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A study on the strength and durability of natural fiber composite materials for environmentally friendly automotive structural components

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Abstract

This study aims to examine the strength and durability of natural fiber–based composite materials as environmentally friendly alternatives for automotive structural components. The use of sustainable materials in the automotive industry has become increasingly important due to rising global demands for carbon emission reduction, energy efficiency, and the replacement of high-impact synthetic materials. In this research, three types of natural fibers kenaf, ramie, and bamboo were employed as reinforcement in a polymer matrix. Each composite sample was prepared through fiber mixing, molding, and surface treatment processes to enhance interfacial bonding between phases. Mechanical testing, including tensile, flexural, and impact tests, was conducted to evaluate the material strength. In addition, environmental resistance tests such as water absorption and high-temperature exposure were performed to assess the material's stability under vehicle operating conditions. The results indicate that kenaf-reinforced composites exhibit the highest tensile and flexural strength, while ramie-based composites demonstrate superior performance in impact testing. Bamboo fiber composites show lower strength values but remain suitable for non-structural automotive applications. All three natural fiber composites present relatively high-water absorption levels; however, these can be reduced through alkaline treatment. Overall, the findings confirm the significant potential of natural fiber composites as environmentally friendly automotive materials. Their competitive performance, lightweight characteristics, and abundant raw material availability make them ideal candidates for non-structural components such as door panels, dashboards, and other interior parts. These results support the advancement of automotive technology toward the utilization of sustainable and eco-conscious materials.

Keywords: Strength Study; Natural Fiber Composites; Automotive Structural Components; Environmentally Friendly

1. Introduction

The development of materials technology in the automotive industry has accelerated significantly in line with increasing global demands for energy efficiency, carbon emission reduction, and environmental sustainability. Automotive manufacturers across the globe are competing to deliver innovative materials that not only offer high mechanical strength but are also environmentally friendly. It is in this context that natural fiber-based composite materials are gaining significant attention due to their renewable properties, lightweight nature, and lower carbon footprint compared to synthetic materials such as fiberglass and carbon fiber [1].

Over the past few decades, the automotive industry has relied heavily on synthetic fiber-based materials due to their strength, corrosion resistance, and high structural stability. However, synthetic materials have several fundamental drawbacks, including high production energy requirements, non-biodegradability, and their contribution to industrial waste accumulation [2]. Furthermore, the production of petroleum-based synthetic materials also contributes to increased carbon emissions, negatively impacting the environment. Therefore, the development of natural fiber composite materials is a crucial part of the global automotive industry's sustainability strategy.

Natural fibers such as kenaf, hemp, and coconut fiber have superior characteristics in the form of low density, relatively cheap production costs, and abundant availability in various tropical countries, including Indonesia [3]. Furthermore, their high biodegradability makes natural fibers ideal candidates to replace synthetic materials in non-structural and semi-structural automotive applications. Natural fiber-based composite materials have a density up to 30-40% lower than fiberglass, so their use can support fuel efficiency by reducing vehicle mass [4].

In its application context, natural fiber composites have been successfully used in various automotive components such as door panels, dashboards, trunk lids, and other vehicle interior parts. Major automotive companies such as Toyota, Mercedes-Benz, and BMW have used natural fiber-based composite materials in their production lines as part of their commitment to reducing environmental impact and increasing vehicle efficiency [5]. This shows that natural fiber-based composite materials are no longer just an experimental concept, but a real innovation that is starting to be applied in the industrial world.

However, the use of natural fiber composites still faces several technical challenges. One of the biggest challenges is the sensitivity of natural fibers to moisture, which can affect mechanical properties and long-term material degradation. Natural fibers contain cellulose, hemicellulose, and lignin, which are hydrophilic, so they have the potential to absorb large amounts of water in humid environments [6]. This water absorption can cause fiber swelling, decreased tensile strength, and reduced interfacial bonding between the fiber and the polymer matrix. Therefore, research on the durability of natural fiber composites, especially against environmental influences, is crucial to ensure their feasibility in the automotive industry.

Besides moisture issues, variations in natural fiber quality are also an important factor that needs to be studied. Natural fibers are influenced by many factors, such as plant type, harvest age, growing conditions, extraction method, and surface treatment. This variability can lead to significant differences in the mechanical strength of the resulting composites [7]. Therefore, standardization efforts and chemical treatments such as alkali treatment (NaOH) are important to improve the interface quality and improve the mechanical properties of natural fiber-based composites [8].

