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Wear Resistance of Fiber-reinforced Nanoparticle Hybrid Mixture

Mustafa Ahmed Rajab 1[a], Mazin Mahmood Yahiya 2[b,c], Noor A. Hameed 3[d], Mudhar A. Al-Obaidi 4[a,e*] and Rasool R. K. Al-Arkawazi 5[e]

[a] *Middle Technical University, Technical Institute of Baquba, Dayala – Iraq*
[b] *Bilad Alrafidain University College, Dayala – Iraq*
[c] *University of Diyala, College of Engineering, Dayala – Iraq*
[d] *University of Diyala, Al-Muqdad College of Education, Dayala – Iraq*
[e] *Middle Technical University, Technical Instructor Training Institute, Baghdad – Iraq*
* *Corresponding author. Tel.: +0-964-771-506-1121; e-mail: dr.mudhar.alaubedy@mtu.edu.iq*

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ABSTRACT

Composite materials have come to be associated with contemporary, and they are desired in practically every area of our ordinary routine. Composites have gained popularity due to their properties such as durability, strength, and reduced energy consumption during the production process, and low shipping costs. However, there is still a need to enhance the structure of composite materials by upgrading production techniques towards nanocomposites, which would allow the introduction of composite materials with high strength and stiffness. The current study investigates the reinforcement against wear resistance of a hybrid mixture combining epoxy and phenol formaldehyde using a combination of carbon fibers and alumina nanoparticles. To systematically carry out this investigation, the hardness properties of the synthesized composites besides the influence of different sliding velocities on the wear resistance have been addressed. The results present the prosperity of the synthesized hybrid mixture reinforced by carbon fibers and alumina nanoparticles, which introduces the lowest wear rate (highest wear resistance) compared to the hybrid mixture composite, carbon fibers-reinforced hybrid mixture, and alumina-reinforced hybrid mixture. This has been attributed to the randomly distributed nanoparticles and fibers within the hybrid mixture of epoxy and phenol formaldehyde.

Keywords: *Wear resistance, Epoxy, Phenol formaldehyde, Carbon fibers, Alumina nanoparticles.*

1. INTRODUCTION

Wear is defined as the gradual loss of material from a surface caused by constant rubbing or sliding between surfaces [1]. Depending on the nature of the corrosion, most materials can exhibit either moderate or severe corrosion behaviors [2]. The corrosion mechanism is affected by changes in surface roughness. Increasing the surface roughness of hard polymers, in particular, causes the formation of longitudinal plowing trenches, which accelerates the corrosion rate of hard and brittle polymers due to friction with smooth surfaces [3]. On the other hand, the resistance of a surface to external load penetration is referred to as its hardness. The hardness concept can be thought of as a scale for the plastic deformation that a material can undertake when exposed to external stress [4].

A composite material is a material that is made up of two or more different types of materials, which are combined in a way that allows them to work together to create a new material with specific properties. Composites can be made up of different combinations of materials, including polymers, metals, ceramics, and other materials. Polymers are a type of material that is composed of long chains of repeating molecular units. Many polymers are commonly used as the matrix or binder material in composite materials. The polymer matrix provides the composite with its shape and durability and also helps to hold the other materials in place. In this regard, the polymers offer unique qualities such as lightweight, chemical resistance, and corrosion resistance, as well as a homogeneous structure, which introduces a distinct physical behavior as well as design flexibility. Polymers have drawn the interest of engineers, materials scientists, and technicians due to their ease of fabrication, strength, high hardness, corrosion resistance, and durability, and have become the materials of the twenty-first century to meet aerospace, missile, and marine prerequisites, as well as medical technologies [5]. The use of polymeric materials enables more design freedom, and in many circumstances, these materials provide a safe or cost-effective engineering solution for a variety of industrial applications [6].

