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Analysis of Determinants of Carbon Fiber Strength: A Review

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Abstract. In globalization and material advancement, carbon fiber has become a strategic solution in addressing sustainability challenges, especially in the automotive and aeronautical sectors, thanks to its superior lightweight and strength properties. This research aims to assess the various factors that influence the strength of carbon fibers and their potential integration in composites. The approach chosen is a literature review, which collects and synthesizes the results of recent studies to develop a thorough understanding of the strength and applications of carbon fibers. The findings of this study show significant improvements in tensile strength and weight reduction through the modification of carbon fiber with materials such as dopamine and its integration in aluminum matrix composites. Carbon fiber promises to be an important advance in developing composite materials that not only support sustainability but also adapt to the technical needs of contemporary industries. These results urge further research on efficient production methods to maximize the use of carbon fiber in wider applications.

Keywords: carbon fiber; composite; tensile' strength

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1. Introduction

Vehicle emissions significantly contribute to air pollution, especially in urban areas such as Beijing, China, where mobile sources account for the majority of fine particle emissions (1). Studies show that on-road vehicle emissions, especially from passenger vehicles and heavy-duty trucks, play a major role in increasing air pollution levels in metropolitan areas, with high emissions of carbon monoxide and total hydrocarbons in urban areas and nitrogen oxides and fine particles outside urban areas (2). The impact of transportation sector emissions on global health is substantial, with estimates suggesting that transportation-related emissions were associated with hundreds of thousands of PM2.5 and ozone-related deaths globally in 2015, resulting in years of life loss and health damage (3).

Effective control measures, such as eliminating high-emission vehicles and implementing alternative energy replacements, have been identified as important strategies to reduce vehicle pollutant emissions and reduce the associated health burden (4). Fuel-efficient vehicles play an important role in minimizing pollution by reducing fuel consumption and emissions. Studies highlight various technologies and approaches to improve fuel efficiency and reduce environmental impact. Research in India emphasizes the potential benefits of fuel-efficient technologies for heavy-duty vehicles in reducing petroleum consumption and carbon dioxide emissions, especially in highly polluted cities (5). In addition, experiments with devices such as tribological optimization on diesel engines, can reduce fuel consumption and emissions (6). a more forward-thinking approach lies in adopting electric vehicle technology with efficient designs and high-performance components. This technology holds significant potential to substantially reduce exhaust emissions, providing a cleaner and more environmentally friendly solution (7).

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Furthermore, other research suggests that by reducing weight, vehicles emit less greenhouse gases, contributing to a reduction in the overall carbon footprint of the automotive industry (8). Moreover, the automotive industry continues to adapt amid the global energy crisis, which pressures manufacturers to find ways of fuel efficiency and emission reduction (9). One effective solution is the use of lighter materials. The effectiveness of these materials is driven by their lightweight yet sturdy characteristics, allowing manufacturers to meet stricter emission standards without compromising vehicle performance (10). In addition, reducing vehicle weight directly contributes to improved fuel efficiency. For example, a 10% decrease in vehicle weight can lead to a 5-10% increase in fuel economy, which translates to significant fuel savings over the life of the vehicle (11). Furthermore, lighter vehicles require less energy to move, which translates to lower fuel consumption. Other research has shown that a 10% reduction in vehicle weight can lead to a 6-8% increase in fuel economy (12).

Other research has shown that reducing vehicle mass can significantly lower energy consumption, the savings of which are quantified through the Energy Reduction Value (ERV) coefficient (13). This is in line with the finding that CFRP exhibits good tribological performance, with a low coefficient of friction and wear rate, where the performance is affected by friction load and speed (14). This is in line with the finding that CFRP exhibits good tribological performance, with a low coefficient of friction and wear rate, where the performance is affected by the load and friction speed (15).

2. Methodology

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 picture below (16).

