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COMPARATIVE PERFORMANCE OF POLYMERIC COMPOSITES FOR ORTHOPEDIC APPLICATIONS

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ABSTRACT
This study presents a comparative analysis of epoxy and high-density polyethylene (HDPE) composites reinforced with Kevlar fibers (KF) and carbon fibers (CF) for potential use in orthopedic implants. The mechanical performance of these composites is evaluated by the tensile testing and fatigue resistance analysis. It was found that epoxy composites reinforced by Kevlar demonstrated superior tensile strength, reaching approximately 121 MPa, while epoxy reinforced by carbon fibers achieved around 50.8 MPa, compared to 28.5 MPa for Kevlar-reinforced HDPE and 25.3 MPa for carbon-reinforced HDPE. The elastic modulus of Kevlar-reinforced epoxy was significantly higher (0.6 GPa) than that of carbon-reinforced epoxy (0.28 GPa), while Kevlar-reinforced HDPE and carbon-reinforced HDPE showed lower values compared to epoxy composites. Fatigue resistance tests revealed that Kevlar-reinforced epoxy endured up to 1885 cycles at a deflection of 4 cm, outperforming carbon-reinforced epoxy, that withstood 1275 cycles. Similarly, Kevlar-reinforced HDPE exhibited improved fatigue resistance (1200 cycles) compared to carbon-reinforced HDPE (1000 cycles). These results indicate that epoxy composites are better suited for high-stress applications, such as femur fracture plates, due to their high strength, stiffness, and fatigue resistance. In contrast, HDPE composites, while mechanically inferior, offer greater flexibility and biocompatibility, making them suitable for applications where ductility and low tissue reactivity are critical. It was observed that both Kevlar and carbon fibers significantly enhance the mechanical properties of the composites, especially Kevlar that provides superior reinforcement in terms of tensile strength and fatigue resistance. The findings provide valuable insights for selecting the appropriate composite material based on specific orthopedic application requirements, with epoxy composites being preferred for high-stress environments and HDPE composites for applications that requiring more flexibility.

KEYWORDS
Orthopaedic implants, Kevlar fibers, carbon fibers, high-density polyethylene, polymer composites, epoxy, mechanical strength.

INTRODUCTION
Fiber-reinforced polymer composites have gained significant attention in biomedical applications due to their unique combination of high strength, lightweight nature, and

tunable mechanical properties, [1 - 3]. These materials are particularly advantageous in designing orthopedic implants, where achieving a balance between mechanical performance and biocompatibility is critical, [4 - 9]. Among the variety of reinforcement fibers, Kevlar and carbon fibers stand out for their superior tensile strength and fatigue resistance, making them ideal candidates for load-bearing applications, [2, 10 - 14].

Polymers, both as standalone materials and as matrix components in composites, have seen widespread use in orthopedic applications, [6, 15 - 17]. For instance, ultra-high molecular weight polyethylene (UHMWPE) has been extensively employed in joint replacements due to its excellent wear resistance and biocompatibility, [18, 19]. Polymethyl methacrylate (PMMA) is commonly used as bone cement, providing robust fixation for implants, [20]. Moreover, biodegradable polymers such as polylactic acid (PLA) and polyglycolic acid (PGA) are gaining traction for temporary implants and scaffolds, facilitating bone regeneration while gradually degrading within the body, [21].

Previous studies have highlighted the advantages of polymer composites in orthopedic implants. Previous studies demonstrated that carbon fiber-reinforced epoxy composites exhibit higher tensile strength and stiffness compared to traditional metallic implants, addressing issues such as stress shielding and load distribution, [7, 8, 14, 16, 22 - 24]. Similarly, many has explored Kevlar-reinforced polyethylene composites and reported significant improvements in fatigue resistance and impact toughness, making them suitable for high-mobility applications like spinal implants [14]. Additionally, investigations into hybrid fiber systems, such as those combining carbon and other fibers, have shown promise in balancing stiffness and flexibility for femoral and tibial implants, [12, 14, 22, 23].