In the same context, the reinforcement of composites with carbon fibers in one or more orientations, results in strength and rigidity from the fibers. This in turn would introduce a composite of a lightweight structural material. The reinforced constituent materials of the composites have significantly different chemical and physical features and are combined to form a material with qualities that differ from the individual constituents. Composite materials, which are reinforced with fibers and nanoparticles, are a significant step forward in the ongoing quest for material enhancement. Nature is filled with examples and applications of putting the concept of composite materials into practice [7]. After reinforcing resins with fiberglass, sophisticated compounds were used in the twentieth century. Fiberglass materials, for example, were used to make boats and aircraft. The widespread usage of composite materials increased in the 1970s as a result of the invention of novel fibers such as carbon, boron, and aramids, as well as new composite materials with nanoparticle reinforcement [6]. Spare parts and tires for automobiles, airplanes, telephones, computers, artificial limbs for the human body, and a variety of other material commodities are instances of polymers' current reality. For example, carbon fiber-reinforced polymer composites are commonly used in the aerospace and automotive industries. These composites are made up of a polymer matrix reinforced with carbon fibers. The polymer matrix helps to hold the carbon fibers in place and provides the composite with its strength and stiffness.

Several scholars were interested in evaluating the physical properties of different combinations of composites. For instance, the reinforcement of epoxy composites by adding fibers was also conducted by Rajmohan and Koundinya [4] by measuring different physical properties of epoxy composites. It was concluded that there was a significant improvement in tensile and flexural properties of epoxy composites after using carbon fibers which enables the composites to be employed in aerospace, marine, and military applications. Also, Basarkar and Singh [6] studied the mechanical properties including the tensile, bending, and hardness of unsaturated polyester resins reinforced with silica particles using different weight percentages between 10 – and 40%wt. The results showed an increase in tensile strength and flexural strength when increasing the concentration of nanoparticles.

This study attempts to introduce nanocomposites as a superior type of composite material with enhanced structure and upgraded physical properties. Specifically, this study would investigate the prosperity of reinforcing the composite of epoxy and phenol formaldehyde with carbon fibers and alumina nanoparticles via evaluating the wear resistance property.

2. MATERIAL AND EXPERIMENTAL APPARATUS

2.1. Materials

1. Epoxy resins: An epoxy resin component of sikadur (52LP) of 3 g was used as the base in this investigation.
2. Phenol formaldehyde resin: This is one of the ancient resins that has been widely utilized in the industry. This resin was produced in the presence of an acidic catalyst with poly-condensation of phenol and formaldehyde. Specifically, the alumina nanoparticles resin (98.5% Al2O3 (ɤ) kama alumina powder) was made by reacting phenol with formaldehyde to produce thickening chemicals.
3. Carbon fiber: Carbon fibers were used to strengthen the layers. The carbon fibers contain polyacrylonitrile (PAN), isotropic pitch, mesosphere pitch, and regenerated cellulose. The polymer was cast with fibers using a weight fraction of 30%, which is an appropriate ratio in terms of cost and durability.

The samples were prepared containing 90% epoxy resin 9% of phenol formaldehyde resin and 1% of alumina nanoparticles while supplemented with carbon fibers. Tables 1 and 2 introduce the actual properties of resin materials and carbon fiber used in this investigation for the preparation of samples.

2.2. Experimental apparatus

A series of tests were performed to assess the physical properties of the hardness and wear resistance of the reinforced composites. In this regard, a TH2010 Shore Durometer (Figure 1) was used to measure the hardness of the samples in the current investigation at room temperature.

To systematically determine the influence of the added materials (carbon fibers and alumina nanoparticles), the hardness and wear resistance of the reinforced composites were compared to the properties of the original material (epoxy resins and phenol formaldehyde). The wear test was carried out at room temperature utilizing a pin-on-disk tester in Diyala University/Department of Mechanical Engineering's metallurgical laboratory. A schematic diagram of the pin-on-disk is shown in Figure 2. The device comprises a spinning electric motor that transmits motion from the electric motor to the disc. The disk has an angular velocity of 700 rotations per minute. In this regard, the rate of wear was measured for the composite materials using a fixed load of 10 Newton for an operational time of 10 minutes. The rate of erosion was calculated by weighing the sample before and after testing, with the difference representing the amount of corrosion residue [6]. Table 3 shows sample dimensions and standard specifications for test samples.

