largest forest area (USAID, 2019), consisting of 120,495,702 ha forest area with 57.12% productive forest area (MoEF, 2019). In 2017, wood and wood products were the only products to rank in the top 10 Indonesian export commodities, representing 34% of total forest product exports (Puruwita & Oktora, 2019). The most prospective Indonesian timber market is its export efforts to Japan.

As shown in Table 7. 2 (Samejima, 2020), Indonesian wood exports to Japan in the form of logs have been recorded since 1939. The embargo on log exports then enabled subsidies for plywood exports to new markets, particularly Japan, from 1985 to 1990, owing to the Indonesian government's program of establishing wood processing plants for forest concession holders (Brown et al., 2005), which was followed by an increase in the value of plywood output (Brockhaus et al., 2012; Indonesia, n.d.). This situation is inextricably linked to several government policies, such as the 1985 ban (Table 7. 2) on log export, the imposition of hefty export tariffs on sawn wood, and laws requiring holders of Forest Business Rights (HPH) to have a timber processing sector (Brockhaus et al., 2012; Nakayasu, 2013).

Table 7. 2 History of the wood production in Indonesia to Japan.

Year	Occurence

1939	Japan imports Indonesian (Kalimantan) dipterocarp logs for plywood.
1949	Timber exports were not active throughout President Soekarno's tenure (1949-1965)
1967	During the reign of President Soeharto, log exports resumed (1967-1998)
1973	The first plywood manufacturing firm was formed in North Sumatra and South Kalimantan.
1974	Plywood manufacturer established in Java
1984	APKINDO invented and monopolized exports of plywood.
1985	All log exports are forbidden in order to develop Indonesia's plywood industry.
	Japan relocates its log supply from Indonesia to Sarawak (Murashima and Araya 2000)
1990	Indonesia's plywood export boom hits Japan (10.6% export value, bankrupting hundreds of Japanese enterprises)
1998	Apkindo monopoly and log export ban ended
1999	Forestry authority is under District Government (Forest Law)
	Logs were illegally harvested for domestic and export use.
2000	Smallholder plantations of fast-growing tree species (*Albizia falcataria*), which are the most widely planted, have become highly active, particularly in Java.
2001	Indonesia again prohibits log exports
	Forestry authority was returned to the Ministry of Forestry from the District Government.
2004	President SBY (2004-2014) shuttered plywood manufacturers using illegal timber to combat illegal logging.
2008	Indonesia's plywood exports to Japan have decreased by 65% over the past four years
2016	Industrial plantation forest production accounts for 66% of Indonesia's total log production.

APKINDO: The Indonesian Wood Panel Association; SBY: Susilo Bambang Yudhoyono

Source: Research Documentation, 2021.

Japan is the second largest importer of Indonesian wood, according to the World Integrated Trade Solution's projections for the growth of Indonesia's wood exports per country from 2015 to 2019 (WITS, 2022). China is by far the largest importer of Indonesian timber, whereas the United States, Republic of Korea, Saudi Arabia, Malaysia, and Australia are the greatest importers of Indonesian timber after Japan.

In the context of Indonesian wood exports, this is since the expansion of China's furniture and processed wood industries necessitates the importation of wood from other nations. On the other side, China is establishing an industry for the re-export of wood, specifically plywood, which requires vast quantities of plywood. Each year, the value of Indonesia's wood shipments to China rises, aided by China's economic growth. In the meanwhile, Japan imports wood from other countries, particularly Indonesia, due to the substantial local demand for wood, which cannot be met by domestic production.

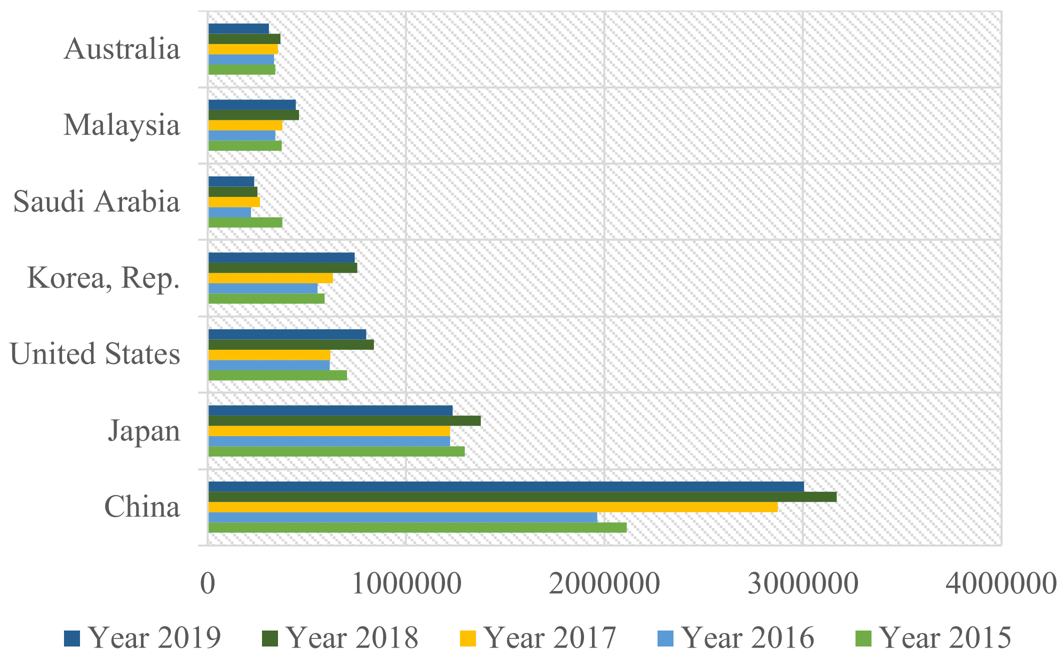


Figure 7. 2 Indonesian wood exports by country.

Source: World Integrated Trade Solution (WITS, 2022).

Since the re-imposition of a restriction on the export of Indonesian logs in 2001, Indonesia's international timber trade has concentrated on the export of plywood, whose quality is improving. Plywood has recently become one of Indonesia's most crucial wood products for Japan (Simanjuntak & Nurmalina, 2017). With the rising economic trend, Japan has positioned Indonesia as one of the top exporters of rainforest products, including plywood, pulp, and sawn wood (Makkarennu et al., 2015).

The Indonesian policy has been shown to support expanding the national timber processing industry, resulting in significant increases in Indonesia's plywood exports. Indonesia was the largest exporter of plywood from 1988 to 2002, with a steadily rising export value. Even Indonesia, particularly for tropical plywood, might be regarded as a market leader (Dwiprabowo, 2009). However, the value of Indonesia's plywood exports has been declining since 2002 in the global market (ITC, 2022). China exported more plywood than Indonesia, with an average worldwide market share of 25.38% from 2001 to 2020, compared to Indonesia (15.11%).

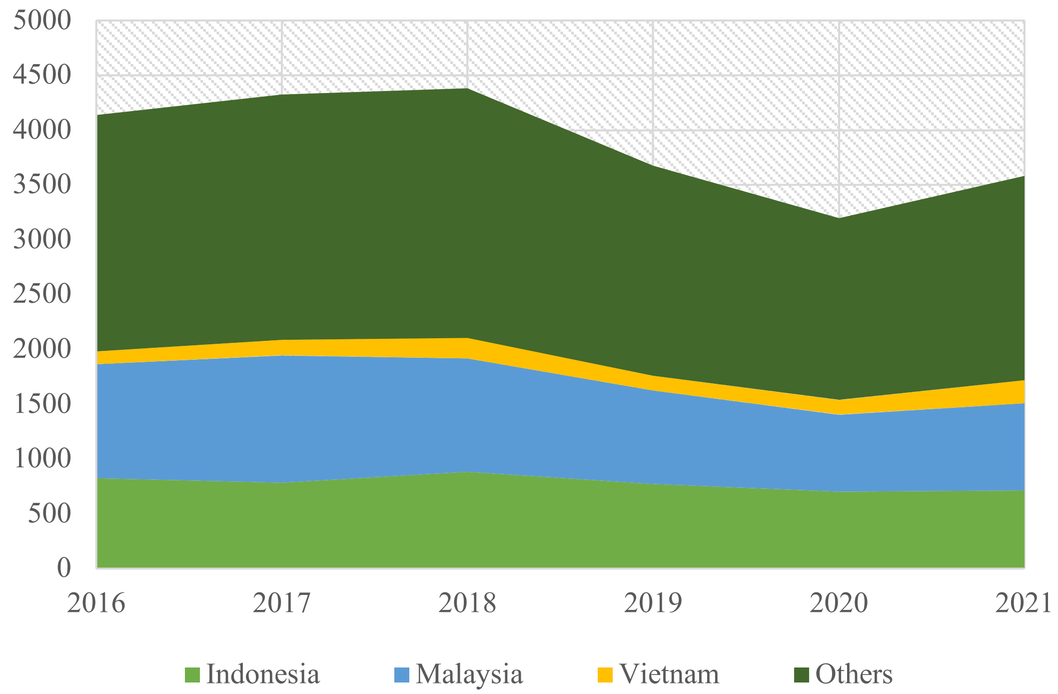


Figure 7. 3 Source of plywood consumed in Japan.

Source: Japan Forestry Agency, 2020-2021 (Japan Forestry Agency, 2021)(Japan Forestry Agency, 2022).

Nevertheless, following data on exports to Japan, Indonesia remains one of the leading exporters in the Japanese market. Malaysia and Indonesia are Japan's primary sources of tropical plywood at present. According to the most recent statistics from the Japanese Forestry Agency for 2021 (Figure 7. 3), Japan's plywood imports increased by 12% from the previous year to 1.87 million m^3 in 2021. The volume has been declining since 2019 alongside rising costs. However, this trend reversed in 2021 due to a deficiency of domestic supplies.

In 2021, the largest exporters of plywood to Japan were Indonesia (42% share), Malaysia (38% share), and Vietnam (11% share) (Japan Forestry Agency, 2022). Indonesia's plywood exports to Japan increased 2% from the previous year to 715 thousand m^3, equal to Malaysia's performance.

Late in 2021, to avoid port congestion in the United States, Indonesia switched its export destination from the United States to Japan, causing a rise in Japan's imports. In contrast, Malaysia and Indonesia are not necessary providers of round logs and sawn wood to Japan (Malau et al., 2022). Therefore, except for paper and pulp, Japan remains the major importer of Malaysian and Indonesian wood products.

