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TRIBOLOGICAL PROPERTIES OF WOVEN CARBON FIBRE COMPOSITE FOR WIND TURBINE BRAKE PADS

Atia A. M.[1], Atia K. M.[2], Badran A. H.[2]

[1]Department of Mechanical Design and Production Engineering, Faculty of Engineering, Assiut University, EGYPT.
[2]Department of Production Engineering and Mechanical Design, Faculty of Engineering, Minia University, El-Minia, EGYPT.

ABSTRACT
The established challenge in contemporary mechanical engineering lies in the enhancement of materials for applications involving wear. This study focuses on analyzing the wear mechanism of brake pads by employing epoxy reinforced with carbon fiber. The fabrication involved the lay-up process, and curing time reduction was achieved through elevated temperatures. The number of the carbon fiber layers examined was 2, 3, 4, 5 and 6. To investigate the wear rate characteristics of the carbon fiber composite (CFC), a pin-on-disc apparatus with varying rotational speeds, convertible to linear distance, was utilized.

The results reveal that wear decreased when toughness increased. As the fiber content increased, wear decreased. Besides, the delamination of the carbon fibers and the separation of individual layers within the composite structure were the wear mechanism of the composites.

KEYWORDS
Carbon Fiber Composite, Wind Turbine Brake, Coefficient of Friction, wear rate.

INTRODUCTION
Composite materials are increasingly being used in wear applications due to their high strength, stiffness, and wear resistance. They can be tailored to meet the specific requirements of a given application, and they often offer significant weight savings over traditional materials. Some of the most common composite materials used in wear applications include glass fiber-reinforced plastic (GFRP), carbon fiber-reinforced plastic (CFRP), and Kevlar-reinforced plastic, [1-4].

Epoxy-reinforced composite materials can be used in a variety of wear applications, including conveyor belts, gears, bearings, and brake pads. They are resistant to wear and tear, and they can withstand harsh environments offering several advantages over traditional materials in wear applications, including high strength, low weight, corrosion resistance, and customizability. As a result of these advantages, composite materials are increasingly being used in a wide variety of wear applications, [5, 6].

Carbon fiber in epoxy is a composite material that is made by weaving carbon fibers into a fabric and then impregnating the fabric with epoxy resin. The resulting material is strong, lightweight, and corrosion-resistant. It is often used in applications where strength and weight are critical, such as in aerospace, automotive, and sporting goods. Epoxy resin is a thermosetting resin that cures at room temperature. Otherwise, the curing process can be accelerated by using heat or pressure. The cured composite material is then cut to sizes and shaped, [7, 8].

The wear mechanism of epoxy carbon fiber composites is complex and can be affected by several factors. The most common wear mechanisms are abrasion, delamination, and fatigue. Abrasion is caused by the rubbing of two surfaces against each other. Delamination is the separation of the fibers and matrix from each other. Fatigue is the gradual breakdown of a material under repeated loading, [9-12]. The wear of epoxy carbon fiber composites can be reduced by surface treatment, fillers, and coatings. Surface treatment can make the surface harder and more resistant to abrasion. Fillers can improve the wear resistance of the epoxy resin. Coatings can protect the surface of the composite from wear. The wear of epoxy carbon fiber composites is an important consideration in the design of any application where the composite will be subjected to wear. By understanding the wear mechanisms and the methods for reducing wear, engineers can design composites that are both strong and durable, [13-16].

However, brake pads are an essential part of many engineering applications such as wind turbines, as they help to control the speed of the turbine and prevent it from spinning out of control. Brake pads are made of a variety of materials, including organic, sintered, and composite materials. Brake pads need to be replaced periodically, depending on the amount of use they receive. The average lifespan of a brake pad is about two years. However, if the wind turbine is used in a harsh environment, such as a desert or coastal area, the brake pads may need to be replaced more often, which brings a huge challenge for researchers for wear material improvement, [17].

Many previous studies focused on studying the frictional properties of composite materials. Ertan R. and Yavuz N., [17], evaluated the effects of manufacturing parameters on tribological properties in order to determine the optimal parameters for enhanced tribological behavior. If optimal values are selected, the tribological behavior and manufacturing cost of brake lining can be significantly enhanced.