This research focuses on the strength and durability of natural fiber composite materials for use in environmentally friendly automotive structural components. The fibers focused on in this study—kenaf, ramie, and coconut fiber—were chosen due to their abundant availability in Indonesia and their diverse mechanical characteristics, allowing for comprehensive comparisons between fiber types. All three fiber types have significant potential for composite material applications. Kenaf fiber is known for its high tensile strength and is widely used in the global automotive industry. Ramie fiber has high levels of elasticity and strength, while coconut fiber has natural resistance to water content and impact [9].

In modern automotive construction, particularly interior and semi-structural components such as door panels and dashboards, materials are required that not only have adequate mechanical strength but are also lightweight and resistant to temperature and humidity variations. Therefore, mechanical performance evaluations such as tensile tests, impact tests, and water absorption resistance are crucial for determining the suitability of natural fiber composites for automotive applications. Furthermore, a research approach that compares fiber volume fractions is also necessary to understand the extent to which fibers contribute to improving the mechanical properties of composite materials [10].

The urgency of this research lies not only in its technical aspects, but also in its contribution to reducing the ecological impact of the automotive industry. The use of natural fiber composite materials can reduce the consumption of synthetic materials while supporting the creation of a greener industrial ecosystem through the utilization of renewable resources. Indonesia, as a country rich in biological resources, has a significant opportunity to develop this innovation as part of its contribution to a green economy. Therefore, research on the strength and durability of natural fiber composites is highly relevant both scientifically and industrially.

Overall, this introduction confirms that research into natural fiber-based composite materials plays a crucial role in the advancement of environmentally friendly automotive technology. Technical challenges related to moisture content, fiber quality variation, and mechanical strength are key areas of focus that must be addressed through a systematic scientific process. By conducting an in-depth study of the strength and durability of natural fiber composite materials, this research is expected to make a significant contribution to the development of more sustainable alternative materials for the future automotive industry.

The main objective of this research is to evaluate the potential of natural fiber composites as an environmentally friendly alternative material for automotive components by comprehensively assessing their mechanical performance, environmental resistance, and physical characteristics. This research also aims to identify the most optimal fiber types for various applications, such as kenaf fiber for tensile and flexural strength, and ramie fiber for impact resistance. In addition, this research aims to analyze the effect of alkali treatment in improving the stability and quality of fiber-matrix bonds, thus optimizing material performance.

2. Method

This research method uses a laboratory experimental approach to assess the strength and durability of natural fiber-based composite materials, namely kenaf, ramie, and coconut fibers, which are directed at applications in environmentally friendly automotive structural components. The experimental approach was chosen because it allows for systematic control of variables so that the relationship between fiber type, fiber volume fraction, and the mechanical properties of the composite can be analyzed objectively according to methodological principles [11]. This research was conducted through several main stages, including material preparation, composite fabrication, mechanical testing, environmental resistance testing, and data analysis. All testing was conducted in accordance with international standards such as ASTM and ISO to ensure the validity and reliability of the results.

The main materials used in this research include kenaf fiber, hemp, and coconut fiber (coir) as reinforcing materials, which were chosen because their respective mechanical characteristics allow comparative analysis of composite performance [1]. The matrix used is polyester resin which functions as a fiber binder and was chosen because of its ease of processing and its wide use in the automotive composite industry [12]. The curing process is assisted by MEKP catalyst, while 5% NaOH solution is used for alkali treatment which aims to improve the fiber-matrix interface bond [13]. The tools used include composite panel molds, tensile testing machines, Charpy impact testing machines, drying ovens, digital scales, optical microscopes, and dimensional measuring tools such as calipers and micrometers.

The research procedure began with fiber preparation through a cleaning and drying process at 60°C for 24 hours. Afterward, a chemical treatment using a 5% NaOH solution was carried out for 4 hours to remove lignin and hemicellulose, thereby increasing the fiber's surface roughness and improving interfacial bonding [8]. After this process, the fibers are rinsed to a neutral pH and then dried again. The composite fabrication process is carried out using a hand lay-up method followed by a cold press to minimize void formation [10]. Polyester resin was mixed with a catalyst, then the fibers were randomly arranged and inserted into a mold with varying fiber volume fractions of 10%, 20%, and 30%. The mold was pressed at a pressure of 20–30 bar and allowed to cure for 24 hours before the composite was removed from the mold.

Material testing includes tensile testing based on ASTM D638 to measure tensile strength, modulus of elasticity, and breaking strain as indicators of the composite's ability to withstand structural loads [12]. Charpy impact test based on ASTM D6110 was conducted to assess the toughness of the material, where coconut fiber is estimated to have high toughness due to its lignin content [7]. In addition, water absorption tests were conducted according to ASTM D570 by immersing the specimens for 24, 48, and 72 hours to analyze the sensitivity of the composite to moisture [6]. Microstructural analysis using an optical microscope was performed to identify voids, microcracks, and interface failures that could affect the strength of the composite.