Following the two-digit HS categorization, Indonesia produces and trades four forest product commodities: wood, wood products, pulp, paper, and furniture. Timber and wood products are the only forest product commodities listed in the top ten export commodities in 2017, contributing to 34% of total forest product exports (Puruwita & Oktora, 2019). On the other hand, plywood (HS 4412) accounts for the most significant proportion of wood and wood products, comprising 42% in 2017.

Albasia, the major material for plywood from Indonesia, is included in the HS 4412 classification in worldwide exports. Albasia is commonly used to make plywood, laminated veneer lumber (LVL), and wood plastic composites (WPC)(Arnandha et al., 2017).

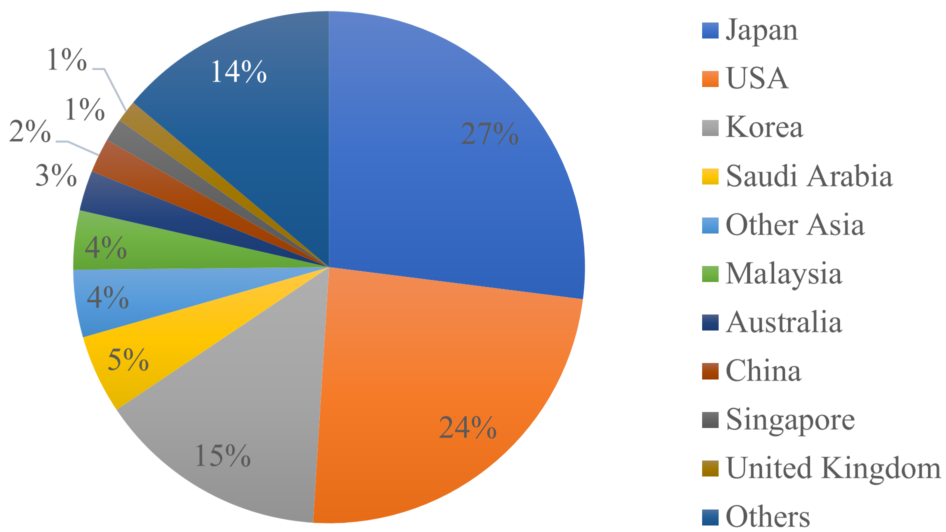


Figure 7. 4 Market share of Indonesian HS 4412 export destination countries

Source: Research Documentation, 2022.

In 2020, the export value of Indonesia's 4412 commodity category was $1.74 billion (Trend Economy, 2021). Figure 7. 4 depicts a diagram of Indonesia's 2020 export destinations for plywood, veneer panels, and similar laminated wood. Japan is the top export destination for the HS 4412 category, with 27%, followed by the United States (24%), Korea (14.6%), Saudi Arabia (4.98%), and the rest other nations.

7.2.1.4. Albasia Product

7.2.1.4.1. Trends of albasia *in Indonesia*

7.2.1.4.1.1. Domestic wood product

Albasia is a fast-growing tree, making it a lightweight, easy-to-manufacture material, but it is insufficient as a structural component, and its price is generally relatively cheap. With these properties, this wood has been chiefly utilized locally for low-value-added products and has been overlooked as a high-value-added industrial wood. The use of Albasia wood is generally used for the manufacture of furniture such as tables, drawers, or multipurpose boxes. However, some West Java residents still utilize it as wall material in their primary dwellings (Chandra et al., 2018).

7.2.1.4.1.2. Its cultivation as a sustainable wood product

Albasia is a well-known easy-to-grow plant with simple cultivation requirements (Z. Siregar et al., 2008). In Garut, West Java, local populations have reported that albasia wood is typically planted on privately owned property or in residential yards (Julian et al., 2021).

Albasia product is environmentally friendly since the trees are produced on privately held land rather than in wild forest areas. In addition, private tree planting is an indicator of community growth, which is perceived as supplementary to environmental conservation.

7.2.1.4.1.3. Current status of albasia production

Due to its potential, the Indonesian government prioritizes albasia as the primary export of wood material. However, this does not mean that the domestic market only cultivates the wood. On the contrary, by accepting products that are rejected on the international market, the domestic market can support the export industry (Araya, n.d.).

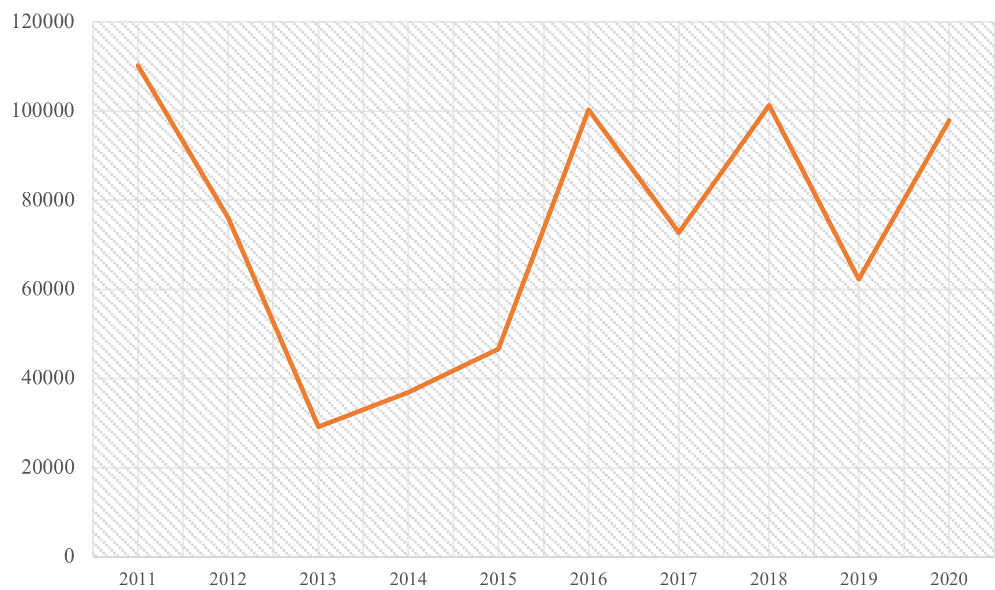


Figure 7. 5 Production of Albizia falcataria cultivators.

Source: The Central Bureau of Statistics (The Central Bureau of Statistics of Indonesia, 2022).

The Central Bureau of Statistics reported fluctuations in albasia production (see Figure 7. 5). The lowest production in the 2011-2020 period was in 2013. On the contrary, the highest output after the most insufficient production occurred in 2016 and 2020, although the presentation was not as high as in 2011(The Central Bureau of Statistics of Indonesia, 2022).

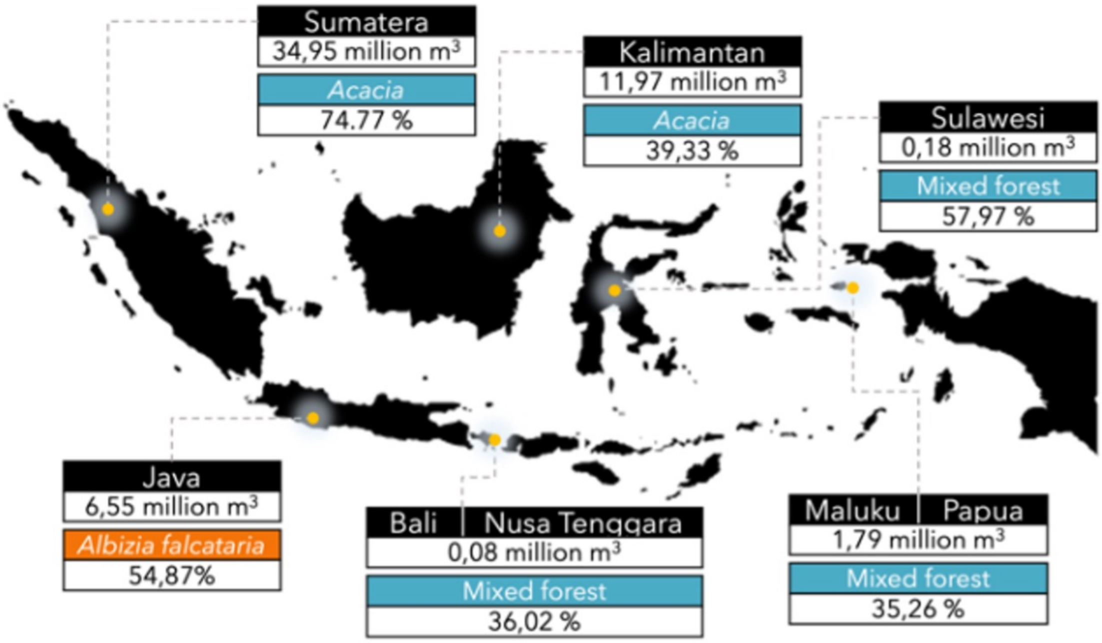


Figure 7. 6 The most significant production of logs by the island in Indonesia, 2018.

Source: Forestry Production Statistics, 2018 (Badan Pusat Statistik, 2018).

Indonesia is the largest island nation on earth. To determine the distribution of albasia wood in Indonesia, we collected quarterly forest statistics from the Central Bureau of Statistics. Based on Forestry Production Statistics 2018, the total production of logs in Indonesia is 55.52 million m^3 (Badan Pusat Statistik, 2018). Figure 7. 6 shows that albasia wood leads the primary log products produced in Java, contributing to 6.55 million m3, or 54.87% of all logs produced in Java and 11.8% of all logs produced in Indonesia.

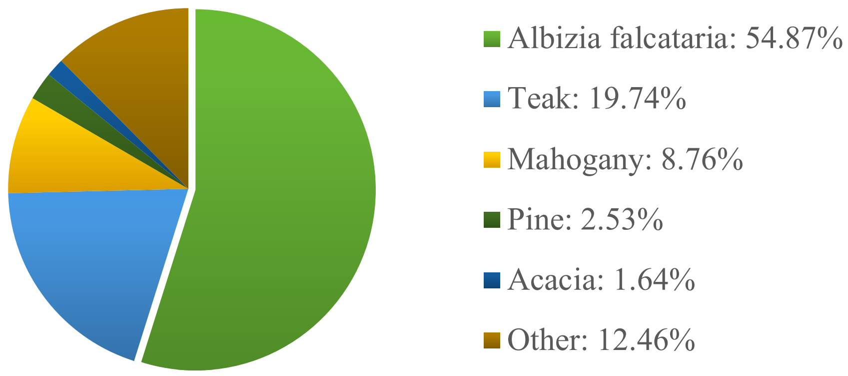


Figure 7. 7 Percentage of main log production in Java Island

Source: Forestry Production Statistics, 2018 (Badan Pusat Statistik, 2018).