The choice of matrix material plays a pivotal role in determining the overall performance of the composite. Thermoplastic high-density polyethylene (HDPE) and thermosetting epoxy are two commonly used matrices, each with distinct characteristics. HDPE is known for its ductility, chemical resistance, and ease of processing, which make it suitable for applications requiring flexibility and resilience, [25]. Conversely, epoxy exhibits superior rigidity, thermal stability, and adhesion to fibers, favoring applications demanding high stiffness and load-bearing capacity, [18, 22].

This paper aims to compare the mechanical performance of Kevlar and carbon fiber composites fabricated using HDPE and epoxy matrices. The comparison is focused on results obtained under a tensile strain rate of 10 mm/min, a common parameter in both studies. Specifically, the goal is to elucidate how the thermoplastic and thermosetting nature of the matrix materials influences tensile strength, modulus of elasticity, and suitability for biomedical applications.

The study draws on two investigations; one that evaluated HDPE composites reinforced with Kevlar and carbon fibers, and another that explored epoxy composites reinforced with the same fibers. By analyzing the interplay between reinforcement materials and matrix types, this comparison provides insights into optimizing composite designs for specific orthopedic applications.

EXPERIMENTAL

Materials

The materials used in this study are summarized in Tables 1 and 2, detailing their mechanical properties.

Table 1 Mechanical properties of HDPE and epoxy matrices.

Property	HDPE	Epoxy
Density (g/cm³)	0.96	1.1
Tensile Strength (MPa)	32	179
Tensile Modulus (GPa)	1.25	10.4
Elongation at Break	High (ductile)	Low (brittle)

Table 2 Mechanical properties of reinforcement fibers.

Property	Kevlar	Carbon Fiber
Tensile Strength (MPa)	3600-4100	3530
Tensile Modulus (GPa)	131	230
Density (g/cm³)	1.44	1.76

Specimen Fabrication of HDPE Composite:

Reinforced cervical fusion plates were constructed using a rectangular die to produce multiple specimens in one plate in dimension of 120 × 160 and 4mm thickness. Figure 1 shows the die design and its components.

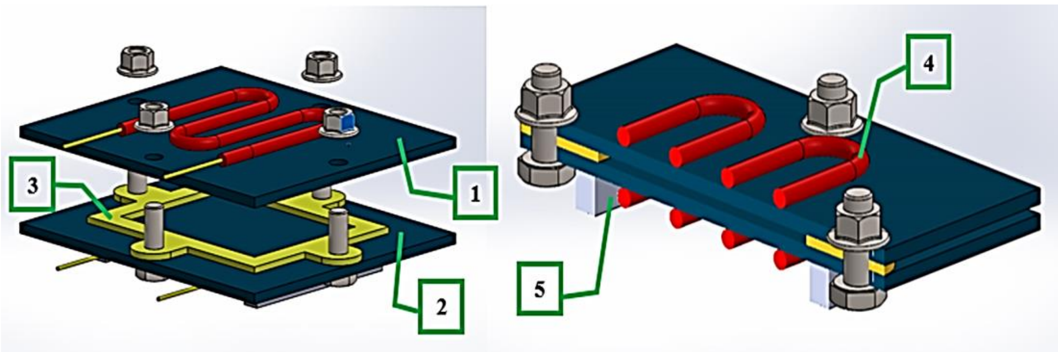


Fig. 1 The arrangement of the die, (1) Upper plat, (2) Lower plate, (3) Spacer, (4) Heater, (5) Base support.