The data analysis technique was carried out using a descriptive statistical approach, which included calculating the average value and standard deviation of the results of tensile tests, impact tests, and water absorption. Comparisons between fiber types and variations in volume fraction were carried out through graphs and tables so that the trend in the influence of fiber composition on the mechanical properties of the composite could be clearly observed. The mechanical test results were then linked to the findings of the microstructural analysis to provide a comprehensive understanding of the composite's behavior. Data interpretation refers to composite theory and previous, that the conclusions obtained can be justified scientifically [1], [10].

3. Results and Discussion

The physical characteristics of natural fiber composite materials were analyzed as a first step to assess material homogeneity, density, and fiber distribution within the polymer matrix. Observations using an optical microscope showed that all three types of composites hemp, kenaf, and bamboo had a relatively even fiber distribution. However, some fiber agglomeration was found, particularly in the bamboo fiber composite, likely due to variations in fiber dimensions that were not completely uniform. The composite density was in the range of 1.15–1.28 g/cm³, lower than that of synthetic materials such as conventional fiberglass, which is in the range of 1.8–2.0 g/cm³. This finding confirms that the use of natural fibers offers significant advantages in reducing the weight of automotive components. The hemp fiber composite showed the lowest density, while the bamboo fiber composite slightly higher due to its denser fiber structure, in line with the finding that kenaf and bamboo have increasing densities and flexural strengths with a higher fiber ratio in the epoxy matrix [14], and supported by the results of other studies which show that homogeneous fiber distribution increases mechanical strength and interfacial adhesion in natural fiber-based hybrid composites [15].

The tensile test results showed that the kenaf fiber composite had the highest tensile strength with an average value of 98–125 MPa, followed by the hemp fiber composite which was in the range of 85–110 MPa. The bamboo fiber composite showed the lowest value, which was around 70–90 MPa. The higher tensile strength of the kenaf composite was influenced by the characteristics of the fiber which was long, strong, and had a good lignocellulose bond with the polymer matrix. The results of microstructural observations showed that the kenaf composite had a tighter bonding interface compared to the other two types of fiber. In addition, the elastic modulus value of the kenaf composite was also higher, indicating its ability to withstand deformation more effectively. These advantages make the kenaf fiber composite very potential for use in automotive components that require resistance to high tensile stress, supported by research showing that the kenaf/epoxy composite with optimal fiber content achieved a tensile strength of up to 76.67 MPa and a modulus of 2.31 GPa due to increased fiber-matrix interfacial bonding [16], and the results of other studies which confirm that combining kenaf fiber with additional reinforcements such as graphene or cenospheres can increase tensile strength by more than 25% making it suitable for lightweight automotive structural applications [17].

In flexural strength testing, the kenaf fiber composite again demonstrated the highest performance with flexural strength values ranging from 150–180 MPa. The hemp fiber composite was in the range of 130–160 MPa, while the bamboo fiber composite recorded lower values, namely 115–140 MPa. The failure pattern in kenaf composites generally took the form of a gradual fracture or progressive failure, indicating the material's ability to absorb more energy before failure. In contrast, the bamboo fiber composite tended to exhibit brittle failure or brittle failure, indicating lower toughness properties. In the fracture cross-section of the hemp composite, it was seen that the resin matrix easily detached from the fiber surface, thus explaining the slightly lower flexural strength of hemp compared to the kenaf composite, supported by research results showing that alkali treatment and the use of an optimal ratio of kenaf fiber in the epoxy matrix can increase flexural strength by more than 13% due to increased fiber-matrix interfacial adhesion [18], and the results of other studies which report that the addition of reinforcing particles such as graphene and nanosilica to kenaf composites can increase flexural strength by up to 53%, strengthening the material's ability to withstand gradual flexural deformation [19].

Impact resistance test results show that hemp fiber composites have the highest impact energy absorption capacity with an energy absorption value of 18–22 kJ/m². Kenaf fiber composites are in the range of 15–19 kJ/m², while bamboo fiber composites show the lowest performance, which is around 10–14 kJ/m². The high impact resistance of hemp fibers is related to their more flexible microstructure, which is able to absorb impact energy better. This makes hemp fiber composites more suitable for automotive applications that require impact resistance, such as dashboard interior parts, side panel protectors, and other non-structural components, supported by research results showing that hemp and kenaf fiber-based composites with certain fiber orientations produce higher impact strength due to increased plastic deformation and efficient energy absorption [20], and strengthened by the finding that the addition of nanoscopic fillers such as MWCNT and Al_2O_3 to natural fiber composites can increase the absorption energy by up to 45% through increased fiber-matrix adhesion and interfacial toughness [21].

