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Study Mechanical Properties for Polymer Composite Reinforced by Carbon Fibers and Copper Oxide Particles (CuO) Used in Make Prosthetic Limb

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ABSTRACT

In the quest to advance the material science underpinning prosthetic limb technology, this study explores the mechanical fortification of unsaturated polyester-based composites via the incorporation of unidirectional carbon fibers and micro-scale copper oxide (CuO) particulates. The mechanical attributes scrutinized include hardness, impact resistance, compressive and tensile strengths, and flexural robustness. The fabrication process entailed manual molding techniques to yield homogenized composite samples. It was observed that the integration of carbon fibers markedly augmented the composite's mechanical performance. Specifically, the carbon fiber-reinforced specimens demonstrated a maximum hardness of 85.4 N/mm^2, an impact strength cresting at 6.27 KJ/m^2, a compressive strength peaking at 24.5 MPa, a tensile strength apex of 20 MPa, and a superior bending strength of 39.09 MPa. Conversely, the incorporation of CuO particles yielded mixed outcomes. While there was a notable increment in hardness strength to 83.5 N/mm^2 and a modest rise in impact strength to 0.70 KJ/m^2, a diminution was witnessed in compressive, tensile, and bending strengths, which dwindled to 8.33 MPa, 5.07 MPa, and 9.54 MPa, respectively. The findings underscore the efficacy of carbon fiber reinforcements in significantly bolstering the structural integrity of composite materials destined for prosthetic applications, outperforming the enhancements provided by CuO particles. This research underscores the potential for carbon fiber to act as a pivotal reinforcement agent in the development of high-performance prosthetic limbs, providing a robust framework for future material innovation. The study's implications extend to the design of lightweight, durable prosthetic components that can endure the multifaceted demands placed on them during use. Future investigations could pivot towards optimizing fiber-matrix interfaces and exploring hybrid reinforcement strategies to further push the boundaries of prosthetic material capabilities.

1. INTRODUCTION

Composite materials, constituted by the synergistic reinforcement of disparate elements, have garnered escalating prominence in an innovation-driven global landscape, attributed to their bespoke properties [1]. The fabrication of such materials is marred by complexities including substantial energy requisites, economic burdens, and raw material consumption [1]. Yet, the burgeoning application of composites, driven by their exceptional resilience to environmental adversities, has rendered them indispensable in a spectrum of strategic domains, notably in the realm of prosthetic limb development [2].

The domain of polymeric-based composites is distinguished by its superior attributes and benefits, positioning these materials at the forefront of current utilization [3]. Polymers, renowned for their lightweight, manufacturing ease, economic viability, formability, diminished moisture affinity, and low-energy consumption, surpass traditional materials such as unsaturated polyester, particularly in prosthetic applications where weight reduction is paramount [4, 5].

Mechanical enhancement of polymers is conventionally achieved through the reinforcement with fibers or particulates [6, 7]. The incorporation of fiber-reinforced composites has been revolutionary across diverse engineering and technological spectrums, offering a panacea to stringent performance demands [8-10]. The prosthetic limb sector has witnessed a surge in the adoption of carbon fiber-reinforced composites, courtesy of their exemplary specific strength, hardness, reduced density, and the facilitation of intricate design and functional integration [11, 12]. The industrial preference for fibers, which typically emanates from naturally occurring materials refined through specialized processes to meet tailored property specifications, is testament to their aligned performance merits [13, 14].

Prosthetic limbs-synthetic appendages designed to emulate the aesthetics and functionality of lost limbs-necessitate materials that are not only lightweight and robust but also costeffective, with a socket as the critical interface for load transference from the residual limb to the prosthetic [15]. The prevalence of amputations, propelled not solely by conflict-induced injuries but increasingly by age-related ailments such as diabetes and peripheral vascular diseases, has accentuated the role of prosthetics in contemporary healthcare [16]. The provision of prosthetic limbs thus emerges as a critical intervention for individuals bereft of their natural limbs due to various etiologies [17].

