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Review of Carbon Fiber Based on Physical and Mechanical Properties in Vehicle Frame

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ABSTRAK

Penelitian ini bertujuan untuk mengkaji sifat fisik dan mekanis serat karbon serta potensi penggunaannya untuk meningkatkan efisiensi kendaraan. Fokus utama adalah mengurangi berat kendaraan, meningkatkan efisiensi bahan bakar, dan menurunkan emisi karbon. Serat karbon memiliki kekuatan tarik lebih dari 6 GPa, modulus elastisitas lebih dari 600 GPa, dan densitas 1,8–2,0 µg cm^3. Penggunaannya dalam kendaraan dapat mengurangi berat hingga 86%, meningkatkan efisiensi bahan bakar hingga 20%, dan menurunkan emisi karbon secara signifikan. Struktur komposit sandwich serat karbon dengan inti sarang lebah aluminium meningkatkan kekuatan dan mengurangi berat hingga 36%. Serat karbon juga meningkatkan ketahanan rollover kendaraan hingga 64% dan penyerapan energi hingga 60%. Namun, biaya produksi yang tinggi menjadi tantangan utama, dengan bahan prekursor seperti poliakrilonitril (PAN) menyumbang sekitar 50% dari biaya. Alternatif berbasis biomassa, seperti lignin dan limbah pertanian, dapat mengurangi biaya, meskipun masih memerlukan pengembangan lebih lanjut. Penelitian menunjukkan bahwa integrasi serat karbon daur ulang pada struktur hibrida logam-polimer dapat mengurangi berat kendaraan hingga 48% dan meningkatkan kinerja struktural. Penelitian ini menekankan pentingnya inovasi manufaktur dan eksplorasi bahan alternatif untuk memaksimalkan pemanfaatan serat karbon.

Kata Kunci : karbon, fisik, mekanis, serat, sifat mekanik.

ABSTRACT

This research aims to assess carbon fibre's physical and mechanical properties and potential use to improve vehicle efficiency. The main focus is to reduce vehicle weight, improve fuel efficiency, and lower carbon emissions. Carbon fibre has a tensile strength of more than 6 GPa, a modulus of elasticity of more than 600 GPa, and a density of 1.8-2.0 g/cm³. Its use in vehicles can reduce weight by 86%, improve fuel efficiency by 20%, and significantly reduce carbon emissions. The carbon fibre sandwich composite structure with an aluminium honeycomb core increases strength and reduces weight by 36%. Carbon fibre also improves the vehicle's rollover resistance by 64% and energy absorption by 60%. However, high manufacturing costs are a major challenge, with precursor materials such as polyacrylonitrile (PAN) accounting for about 50% of the cost. Biomass-based alternatives, such as lignin and agricultural waste, can reduce costs, although they require further development. Research shows that integrating recycled carbon fibre in metal-polymer hybrid structures can reduce vehicle weight by 48% and improve structural performance. This research emphasizes the importance of manufacturing innovation and the exploration of alternative materials to maximize the utilization of carbon fibre.

***Keywords**: carbon, fibre, mechanical, physical, mechanical properties.*

INTRODUCTION

Road transportation activities contribute significantly to air pollution through emissions of hazardous gases and particulates, which impact air quality and exceed safe thresholds in many regions. In understanding the impact of human activities on the environment, the role of road transportation in contributing to air pollution has received significant attention. Motor vehicles on the road contribute significantly to air pollution, contributing between 4% and 33% of volatile organic compounds (VOCs), nitrogen oxides (NO_x), and fine particulate matter ($PM_{2.5}$) in the Continental United States (CONUS), in January, these emissions can increase surface ozone (O_3)

concentrations by up to 13.1% in some areas, while in July, they increase O_3 and $PM_{2.5}$ concentrations by 15% to 20% [1]. In addition, in a study conducted in Bystrica [2], particulate matter $PM_{2.5}$ and PM_{10} from traffic contributed about 25% and 17% in busy lanes and 11% in areas outside the main transportation corridors. Annual concentrations reached 16.71 µg/m³ for $PM_{2.5}$ and 15.57 µg/m³ for PM_{10}, with $PM_{2.5}$ peaks exceeding the WHO yearly limit, signaling significant pollution from non-vehicle exhaust emissions.