Peng Zhang and et al., [12], evaluate the braking performance of copper-based brake pads containing different amounts of carbon fiber (CF). The optimal amount of CF for improving braking performance was found to be 0.4 wt. %. Moreover, adding 0.4% carbon fiber to copper-based brake pads can improve their braking performance in terms of wear resistance and friction coefficient. This makes them a more suitable choice for applications where high-speed emergency braking is required, such as in high-speed trains and automobiles.

Ramadan M. A., [4], presented an article that found that adding continuous and aligned carbon fiber to epoxy, as well as filling the resulting composite with vegetable or mineral oil, can significantly improve its resistance to friction and wear. This could make these composites more suitable for use in various applications. Bulent Ozturk and et al., [3], evaluated how resin type and fiber length affected the mechanical and friction properties of automotive braking materials. The results of this study revealed that both resin type and fiber length influenced the mechanical and friction properties of the friction materials. The wear resistance of the composites was improved by increasing the fiber length. The coefficient of friction and the wear resistance of the composites correlated well. According to the findings of this study, automobile brake producers could consider adopting resins with high wear resistance and fibers with long lengths to improve the performance of their brake materials.

J. Gururaja Rao and et al, [14], developed a study with indicates the friction and wear performance of the brake discs by simulating aircraft landing braking energies (normal and overload) corresponding to one interface using a disc-on-disc dynamometer. The results showed that the type of polymeric reinforced by carbon influenced the nature of the friction film formed, which in turn affected the wear rate of the Carbon/Carbon brake discs. The matrix characteristics additionally affected the mechanical properties and the friction film formed affected the coefficient of friction of each type of disc.

Based on the information provided above, the authors conducted this study to investigate how brake pad wear occurs and increases the resistance to wear, which applies to most moving parts, especially in wind turbines.

EXPERIMENTAL WORK

In this study, epoxy resin was reinforced with carbon fibers. This is done by using the lay-up method, and the researchers used the temperature to accelerate the hardening time of the composite material. The specimen's dimensions are 10 cm in length, 5 cm in width, and 0.3 cm in thickness. The layers of woven carbon fiber have been distributed in composite as 2,3,4,5 and 6 layers with volume fractions (VF) of 16, 24, 32, 40, and 49 respectively. In Fig. 1, an illustration of three different traveling distances is presented. Three diameters (A, B, and C) were selected of 110, 130, and 150 mm to produce different linear velocities. Figure1 shows the test rig (Pin on Disk), where Fig. 1, A represents the diameters on the rotating disk, while Fig. 1, B illustrates the details of the test rig.

Additionally, the testing time for each sample has been set at five minutes to get the behavior of steady-state wear. Considering the use of sandpaper for each test separately. Besides, the Arduino kit has been used to collect data related to the friction coefficient values during the test. Furthermore, a microscope examination is used to investigate the friction surfaces in the tested samples to clarify the reasons for the wear values and the friction coefficient for different conditions.