The foregoing discussion delineates the substantial strides made in the composite materials sector, with a particular focus on their transformative impact on prosthetic limb technology. This paper seeks to further this discourse by examining the mechanical fortification of polymer composites through the strategic integration of carbon fibers and copper oxide particles. The ensuing analysis encapsulates the nuanced interplay between material composition and mechanical proficiency, illuminating the prospects of advanced prosthetic design.

2. MATERIALS AND PREPARATION

2.1 Base material

Unsaturated Polyester Resin: A transparent liquid with medium viscosity ranging between (400-600), an elasticity modulus between (2.06-4.41 GPa), thermal conductivity of (0.17), specific heat ranging between (710-920), and a density of (1.2 g/cm³) according to the manufacturer's specifications. The resin, of Saudi origin, is processed into a solid material by adding a hardener, which is a transparent compound of Methyl Ethyl Ketone Peroxide (MEKP) at a rate of (29) per (100 grams). After approximately 30 minutes, the resin transforms into a gelatinous (gel) substance at room temperature.

2.2 Reinforcement materials

Carbon Fibers: Consisting of fine and thin fibers with a diameter ranging between (0.005-0.010 mm), a density of approximately (1800 kg/m³), and an elasticity modulus of about (370 kPa). Most components of carbon fibers are carbon particles. They were used in volumetric fractions of (2%, 4%, 6%, 8%), as illustrated in Figure 1(a).

Copper Oxide: A fine black powder with particle size (95.0), insoluble in water, a melting point of (1134) degrees Celsius, and a boiling point of (2000) degrees Celsius according to the manufacturer's specifications. It was used in volumetric fractions of (1%, 2%, 3%, 4%), as depicted in Figure 1(b).

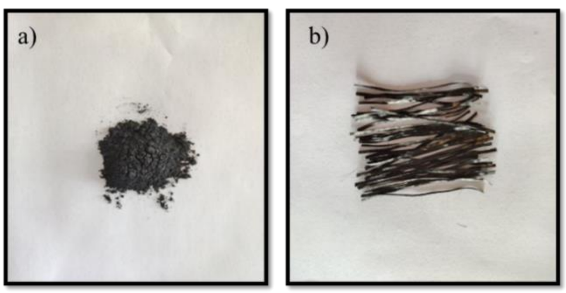

Figure 1. Reinforcement materials used (a): Carbon fiber; (b): Copper oxide particles

3. SAMPLE PREPARATION

The manual molding method was employed to prepare the samples using an aluminum mold. Initially, the mold was prepared by cleaning it with ethyl alcohol and coating it with a lubricating substance to ensure that the samples do not adhere to the mold after solidification and heat treatment.

Subsequently, the unsaturated polyester resin was weighed using a sensitive balance according to the required quantity. The carbon fibres and copper oxide were also weighed on the same balance after calculating or determining the volumetric fraction of particles (Vf) using the weight fraction of particles (Ψ). This calculation can be performed through volumetric relationships using the following mathematical equations (1, 2, 3) [18]:

$$Vf = \frac{1}{1+\frac{1-\Psi}{\Psi} x \frac{\rho_f}{\rho_m}} \quad (1)$$

$$\Psi = \left(\frac{W_f}{W_c}\right) x100\% \quad (2)$$

$$W_c = W_f + W_m \quad (3)$$

where,

W_c, W_m, W_f: The weight in grams of the reinforced material, the matrix, and the composite material, in that order.

ρ_f , ρ_m : The density, expressed in g/cm³ units, of the reinforced and composite materials.

When pouring the carbon fiber samples, a small amount of resin is placed in the mold after adding the hardener and placing the carbon fibers. The resin is then poured into the mold, and the process is repeated according to the volumetric fractions. Four samples were poured in total. In the case of pouring copper oxide samples, copper oxide is gradually added to the resin with continuous stirring to prevent the formation of bubbles. The hardener is then added, and the mixture is poured into the mold. The process is repeated for all volumetric fractions, resulting in the pouring of four samples as well. The samples are left inside the mold to solidify.