Figure 1 Hardness test (TH210 Shore Durometer)

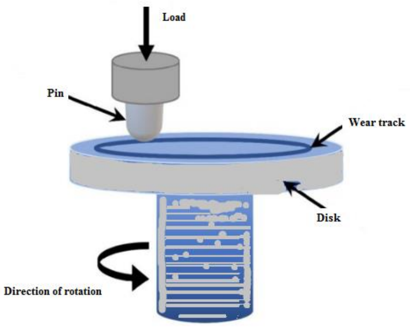


Figure 2 A schematic diagram of the pin-on-disk

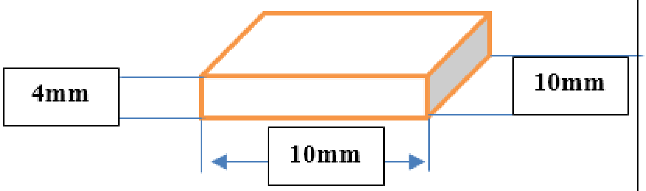
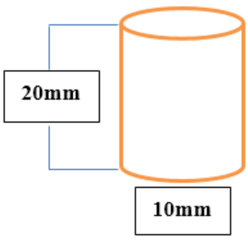
Table 1 Resin materials and their properties [6, 8, 9]

Specification	Epoxy	Phenol Formaldehyde
Appearance	Comp. (A): Yellowish Comp. (B): Brownish	Pale brown liquid
Solid content		50% - 52%
Celatin at 130 ^oC		10 – 15 min
Specific gravity	1.11 - 1.18 gm/c.c	1.15 – 1.20 gm/c.c
PH	-	8.0 – 8.5
Water tolerance		Infinite
Free phenol content		1.0 – 1.5 %
Free formaldehyde content		6 – 7 %
Viscosity at 25 ^oC	250 mPa.s	150 – 350 mPa.s
Density 20 ^oC	Comp. (A/B:1.1) (kg/l) (mixed)	1.21 kg/l
Shelf-life at 25 ^oC	12 month	45 days from the manufacture
Pot life 2 kg at 20 ^oC	60 min	120 min
Mechanical strength at 20 ^oC and 10 days	Compressive = 53 N/mm^2 Flexural = 50 N/mm^2 Tensile = 25 N/mm^2	Compressive = 66 N/mm^2 Flexural = 59 N/mm^2 Tensile = 48 N/mm2
Coefficient of thermal expansion	$89x16^{-6}$ m per -20 to 60 ^oC	$99x16^{-6}$ m) per -10 to 60 ^oC

Table 2 Specifications of carbon fiber

Property	Tensile Strength	Compressive Strength	Elastic Modulus (GPa)	Density (g/cm^3)
Carbon fibers	3–7 (GPa)	1–3 (GPa)	200–935	1.75–2.20

Table 3 Samples dimensions and standard specifications of the testing specimens

Property	Dimensions of the samples	Standard specifications
Hardness		ASTM-D2240
Wear		ASTM-G99

3. RESULTS AND DISCUSSION

3.1. Evaluation of hardness property

Figure 3 depicts the hardness property of different samples of composite materials of epoxy resins and phenol formaldehyde resins (ER) reinforced by carbon fiber (CF) and alumina nanoparticles (Al2O3). Despite the significant improvement of hardness due to adding carbon fibers to ER, the hardness tests of the synthesized composites have ascertained the improvement of the hardness property as a result of utilizing the alumina nanoparticles in ER. This is particularly shown in Figure 3 as the hardness of ER+ Al2O3 is higher than those of ER and ER+CF. The homogenous particle distribution of alumina nanoparticles within the combination of ER resins can be attributed to the reason behind this. Furthermore, this phenomenon can be attributed to the larger density of agglomerated nanoparticles of alumina powder compared to the obtained density of the hybrid mixture reinforced by fibers. Thus, it is fair to admit that the particle size of the incorporated nanoparticles (alumina powder) has a direct impact on the hardness. Basically, gaps play an essential role in the porosity increase inside the composite material and therefore it is preferable to remove them during the preparation process. The SEM picture of the hybrid composite of epoxy, phenol formaldehyde, carbon fibers, and alumina nanoparticles is shown in Figure 4.

Particularly, as the proportion of gaps decreases, the hardness values will increase with decreasing particle size. As experimentally indicated, it was difficult to penetrate the base material of the synthesized composite of alumina powder. In other words, the presence of nanoparticles (alumina) has improved the hardness property of the composite to a significant extent due to its low particle size which reduced the porosity. Rajmohan and Koundinya [4] indicated that an increase in grain size can lead to a decrease in the hardness as a result of the decrease in the proportion of the base material. This means that there is a weakness in the cohesion of the hybrid mixture composition. More importantly, Figure 3 introduces the fact of a superior improvement of hardness property for the combination of alumina and carbon fibers with ER.