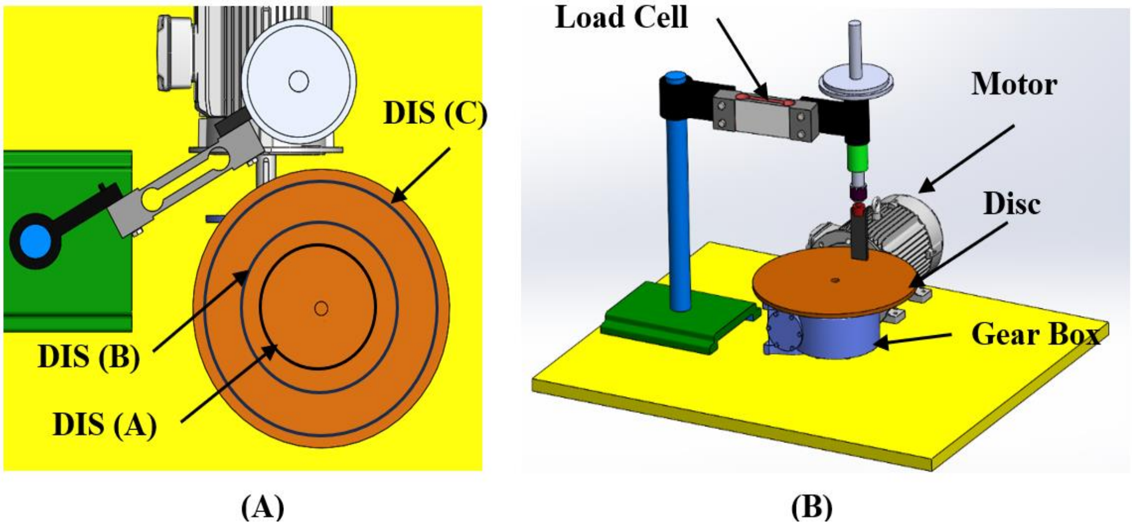

Fig. 1 Details of the teste rig.

RESULTS AND DISCUSSION

The percentage of carbon fiber in epoxy resin affects the coefficient of friction. In general, as the volume proportion of carbon fiber in composites increases, so does the coefficient of friction. Carbon fiber is tougher than epoxy resin because it has a lower coefficient of friction. As a result, the overall coefficient of friction increases as the amount of carbon fiber in the composite increases. As can be noticed from Fig. 2, the coefficient of friction may demonstrate a high value at the lowest volume fraction, and then decrease as the volume fraction continues to increase. This is because the wear rate of the composite also increases as the volume fraction of carbon fiber increases.

Therefore, at a certain point, the increase in wear rate outweighs the increase in friction, and the overall coefficient of friction decreases, [16]. Other parameters, such as the nature of the epoxy resin, the surface finish of the composite, and the operating conditions, influence the influence of the volume fraction of carbon fiber on the coefficient of friction. However, in general, one of the most important elements influencing the coefficient of friction of carbon fiber/epoxy composites is the volume percentage of carbon fiber. Nonetheless, the effect of carbon fiber volume percent on the coefficient of friction is not necessarily linear.

Coefficient of fraction and normal load

Furthermore, in most cases[18], the coefficient of friction decreases with increasing normal load. This is because as the normal load rises, the area of contact between the two surfaces grows. This increase in intensity area of contact means that there are more asperities on the surfaces that can interlock, which reduces the frictional force. However, in some circumstances, the coefficient of friction might rise as the usual load increases. For instance, this could happen if the surfaces are very smooth, and the normal load is high enough to cause plastic deformation of the surfaces. In this case, the increased area of contact is not due to interlocking asperities, but rather to the formation of a thin layer of plastically deformed material between the two surfaces. This layer of material has a higher coefficient of friction than the original surfaces, which can lead to an increase in the overall frictional force.

