Mechanical Properties of Carbon/epoxy-HA Hybrid Composites for Potential External Fixation Bone Plates

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Abstract: Lightweight, biocompatible materials with high mechanical strength and low stiffness comparable to that of human cortical bone are essential to replace traditional high-stiffness metallic bone plates. This study investigates hybrid composites comprising treated woven carbon fiber (TC) as reinforcement in epoxy (E) with varying concentrations of hydroxyapatite (HA) microparticles (0, 1, 2, 3, 5, and 7 vol.%). The goal is to develop composite materials with mechanical properties closely matching those of cortical bone. Tensile, flexural, and hardness tests were conducted to evaluate their mechanical behavior. The TC/E-HA1 composite demonstrated optimal tensile and flexural strength. All types of composites exhibited Young's modulus, flexural modulus, and tensile strain values within the range of cortical bone, while their overall strength surpassed that of bone but remained lower than metallic bone plates. The findings suggest that TC/E-HA composites are promising candidates for external fixation bone plates.

Keywords: carbon fiber; epoxy; external fixation bone plate; hybrid composite; hydroxyapatite; mechanical properties

1. Introduction

Many studies have reported various types of composites, particularly polymer composites, for medical applications such as denture bases, prosthetic sockets, and ankle-foot orthoses (AFOs) [1–5]. These studies involved reinforced thermoplastic polymers (e.g., PMMA) [1] and thermoset epoxy [6] with a combination of natural and synthetic fibers [7], natural fibers mixed with natural fibers [4], and natural fibers combined with organic and inorganic particles [8]. These types of composites have been utilized as alternative materials for prosthetic sockets [4], dental components [1], and AFOs [5]. Another key application of such materials is for bone plates used in internal and external fixation.

This study primarily investigates external bone plate materials, which differ functionally from internal bone implants. External bone plates serve as protective structures for fractured or damaged cortical bones, aiding in the maintenance of bone stability and alignment throughout the healing process. Cortical bone, being dense, acts as a protective layer for the internal bone tissue. Since the 1960s, bone plates have typically been manufactured using metallic materials such as titanium alloys and stainless steel (SS), which exhibit high mechanical strength and stiffness of 110–117 GPa and 189–205 GPa for Young's modulus of Ti-alloy and SS, respectively [9,10], significantly exceeding that of human cortical bone (7-25 GPa) [11]. Additionally, metallic materials are often heavy. Hence, there is a critical need to develop alternative lightweight materials with high mechanical performance but with stiffness close to those of cortical bone. Materials with excessively high stiffness may lead to adverse effects during bone healing, such as stress shielding. In this regard, polymer composites offer promising alternatives to ceramic-based composites which are typically brittle and metals, which are too stiff [12]. While composite materials for external fixation bone plates, particularly polymer-based composites have been previously investigated, recent research in this area remains limited [13–16]. Most prior studies have focused on composites for internal fixation [17,18] or as biomaterials for bone regeneration [19,20]. Nevertheless, there is continued interest in developing materials with high tensile strength and low Young's

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modulus, mimicking the mechanical characteristics of cortical bone, typically 124–174 MPa for tensile strength and approximately 17.7 GPa for Young's modulus [12,20], or more broadly 50–150 MPa and 7–25 GPa, respectively [11]. For materials used in biomedical applications, particularly for bone plates, biocompatibility is paramount. Although the focus of this study is on external fixation, the materials will still be in partial contact with the bone during the healing process.

Bone plays a crucial role in the human body, providing structural support, shaping the body framework, and facilitating movement. It comprises collagen as a matrix component that imparts tensile strength, while its primary mineral constituent, calcium phosphate in the form of hydroxyapatite (HA) provides compressive strength [21]. Carbon fiber-reinforced epoxy composites (CFRE) have previously been developed as materials for external bone plates, such as those used in femoral applications. Simulation studies comparing CFRE to conventional metal plates have shown that femoral stress on the anterior and posterior sides is higher when using CFRE plates, influencing stress distribution on the lateral side of the femur as well. These differences have been reported to be within the range of 20–30% [22]. Pervan et al. [23] performed stress analyses comparing CFRE with SS, finding that CFRE significantly reduces both stress and structural weight up to 44%, making it advantageous for enhancing patient mobility and comfort during recovery. Additionally, a previous study demonstrated the mechanical suitability of CFRE composites for orthopedic bone plate applications, and highlighted their potential for safe integration with human bone tissue [13].