The percentage of main log production in Java Island in 2018 is represented in Figure 7. 7. Aside from albasia, the primary log production in Java is dominated by Teak, Mahogany, Pine, and Acacia. While Acacia dominates the highest log production by type in Sumatra, Kalimantan is also dominated by *Acacia* at 39.33%, Sulawesi has a mixed forest at 57.97%, Maluku and Papua have a diverse forest at 35.26%, and Bali and Nusa Southeast also have a mixed forest at 36.02%.

7.2.1.4.2. Trends of albasia market in Japan

7.2.1.4.2.1. Product utilization

As a fast-growing tree species, albasia is solid wood with a distinctive white color and a coarse surface. This product sells well in Japan as a do-it-yourself (DIY) material due to its robust qualities and bright color.

Japanese cedar (*Cryptomeria japonica*) is an evergreen tree species frequently used to manufacture wood products for structural and ornamental uses in Japan due to its rapid growth rate and advantageous processing characteristics (Yang et al., 2016). Reddish or yellowish is the color of Japanese cedar wood (Cheng & Chang, 2008). Customers prefer albasia wood to Japanese cedar due to its lighter hue and more outstanding suitability for minimalist interior design. Therefore, the albasia product is popular among the Japanese.

7.2.1.4.2.2. Japanese legality and standard verification

Figure 7. 8 Albasia product in the Japanese store.

Source: Research Documentation, 2022.

In 1953, the Japanese government established the Japan Agriculture Standard (JAS) to standardize veneer and plywood commodities (Goto, 2012). The 1971 modification of the Building Standards Act mandates using JAS-certified materials in the construction of significant building constructions. Therefore, any foreign wood entering Japan must adhere to the JAS standard. As a result, it is simple to determine the origin of timber sold on the Japanese market, as JAS-certified wood carries its natural wooden source stamp.

In addition, the Japanese government has sponsored an active campaign against illegal logging and ensured that, since the 2000s, only legal wood products had been purchased by Japan. In 2016, Japan passed the Law for the Promotion of the Use and Distribution of Legally Harvested Wood and Wood Products (Clean Wood Act) (Clean Wood Act, 2017).

Regarding Figure 7. 9, obtained from one of Japan's building material suppliers, the commercially available albasia wood has the SVLK logo. In 2009, the Indonesian government applied for SVLK (Timber Verification and Legality System), which intended to track and classify legitimate timbers (Nurkomariyah et al., 2019). Under the SVLK rule regulated by the Indonesian Ministry of Industry, it is regarded permissible in the chain of harvesting, processing, transporting, and trading as an export-oriented destination (Susilawati et al., 2019b). As a result, the system positively influenced the value of Indonesian plywood exports, which increased after Indonesia implemented it.

Figure 7. 9 Albasia product in the Japanese store in SVLK logo.

Source: Research Documentation, 2022.

7.2.1.4.2.3. Japanese market

In contrast to its usage in the local Indonesian market, albasia is now commonly available in the do-it-yourself sections of various Japanese stores (Figure 7. 8) and is also widely available on the Japanese online marketplace (Table 7.3).

Based on field observations, multiple businesses in the Kitakyushu region of Fukuoka, Japan, sell several varieties of albasia items from Indonesia (see Table 7. 4).

Table 7. 3 Product in the Japanese online market

No	Japanese online store	Product
1	Amazon japan	Original wood
2	Home center Kohnan	Original wood
3	Rakuten Mokuzaiya	Laminated wood

Source: Research Documentation, 2022.

Table 7. 4 Product availability in the Japanese stores.

No	Japanese store	Product
1	Nafco	Laminated wood
2	Hallo Day	LVL chambering (solid); shelf board; laminated wood

Source: Research Documentation, 2022.

7.2.1.4.5. Conclusion

1) The demand for wood from Indonesia to Japan began with logs in 1970, continued with the popularity of plywood starting in 1990, and entered the 2000s when albasia wood, a fast-growing tree species, made this wood famous in Japan as well.
2) Japan is the second largest importer of Indonesian timber by country, whereas, in the HS 4412 category, Japan is Indonesia's top export destination.
3) Albasia wood has become the most valuable wood product in Java, representing 54.87 % of all logs produced in Java (6.55 million m3).
4) Due to its white color, albasia wood products are currently popular as a do-it-yourself material in Japan and are accessible in building supply stores and the online marketplace.

7.2.1.4.6. Suggestion

In the last five years, Japan's demand for Indonesian wood has been slightly lower than Malaysia's, so the Indonesian government should make more tremendous efforts than Malaysia to improve this demand. In addition, further research must include comparisons and pricing competitiveness for albasia wood in offline and online stores across the Japanese market and with other woods from both the Japanese domestic market and foreign wood competitors.

7.2.2. Japanese cedar

Currently, Japan imports significant quantities of timber and forest products, and the environmental significance of forests relative to timber production is growing. As one of the most abundant softwoods in Japan, the Japanese Cedar accounts for 43% of the country's plantation forest area (Forestry Agency of Japan, 2015). Japanese cedar (*Cryptomeria japonica* D.Don; sugi) is softwood species, one of the most commonly planted trees in Japan due to its high value as a furniture and siding industry (CHERDKEATTIKUL & IDA, 2019). Due to the variability of Japanese cedar, several types of this species exhibit color differences (i.e., reddish, yellow) (Cheng & Shang-Tzen Chang, 2008).

Japanese cedar is a prominent wood material in Japan, and its wood quality has been the subject of extensive study (Kumagai et al., 2014). The development of novel wood products made from Japanese cedar has been a national priority for more than two decades, as its growth has increased year after year (Hayashi & Miyatake, 2015). Numerous initiatives have been undertaken to expand the market for Japanese cedar as a construction material. Until the 1990s, Japanese cedar as a raw material was not readily adopted by the glued laminated timber (GLT) industry in Japan due to issues with its wood quality, specifically lower properties and yield rates than the major imported wood species in Japan (Miyatake A, 2009). Several Japanese research institutes have therefore conducted a series of intensive studies on the modification of Japanese Cedar wood.

7.3. Materials and methods

In this study, Indonesian albasia wood and Japanese cedar wood boards were obtained from a building material supply industry in Kitakyushu City, Fukuoka Prefecture, Japan.

7.3.1. Preparation of wood specimens

Samples were taken in accordance with the requirements and methods specified in the Japanese Industrial Standard (JIS) Z 2101: 2009 (Japanese Standards Association, 2009) for testing mechanical and physical properties of wood. The defect-free boards had the following dimensions: 13.5 × 150 × 910 mm (thickness x width x length) wrapped in plastic from the manufacturer. All specimens were pre-conditioned to a temperature of 20 °C and humidity of 60% before the experiment. To make the smaller pieces of wood to be compressed, the albasia wood board was then cut into 13.5 x 15 x 910 mm (thickness x width x length) using a table saw.

7.3.2. Experiment Procedures

Experiments were conducted in the high-temperature and -pressure apparatus HTP-50/130 (HISAKA Company, Osaka, Japan) at The University of Kitakyushu's Graduate School of Environmental Engineering in Kitakyushu, Japan. The apparatus included a processing tank and a boiler-setting machine. Table 7. 5 displays the manufacturing conditions for this experiment. The consolidation phases of the densification process for albasia wood and Japanese cedar wood consist of the preliminary vacuum phase, the softening phase, the final vacuum phase, the compressing phase, and the chilling phase.

Table 7. 5 Manufacturing conditions.

Type	**Sample**	**Softening Temp. (℃)**	**Softening time (min)**	**Cooling time (h)**	**Adhesive (g)**	**Isocyanate (g)**	**Weight (g)**
Albasia	FS-1	140	30	24	700	105	4000
	FS-2	140	30	24	700	105	4000
	FS-3	140	30	24	700	105	4000
	FS-4	140	30	24	700	105	4000
Japanese Cedar	JS-1	140	30	26	800	120	4500
	JS-2	140	30	23	700	105	4500
	JS-3	140	30	23	700	105	4500
	JS-4	140	30	23	700	105	4500

Source: Research Documentation, 2023.

The first step was to collect and weigh 4000 g of small cut wood before placing them in the processing tank. The wood is then treated beginning with a five-minute *preliminary vacuum phase*, followed by a *softening phase* involving heating and maintaining temperatures. According to previous research, the minimum temperature necessary (F. Kollmann & Schneider, 1963), while the optimal temperature is 140°C. Ten minutes are required to attain the desired temperature of 140°C during the heating process. This procedure minimizes defects resulting from temperature differences between the wood sample and the processing environment. From this point forward, the temperature-maintenance process can take up to 30 minutes. After the softening phase is complete, a 5-minute *final vacuum phase* is administered.

Immediately following the softening phase, the adhesive and isocyanate are mixed with the softened wood. The wood parts are evenly coated with a mixture of 700 g adhesive and 105 g isocyanate in the mold device. After the combining of the adhesive and isocyanate has been completed, move on to the *compressing phase*. During the compressing phase, two machine cylinders press the mold device's upper steel plate. The spring back phenomenon following treatment has been defined as the lost compression effort (Yuhe & Muehl, 1999). The temperature difference between wood and ambient air becomes significant after heating. In order to minimize fracture defects in the wood after the treatment, the *cooling phase* is carried out in the processing environment until the temperature reaches that of the external environment. After the treatment procedure was complete, all specimens were stored for up to 360 hours by periodically weighing them until the mass difference for testing was negligible.

7.3.3. Determining of Physical Properties

The density of compressed wood refers to the Japanese Industrial Standard (JIS) Z 2101: 2009 (Japanese Standards Association, 2009) was determined using the following equation (1):

$$\rho_w = \frac{m_w}{v_w}$$

where ρ_w represents the density; m_w represents the mass; and v_w represents the volume, at moisture content *w*. The mass of the wood sample was determined using a digital scale with an accuracy of 0.01 g (A&D: FZ-5000i). The volume of the wood was measured using a caliper with an accuracy of 0.01 mm (Mitutoyo: ABSOLUTE Digimatic Scale Units-572 Series 0-8in/0–200 mm), with a 0.01 mm accuracy.

7.3.4. Determining of Mechanical Properties

7.3.4.1. Compressive strength test

Selected specimens of albasia and Japanese cedar were tested for their compressive strength in accordance with the Japanese Industrial Standard (JIS) Z 2101: 2009 and the British Standard (BS) 373: 1957, respectively (Japanese Standards Association, 2009)(British Standard, 1957). In order to better comprehend the compressive strength properties of wood, longitudinal and tangential compression tests were prepared. Each specimen of albasia and Japanese cedar, control and treated wood, as well as the loading direction of the test specimens, were prepared with comparable dimensions of 60 x 30 x 30 mm (thickness x width x length).