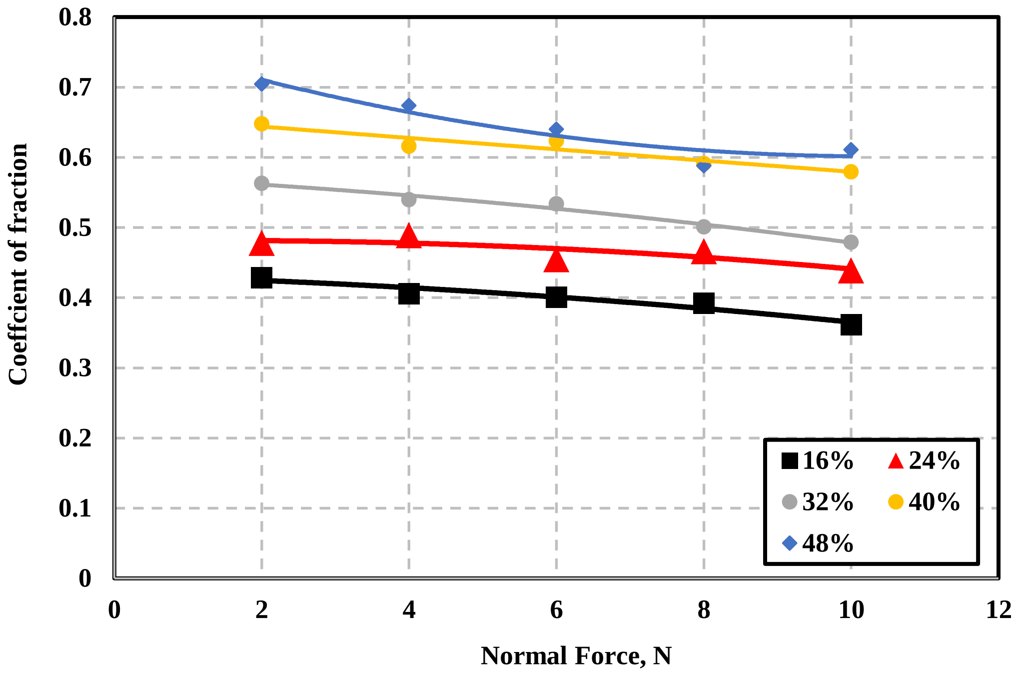

Fig. 2 The relation between the coefficient of friction and normal force for all Reinforced percentages of carbon fiber.

By examining and studying the images obtained using an optical microscope, we can determine the mechanism of wear occurrence. Certainly, a laboratory cleaning procedure was performed on the surface of the samples used in the study. By investigation of the following images Fig 3, A, it can be noticed that the composite layers are presented. In accordance with established scientific understanding and empirical evidence, delamination represents a prominent mode of failure characterized by the fracture of a material into distinct layers. This phenomenon assumes particular significance as a critical failure mechanism within laminated epoxy reinforced by carbon fiber, wherein the through-thickness strength is notably diminished which will lead to decreased wear resistance.

As shown in Fig. 3, B the consistency of the wear mechanism is also evident in the illustration, as it shows the beginning of a clear dislocation in the connection between the reinforcement material and the matrix, see the dashed circle. It is noticed that the appearance of the fiber phase as a black space is an indicator of the hybrid wear mechanism that occurs.

Normal load Vs Wear rate for all VF

As the volume fraction of carbon fiber increases, the wear rate decreases. This is because carbon fibers are very strong and wear-resistant, so they help to protect the epoxy resin from wear. In one study[6], the wear rate of carbon fiber epoxy composites was found to decrease by up to 18.5% when the volume fraction of carbon fiber was increased from 3% to 9%. This was true for both dry and wet wear conditions. The reason for this is that carbon fibers are very hard and abrasive. When they are embedded in the epoxy resin, they help to prevent the resin from being worn away. The fibers also help to distribute the load more evenly, which reduces the stress on the resin and makes it less likely to crack or wear.