Previous studies have fabricated laminated hybrid composites such as carbon/flax/epoxy for bone plate applications by sandwiching unidirectional flax/epoxy between unidirectional carbon/epoxy [13] and unidirectional flax/epoxy between unidirectional glass/epoxy (glass/flax/epoxy) [15]. The results showed that Young's modulus of carbon/flax/epoxy [13] and glass/flax/epoxy with 0° fiber orientation [15] were both higher than 25 GPa. However, the glass/flax/epoxy composite with 45° fiber orientation exhibited a modulus that fell within the tensile range of cortical bone [15]. Other prior studies have evaluated the stiffness of epoxy-based composites reinforced with glass, Kevlar, or carbon fibers. These studies concluded that CFRE composites could effectively replace metal-based external bone plates. Nevertheless, reviews of CFRP laminate composites have highlighted issues such as debonding due to insufficient bonding between carbon fibers and the polymer matrix [24] Improvements have been suggested through the addition of micro/nano fillers [25,26] or carbon fiber surface treatment [27] to strengthen the interfacial adhesion and enhance composite performance.

Recent studies have proposed the development of epoxy composites reinforced with short carbon fibers and nano-hydroxyapatite (HA) for orthopedic fixation plates [28]. However, their mechanical properties were significantly inferior to those of carbon/flax/epoxy and glass/flax/epoxy composites [13,15], both with and without nano-HA additions. A key limitation stems from the agglomeration tendency of nano-HA particles, which increases the viscosity of the epoxy matrix and hinders homogeneous mixing. As a result, particle clumping leads to poor filler dispersion, ultimately degrading mechanical performance [28]. These findings underscore the importance of optimizing both the concentration and dispersion method of fillers to achieve desirable mechanical properties, especially when using HA as reinforcement.

Studies on composites combining carbon fiber, epoxy, and HA, especially with HA in microparticle rather than nanoparticle form remain rare. Therefore, this research focuses on the fabrication of woven carbon fiber/epoxy composites filled with microparticle HA, with mechanical properties evaluated through tensile, flexural, and hardness testing. The study aims to exceed the mechanical performance reported in previous literature [28] while achieving material properties that closely approximate those of human cortical bone. Young's modulus is emphasized as a key biomechanical indicator of mechanical biocompatibility. Additionally, this study seeks to identify the optimal balance between mechanical performance and biocompatibility, contributing to the development of advanced composite materials for external bone fixation applications.

2. Materials and Methods

2.1. Materials

The matrix material used in this study was Eposchon epoxy, a two-part system composed of Epoxy Resin (A) based on Bisphenol-A epichlorohydrin and Hardener (B) made from polyaminoamide, mixed in a 1:1 weight ratio. Although specific datasheets for the product were not available, such formulations are categorized as DGEBA–polyaminoamide systems, which are well characterized in literature. Typical properties include a viscosity of 1000–1200 mPa·s at 25 °C, density of ~1.2 g/cm³, and glass transition temperature (Tg) between 60–80 °C. After curing, the matrix exhibits a Young's modulus of 2–3 GPa, depending on processing conditions [29,30]. Hydroxyapatite (HA) microparticles derived from animal bone waste were used as bio-ceramic fillers. Woven carbon fiber (C) with a 12K filament count and 200 GSM in SPREAD TOW configuration was also obtained locally. Both HA microparticles and carbon fibers served as reinforcement agents for the epoxy matrix to improve its mechanical performance and bioactivity.

2.2. Composite Fabrication

Prior to composite fabrication, surface treatment of the carbon fiber was conducted by immersing it in liquid nitrogen for 10 minutes to induce surface roughness, as illustrated in Figure 1. This treatment enhances interfacial bonding between the carbon fiber and epoxy matrix, consistent with the findings reported in [27)]. The HA microparticles were dried in an oven at 100°C for 30 minutes to reduce moisture and minimize agglomeration. The dried particles were then sieved using a 200-mesh screen. Subsequently, HA microparticles were mixed with the E using a conventional mechanical stirrer at 70 rpm for 5 minutes. Composite laminates were fabricated with a composition of 20 vol% of C (arranged in 6 layers) and 80 vol% of E containing varying HA microparticle concentrations (0, 1, 2, 3, 5, and 7 vol%). The hand lay-up method was used in conjunction with hot press molding at 100°C for 45 minutes. Table 1 outlines the specimen types and their compositions, while Figure 2 depicts the overall fabrication process.