Meanwhile, in an effort to tackle air pollution, the adoption of fuel-efficient vehicle technology has shown a significant impact on reducing harmful emissions. Fuel-efficient vehicles, especially those that meet Euro 6/VI standards, play an important role in significantly reducing emissions of pollutants, including $PM_{2.5}$ and NO_x [3]. Recent studies have revealed that increasing fuel injection pressure from 160 to 185 kPa reduces nitrogen oxide (NO_x) and carbon monoxide (CO) emissions by 15% each, hydrocarbons (C_xH_y) by 54%, and solid particles (SP) by 33%, indicating that improving fuel efficiency in vehicles contributes significantly to emissions reduction [4]. In an effort to reduce the environmental impact of motor vehicles, another study revealed the application of the Automatic Engine Start-Stop system has proven effective in reducing fuel consumption and emissions by up to 10% and minimizing vehicle idling time, providing an overall increase in fuel efficiency of about 12% [5]. On the other hand, fuel-efficient vehicle technologies, such as thermal energy storage systems (TESS) with phase change materials (PCM), improve the efficiency of three-way catalysts (TWC) and reduce CO and HC emissions by 8.2% and 10.6%, respectively, during vehicle use [6]. Furthermore, a behavioral study in Nepal showed that promoting the adoption of fuel-efficient electric motorcycles through encouragement and information framing can positively influence consumer preferences, addressing air pollution challenges in densely populated cities [7]. Overall, fuel-efficient vehicles play an important role in minimizing pollution through various technological advancements and behavioral interventions.

Carbon fiber has several advantages that can make vehicles lighter, more fuel efficient, lower emissions, and stronger as proven by several previous studies. Carbon fibre composites are used in vehicles to reduce weight, thus leading to decreased fuel consumption and lower emissions during the use stage [8]. Carbon fibre in cars can significantly reduce weight, leading to improved energy efficiency and performance. Carbon fiber-reinforced plastic (CFRP) materials offer outstanding specific stiffness, specific strength, and fatigue properties compared to traditional metals, making them ideal for weight reduction in automotive applications [9]. Moreover, advances in manufacturing techniques, such as automated fibre placement and hand layout, have enabled the production of lightweight carbon fibre components with high strength and reliability, further promoting the adoption of CFRP for weight reduction in vehicles [10][11]. Overall, the integration of carbon fibre materials in cars not only reduces weight but also improves fuel efficiency.

RESEARCH METHODS

The method used is literature review, which evaluates the quality and new findings of a scientific paper. the researcher analyzed several literatures and then compiled the results. this analysis is in the form of a table that includes the title of the study, the year of the study, the research method, and the results of the study. After being analyzed and discussed in depth, the researcher will get a summary that can be included in the next chapter. the literature journals used are the latest journals with a maximum limit of the last ten years as shown in the Figure 1 [12].

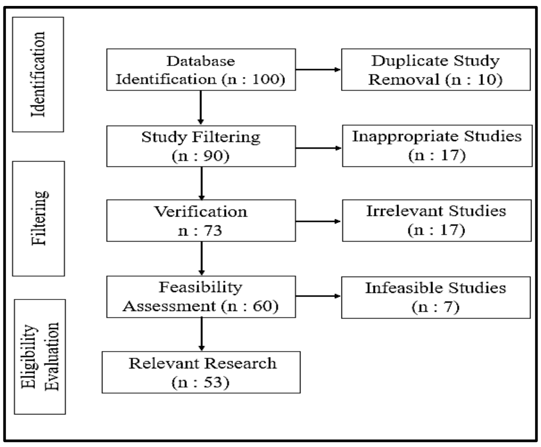

Figure 1. Flow Chart of Literature Review

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RESULTS AND DISCUSSIONS

Characteristics of Carbon Fibre

Carbon is an important chemical element with a variety of isotopes that have both stable and radioactive properties, as well as wide applications. Carbon is a chemical element in the periodic table that occupies the sixth position with a molar mass of 12.011 g/mol. Since 1961, the calculation of relative atomic mass has been based on the carbon-12 (C-12) scale, which is determined to be exactly 12.00000. The element carbon has seven isotopes, with 98.89% consisting of the C-12 isotope and 1.108% of the C-13 isotope, both of which are stable. Meanwhile, the other five isotopes (C-10, C-11, C-14, C-15, and C-16) are radioactive and decay through the emission of beta particles, both negative and positive. Isotope C-14, which has a half-life of about 5,568 years, is widely utilized in carbon dating techniques [13].