The spacer has two main functions, the first is to avoid any leak during melting of HDPE and the second is to reach the desired specimen thickness. Therefore, a layer HDPE powder is placed on lower die inside the heightening plate. Reinforcement fibers are arranged in such way parallel to lateral direction (120 mm), where anotherlayer of powder is placed to cover reinforcement fibers to produce a regular composite thickness. There are double heating system and thermocouple sensor to monitor and control temperature keeping it at 130 °C for 10 minutes to ensure no powder particle left unmelted, which will eventually achieve the best matrix-enforcement adhesion. The produced specimens have been reinforced with CF and KF at fibers content of 2 vol. %. Figure 2 shows specimen dimension used in tension test.

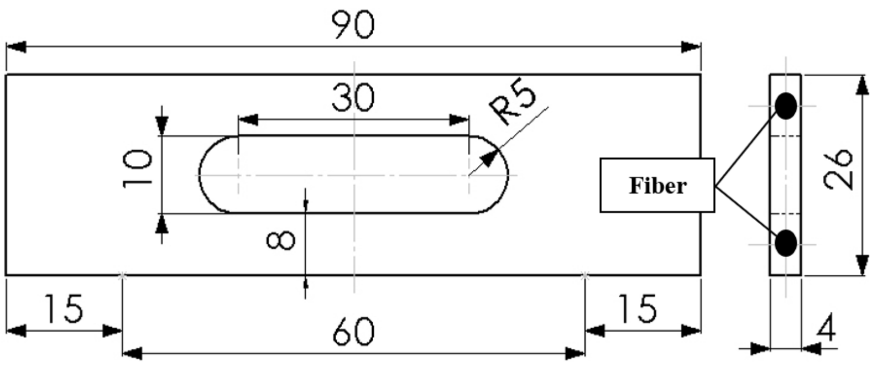


Fig. 2 Specimen of tensile test.

Specimen Fabrication of Epoxy Composite

The fabrication of the proposed composites was achieved using the lay-up technique. The low viscosity of the epoxy resin facilitated good penetration into the woven fiber. Additionally, the low viscosity characteristic of the epoxy allowed entrapped air bubbles to rise to the surface and dissipate more efficiently. The absence of voids and air bubbles within the composite structure is vital to mitigating the formation of stress concentration zones, which could compromise the materials integrity and mechanical performance.

Testing Equipment

The mechanical testing was conducted using a Universal Testing Machine, shown if Fig. 2, with a capacity of 30 tons for tensile testing and a plane-bending fatigue test machine, Fig. 4, for fatigue testing. Tensile tests followed ASTM D3039 standards, with a strain rate of 10 mm/min. Fatigue testing involved cyclic loads applied at a motor speed of 1420 rpm, with deflection 4 cm. Specimens were clamped on one end and subjected to oscillatory bending loads to simulate physiological conditions.

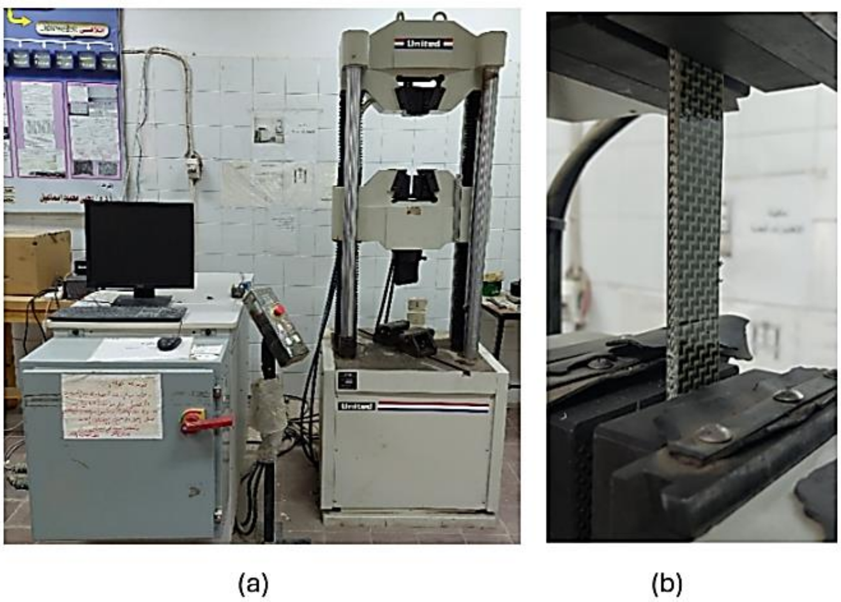


Fig. 3 (a) United SHFM Hydraulic Tester. (b) Epoxy fiber composite.