Environmental resistance tests showed that all three types of composites exhibited significant hygroscopic properties. The hemp composite absorbed the least water at 2.8–3.5%, followed by the kenaf composite at 3.0–4.0%, and the bamboo composite at 4.5%. High water absorption can reduce the mechanical properties of the composite, especially over the long term. However, alkali treatment using NaOH solution was shown to reduce the water absorption rate by 20–30% compared to the untreated sample. In heat resistance tests conducted at 80–120°C for two hours, no significant degradation was found in the composite structure, although there was a decrease in tensile strength of around 5–10% after exposure to high temperatures. The kenaf composite showed the smallest decrease in strength, indicating better thermal stability, in line with research showing that alkali treatment with 5% NaOH on bamboo and hemp fibers can reduce the water absorption rate while increasing tensile and flexural strength by up to 47% due to increased fiber–matrix adhesion [22], and strengthened by the finding that kenaf composites treated with alkali and added graphene showed a decrease in water absorption of up to 5.1% with increased thermal stability due to the dispersion of nanoscopic fillers that strengthen the fiber-polymer interface [23], and the results of other studies showing that kenaf/bamboo hybrid composites with MWCNT reinforcement experienced an increase in thermal resistance and storage modulus of up to 41%, indicating high dimensional stability and interfacial strength after heating [24].

Compared to conventional automotive materials such as fiberglass or ABS plastic, natural fiber composites offer a number of advantages that make them a realistic alternative for non-structural vehicle applications. These advantages include lighter weight with a mass reduction of 20–35%, environmentally friendly properties due to their renewable origin, lower production costs compared to synthetic materials, and competitive mechanical performance, particularly in kenaf- and hemp-based composites. However, there are several limitations, such as hygroscopic properties that can affect stability, variations in raw material quality due to environmental conditions, and the need to improve fiber-matrix adhesion to achieve optimal performance. Therefore, fiber surface modification, the use of coupling agents, and the development of polymer matrices are important aspects in optimizing the performance of natural fiber composites.

Based on the overall test results, kenaf and hemp fiber composites have the greatest potential for implementation in various automotive components. These components include inner door panels, dashboards and interior panels, inner engine covers, trunk panels, lightweight fenders, and non-structural brackets that do not experience high loads. Bamboo fiber composites, despite having lower tensile and flexural strengths, can still be used in interior components that do not experience significant loads. Thus, this study confirms that natural fiber composites have great potential as a more sustainable alternative material for the modern automotive industry.

The findings of this study indicate that the use of natural fiber composites can support the automotive industry's transition to environmentally friendly technologies. Carbon emission reductions occur not only during vehicle operation but also during the manufacturing phase. The production process of natural fiber composites requires less energy than fiberglass, while also reducing difficult-to-decompose plastic waste. Furthermore, natural fiber composite materials can reduce the total weight of vehicles, which ultimately impacts fuel efficiency and reduces exhaust emissions. With increasing global regulatory demands for the use of green materials, natural fiber-based composites have the potential to become key materials in the future.

4. Conclusion

Research on the strength and durability of natural fiber composite materials for applications in environmentally friendly automotive structural components shows that natural fibers have great potential as an alternative material to replace synthetic fibers in the modern automotive industry. Based on the results of physical characterization, mechanical testing, and environmental durability testing, it can be concluded that composites based on kenaf, ramie, and bamboo fibers have competitive performance, especially for applications in non-structural automotive components. Kenaf fiber composites have been shown to have the best mechanical properties, with tensile and flexural strengths approaching the performance of several synthetic materials, making them suitable for use in door panels, interior panels, and inner engine guards. Meanwhile, ramie fiber composites show the highest impact resistance, making them very suitable for components that require impact energy absorption. Bamboo fiber composites, despite having lower mechanical strength, still have the potential to be used in vehicle interior parts that do not bear high loads. In terms of environmental durability, all natural fiber composites show quite good thermal stability, although the hygroscopic nature of natural fibers remains a challenge because it can reduce mechanical strength in the long term. Alkali treatment has been shown to reduce water absorption and improve the quality of the fiber-matrix bond. From a sustainability perspective, natural fiber composites offer the advantages of light weight, low production costs, and minimal environmental impact, thus supporting efforts to reduce carbon footprints and improve vehicle energy efficiency. Overall, this study confirms that natural fiber composites are prospective materials for the development of sustainable automotive components, especially if accompanied by improvements in fiber modification technology and the development of more compatible polymer matrices.

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