Carbon fibres exhibit complex chemical and physical structures characterized by high strength, lightweight, and resistance to high temperatures and chemicals. The physical structure of carbon fibres typically includes micro-scale diameter and fibrous morphology, with diameters ranging from 196 to 331 nm depending on the carbonization temperature [14]. The internal structure of carbon fibres can vary significantly based on precursor materials and processing conditions. For example, PAN-based carbon fibres exhibit a compact surface layer with a loose core containing microvoids, and their elastic modulus and nano hardness are significantly higher at the surface than at the core [15]. The graphene sheets in PAN-based fibres are aligned along the fibre direction. In contrast, pitch-based fibres show radial transverse structures or random onion-like structures depending on the spinning conditions [16]. The chemical structure of carbon fibres involves a transition from a linear structure to a graphite-like structure during carbonization, with the presence of π-π*, σ-π*, and n-π* transitions [14]. To optimize fibre performance in composite structures, fibre orientation should be designed to follow the load path and geometric shape, with the arrangement in parallel aligned unidirectional patterns or quasi-isotropic patterns arranged at 0°, 90°, and 45° angles, as shown in Figure 2 [17].

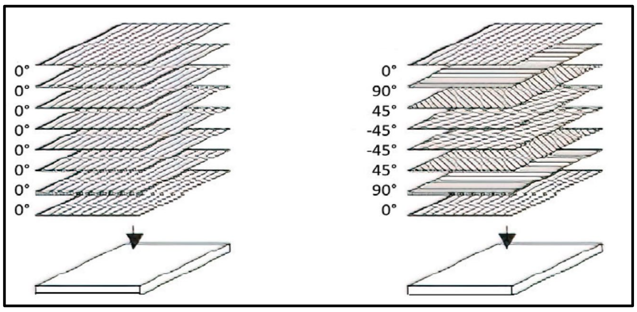

Figure 2. Laminat Unidirectional and Quasi-Isotropic [17]

The matrix into which the carbon fibres are embedded can be either thermoset or thermoplastic polymers. The most commonly used matrices include epoxy resins, polyesters, and unsaturated resins [18]. Carbon fibres have a degree of graphitization, and the arrangement of carbon atoms can be affected by carbonization temperature and spinning conditions, with higher temperatures causing more graphitic structures [19]. In addition, the surface of carbon fibre is mainly composed of C-C, C-O, and C=O groups, which develop during the carbonization process[19]. Carbon fibre, which is composed of carbon atoms with a diameter of 5-10 micrometres, has a tensile strength of more than 6 GPa, an elastic modulus of more than 600 GPa, and a density of 1.8-2.0 g/cm^3 [20]. Overall, the unique combination of chemical and physical structure makes carbon fibres highly versatile for various applications [21].

Carbon Fiber Applications

The automotive industry continues to experience rapid development in an effort to improve vehicle performance and efficiency, especially with a focus on the use of lightweight materials such as carbon fibre. The use of carbon fibre in-vehicle components has been proven to significantly reduce vehicle weight, which has a direct impact on improving fuel efficiency and reducing carbon emissions. Carbon fibre has high specific stiffness and specific strength, as well as superior fatigue properties compared to commonly used metals, making it an ideal material for automotive applications [9]. The integration of recycled carbon fibre with metal-polymer hybrid technology has resulted in significant weight reduction and improved structural performance [22]. The study shows the importance of fast and low-cost manufacturing technologies for automotive applications. In addition, the use of a carbon fibre reinforced composite sandwich structure with an aluminium honeycomb core can increase the strength and stiffness of the material while reducing the weight of the vehicle [23].

Carbon fiber in vehicle components improves performance that has been tested from several studies. Modification of carbon fibre and epoxy matrix increased the tensile strength by 64%, fracture toughness by 51.4%, and energy absorption by 93.3 J/mm [24]. In addition, aluminium composite bumpers with carbon fibre are 36.4% lighter than steel bumpers, thereby improving crash safety, energy saving, and emission reduction [25]. Furthermore, carbon fibre polymer (CFRP) increases energy absorption by 60% and rollover resistance by 64%, with a minimum weight gain of 15% [26]. A carbon fibre reinforced polymer (CFRP) strut bar design replaces conventional steel bars, with up to 48% weight reduction and improved vehicle performance through fuel efficiency and reduced carbon emissions [27]. In addition, a recycled carbon fibre-reinforced plastic/metal hybrid engine mount (PMH) was designed to increase structural strength and reduce weight by 36% compared to traditional steel models [28]. Furthermore, the carbon fibre-aramid reinforced Composite Impact Beam, designed for side door protection, has a deflection of 0.137 mm, Young's modulus of 0.920 MPa, and a maximum pressure withstand capability of 5.26 MPa [29]. However, graphene additives in carbon fibre composites show great potential for reducing weight and improving structural performance, although the high cost is still a challengex [30].