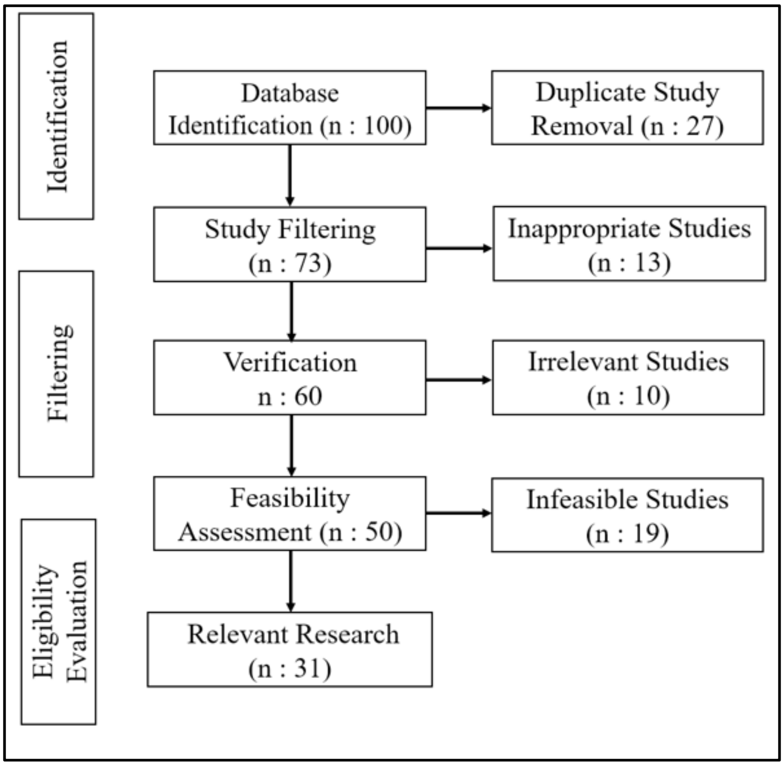

Figure 1. Flow chart of literature review

3. Carbon Fiber Strength

3.1 Effect of Carbon Fiber on Strength

To understand the benefits of the latest materials technology, this research focuses on the Effect of Carbon Fiber on Material Strength, which involves a series of tests to examine the impact of carbon fiber addition on the mechanical strength of various composites. The tests included measurements of adhesive strength, compressive strength, elastic modulus, and tensile and flexural strength of the materials. The results of this research are expected to provide new insights into the application of carbon fiber in designing more effective and efficient materials. The table below presents data that illustrates the significant effect of carbon fiber addition on increasing the strength of composite materials.

Table 1. Table of effect of carbon fiber on strength at various factors

No.	Factor	Value
1	CFRP Adhesive Strength After EMP	115%
2	Carbon Fiber Compressive Strength	71%
3	Elastic Modulus	160 GPa
4	Tensile Strength of Composite	130.16 MPa
5	Flexural Strength of Composite	98.53 MPa
6	Flexural Strength of Double Helix Structure	1349.45 MPa
7	Compressive Strength at 0° Orientation	1175 MPa

From the table above, it can be seen that recent studies have shown that adding carbon fibre can increase the adhesive strength of CFRP by up to 115% (17), increasing the compressive strength of carbon fiber by 71% reference (18). Achieving an elastic modulus of up to 160 GPa, significant (19) and tensile and flexural strengths of 130.16 MPa and 98.53 MPa, respectively (20) . Furthermore, a double helical structure with variable angles showed a flexural strength reaching 1349.45MPa (21) and a compressive strength that reached 1175 MPa (22). Interestingly, this study shows how significant improvements in mechanical properties can be achieved through innovations in carbon fibre applications, offering great potential for the future development of composite materials.

3.2 Effect of Carbon Hybrid Material on Strength

The development of materials that are lighter yet capable of providing superior mechanical strength is key in the design of products that are not only efficient but also environmentally friendly. A literature review on carbon fiber and its composites was conducted to gain an in-depth insight into current trends, identifying them as promising future materials. These materials offer exceptional strength and are very lightweight, making them an ideal choice across various sectors, including the automotive industry and sustainable engineering. The ability of carbon fiber to be upgraded and combined with other materials has opened up new opportunities in tensile strength enhancement, which is crucial in structural applications. The following table summarizes recent developments in carbon fiber tensile strength enhancement through various material innovations and combinations, as researched by previous researchers.

Table 2. Table of Effect of Carbon Hybrid Material on Strength

No.	Factor	Value
1	Carbon Fiber	Density: 1.80 g/cm^3 Diameter: 5-10 μm Tensile Strength: 2000-5000 MPa Tensile Modulus: 200-600 MPa
2	Carbon Fiber with Dopamine	Tensile Strength: +10.6%
3	Aluminum Matrix Composite with Carbon Fiber	Weight Reduction: 36.4% vs. steel
4	Carbon Fiber and Pineapple-Banana Fiber Core	Density: 1.80 g/cm^3 Diameter: 5-10 μm Tensile Strength: 2000-5000 MPa Tensile Modulus: 200-600 MPa
5	Nylon Carbon Fiber Filament	Tensile Strength: +10.6%
6	PLA Carbon Fiber Filament	Weight Reduction: 36.4% vs. steel