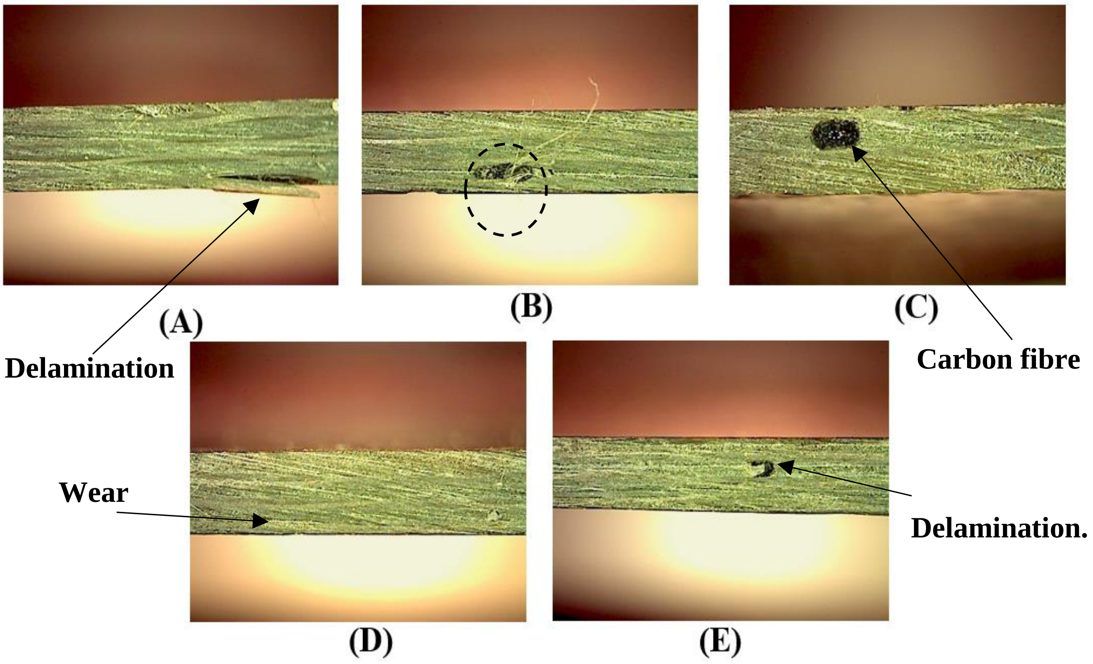

Fig. 3 Illustration of the wear of the carbon fibers.

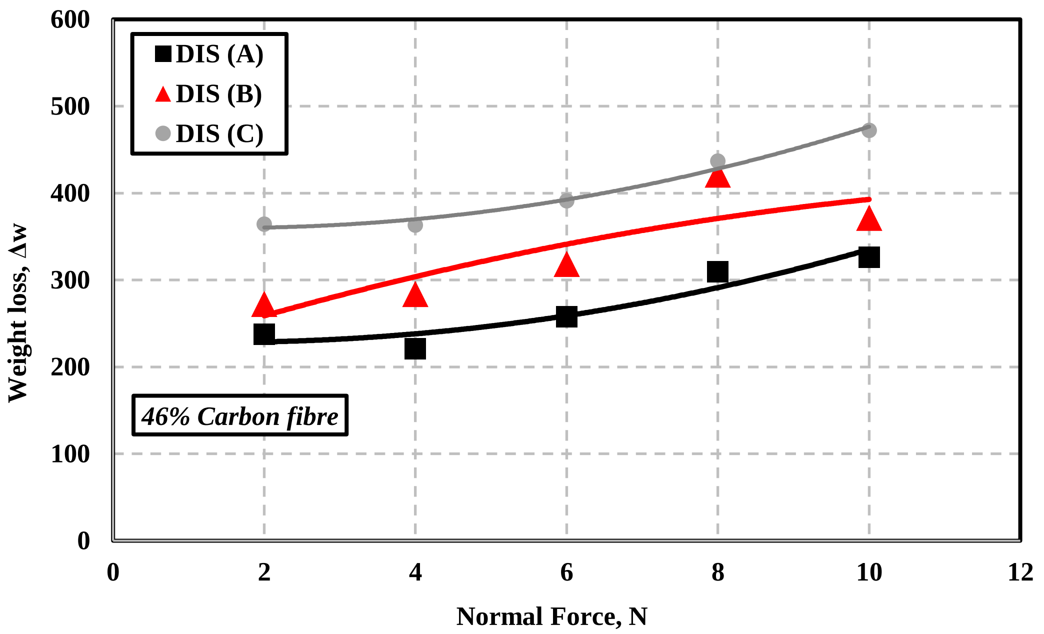

Fig. 4 The illustration of the relationship between weight loss and the normal force for all composite's volume fraction.

Wear rate and toughness

Toughness, defined as a material's capacity to absorb energy prior to fracturing, stands as a pivotal metric in materials science, particularly concerning resistance to impact and shock. This parameter gauges a material's ability to deform plastically without succumbing to breakage. Simultaneously, wear resistance denotes a material's aptitude to withstand the removal of material from its surface due to friction, abrasion, or other mechanical actions, reflecting its endurance under wear conditions.