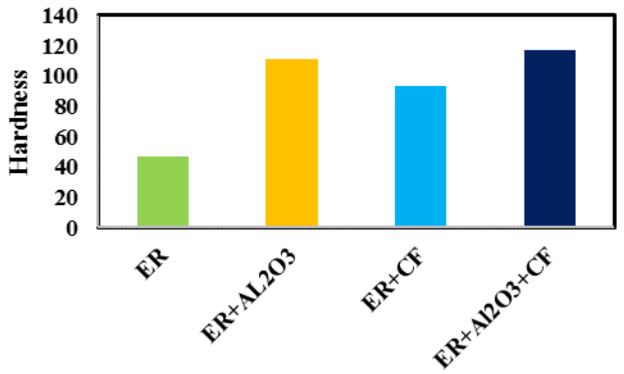


Figure 3 Hardness of composite materials when reinforced by alumina nanoparticles and carbon fiber

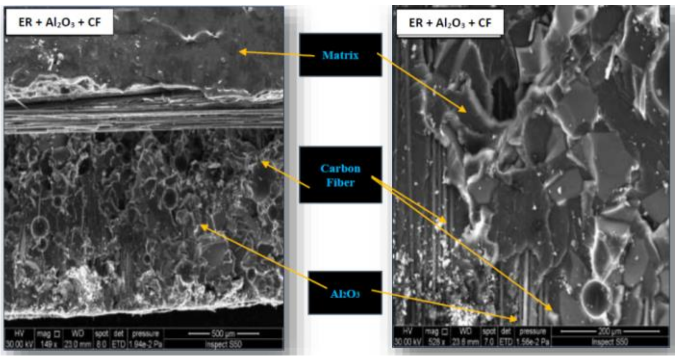


Figure 4 SEM images of the hybrid composite

3.2. Evaluation of wear resistance

Using a fixed load of 10 Newton, this section attempts to experimentally investigate the effect of sliding velocity on the wear rate of the synthesized samples of epoxy and phenol formaldehyde (ER), ER and alumina nanoparticles (ER+ Al2O3), ER and carbon fibers (ER+CF), and ER+ Al2O3+CF. The experiments were carried out using different sliding velocities between 1 m/s to 7.5 m/s for a specified 10 minutes for each experiment.

Figure 5 shows the relationship between the wear rate and sliding velocity (between the sample of the wear test and the rotating hard disk of the wear test device) for the four tested samples of epoxy and phenol formaldehyde resins (ER), ER, and alumina nanoparticles (ER+ Al2O3), ER and carbon fibers (ER+CF), and ER+ Al2O3+CF. Clearly, it can be stated that increasing the sliding velocity has caused an increase in the wear rate for the whole tested samples, which means a lower wear resistance. There are several reasons that can interpret this phenomenon as listed below;

Temperature: As the sliding velocity rises, more heat is generated at the contact interface between the two surfaces, potentially raising the composite's temperature. Temperature increases can cause thermal degradation of the matrix material, reducing its mechanical characteristics and increasing wear rate.

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Adhesion and abrasion: As sliding velocities increase, the contact between the two surfaces becomes more severe, resulting in more adhesion and abrasion forces. This can cause more serious damage to the composite surface and accelerate wear.

Fatigue: At high sliding velocities, cyclic stresses in the composite material can be created, resulting in fatigue damage and a greater wear rate. As a result, while assessing the wear rate of a composite material, it is critical to examine the sliding velocity and understand its implications on the composite's mechanical properties.

Figure 5 shows that ER has the highest wear rate (lowest wear resistance) for the whole tested sliding velocities. These resins alone have low wear resistance, as they are relatively soft and prone to wear and deformation under stress.