7	Carbon Fiber with D51N	Density: 1.80 g/cm^3 Diameter: 5-10 μm Tensile Strength: 2000-5000 MPa Tensile Modulus: 200-600 MPa

With extraordinary strength in lightweight materials, carbon fiber is the belle of today's technological innovations. This fiber has a density of 1.80 g/cm^3, a tensile strength of 2000-5000 MPa, and a tensile modulus of 200-600 MPa (23) . Modification with dopamine increases the tensile strength by up to 10.6% (24) . In aluminum composites, carbon fiber reduces the weight of the bumper by 36.4% compared to steel (25). A composite of carbon fiber and pineapple banana produced a flexural strength of 113.67 MPa after processing at 900°C (26). Nylon carbon filaments have a tensile strength of up to 23,899 MPa, while PLA reaches 24,552 MPa (27). The D51N copolymer increased the tensile strength by 64% (28). This shows the great potential of carbon fibers and their composites for lightweight yet strong structural applications, especially in the automotive and sustainable materials industries.

3.3 Effect of Carbon Fiber Pattern on Strength

The influence of hybrid materials on carbon fiber performance cannot be underestimated, where fiber direction plays a crucial role in determining the strength as well as the overall mechanical properties of the composite. In addition to a resin composition, fiber orientation in carbon fiber results in significant differences in its mechanical properties. The following table details how variations in fiber orientation- such as 0°, 45°, 90°, and other orientation combinations affect the tensile strength, tensile modulus, tensile strain, flexural modulus and impact strength of composite materials. This provides insight into how structural design and material selection can be optimized for specific applications based on the desired mechanical requirements. The study also highlights the importance of a deep understanding of how these components interact in the context of hybrid materials to develop strong, lightweight and efficient solutions in terms of material usage.

Based on the research that has been done, variations in resin type, fiber orientation, and hybrid materials have a significant effect on the mechanical properties of carbon fiber composites. The 0° fiber orientation showed the highest tensile strength, such as in sample LY5/4, with a tensile modulus of 1059 MPa and a tensile strength of 90.0 MPa. In contrast, 90° fiber orientation decreased the tensile strength due to the anisotropy of the material. The combination of ±35°, ±45°, and 90° fiber orientations in hybrid materials resulted in balanced mechanical performance, such as sample EM5/5 with a tensile strength of 97.0 MPa and good flexural modulus (29) Interestingly, the variation in fiber orientation affected the tensile strength and improved the load distribution in the material. These findings suggest that resin type selection and fiber direction optimization can improve composite performance to suit specific application needs.

Other studies have also shown that the fiber orientation of carbon composites affects their mechanical properties. At 0° orientation, the maximum tensile stress reached 2857 MPa, while the highest tensile strain of 7.1% occurred at 45° orientation (30). The 90° orientation produced the best tensile strength of 29.43 MPa, with an impact energy absorption of 2.622 J and an impact price of 0.033 J/mm^2 (31). The tensile strength of unidirectional carbon fiber composites reached 2800 MPa at 0° orientation but dropped drastically to 40 MPa at 90° orientation due to anisotropy (22). A 35° fiber orientation provided the best combination of tensile and flexural strength (29). These results illustrate that fiber orientation significantly affects mechanical properties, which can be optimized according to the application.

4. Conclusion

A comprehensive literature review identified and analyzed the determinants of carbon fiber strength and its application in developing efficient and sustainable composites. Due to their exceptional strength, it was found that carbon fibers are making significant contributions to the automotive industry and sustainable engineering, particularly in efforts to reduce vehicle weight and improve fuel efficiency. Of particular interest from the results of this review is that the modification of carbon fibers with dopamine and their integration in aluminum matrix composites showed significant improvements in tensile strength and weight reduction, which supports the wider use of these materials in various structural and functional applications. The research also highlighted that fiber orientation in composites has a major impact on the material's mechanical properties, where proper fiber orientation can improve the strength and toughness of composites. Furthermore, using carbon fibers in combination with other materials such as nylon and PLA also showed improvements in relevant mechanical properties, paving the way for further exploration of hybrid composites. Carbon fibers and their composites are key to a lighter, stronger, and more energy-efficient materials revolution. However, additional studies are needed to optimize the manufacturing process and lower production costs to be more widely adopted in the industry.

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