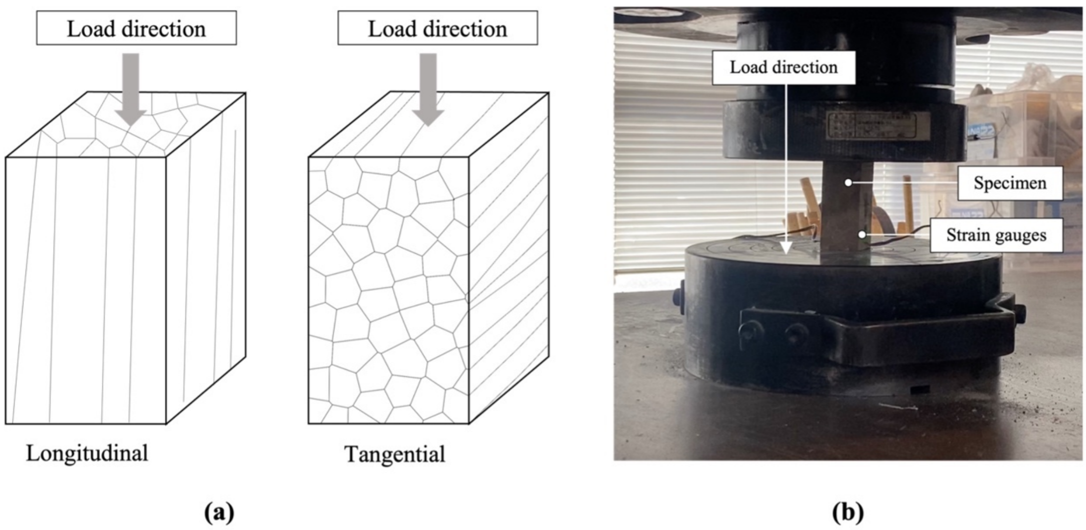


Figure 7. 10 Loading application of compressive strength test.

Source: Research Documentation, 2023.

Figure 7. 10 shows the loading application of compressive strength test. The compressive strength tests were conducted using a universal material testing machine, UH-2000kNXR (Shimadzu Corporation, Japan), with a computer-controlled servo-hydraulic system, operating frequency of 60 Hz, and maximum load capacity of 2000 kN. The test was load-controlled at a rate of 0.5 MPa/s, and the SFRC axial strain was measured by averaging the signals from two displacement strain gauges (Tokyo Measuring Instruments Lab, type LFLAB-10-11-5LJC-F, gauge length 10 mm) that

were mounted to the specimen. When the load stabilizes during continuous pressing, the test is terminated. All values were adjusted to a 12% moisture content in accordance with the specifications of each applicable standard. The compressive strength is calculated using equation in accordance with the previously mentioned standards:

$$\sigma_c = \frac{P}{A}$$

$$\varepsilon_c = \frac{\Delta l}{l}$$

σ_c = Compressive strength (MPa)

P = Maximum load (N)

A = Cross sectional area of sample (mm^2)

l = Target point distance (mm)

Δl =Shrinkage corresponding to ΔP (mm)

When shrinkage is measured, the proportional stress of compression and the Young's modulus of compression of the wood are calculated by the following formula.

$$\sigma_{cp} = \frac{P_p}{A}$$

$$E_c = \frac{\Delta P l}{\Delta l A}$$

σ_{cp} = Compressive proportional limit stress (MPa)

E_c = Compressive Young's modulus (N/mm^2)

P_p = Proportional limit load (N)

A = Cross sectional area of sample (mm^2)

ΔP = Difference between the upper and lower load limits in the proportional limit region (N)

Maximum force measured (Pmax) is used to calculate compressive strength. The compressive strength at proportionate limit is the highest stress that a material can withstand while exhibiting no permanent distortion (Rowell et al., 2012). Graphically, it represents the endpoint of the linear range of the stress-strain curve (Báder & Németh, 2019). Using the equation, the compressive strength at the proportionate limit was also computed based on these factors.

7.3.4.2. Bending strength test

To determine the maximum bending strength, control and compressed specimens were tested using three-point static bending strength tests in accordance with the Japanese Industrial Standard (JIS) Z2101-94: 1994.

Compressed wood and control wood test specimens were cut to dimensions of 30 mm (radial direction), 30 mm (tangential direction), and 480 mm (longitudinal direction) for the three-point bending test.

The parameters of the loading procedure were determined based on the estimated maximum load (Fmax), which was derived from the bending strength test conducted until failure. For the three-point static bending strength tests, the span between lower supports was 420 mm. The central loading point was fixed. The test was conducted at a rate of 0,08 mm/s. Figure 7. 11 illustrates a schematic illustration for three-point bending test setup.

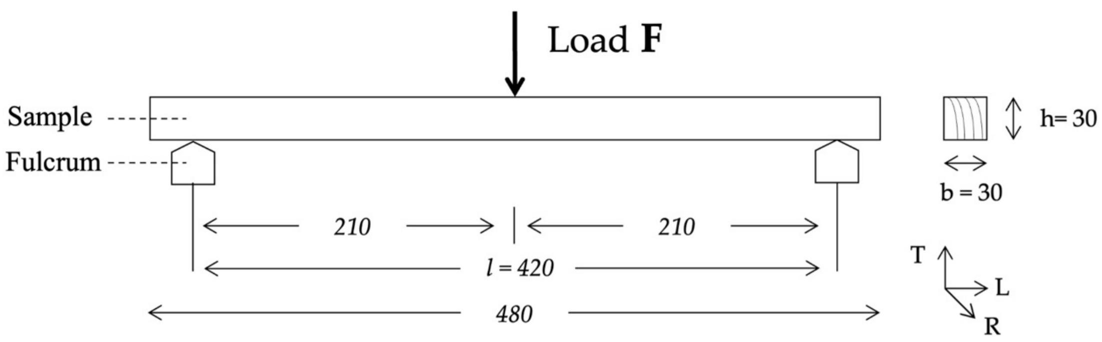


Figure 7. 11 Schematic Illustration for three-point bending tests. Dimensions are presented in mm.

Source: Research Documentation, 2023.

The modulus of rupture (MOR) of the samples were calculated after cyclic loading. These calculations were carried out according to equation,

$$\sigma_b = \frac{Pl}{4Z}$$

σ_b = bending strength of the wood (MPa)

P = maximum load (N)

l = distance between fulcrums (mm)

Z = Section modulus (mm)

If the declection is measured, the proportional bending limit stress (σ_{bp}) of the wood and the approximate Young's modulus in bending (E_b) are calculated by the following formula:

$$\sigma_{bp} = \frac{P_p l}{4Z}$$

$$E_b = \frac{\Delta P l^3}{48 I \Delta y}$$

σ_{bp} = bending proportional limit stress (MPa)

E_b = Apparent Young's modulus im bending (N/mm^2)

P_p = proportional limit load (N)

l = distance between fulcrums (mm)

Z = section modulus (mm)

I = Moment of inertia (mm)

ΔP = Difference between upper and lower limit load in proportional limit region (N)

Δy = Mid-span deflection corresponding to ΔP (mm)

7.4. Results and Discussion

7.4.1. Physical properties

7.4.1.1. Visual assessment of wood surface

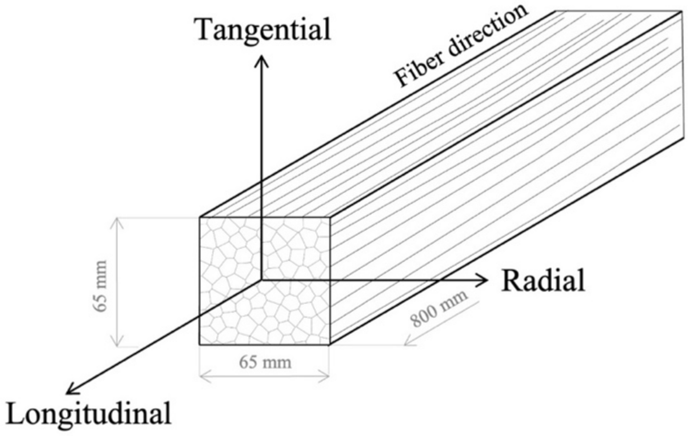


Figure 7. 12 Shape and dimensions of the specimens.

Source: Research Documentation, 2023.

Due to its soft color and rough wood texture, the demand for albasia wood boards supplied by the Indonesian processing industry is extremely high worldwide, particularly on the Japanese market (Nemoto, 2002a). In contrast to albasia wood, Japanese cedar wood is reddish and yellow. In Figure 7. 12, which depicts the tangential, longitudinal, and radial directions, the directions and dimensions of the treated wood specimens are displayed. The color of the wood can alter during and after densification at high temperatures and pressures (Bekhta & Niemz, 2003).

Figure 7. 13 displays the surface appearance of treated albasia wood, as well as treated Japanese cedar wood in Figure 7. 14. The cross-sectional surface view of the wood in the longitudinal direction reveals a structural shape with a Voronoi diagram in which both albasia wood and Japanese cedar wood exhibit parametric quality irregularities. In the meantime, the surface of the wood in both radial and tangential dimensions reveal the direction of the treated wood fibers. The Voronoi diagram of treated albasia and Japanese cedar wood has a densified wood lattice with glue and isocyanate-filled voids. The use of cross-sectional views of wood surfaces with Voronoi diagrams could become a new trend in architectural woodwork.

Figure 7. 13 Treated albasia wood (Left: Cross section); (Right: Fiber direction).

Source: Research Documentation, 2023.

Figure 7. 14 Treated Japanese cedar wood (Left: Cross section); (Right: Fiber direction).

Source: Research Documentation, 2023.

Both albasia and Japanese cedar wood samples revealed that the treated wood was darker than before treatment. When wood undergoes thermal processing, the decrease in luminosity and increase in color difference are due to the presence of formation byproducts (Kocaefe et al., 2008), which is caused by the decrease in hemicellulose content, particularly pentosan (Bourgois et al., 1991). The oxidation of polysaccharides and lignin results in the formation of phenolic compounds, which are potentially discoloring (Fengel & Wegener, 1989).