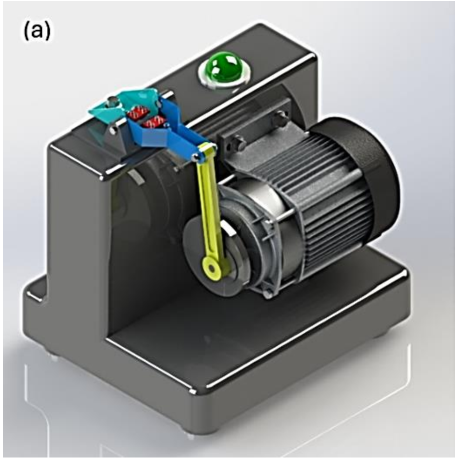
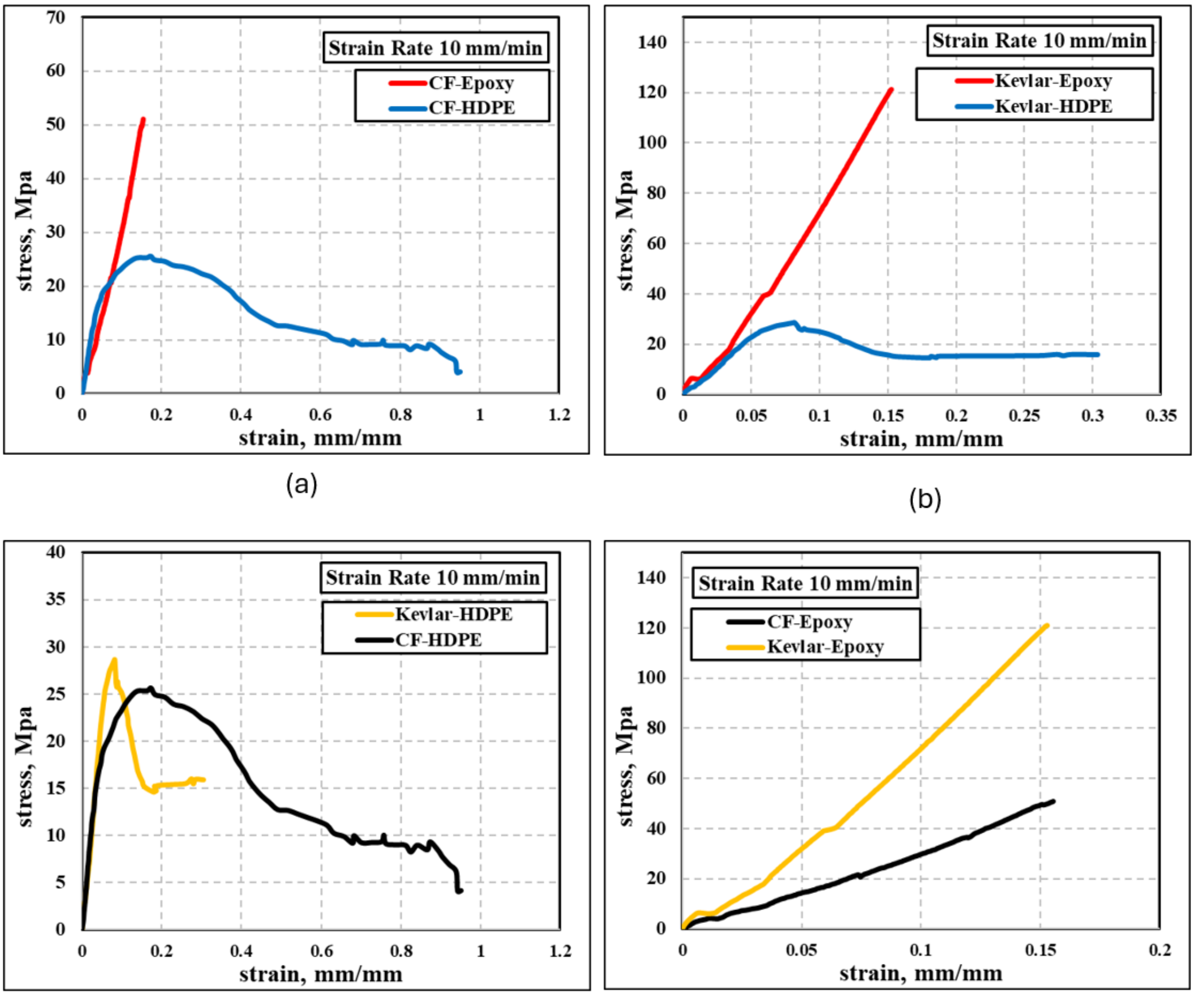