Weight Reduction

The lightweight properties of carbon fibre are critical to fuel efficiency and vehicle performance due to several interrelated factors. Primarily, reducing vehicle weight directly reduces the energy required for propulsion, thereby improving fuel efficiency and reducing greenhouse gas emissions. This is particularly important in the automotive industry, where the shift from traditional steel to lightweight materials such as carbon fibre composites has been a major trend over the past 30 years [31]. For example, composite leaf springs made of carbon fibre not only reduce weight but also meet mechanical performance requirements, such as bending stiffness and material strength, which are important for automotive applications [32]. In addition, the use of advanced materials such as dual-phase steel, which combines high strength with reduced weight, further contributes to the lightweighting of vehicle body frames, improving efficiency and performance [33].Carbon fibre composites also offer superior mechanical properties, such as high tensile strength and modulus, which are essential for load-bearing and impact-absorbing structures in vehicles [34]. In addition, the application of carbon fibre in multicellular plate structures for transport vehicles has shown significant weight savings, up to 86%, compared to all-steel structures, without sacrificing stiffness and vibration damping [35].

Meanwhile, this weight reduction is not only beneficial for fuel efficiency but also for improving overall vehicle performance and safety. In addition, the lightweight and high-strength characteristics of carbon fibre composites make them ideal for applications that require high load resistance and durability, such as in the design of new clamps for ultra-high voltage transmission lines, which experienced a weight reduction of 36.46% [36]. The automotive industry's focus on vehicle weight reduction is also driven by the need to meet stringent emissions regulations and increase the driving range of electric vehicles (EVs), where lightweight materials help reduce the increased noise and vibration associated with EVs [37]. In addition, optimization methods, such as response surface methods, have been used to achieve significant weight reduction in vehicle frames, further improving performance and efficiency [38]. The versatility of carbon fibre composites, which can be manufactured using various techniques, such as the open-mould hand layup process, also makes it economically feasible to be widely used in the automotive industry [39].Overall, the integration of carbon fibre and other lightweight materials in vehicle design is a key strategy for improving fuel efficiency, performance, and sustainability in modern transportation [40].

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Comparison with Other Materials

When comparing steel to carbon fibre for vehicle frames, several key factors arise, including weight, strength, stiffness, and performance under various conditions. Carbon fibre is significantly lighter than steel, which can lead to a substantial weight reduction in the vehicle frame. For example, replacing steel with carbon fibre-reinforced polymer (CFRP) in an electric minibus chassis can reduce the chassis weight by 9% while increasing torsional stiffness by 7% and Specific Energy Absorption (SEA) by 9% [41]. In addition, carbon fibre is five times stronger and twice as stiff as steel, making it an ideal material for high-performance applications [42]. In terms of structural behaviour, the bolted hybrid composite steel chassis can reduce the total chassis weight by about 22.7% compared with the full steel chassis, which can extend the mileage of electric vehicles by more than 20% [43]. Carbon fibre also performs better under extreme temperatures, maintaining structural integrity where steel may deform [44]. Meanwhile when comparing aluminium and carbon fibre for vehicle frames, several factors, such as weight, strength, crash resistance, and cost, must be considered. Carbon fibre reinforced polymers (CFRP) offer high specific strength and stiffness, making them ideal for lightweight, high-performance applications, such as automotive frames and components [45].

High Production Cost

The high cost of carbon fiber is driven by expensive precursor materials and complex production processes, although alternative biomass feedstocks are being developed to improve efficiency and scalability. Expensive precursor materials and complex manufacturing processes mainly drive the high cost of carbon fibre production. Polyacrylonitrile (PAN), the most common precursor, accounts for about 50% of the total carbon fibre production cost due to its high price and the energy-intensive process required for conversion into carbon fibre [46]. Alternative precursors such as biomass-derived materials (e.g., rayon, lignin, glycerol, and lignocellulosic polysaccharides) have been explored to reduce costs and dependence on fossil fuels. Still, these alternatives also face challenges in terms of production efficiency and material properties [47]. For example, lignin, a promising low-cost precursor, requires further process optimization to achieve the desired mechanical properties and scalability for industrial applications [48].