Figure 5 also ascertains that the reinforcements of ER by alumina nanoparticles or carbon fibers or both of them have positively affected the wear rate. In general, the wear resistance of composites increases with the addition of reinforcing materials such as fibers or nanoparticles. Among the tested composites of ER+CF, ER+ Al2O3, and ER+ Al2O3+CF, the wear resistance can be ordered from lowest to highest:

1. ER and carbon fibers (ER+CF): Adding carbon fibers to an epoxy resin and phenol formaldehyde resin composite material can considerably improve the mechanical characteristics and uniformity of the material. Thus, the addition of carbon fibers to the resin matrix significantly improves the wear resistance, as the high strength and stiffness of the fibers can help distribute and resist wear forces. Carbon fibers are noted for their high strength, stiffness, and low weight, which can improve the composite's strength and stiffness [10]. The fiber is also chemically resistant, making it suitable for use with epoxy and phenol formaldehyde resins. In terms of molecular structure, the insertion of carbon fibers within the composite can form a three-dimensional network structure, providing greater mechanical interlocking and improving load transfer between the fibers and the matrix. This can increase composite uniformity and lessen the possibility of delamination or fiber pull-out [11]. To attain ideal mechanical properties, the carbon fibers must be

evenly distributed and appropriately aligned within the composite. To achieve good bonding between the fibers and the matrix, the curing process of the epoxy and phenol formaldehyde resins must also be carefully managed. Overall, the incorporation of carbon fibers can significantly improve the mechanical characteristics, such as hardness (Figure 4) and homogeneity of epoxy resin and phenol formaldehyde resin composite material. However, it should be noted that carbon fibers can also be brittle, and under certain conditions, they may fracture or delaminate, which can reduce the overall wear resistance.

2. ER and alumina nanoparticles (ER+ Al2O3): The inclusion of alumina nanoparticles (Al2O3) in an epoxy resin and phenol formaldehyde resin composite material can increase mechanical characteristics and homogeneity, notably in terms of hardness and wear resistance. The nanoparticles have a large surface area to volume ratio, which increases their reactivity and capacity to create strong chemical interactions with the matrix material [12]. Thus, the addition of alumina nanoparticles can increase the wear resistance of the composite ER, as the hard and abrasive particles can help protect the matrix from wear. In terms of molecular structure, the addition of alumina nanoparticles within the composite can generate a three-dimensional network structure, providing extra mechanical interlocking and improving load transfer between the particles and the matrix. This can improve the composite's hardness and wear resistance. Furthermore, the addition of alumina nanoparticles can help increase the composite's homogeneity. The small size of the particles allows for better dispersion within the matrix and less agglomeration, which reduces the likelihood of flaws and improves material uniformity. However, the degree of bonding between the particles and the matrix can affect the overall wear resistance, and poor bonding can result in particle detachment and reduced wear resistance. To achieve ideal mechanical qualities, the concentration and dispersion of the nanoparticles within the matrix must be carefully controlled. The curing process of the epoxy and phenol formaldehyde resins must also be carefully managed to achieve optimal particle-to-matrix adhesion. Overall, the inclusion of alumina nanoparticles can significantly improve the mechanical characteristics and homogeneity of an epoxy resin and phenol formaldehyde resin composite material, notably in terms of hardness and wear resistance. Thus, the inclusion of carbon fibers in this composite would resolve this issue.

3. ER+CF+ Al2O3: The addition of carbon fibers and alumina nanoparticles (Al2O3) to an epoxy resin and phenol formaldehyde resin composite material can considerably improve the mechanical characteristics and homogeneity of the material. This composite has the highest wear resistance among the composites listed. The addition of both carbon fibers and alumina nanoparticles can create a synergistic effect that improves the wear resistance beyond what each material can achieve individually. The carbon fibers provide strength and stiffness to resist wear forces, while the alumina nanoparticles act as hard, abrasive fillers that help protect the matrix and fibers from wear. In more molecular structure details, the carbon fibers and alumina nanoparticles within the composite can form a three-dimensional network structure, providing more mechanical interlocking and improving load transfer between the fibers/particles and the matrix. This can result in a significant improvement in the composite's strength, stiffness, hardness, and wear resistance. Also, the addition of carbon fibers and alumina nanoparticles can help increase the composite's homogeneity. The small size of the particles allows for better dispersion within the matrix and less agglomeration, which reduces the likelihood of flaws and improves material uniformity. Carbon fibers can also aid in the distribution of nanoparticles inside the matrix, improving the overall mechanical performance of the composite. To achieve optimal mechanical qualities, the concentration, dispersion, and alignment of the fibers and particles inside the matrix must be carefully controlled. To achieve adequate bonding between the fibers, particles, and matrix, the curing process of the epoxy and phenol formaldehyde resins must also be carefully managed. Overall, the addition of both carbon fibers and alumina nanoparticles can significantly improve the mechanical properties and homogeneity of epoxy resin and phenol formaldehyde resin composite material, resulting in a high-performance material with improved strength, stiffness, hardness, and wear resistance. Overall, the combination of ER+CF+ Al2O3 can produce a composite with the highest wear resistance.