7.4.1.2. Influence on density

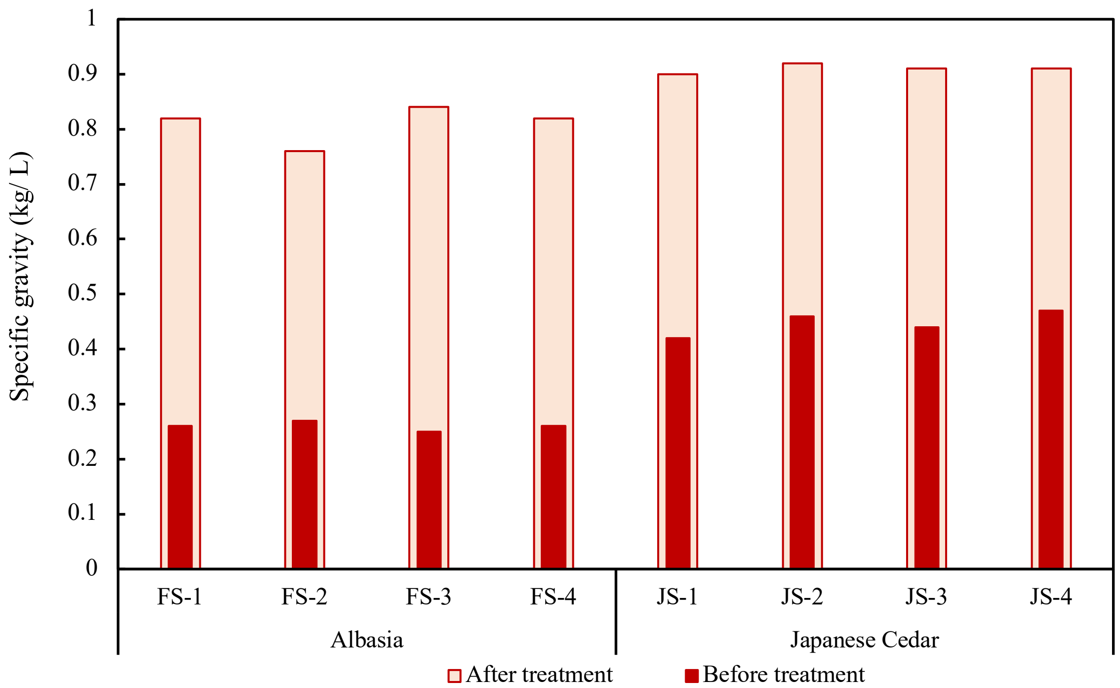


Figure 7. 15 Comparison of the increase in density of albasia and Japanese cedar wood before and after treatment.

Source: Research Documentation, 2023.

The comparison of the increase in density of albasia and Japanese cedar wood before and after treatment is shown in Figure 7. 15. The results demonstrated that the average density of treated albasia wood (0.81 kg/L) was greater than the average density of 0.26 kg/L before treatment ($p < 0.05$). The results also revealed that the average density of treated Japanese cedar wood (0.91 kg/L) was greater than that of untreated wood (0.45 kg/L; $p < 0.05$). The treatment procedure has increased the density of albasia wood by 311.54%, while the density of Japanese cedar has increased by only 203.35%.

Nandika et al. also discovered that the density of tangential board type albasia wood increased when impregnated with 0.5% chitosan solution at the maximum temperature of 140 °C and then compressed at the highest temperature of 190 °C, resulting in an average wood density of 80.70%(Nandika et al., 2014). Meanwhile, high temperature and high pressure treatment on albasia wood boards with the maximum treatment temperature of 140% revealed an average wood density of 112.78% (Julian et al., 2022), as determined by Julian et al.

7.4.2. Mechanical properties

7.4.2.1. Analysis of compressive strength test

Using a universal testing machine, a monotonically increasing compressive load was applied orthogonally to the cross-section of each treated and untreated albasia wood specimen. The analysis of compressive strength test results involves examining the data obtained during the test and interpreting it to gain insight into the material's behavior under compression.

7.4.2.1.1. Analysis of longitudinal compressive strength test

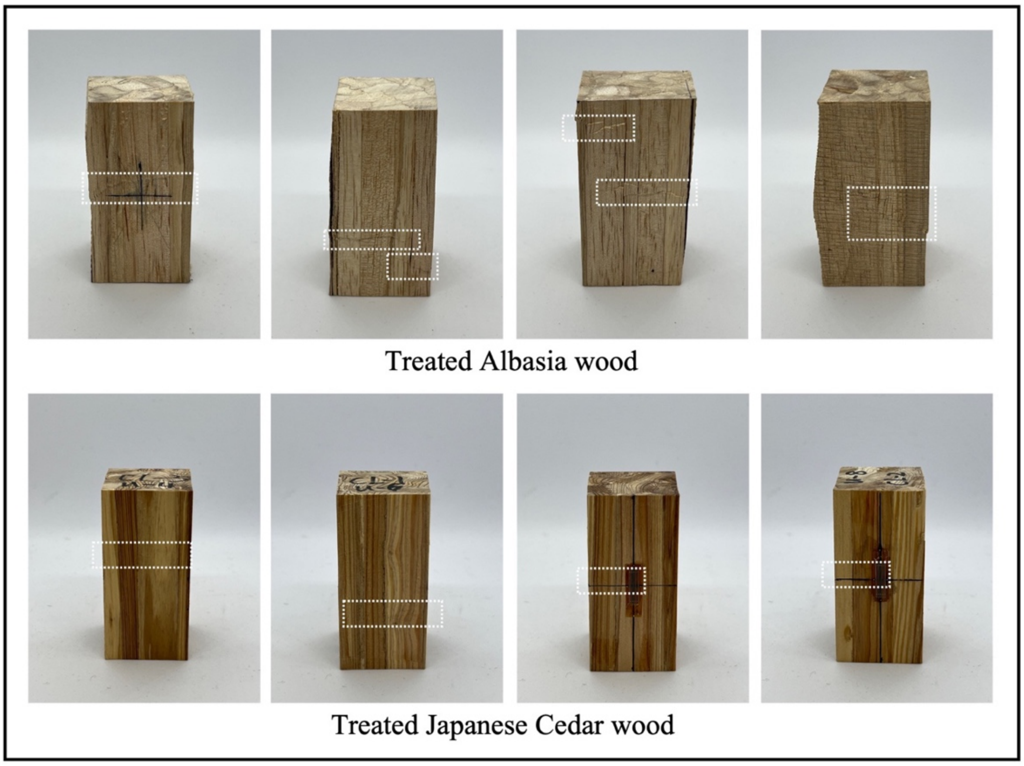


Figure 7. 16 Representative photographs of typical failure patterns of treated albasia and Japanese cedar wood longitudinal compression test.

After compressive strength testing, the failure of the specimen depicted in Figure 7. 16 in the longitudinal direction is readily explicable. In both albasia wood and Japanese cedar wood, the wood cracks have the same parallel transverse direction, confirming that testing to the maximum compressive strength limit induces cracks in all specimen types.

Based on the failure type referring to the wood failure type by Jozsef Bodig & Benjamin A. Jayne, the compressive strength test results in the longitudinal direction show that the sample has a *curshing failure* type in albasia and Japanese cedar treated (see Figure 7. 16). Crushing failure in longitudinal direction in the albasia and Japanese cedar treated wood refers to the collapse or deformation of wood fibers and cells when the material is subjected to compressive forces applied parallel to the grain. This type failure occurs when the compressive load exceeds the material's capacity to resist deformation, leading to the crushing or compaction of the wood structure.

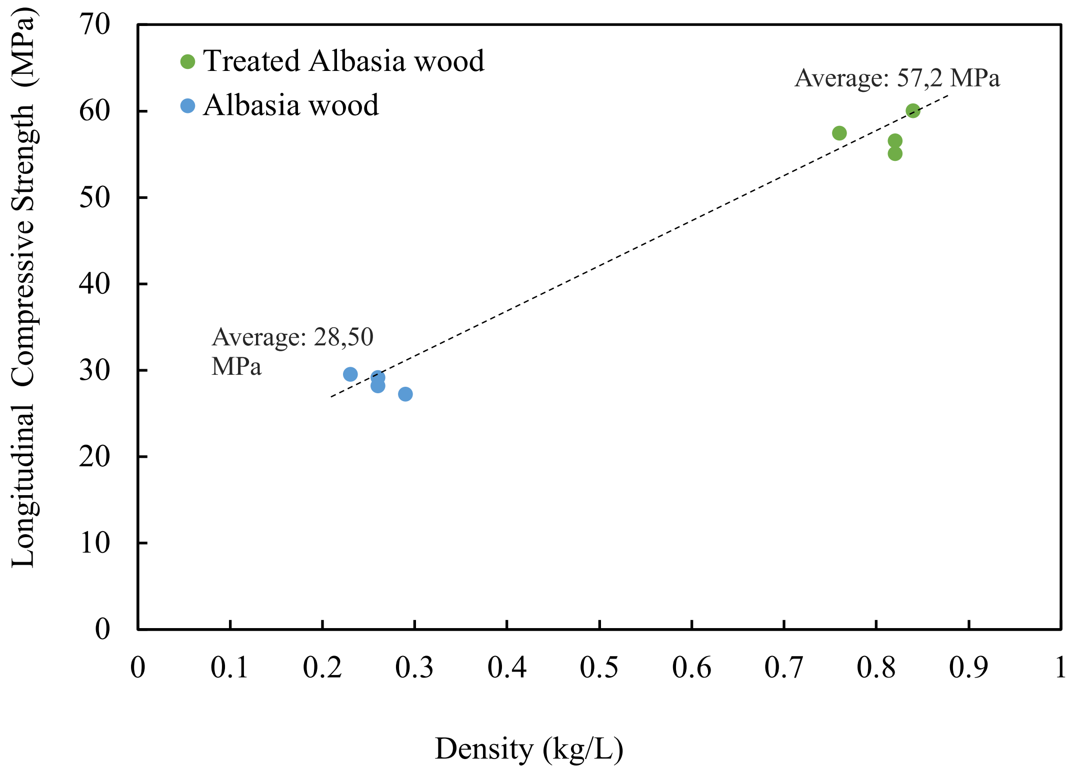


Figure 7. 17 Correlation between specific gravity and longitudinal compressive strength of treated and untreated albasia.

Source: Research Documentation, 2023.

The correlation between specific gravity and longitudinal compressive strength of treated and untreated albasia wood is shown in Figure 7. 17. The results revealed that the average longitudinal compressive strength of treated albasia wood (57,2 MPa) was higher than that of untreated wood 28,50 MPa ($p < 0.05$). Then Figure 7.18 shows the correlation between specific gravity and longitudinal compressive strength of treated and unreated Japanese cedar wood.

Moreover, the results demonstrated that the longitudinal compressive strength of treated Japanese cedar wood (52.0 MPa) was higher than that of untreated cedar wood 32.79 MPa ($p < 0.05$). The treatment procedure raised the longitudinal compressive strength of albasia wood by 200.86%, while the strength of Japanese cedar wood has increased by 158.52%.