Fig. 4 Plane-bending fatigue test machine.

RESULTS AND DISCUSSION



(a) (b)

(c) (d)

Fig. 5 Stress strain curves for kevlar and carbon fibers.

The stress-strain curves for epoxy and high-density polyethylene (HDPE) composites reinforced with Kevlar fibers and carbon fibers provide valuable insights into their

mechanical behavior under tensile loading, Fig. 5. For epoxy composites, the curves exhibit a linear elastic region followed by a sharp drop at failure, indicating brittle fracture behavior. Kevlar-reinforced epoxy demonstrates the highest ultimate tensile stress, reaching approximately 121 MPa at a strain rate of 10 mm/min, while carbon-reinforced epoxy achieves around 50.8 MPa. The steep slope in the elastic region of epoxy composites highlights their high stiffness, making them suitable for applications requiring structural rigidity. In contrast, HDPE composites display a more ductile behavior, with a noticeable yield point and gradual failure.

The elastic modulus, illustrated in Figure. 6 of the composites further underscores the differences in stiffness between the two matrix materials. Kevlar-reinforced epoxy exhibits the highest elastic modulus, reaching approximately 0.6 GPa, while carbon-reinforced epoxy shows a drastically lower modulus of around 0.3 GPa. This high stiffness makes kevlar epoxy composites well-suited for high-stress, high rigid applications, such as femur fracture plates.

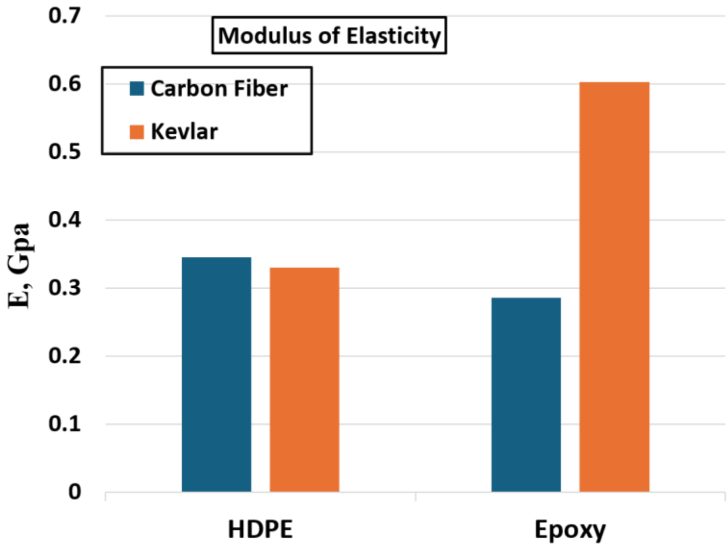


Fig. 6 Modulus of elasticity of both epoxy and HDPE reinforced with Kevlar and carbon Fibers.