It is believed that the presence of both alumina nanoparticles and carbon fibers in the ER has reduced the corrosion rate that existed for the whole utilized sliding velocities between the contacted surfaces, where these particles formed a protective layer. Notably, the wear rate of the tested composite ER+ Al2O3+CF at a high sliding velocity beyond 5.5 m/s has shown the prosperity of having the lowest wear rate and therefore the highest wear resistance compared to other sliding velocities. This can be attributed to an increase in temperature of the sample with increasing sliding temperature, which enables to increase in the homogeneity and uniformity of molecules with a superior filling of the cavities between the components [8]. This in turn introduces more cohesion strength with associated higher hardness values. In this regard, the existence of alumina nanoparticles in ER which are reinforced by carbon fibers has strengthened the hardness property (Figure 3) and introduced a consistent composite with the lower gaps between the particles. In other words, utilizing the high sliding velocity enables to growth of the abrasion of the particles and the sliding of the sample on the turntable besides filling the cavities between the components of the hybrid mixture which introduces a uniform structure. In turn, the surface becomes a softener at a high sliding velocity due to a reduction of the coefficient of friction in ER+ Al2O3+CF under a fixed load, that is associated with an increase in the surface temperature and dropped wear rate.

In summary, the actual tests carried out in this study confirmed the effectiveness of these additives (carbon fibers and alumina) to epoxy and phenol formaldehyde resins in reducing wear rate as a result of enhancing the interaction between the molecules.

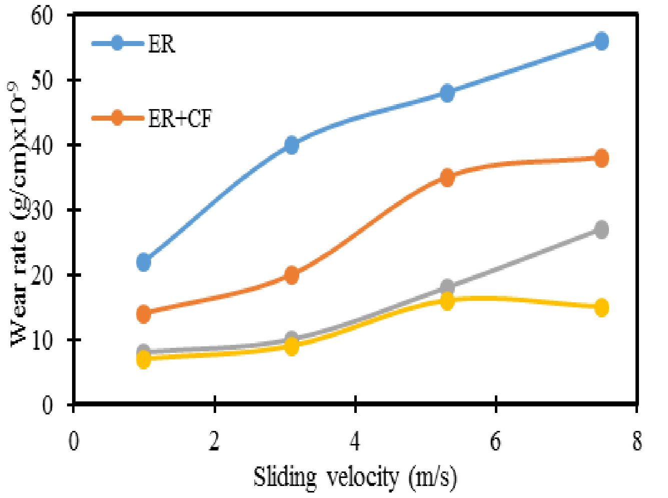

Figure 5 Effect of sliding velocity on the wear rate of different types of hybrid composites

4. CONCLUSIONS

The recent study focused on evaluating the feasibility of carbon fibers and nanoparticles on the improvement of wear resistance of a hybrid mixture of epoxy and phenol formaldehyde for a set of sliding velocities. It can be stated that the wear resistance of a composite is influenced by several factors, including the strength and hardness of the reinforcing materials, the degree of bonding between the matrix and reinforcing materials, and the synergistic effects of different materials. The results showed that the addition of carbon fibers and nanoparticles of alumina can potentially reduce the wear rate of a composite of epoxy and phenol formaldehyde resins, which denotes an increase in wear resistance. Carbon fibers can provide reinforcement to the composite, improving its mechanical properties including the hardness. Meanwhile, nanoparticles of alumina can act as fillers, increasing the hardness and toughness of the composite. More importantly, the optimum wear resistance has been approved for the hybrid mixture of epoxy and phenol formaldehyde reinforced by carbon fibers and alumina nanoparticles at a sliding velocity beyond 5.5 m/s.

It should be noted that testing and characterization of this upgraded composite should be carried out in the future to evaluate the performance of the composite under relevant conditions. By carefully selecting and optimizing these factors, it is possible to create composites with high wear resistance, which can be useful in many industrial and engineering applications.

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