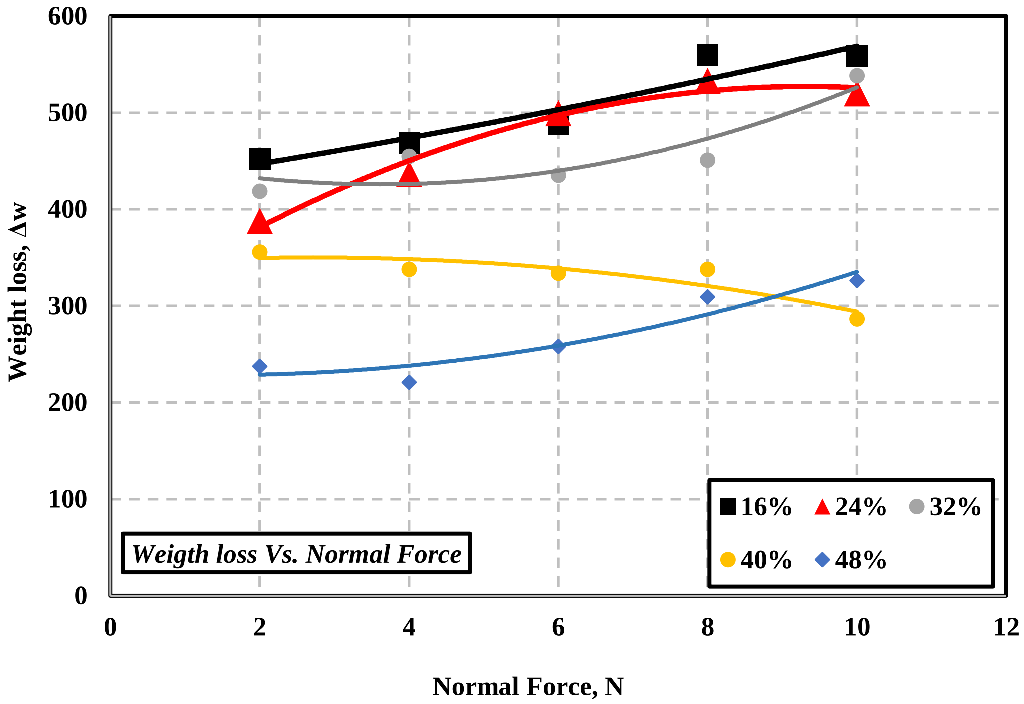

Fig. 5 The illustration of the relationship between weight loss and the normal force for all composites volume fraction.

The intricate relationship between toughness and wear resistance manifests in two distinct ways. Firstly, a direct correlation often surfaces, signifying that heightened toughness generally accompanies increased wear resistance. This interconnection arises from the fact that a tougher material demonstrates enhanced resistance to common wear mechanisms like cracking and breaking. Conversely, a notable trade-off exists between toughness and wear resistance. The tendency for a material to become more wear-resistant as it becomes harder is counterbalanced by a reduction in toughness. This is due to the increased susceptibility of harder materials to cracking and breakage when subjected to impact or stress. So, toughness (UT) can be calculated from the simple as following:

$$UT = \int_0^{\varepsilon f} \sigma \, d\varepsilon \qquad \text{Eqn. (1)}$$

The values of toughness extracted from the stress-strain curves of tested simples, see Fig.1. The equation of the stress-strain curves acquired by finding the equation in Excel is a polynomial function in the order of two. By using Mathematica software,

the extracted equations were integrated as a limited integration from strain zero to failure strain. It can be observed that values of toughness are presented against the volume fraction of carbon fiber, Fig. 8. In addition, the results of the wear test in the condition of (10 N) load are represented in the same curve. So, it can be noticed that there is a remarkable relationship between the toughness and wear resistance of the composite material.