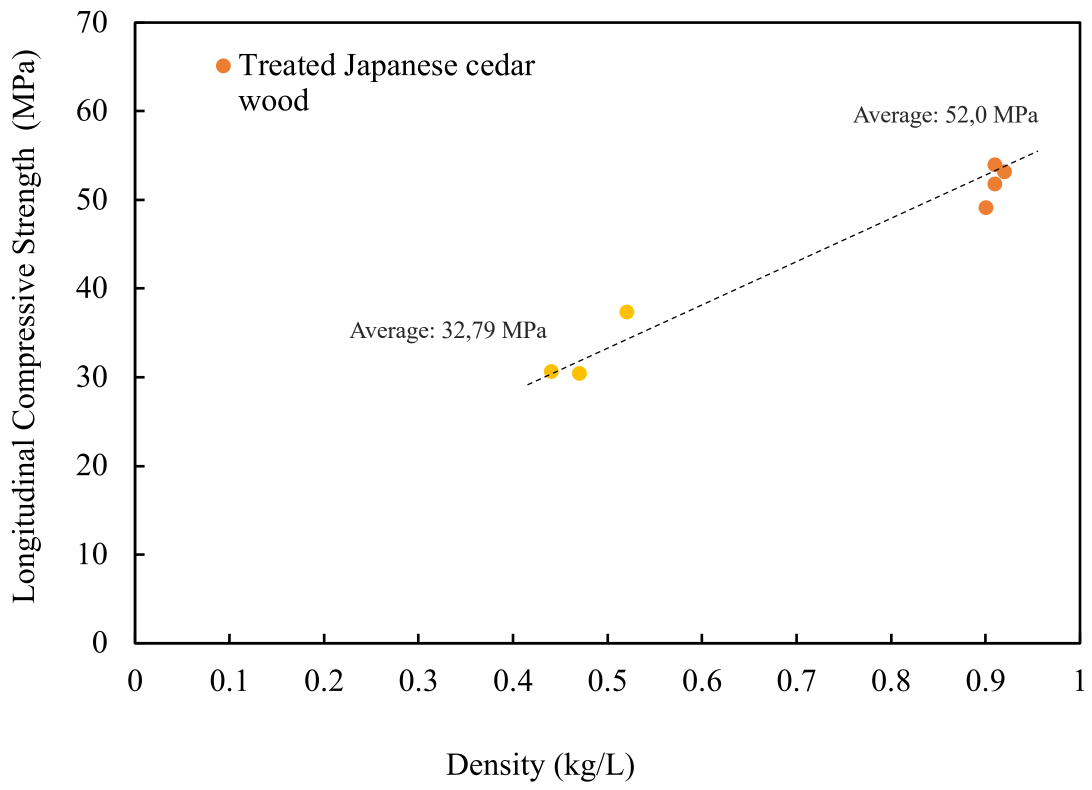


Figure 7. 18 Correlation between specific gravity and longitudinal compressive strength of treated and untreated Japanese cedar.

Source: Research Documentation, 2023.

7.4.2.1.2. Analysis of tangential compressive strength test

After compressive strength testing, the failure of the specimen depicted in Figure 7. 19 in the tangential direction is readily explicable as well. In both albasia wood and Japanese cedar wood, the wood cracks have the same parallel transverse direction, confirming that testing to the maximum compressive strength limit induces cracks in all specimen types.

Based on the failure type referring to the wood failure type by Jozsef Bodig & Benjamin A. Jayne, the compressive strength test results in the tangential direction show that the sample has a *splitting failure* type in albasia and Japanese cedar treated (see Figure 7. 19). Splitting failure in tangential direction on the specimen refers to the occurrence of longitudinal cracks or splits along the grain when the material is subjected to compressive forces applied in the tangential direction.

Figure 7. 19 Representative photographs of typical failure patterns of treated albasia and Japanese cedar wood tangential compression test.

Source: Research Documentation, 2023.

Figure 7. 19 depicts a specimen in the tangential direction whose failure is also easily understood following compression strength testing. In contrast to the test results in the longitudinal direction, the compressive test reveals the maximum compressive strength limit on the surface of the cross section, which has cracks in the diagonal direction following the Voronoi structure direction. In both albasia wood and Japanese cedar wood, the cracks had the same diagonal orientation, and all specimen types exhibited cracks induced by the test to the maximum compressive strength limit.

Moreover, the correlation between specific gravity and tangential compressive strength of treated and untreated albasia wood is shown in Figure 7. 20. The results revealed that the average tangential compressive strength of treated albasia wood (15,1 MPa) was higher than that of untreated wood 1.54 MPa ($p < 0.05$). Then Figure 7. 21 shows the correlation between specific gravity and tangential compressive strength of treated and untreated Japanese cedar wood.

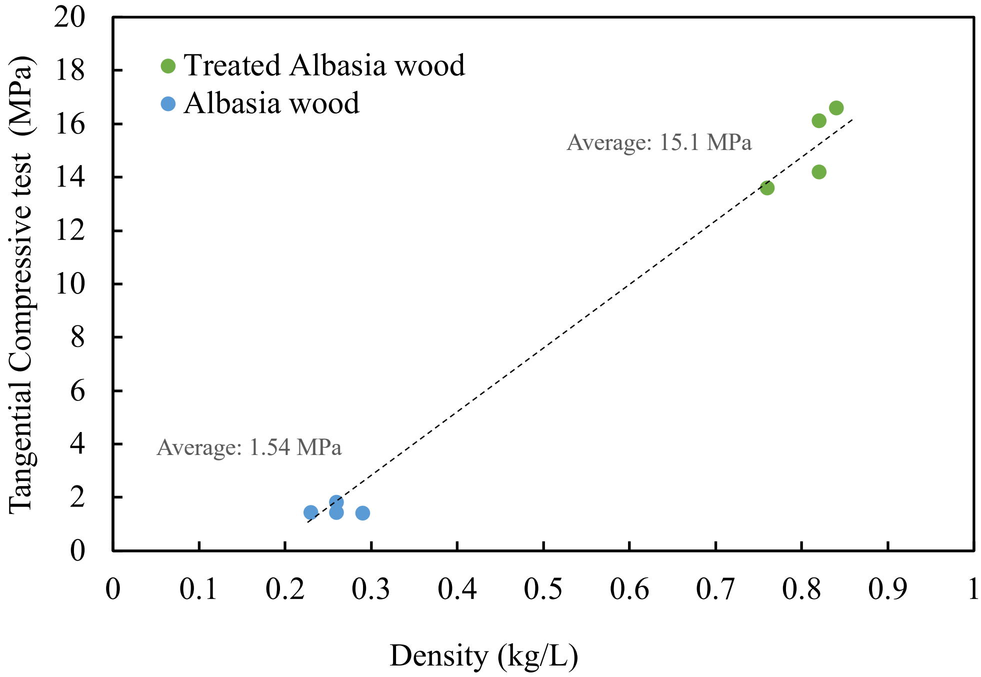


Figure 7. 20 Correlation between specific gravity and tangential compressive strength of treated and untreated albasia wood.

Source: Research Documentation, 2023.

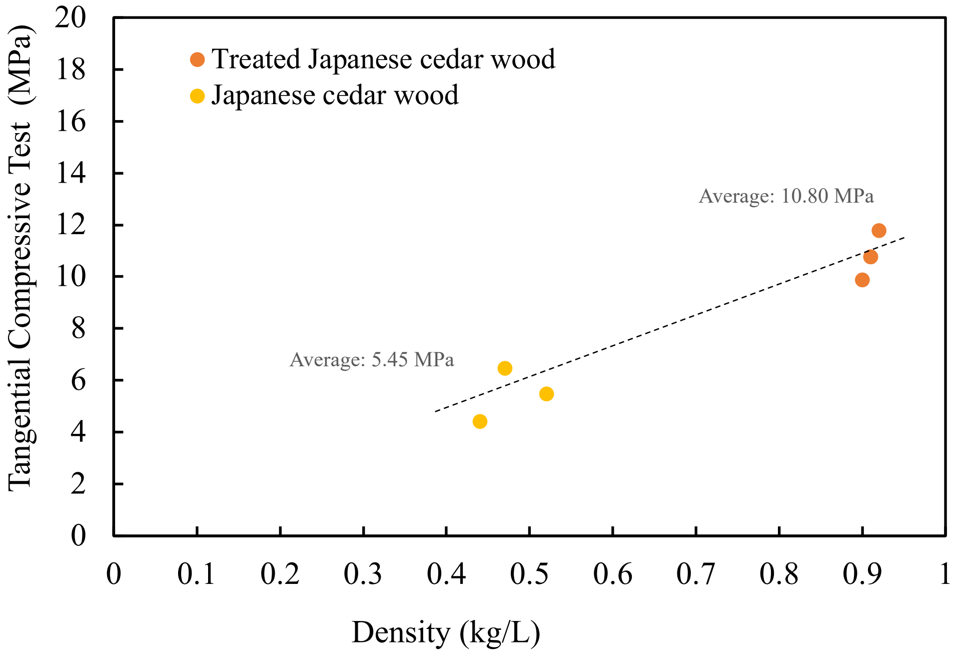


Figure 7. 21 Correlation between specific gravity and tangential compressive strength of treated and untreated Japanese cedar wood.

Source: Research Documentation, 2023.

The results demonstrated that the tangential compressive strength of treated Japanese cedar wood (10.80 MPa) was higher than that of untreated cedar wood 5.45 MPa ($p < 0.05$). The treatment procedure raised the tangential compressive strength of albasia wood by 981.72%, while the strength of Japanese cedar wood has increased by 198.10% (Figure 7. 22)

7.4.2.1.3. Comparative analysis of compressive strength test

Given the compression of the wood cell structure caused by compression, including the narrowing of the cavity (lumen), the increase in wood density and hardness observed in albasia and Japanese cedar subjected to compression treatment is comprehensible. In addition, the pores of the compressed wood are narrowed and partially filled with deposits believed to be the result of adhesives and isocyanates. The structure of untreated wood cells in both albasia and Japanese cedar wood, on the other hand, did not undergo compression.