2.3. Mechanical tests and characterization

The mechanical performance of all fabricated composites was evaluated through tensile, flexural (bending), and hardness tests. For each test condition, five specimens were prepared. Tensile and three-point bending tests were performed using a universal testing machine (UTM, Zwick/Roell Z020) in accordance with ASTM D638-02 and ASTM D790-03 standards, respectively. Hardness was measured using a Shore-D durometer (Digital Shore-D Durometer), following ASTM D2240. For the tensile test, a pre-load of 20 N and a test speed of 10 mm/min were applied, whereas the bending test was performed with a pre-load of 0.2 N and a test speed of 2 mm/min.

Microstructural observations and morphological analysis were carried out using scanning electron microscopy coupled with energy dispersive X-ray spectroscopy (SEM-EDS, JSM IT210 and Zeiss Evo 10) to characterize carbon fiber surfaces (Figure 1), HA microparticles (Figs. 3a and 3b), and fracture surfaces from tensile tests. Cracks induced by bending loads were further examined using an optical microscope (SZ61 Olympus).

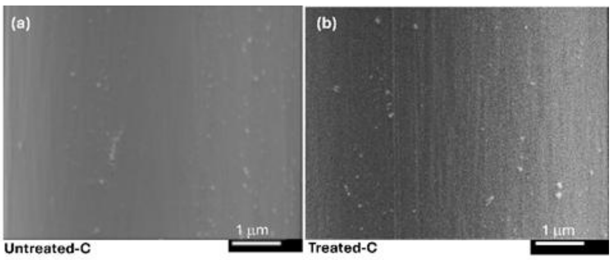

Fig. 1: The difference of (a) untreated and (b) liquid N2 treated C-surfaces showing the striation like surface roughness on the treated C.text

Table 1: The constituents of CNG

Composite-type specimen	CF (vol%)	E (vol%)	HA (vol%)
UTC/E	20	80	-
TC/E	20	80	-
TC/E-HA1	20	79	1
TC/E-HA2	20	78	2
TC/E-HA3	20	77	3
TC/E-HA5	20	75	5
TC/E-HA7	20	73	7

UTC: untreated C, TC: treated C

2.4. Statistical analysis

Statistical evaluation of mechanical properties was conducted using Analysis of Variance (ANOVA) with Minitab-14 software. The analysis compared the mean tensile strength and tensile modulus across six composite groups: one without HA to the five with varying HA concentrations (1, 2, 3, 5, and 7 vol%).

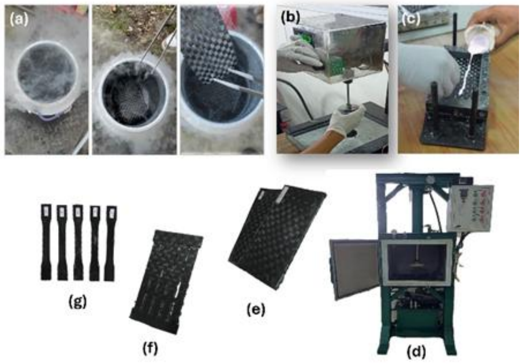

Fig. 2: Composite fabrication process route. (a) CF surface treatment, (b) mixing HA microparticle and E, (c) pouring mixed HA and E on C, (d) hot press molding process, (e) composite sheet products, (f) and (g) composite specimens for tensile testing

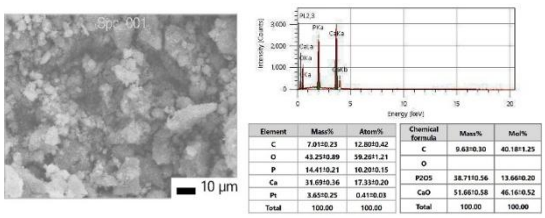

Fig. 3a: SEM-EDS of HA microparticle

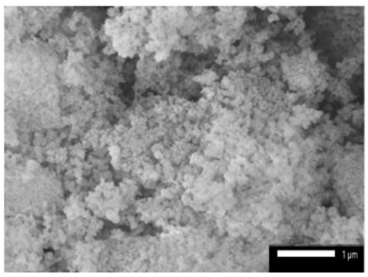

Fig. 3b: SEM micrograph of HA microparticle, showing a clustering trend of particles