In addition, the production of carbon fibres from agricultural waste, such as rice husks and bagasse, has shown potential for cost reduction. Still, the adsorption capacity and structural properties need to be improved for wider applications [49]. In the aviation industry, the integration of carbon fibre-reinforced composites has highlighted significant cost contributions from labour and energy consumption, with a need for innovative manufacturing processes to reduce these costs [50]. The biomedical field also faces challenges with the high cost of carbon fibre materials, especially in the development of 3D-printed prosthetics and implants [51]. In addition, the production of high-quality composite filaments for additive manufacturing requires precise control and innovative feeder designs to maintain consistency and reduce material waste [52]. Despite these challenges, advances in digital twinning and automated production processes in the aircraft industry show promise in addressing some cost-related issues by improving efficiency and reducing waste [53]. Overall, despite significant efforts to lower the cost of carbon fibre production through alternative precursors and innovative manufacturing techniques, achieving cost-effective and high-performance carbon fibre remains a complex challenge.

FUTURE RESEARCH SUGGESTIONS

This research examines the physical and mechanical properties of carbon fiber in vehicle frame applications, an essential aspect of the modern automotive industry. Carbon fiber offers a superior strength-to-weight ratio compared to conventional materials such as steel and aluminum, contributing to improved fuel efficiency and vehicle performance. However, the variability in the carbon fiber manufacturing process must be considered, as it may affect long-term durability and production costs. Additionally, a more comprehensive comparison of various fabrication methods and their impact on mechanical properties is necessary to ensure the findings are applicable to industrial applications. Thus, this research provides valuable insights into the development of lighter, stronger, and more cost-effective vehicle materials.

An interesting finding in this research is the potential use of biomass such as lignin as a carbon fibre precursor, which could reduce production costs, although it requires further development. Recycled carbon fibres also offer a vehicle weight reduction of up to 48% without compromising structural performance. Modification of the carbon fibre and epoxy matrix was able to increase fracture toughness by 51.4% and tensile strength by 64%, showing great potential in the development of energy-efficient vehicles. In conclusion, carbon fibre is a strategic solution to improve fuel efficiency, reduce vehicle weight, and lower carbon emissions. However, the main challenge is the high production cost, which requires innovation in manufacturing techniques and exploration of alternative materials. The implication is that for consumers, carbon fibre-based vehicles offer better fuel efficiency and are environmentally friendly. Meanwhile, for manufacturers, integrating carbon fibre technology enables lighter vehicle designs that are competitive in meeting emission regulations. Therefore, it is recommended that research on biomass-based precursors be increased, more efficient manufacturing techniques be developed, and recycled carbon fiber be utilized for sustainability and cost reduction.

Future research should focus on developing more efficient and economical carbon fiber fabrication techniques to enhance its competitiveness against conventional materials. Optimizing production processes, such as integrating additive manufacturing technology and carbon fiber recycling methods, could help reduce costs without compromising mechanical performance. Furthermore, exploring hybrid composite materials that combine carbon fiber with polymers or lightweight metals could unlock new opportunities for vehicle frame designs that better adapt to varying load conditions. Extensive experimental testing, supported by artificial intelligence-based simulations, can further improve the accuracy of material performance predictions under real-world operating conditions. With this approach, future research can drive more sustainable innovation in the automotive industry while accelerating the adoption of carbon fiber as a key material for energy-efficient vehicles.

CONCLUSION

Carbon fibre in vehicle structures reduces weight, improves fuel efficiency, and lowers environmental impact. This research further highlights the importance of using lightweight materials such as carbon fibre in reducing vehicle emissions, which are a major cause of air pollution, especially in urban areas. With superior physical and mechanical properties, carbon fibre has a tensile strength of more than 6 GPa, an elastic modulus of more than 600 GPa, and a density of 1.8-2.0 g/cm^3. The integration of carbon fibre in the vehicle frame can reduce weight by 86%, improve fuel efficiency by 20%, and significantly reduce carbon emissions. In addition, the use of carbon fiber-based composite sandwich structures can increase strength by 64% and energy absorption by 60%, with a minimum additional weight of 15%.

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