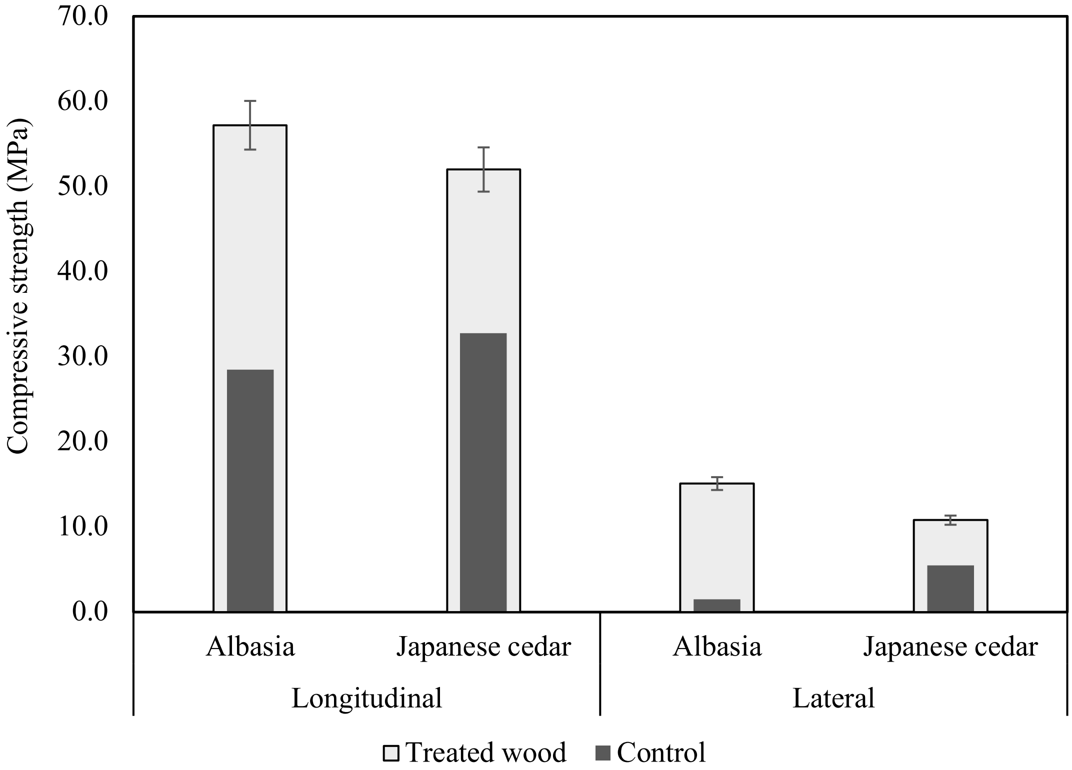


Figure 7. 22 Comparison of maximum compressive strength between control and treated albasia and Japanese cedar wood.

Source: Research Documentation, 2023.

Figure 7. 23 shows the types of fractures that occurred in the wood area of compressed wood specimens following compressive strength testing. Fractures were confirmed in all albasia and Japanese cedar specimen types. However, the compressed wood fractured at (1) and the part glued with isocyanate and glue detached at (2), indicating two distinct types of failure in the compressive strength test.

These types of failures at the wood-wood interface illustrate the strength and weakness of the force between wood and wood, as well as the strength and weakness of the adhesion between glue and wood. Cellulose and hemicellulose are also dissolved during treatment, so the entire failure process cannot be selective for lignin alone. This causes the cellulose chain to shorten and the wood structure to become brittle. In addition, failures resulting from testing at maximum compressive strength are caused by abnormal wood properties, wood adhesives, and the loading device itself (Lin et al., 2017).

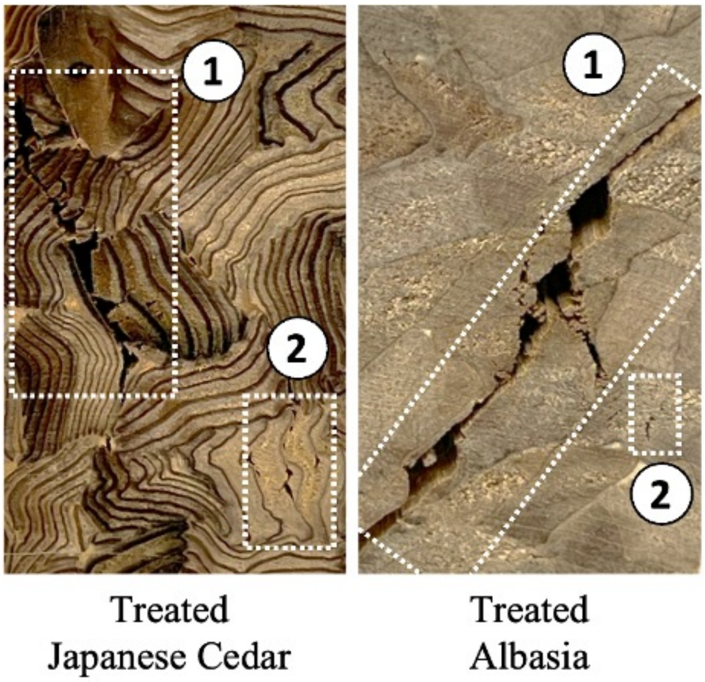


Figure 7. 23 A close-up view of cracks and fractures in the specimen after compressive strength test.

Source: Research Documentation, 2023.

7.4.2.2. Analysis of bending strength test

7.4.2.2.1. Failure mode

Table 7. 6 represents the failure modes of treated and untreated Albasia and Japanese Cedar wood samples. As depicted in the figures, failure always begins at the bottom of the loading point and propagates across the grain when a tangential load is applied. The bending strength test results for both treated albasia and Japanese cedar in this study are simple tension failure types, in accordance with the current failure types.

Simple tension failure occurs when wood breaks or cracks due to tensile stress induced by bending loads. When an object of wood is bent, the outside fibers are put under tensile stress, while the inside fibers are put under tension. Simple tension failure can happen if the tensile stress is greater than the tensile strength of the wood.

The treated albasia and Japanese cedar wood were put under increasing bending loads until they attained their breaking strength during the wood bending test. A simple tension failure can occur if the tensile stress in the outer fibers is too great and exceeds the tensile strength of the wood. The splitting or cracking that characterizes this failure, often starts near the surface. In a wood bending test, a simple tension failure implies that the wood cannot handle the tensile stress brought on by the bending force. Numerous elements, such as the composition of the wood, its microstructure, and its mechanical qualities, can have an impact on this failure.

Table 7. 6 Typical failure pattern after bending strength test.

Albasia	Treated albasia	Japanese cedar	Treated Japanese cedar
			

Source: Research Documentation, 2023.

7.4.2.2.2. Bending strength

Figure 7. 24 shows the relationship between specific gravity and bending strength of treated and untreated albasia wood. The increase in the bending strength of the wood was approximately proportional to the increase in specific gravity. The results indicated that the average bending strength of treated albasia wood (90,1 MPa) was stronger than that of untreated wood 36,91 MPa ($p < 0.05$).

Moreover, the correlation between specific gravity and bending strength of treated and untreated Japanese cedar is shown in Figure 7. 25. The results showed that the average bending strength of treated Japanese cedar wood (137.90 MPa) was greater than that of untreated wood 86.64 MPa ($p < 0.05$). The treatment procedure has increased the bending strength of albasia wood by 244.21%, while the bending strength of Japanese cedar wood has increased by 159.16%.

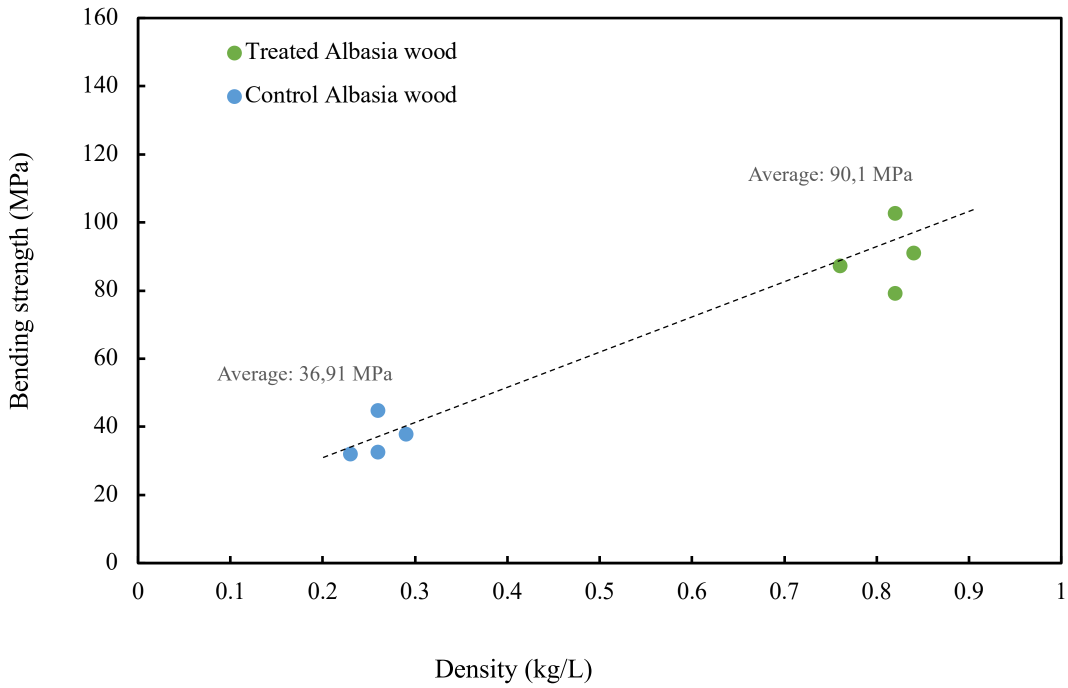


Figure 7. 24 Correlation between specific gravity and bending strength of treated and untreated Japanese cedar wood.

Source: Research Documentation, 2023.

As expected, all densification processes improve the bending properties of wood (Jakob et al., 2022). The compression setting at the treatment temperature influences the strength of compressed wood positively (Fang et al., 2012). In this study, the bending strength of albasia and Japanese cedar was affected by temperature and compression set.

Similar results (Blomberg et al., 2005a) were reported by compacting eight different species and reported an increase in bending strength for all treated wood compared to untreated wood. Esteves et al. (B. Esteves et al., 2017) demonstrated a 40% to 80% increase in bending test results for samples compressedd at higher temperatures. Kutnar et al. (Kutnar et al., 2008) reported a 37% increase in MOE when comparing densified wood to non-densified wood.