Subsequently, the heat treatment begins by placing the samples inside an electric oven at a temperature of (50) degrees Celsius for a duration of (60) minutes to complete the solidification process and achieve optimal interweaving of polymer chains, eliminating any stresses that occur during the pouring process. The samples remain in the oven until the gradual cooling process inside the oven is complete, and the oven temperature reaches room temperature. Afterward, the samples are removed from the oven and the mold, preserved in storage bags, and ready for inspection using testing devices.

4. RESULTS AND DISCUSSION

Hardness testing is a crucial mechanical test that provides insights into the surface resistance to scratching and penetration of the polymeric material. The hardness was tested using the (HUATEC GROUP Hardness HT-6600C Shore D) device manufactured by the Chinese company (HUATEC). This test is significant in the field of artificial limbs to ensure the comfort of the individual's movement through a strong and high-hardness limb.

Figure 2 illustrates hardness test samples for carbon fibers and copper oxide (CuO), respectively. From the results shown in Figure 3 significant increase in hardness values was observed when reinforced with carbon fibers. The hardness strength increases with the volumetric fraction of carbon fibers, with the highest hardness value being (85.4 N/mm) at a volumetric fraction of (8%). This is attributed to the carbon fibers bearing the applied stress, transferring it from the base material to the carbon fibers, thus reducing the pressure on the base material. Generally, the resistance to deformation is proportional to the volumetric fraction of fibers, meaning that as the volumetric fraction increases, the deformation resistance and material hardness increase [19].

The regular distribution of fibers within the composite material leads to the even distribution of energy needed to resist deformation uniformly across the sample [20].

As for copper oxide (CuO) particles, according to the results shown in Figure 3, the hardness strength increases with the volumetric fraction of copper oxide particles. The highest hardness value was (83.5 N/mm²) at the highest volumetric fraction of particles (4%). These fine particles act as a semiconductor material, and their high hardness is a characteristic of semiconductor materials. Therefore, reinforcing the polymer with semiconductor materials increases its hardness. Hardness is also characterized by its impact on the sample surface more than its impact on the interior. Due to this, polymer chains break more at the surface [21]. Additionally, particulate materials increase the surface area of the polymeric composite, resulting in high resistance to deformation [22].

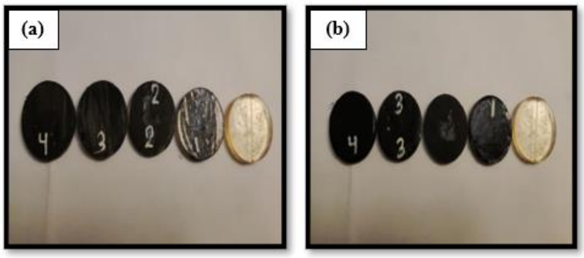

Figure 2. hardness test samples (a): Carbon fiber (b): Copper oxide particles

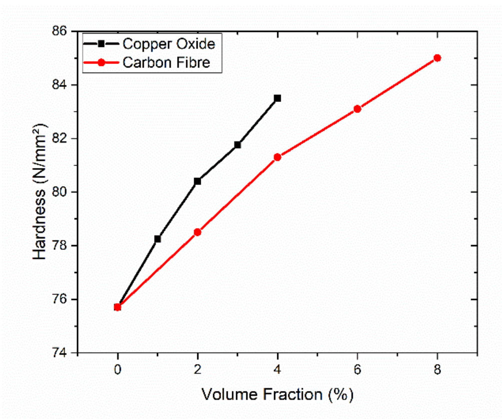

Figure 3. Hardness test results for carbon fibers and copper oxide particles

The impact strength test involves subjecting the sample to rapid dynamic loading, aiming to determine the amount of energy absorbed upon fracture of the prepared polymer composite samples. The samples were examined using the Charpy test device manufactured by the Chinese company (LAREE Yaur Tasting Solution).

Figure 4 shows impact strength test samples for carbon fibers and copper oxide (CuO) particles. Figure 5 illustrates the impact strength results for carbon fibers, indicating a significant improvement in impact strength values for samples when reinforced with carbon fibers.