On the other hand, HDPE composites have a significantly lower elastic modulus, its worth noting that the both Kevlar and carbon have a close elastic values ranging from 0.32 to 0.34 GPa. The lower stiffness of HDPE composites is advantageous for applications requiring flexibility.

In regards of fatigue resistance, Fig. 7, evaluated through plain bending fatigue tests, reveals significant differences between the two types of composites. Kevlar-reinforced epoxy demonstrates superior fatigue resistance, enduring up to 1885 cycles at a deflection of 4 cm, while carbon-reinforced epoxy withstands approximately 1275 cycles under the same conditions.

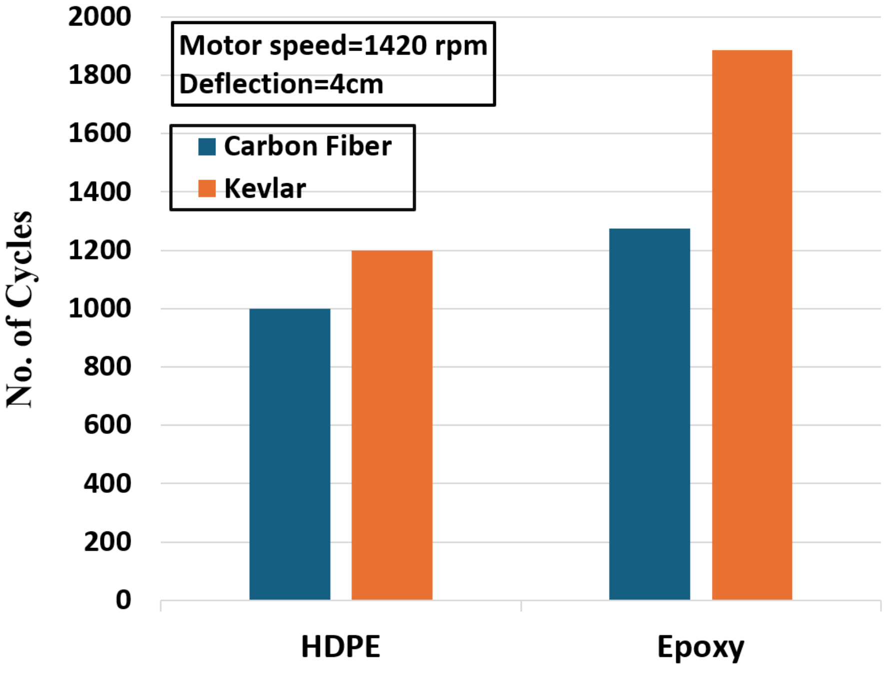


Fig. 7 Endured number of cycles for Kevlar and carbon fibers.

This high fatigue resistance makes epoxy composites ideal for high-stress applications, such as orthopedic implants subjected to dynamic loads. In contrast, Kevlar-reinforced HDPE exhibits improved fatigue resistance compared to carbon-reinforced HDPE, enduring up to 1,200 cycles at a deflection of 4 cm. However, the fatigue performance of HDPE composites is generally lower than that of epoxy composites, particularly at higher deflections, due to the lower stiffness and strength of HDPE.

CONCLUSIONS

1. Epoxy composites reinforced with Kevlar and carbon fibers exhibit superior mechanical properties, making them ideal for high-stress orthopedic applications that requires total fixation.
2. HDPE composites offer greater flexibility, making them suitable for applications that undergoes more physical movement.
3. Kevlar fibers outperform carbon fibers in both epoxy and HDPE composites, ragarding tensile strength and fatigue resistance.
4. Carbon fibers remain a viable reinforcement option, providing moderate improvements in strength and stiffness for both epoxy and HDPE composites.
5. Material selection should be application-specific, with epoxy composites preferred for high-stress environments and HDPE composites for flexible applications.

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