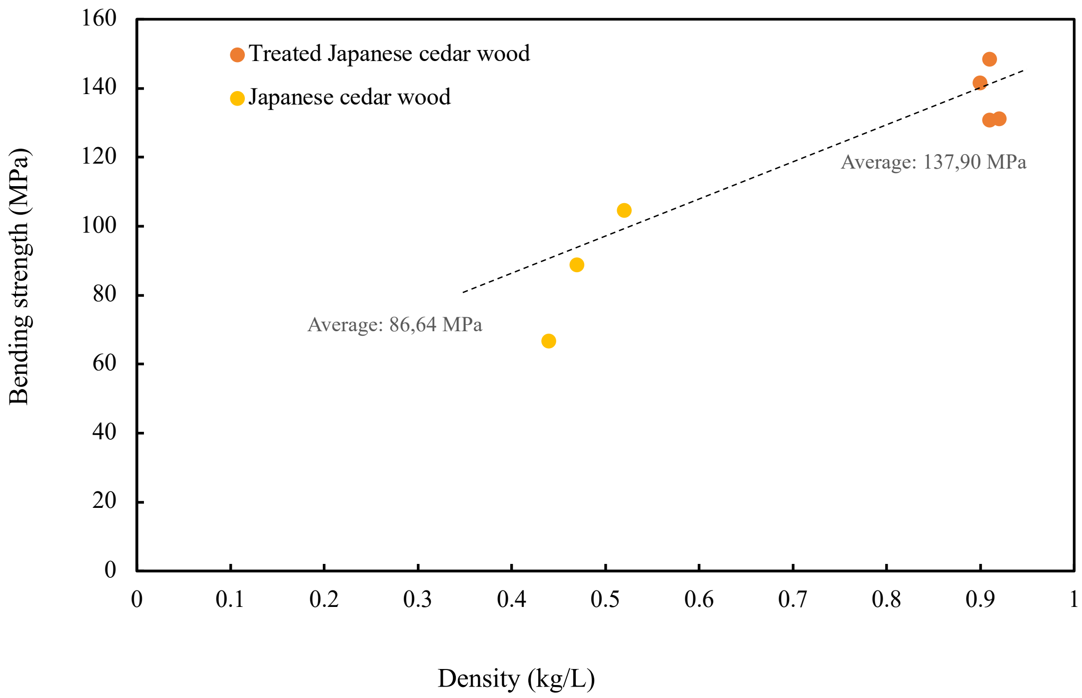


Figure 7. 25 Correlation between specific gravity and bending strength of treated and untreated Japanese cedar wood.

Source: Research Documentation, 2023.

7.5. Conclusions

In this study, the densification method integrating the Voronoi structure affects the physical and mechanical properties of albasia and Japanese cedar wood. The following are the key findings of the study:

1. The Voronoi structural form in the cross-section of treated albasia and Japanese cedar wood can be a novel architectural trend for wood materials.
2. The densification procedure increases the density of albasia wood by 211.54%, and that of Japanese cedar wood by 102.22%.
3. The treatment procedure increased the longitudinal compressive strength of Albasia wood by 100.35% and Japanese cedar wood by 58.54%. Where both compressive strength test results display the same transverse parallel fractures.

4. The treatment procedure increased the tangential compressive strength of Albasia wood by 883.12% and Japanese cedar wood by 98.17%. Where the results of compressive strength tests reveal diagonal orientation fractures that align with the Voronoi structure's orientation.
5. The treatment increased the bending strength of Albasia wood by 144.05% and Japanese cedar by 59.12%. The failure mode of flexural strength is the parallel propagation of tensile outer fiber fractures.

CHAPTER 8:
CONCLUSION AND RECOMMENDATION

CHAPTER 8: CONCLUSION AND RECOMMENDATION

8.1. Summary of Research

The first chapter is introduction part which offer an overview of the research. It provides a research background, problem statement, objectives, scope and limitations, structure of research and framework. The advantages of wood as a sustainable construction material, the trend and potential of Indonesian albasia wood, and wood modification technology are presented as the background of this research. This topic leads to the development of ideas by looking at the trend and potential of abundant and fast-growing Indonesian Albasia wood as a construction material. This part of the research aims to investigate the potential of sustainable Indonesian albasia wood to become a more valuable construction material by improving its physical and mechanical properties through the application of wood modification technology

After structuring the research background and objective, the next chapter is to build a brief understanding and widen the view of this study. Chapter 2 aims at conducting a literature review for in identifying an overview of Indonesian albasia wood, wood as a material, wood modification technology, as well as an overview of previously conducted wood modifications on the physical and mechanical properties of Albasia wood as a preliminary basis for research and finding research gaps.

Chapter 3 provides way of data collection, data analysis, and the target of results. There are two types of distinct data: primary and secondary. In this study, qualitative data from ethnographic studies on the role of albasia wood as a building material in Indonesia and quantitative data from wood modification design experiments are used as primary data. Secondary data, meanwhile, includes literature studies, wood standards, and data from government agencies. This chapter also describes the approach to analysis in qualitative and quantitative research. The research framework is provided in order to comprehend the entire procedure.

To identify the understanding of albasia wood as a construction material in Indonesia, the chapter 4 as a preliminary research is structurally arranged. This research used a qualitative method with an ethnographic approach to obtain a comprehensive picture of construction workers' perceptions of Indonesian albasia wood. The results showed that: 1) The understanding of Albasia wood is derived from the legacy of basic skills training, including the introduction of wood species and grades, woodworking tools, tree planting, felling and cutting wood techniques, and their application in building construction; 2) For rural communities, Albasia wood has been identified as a locally sourced material that is readily accessible from Protected Forest (HL), Convertible Production Forest (HPK), and Non-Forest Areas (APL); 3) In terms of terminology, Albasia wood and carpentry tools are referred to by regional names, where the names differ from one region to another; and 4) In terms of application, although it is a low-value wood, Albasia wood can be utilized as a truss and a bottom truss in simple houses for rural communities in West Java, Indonesia.

The discussion of the potential development of Indonesian albasia wood as a construction material is presented in three chapters, starting from chapter 5 to chapter 7. The chapter 5 aims to determine the influence of densification on the physical properties of Indonesian albasia wood at high temperature and high pressure. The albasia board was subjected to various temperatures (100 °C, 120 °C, 140 °C, sandwich 140 °C). The process of densification influences the material's density properties, colour changes, thickness, compression ratio, equilibrium moisture content, and anatomic properties. This procedure increases the density to 0.62 kg/L, an increase of approximately 112.78% over untreated wood. The increase in wood density results in the decomposition of its chemical components, particularly hemicellulose, which darkens the wood's color and stabilizes its moisture equilibrium. Therefore, thermal compression modification under high temperatures and pressure is a highly effective method for improving the physical properties of fast-growing wood species such as albasia.

To evaluate the effect of thermal densification integrated with Voronoi-inspired patterns in Indonesian albasia wood on its physical and mechanical properties, chapter 6 is provided. The results of this study found that: 1) Wooden slats with a millimeter structure resembling the Voronoi pattern could become a new architectural trend; 2) The treatment increased the density of albasia wood by 211.54%; 3) The EMC stability of the albasia Voronoi composite was more stable than that of the control as a result of its higher density and hemicellulose degradation; 4) Morphological analysis revealed that the interfacial bond of the albasia Voronoi composite was significantly superior to that of the control; 5) The albasia Voronoi composite treatment procedure increased the longitudinal compressive strength of the wood by 100.88%. It also increased the tangential compressive strength by 883.12%; and 6) The Albasia Voronoi composite treatment procedure increased the longitudinal bending strength of the wood by 144.05%. It also increased the tangential bending strength by 859.36%; 7) The tensile strength and elongation at break of Albasia Voronoi composite were about 10 and 2 times higher than the control wood; and 8) In its utilization as a construction material, albasia Voronoi composite may have the potential to be used as columns (tangential direction) and beams (longitudinal direction).

The last part of discussion is chapter 7 which aims to determine focused on the comparison of Voronoi densification treatment between Indonesian albasia and Japanese Cedar which are abundant and fast-growing wood species native to their respective countries. The purpose of this study is to evaluate the effect of thermal densification integrated with the architectural trend of the Voronoi structure on the physical and mechanical properties of albasia and Japanese cedar wood. Evaluations were conducted on the surface appearance, density, compressive and bending strengths of wood. The treatment increased the density of albasia wood by 211.54%, the longitudinal compressive strength by 100.88%, the tangential compressive strength by 883.12%, and the bending strength by 144.05%. In addition, the procedure enhanced the density, longitudinal compressive strength, tangential strength, and bending strength of Japanese cedar wood by 102.22%, 58.54%, and 98.17%, respectively. As anticipated, the Voronoi densification treatment method is extremely promising for improving the physical and mechanical properties of wood and enables the use of fast-growing, low-density wood in structural applications. In the end, this study is expected to provide an overview of the use of albasia wood in Indonesia as well as methods for developing the potential of Indonesian albasia wood as a construction material through wood modification technology.

The last chapter concludes all the results of the research and provides recommendation for the future. Based on the results there are four key findings, they are: 1) Albasia plays an important role in the construction industry for construction workers in Indonesia although its application is still very limited; 2) Wood modification experiments under high temperature and high pressure in this study can improve the density (increased about 112.78%) and anatomical properties of wood; 3) Besides being a new trend in wood architecture, Voronoi wood densification can improve wood density (211.54% increase), longitudinal (100.88% increase) and tangential (883.12% increase) compressive strength, longitudinal (144.05% increase) and tangential (859.36% increase) bending strength, more stable EMC, and better morphology; 4) The effects of the Voronoi wood densification treatment on increasing wood density, longitudinal compressive strength, tangential compressive strength, and bending strength were significantly greater in Indonesian albacia wood than in Japanese cedar wood.

In this study, I argue that the development potential of the abundant and rapidly-growing albasia wood in Indonesia makes it a promising local resource for the construction industry. In the future, it will contribute significantly not only to the field of architecture but also to the environment, as the use of albasia wood will reduce reliance on slow-growing hardwood species sourced from natural forests. This helps to reduce deforestation and preserve valuable ecosystems and biodiversity.

8.2. Future Work

This investigation has yielded a number of findings regarding the potential development of Indonesian albasia wood as a construction material. However, research in this area can certainly still be developed further. Given the limitations identified during the research process, the following recommendations must be considered for future research:

1. To optimize the wood modification techniques used for fast-growing wood species such as Albasia wood, additional research can be conducted. This includes investigating various treatment parameters, such as temperature, time, and chemical solutions, to improve the desired wood properties.

2. Due to the limited resources and research time available for this study, fracture toughness and hardness tests should also be used to evaluate the impact of wood modification treatments on albasia.
3. It is essential to conduct long-term performance evaluations of modified wood products to assess their durability and stability over time. This can include accelerated aging tests on the modified wood, exposure to various environmental conditions, and monitoring its performance in actual applications. Long-term studies will provide invaluable information regarding the effectiveness and durability of wood modification treatments.
4. Life cycle assessment (LCA) provides a deeper understanding of the environmental impact of wood modification. Assessing factors such as energy consumption, carbon footprint, waste generation, and potential recycling or disposal at the end of a product's life will aid in ensuring the long-term viability of wood modification practices.

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