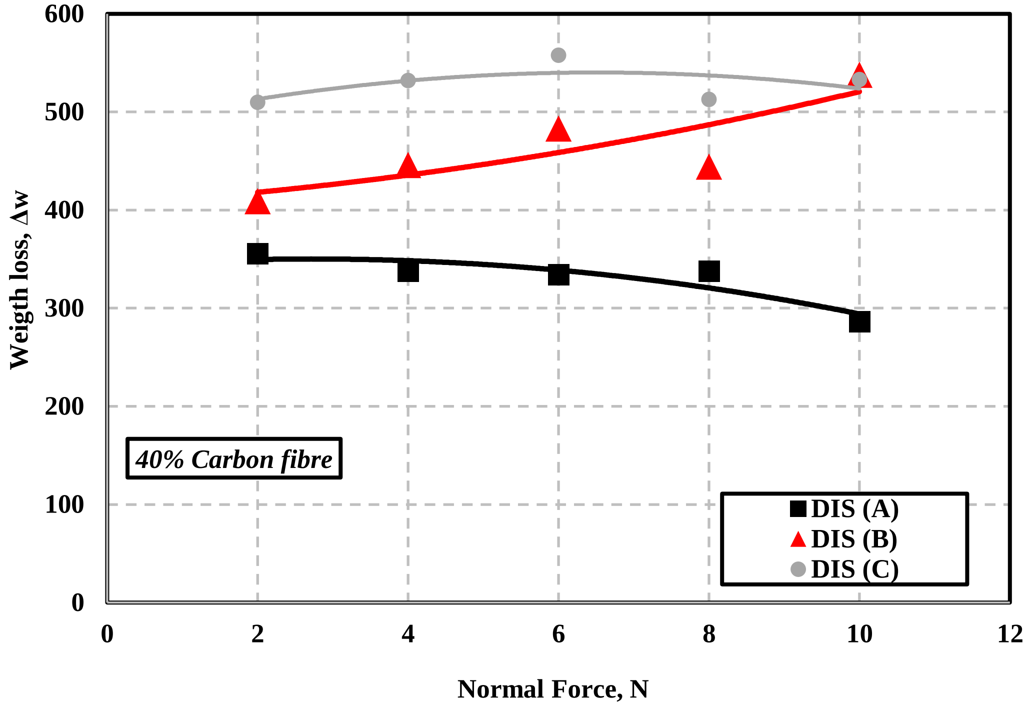

Fig. 6 The illustration of the relationship between weight loss and the normal force for all composites volume fraction.

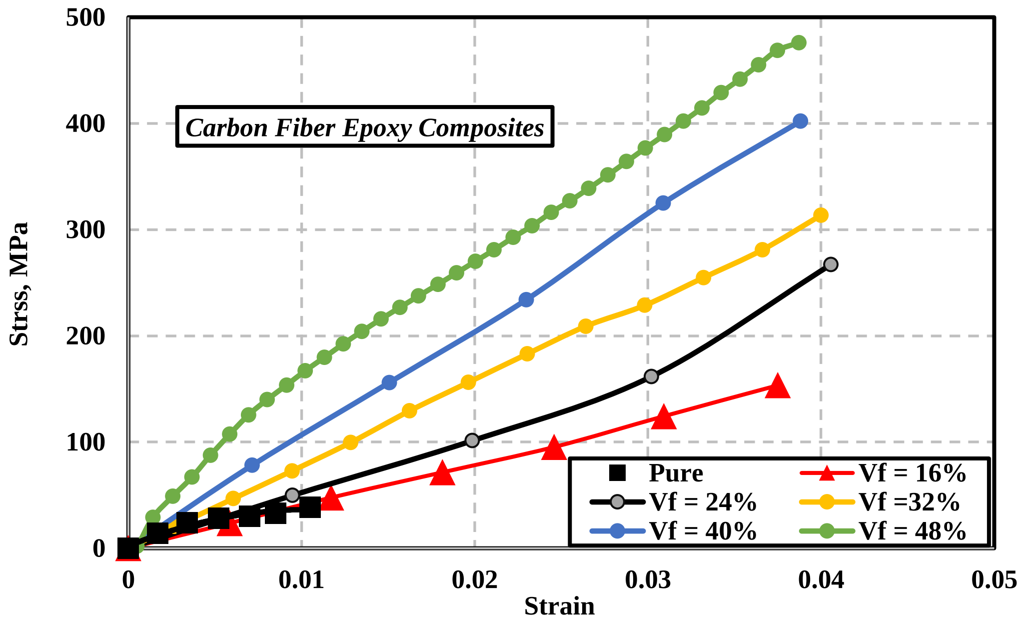

Fig. 7 The stress strain curve of four carbon fiber epoxy composites.