Observing that, as the volumetric fraction of carbon fibers increases, the highest impact strength value was obtained at the highest volumetric fraction (8%) and was (6.27 kJ/m²). The interfacial bonding between the fibers and the base material increased the impact strength. The hardness of the fiber-reinforced samples was improved by pulling the fibers to absorb shock energy [23]. Additionally, carbon fibers are known for their high toughness, preventing crack propagation and distributing stress evenly across the sample, leading to increased impact strength [24, 25].

As for copper oxide, Figure 5, showing the impact strength test results for copper oxide, indicates that the impact strength value increases with the volumetric fraction of copper oxide particles. The highest impact strength value was obtained at the highest volumetric fraction (4%) of copper oxide particles and was (0.70 kJ/m²). These particles bear the majority of the load applied to the sample, hindering crack growth and propagation. This changes the shape and direction of cracks, transforming them into a group of secondary cracks, consistent with previous research [26].

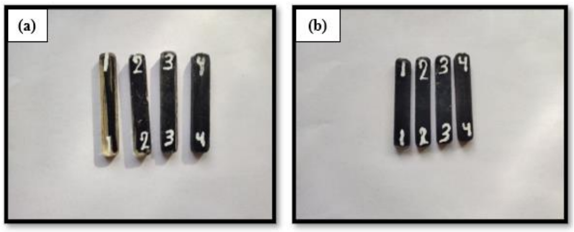

Figure 4. Impact test samples (a): Carbon fibre (b): Copper oxide particles

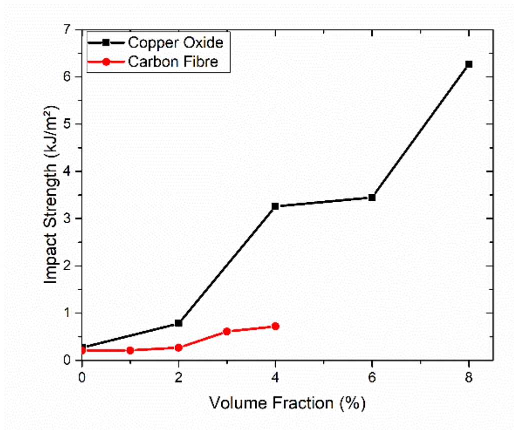

Figure 5. Impact test results for carbon fibers and copper oxide particles

Compressive strength is defined as the maximum pressure a solid material can withstand under direct vertical pressure. It is crucial, especially in prosthetics, where artificial limbs need to be strong and endure high pressures, mimicking the behavior of the original limb. The samples were examined using a device of the type (LYREE Yaur Tasting Solutions) manufactured by the Chinese company (Laree Technology Co. Ltd). Figure 6 illustrates the carbon fiber and copper oxide-reinforced samples used in this test. Figure 7 depicts the compressive strength test results for carbon fibers, showing that the compressive strength value increases with the volumetric fraction of carbon fibers. The highest value obtained was (37.4 MPa) at the highest volumetric fraction (8%) for carbon fibers. This is attributed to the inherent hardness and symmetrical properties of these fibers. They bear the compressive stress applied to the sample, and the stress is transferred along the sample due to its unidirectional orientation. Additionally, carbon fibers absorb the unsaturated polyester resin, significantly affecting the interface between the fibers and the resin, leading to increased compressive strength [27].

As for copper oxide particles (CuO), Figure 7 shows the compressive strength test results. When reinforced with these particles, the compressive strength decreases. The compressive strength decreases as the volumetric fraction of copper oxide particles increases. The highest compressive strength value was (21.89 MPa) at the smallest volumetric fraction (1%). This is because these particles can easily penetrate the interstitial space between polymer chains, reducing free gaps within the composite material. This hinders the movement of polymer chains, resulting in decreased compressive strength [28, 29].