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3. Results and discussion

3.1. Tensile properties

Treatment of carbon fiber with liquid nitrogen (N_2) enhances its surface roughness (Figure 1) by inducing rapid thermal expansion and contraction, which in turn increases the mechanical interlocking potential between the carbon fiber and epoxy matrix. Additionally, this cryogenic treatment chemically removes surface contaminants, thereby generating reactive sites that interact with atmospheric oxygen. The result is the formation of oxygen-containing functional groups, such as hydroxyl (-OH) and carboxyl (-COOH) that enhance chemical bonding with the epoxy matrix through hydrogen bonding or covalent interactions [31)]. Consequently, the tensile strength of the treated carbon/epoxy (TC/E) composite is higher than that of its untreated counterpart (UTC/E), as shown in Figure 4. This result is consistent with previous findings that surface functionalization of carbon fibers improves interfacial adhesion, thereby enabling more efficient stress transfer between the fiber reinforcement and the matrix [32)]. Such interfacial enhancements are critical for optimizing the mechanical performance of composite materials.

The morphology of HA microparticles used in this study is shown in Figure 3. SEM analysis revealed a tendency for particle agglomeration (Figure 3b), consistent with prior observations for nano-HA particles 28). When being added at low concentrations, HA microparticles are uniformly dispersed within the epoxy matrix, enhancing tensile properties such as strength and modulus (Figure 4). Specifically, the TC/E-HA1 composite exhibited the highest tensile strength (426.76 MPa) and tensile modulus (14.98 GPa), indicating effective load transfer between matrix and filler. This improvement results from the combined effects of uniform HA dispersion and the enhanced interfacial bonding afforded by the treated carbon fibers. The induced surface roughness provides more contact points for stress distribution, which synergizes with HA reinforcement to increase mechanical performance. These findings affirm that optimal filler concentration and homogeneity are crucial in achieving desired mechanical characteristics.

However, at higher HA concentrations (>1 vol%), particle clustering disrupts stress transfer pathways and weakens matrix-filler bonding. The resulting interfacial discontinuities act as stress concentrators, thereby reducing tensile strength and modulus. Previous work similarly reported that excessive HA can degrade the interface between carbon fiber and epoxy, ultimately compromising laminate integrity [32)]. These results reinforce the necessity of avoiding overfilling, as it introduces structural vulnerabilities that may cause premature failure under tensile loading.

All TC/E-HA composites exhibited Young's modulus values within the typical range of cortical bone (7–25 GPa) [11)] and their tensile strains were also within the range of 1–3% [33)]. Notably, the tensile strength of TC/E-HA1 is comparable to that of C/flax/E (399.8 MPa) [13)] and G/flax/E (~ 408 MPa) [15)] laminated composites with fibers oriented at 0°. Meanwhile, unidirectional 45° G/flax/E composites achieved a tensile strength of ~351 MPa and a Young's modulus of ~16.51 GPa that are closely aligned with the current study. Both the incorporation of HA microparticles and the utilization of woven carbon fiber contribute to the enhanced tensile performance observed here. Although the tensile strength of TC/E-HA1 exceeds that of cortical bone (50–150 MPa), it remains significantly lower than that of conventional metallic materials such as SS (586 MPa) and Ti alloys (965 MPa) [12)]. This intermediate mechanical profile, characterized by tensile strength higher than cortical bone but lower than metals, suggests that TC/E-HA composites may reduce stress shielding effects commonly observed in high-stiffness metal implants, while maintaining adequate structural support [34,35)].

The stress-strain curves (Figure 5) revealed a linear, brittle fracture behavior in all composite specimens. This trend is consistent with previous observations in CF/flax/E

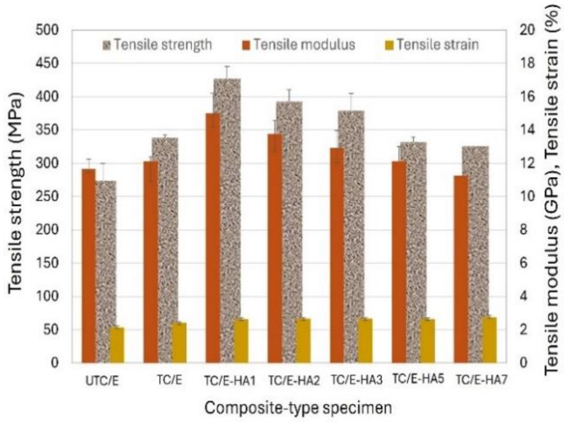

Fig. 4: Tensile strength, tensile modulus, and tensile strain of C/E-HA composite-type specimens