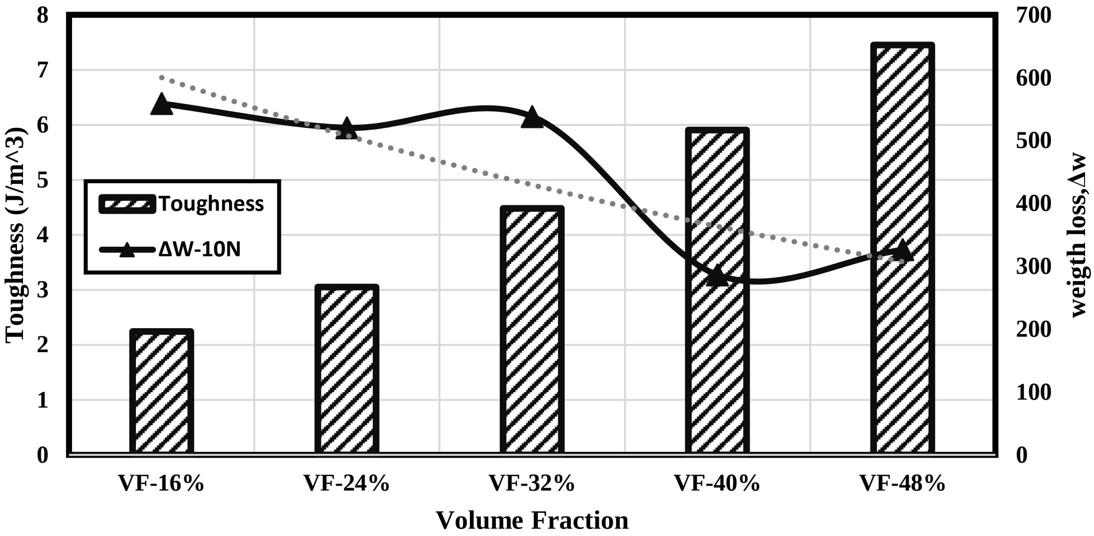

Fig. 8 Comparison between toughness and weight loss of CFC.

Adding carbon fiber as reinforcement to epoxy, it further increases the toughness of the material. This is because the carbon fibers act as a load-bearing network that helps to distribute the stress more evenly throughout the material[8]. This makes the material less likely to fracture, even under high loads, see figure eight. The greater wear resistance of epoxy-carbon fiber composites is due to their increased toughness. This is since carbon fiber aids in the prevention of wear particles. These particles can function as abrasives, causing the material to wear away faster. The increased toughness of epoxy-carbon fiber composites also makes them less likely to delaminate. Delamination is a condition where the layers of material separate from each other. This can happen when the material is subjected to high loads or impact. Delamination can lead to catastrophic failure of the material, [13, 14].

CONCLUSIONS

Based on the present study, the following key points can be summarized regarding the performance of carbon fiber composites as brake pads for wind turbines:

1. The research supports the importance of toughness in brake pad performance. It reveals that when toughness levels increase, weight loss decreases dramatically, demonstrating a positive association between these two factors. This shows that tougher composites have better wear resistance, resulting in a longer lifespan and better performance.

2. The fiber content and weight reduction of CFC composites show a significant link. According to the findings, increasing the content of the carbon fibers in the composite structure results in less weight loss. This means that higher fiber content improves the overall strength and durability of the brake pad, resulting in less wear and tear.

3. The analysis indicates composite layer delamination as the principal mechanism responsible for the observed weight loss. This delamination, which involves the separation of individual layers within the composite structure, can be caused by several reasons, including cyclic loading, thermal stresses, and fatigue. Improving the longevity and performance of CFC brake pads requires minimizing delamination through optimal material selection and production procedures.

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