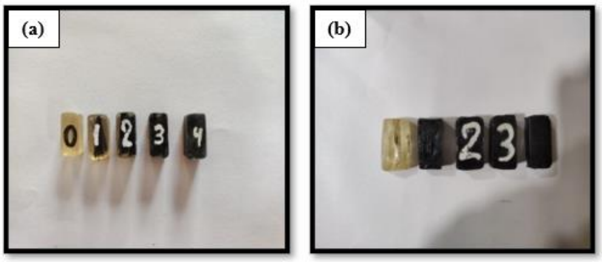

Figure 6. Compressive test samples (a): Carbon fiber (b): Copper oxide particles

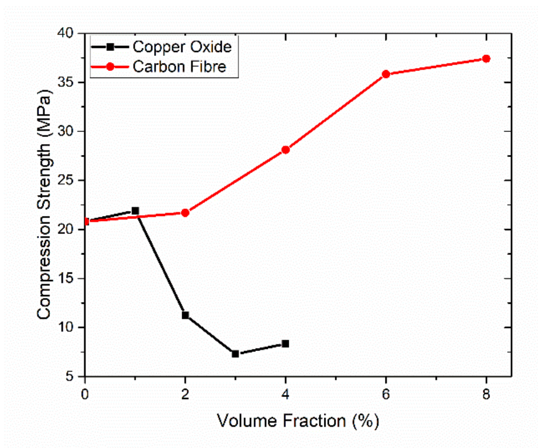

Figure 7. Compressive test results for carbon fibres and copper oxide particles

The tensile test is a crucial mechanical test that determines the maximum pressure a material can withstand, indicating how well an artificial limb can bear pressure. The samples were examined using a Chinese-origin tensile testing machine of type (LARYEE Yaur Tasting Solution) (Figure 8). It illustrates the tensile samples for carbon fibers and copper oxide. Figure 9 presents the results of the tensile strength test for carbon fiber-reinforced samples, showing a significant increase in tensile strength values with increased carbon fiber reinforcement. The highest tensile strength value obtained was (20 MPa) at the highest volumetric fraction of carbon fibers (8%). This is because carbon fibers are characterized by high mechanical properties, such as high tensile strength and flexibility. Carbon fibers bear the majority of the pressure applied to the material [30].

As for copper oxide particles (CuO), Figure 9 shows the tensile strength values for samples reinforced with copper oxide particles. The tensile strength decreases with an increase in the volumetric fraction of particles. The lowest tensile strength value was (7.5 MPa) at the lowest volumetric fraction of particles (1%). This is attributed to the formation of gaps when the particles adhere to each other, making it challenging for the base material to enter and leading to the weakening of the composite material [30]. Additionally, unsaturated polyester resin is a viscous material, and this viscosity prevents the resin from effectively wetting the particles. The particles tend to gather in one place, further weakening the composite [31].

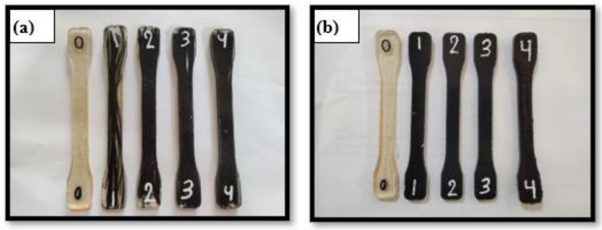

Figure 8. Tensile test samples (a): Carbon fibre (b): Copper oxide particles

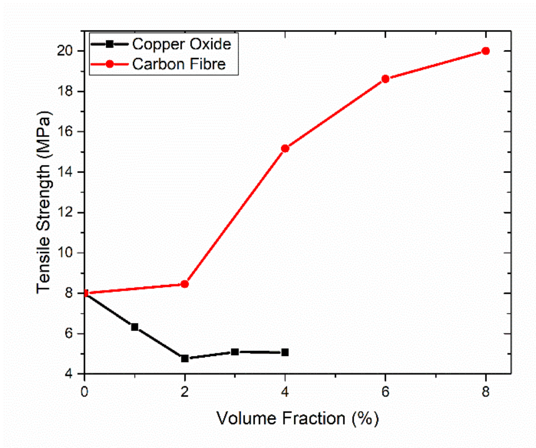

Figure 9. Tensile test results for carbon fibres and copper oxide particles

The bending test is a mechanical test used to determine the mechanical properties under bending loads. It evaluates how well a prosthetic limb can resist bending when subjected to pressure. The samples were tested using a three-point bending test machine (LYREE Yaur Tasting Solutione) (Figure 10). Figure 11 illustrates the bending test samples for carbon fibers, and the results indicate a significant increase in bending strength with increased carbon fiber reinforcement. It is observed that as the volumetric fraction of carbon fibers increases, the bending strength also increases. The highest bending strength value obtained was (39 MPa) at the highest volumetric fraction of carbon fibers (8%). This is because carbon fibers bear the majority of the stress applied to the sample, and the strong bond between unsaturated polyester resin and carbon fibers increases the bending strength. Carbon fibers also have a high wettability with the resin in the liquid state, contributing to a strong interlocking force between the unsaturated polyester resin and the fibers [32].

As for copper oxide particles (CuO), Figure 11 shows the results of the bending strength test for samples reinforced with copper oxide. The bending strength values decrease as the volumetric fraction of particles increases. The lowest bending strength value obtained was (9.1 MPa) at the highest volumetric fraction of particles (4%). This is attributed to the non-uniform distribution of particles within the composite material, leading to the formation of clusters inside the composite material. This clustering prevents the particles from acting as a barrier that hinders the growth and spread of cracks, ultimately weakening the bending strength of the composite material [33].

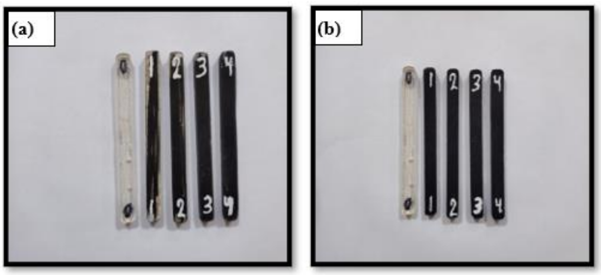

Figure 10. (a) Bending test samples Carbon fiber (b) Copper oxide particles

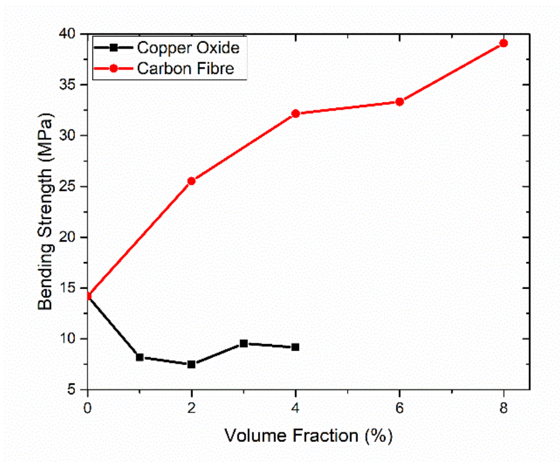

Figure 11. Bending test results for carbon fibres and copper oxide particles

5. CONCLUSIONS

Based on the results obtained, it is evident that carbon fibers have enhanced all mechanical properties significantly. The impact strength improved notably, and the hardness strength showed a considerable increase after reinforcement. Additionally, both compressive and tensile strengths exhibited substantial improvement. Moreover, bending strength also experienced significant enhancement. Consequently, it can be concluded that carbon fibers can be effectively utilized in the manufacturing of artificial limbs, demonstrating exemplary mechanical characteristics. In contrast, the incorporation of copper oxide (CuO) into the polymer exhibited a mixed outcome. While impact strength and hardness strength improved considerably, compressive strength witnessed a significant reduction. Likewise, both tensile strength and bending strength experienced a decline compared to the pre-reinforcement state. Hence, the use of carbon fibers emerges as a far superior choice for artificial limb fabrication when compared to the utilization of copper oxide particles.

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