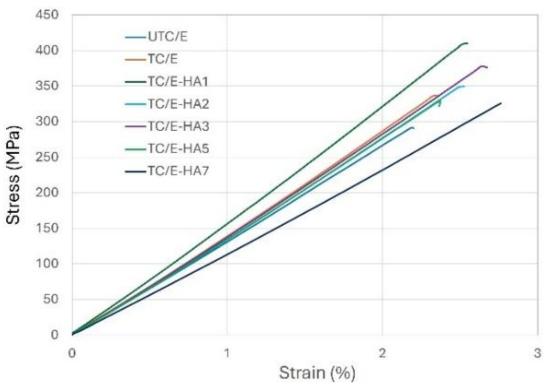

Fig. 5: Stress-strain of C/E-HA composite-type specimens

composites [13]. Interestingly, the strain-at-break in this study was higher than that reported for CF/flax/E. No early or primary failures were observed, corroborating the findings of Saeed et al. [15]. The fracture surfaces (Figure 6) indicate that all specimens experienced some degree of delamination, with TC/E specimens (Figure 6b) showing less severe delamination than UTC/E (Figure 6a), likely due to the C surface treatment. Among the samples, TC/E-HA1 exhibited the least delamination, correlating with its superior tensile strength and modulus. As HA concentration increased, the tendency for particle clustering also rose, leading to non-uniform dispersion. This uneven distribution negatively affects stress transfer from the matrix to the reinforcement and filler, causing a decline in tensile properties. Fracture patterns across all specimens consistently occurred outside the gage length, typically near the lower grip region. These consistent brittle fracture modes and delamination at higher HA content highlight limitations in matrix ductility and filler dispersion. Future work could explore the addition of resin tougheners or alternative dispersion techniques to mitigate HA agglomeration.

Table 2 shows the mean tensile strength, mean Young's modulus, and standard deviation (SD). Tensile strength and Young's modulus values obtained from the mechanical testing machine Zwick/Roel are compared. The study employed analysis of variance (ANOVA) and Minitab-14 software. The variance analysis was performed on seven treatments: i.e., one data group of specimens with untreated C (UTC/E), one data group of specimens with treated C (TC/E), and five data groups of specimens with treated C and HA (TC/E-HA1, TC/E-HA2, TC/E-HA3, TC/E-HA5, TC/E-HA7). Each treatment comprised of 3 data points.

For tensile strength, the ANOVA table showed an F-calculated (F_calculated) of 8.29. Meanwhile, the F-table (F_table) at a significance level of $\sigma = 0.05$, with degrees

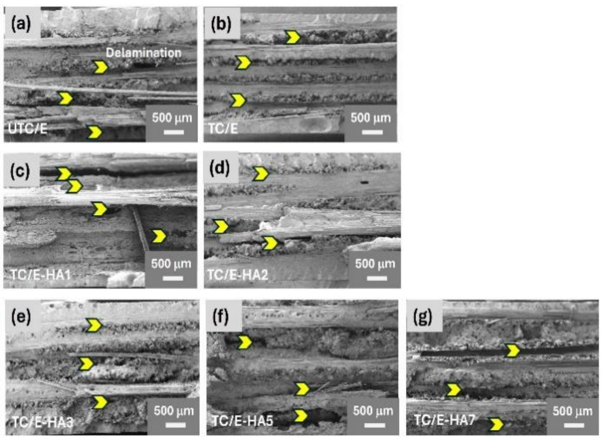

Fig. 6: Tensile fracture surface of C/E-HA composite-type specimens, showing delamination occurred in all specimens (remarked by arrows)

Table 2: Mean and standard deviation (SD) of tensile strength and Young's modulus for the tested specimens

Specimens	Tensile strength (MPa) Mean ± SD	Young's modulus (MPa) Mean ± SD
UTC/E	273.00 ± 25.97	11.65 ± 0.59
TC/E	338.20 ± 4.00	12.13 ± 0.23
TC/E-HA1	426.76 ± 18.83	14.98 ± 1.23
TC/E-HA2	392.34 ± 18.14	13.76 ± 0.80
TC/E-HA3	379.43 ± 25.76	12.92 ± 1.04
TC/E-HA5	331.52 ± 8.00	12.13 ± 0.88
TC/E-HA7	325.81 ± 8.00	11.24 ± 1.31

of freedom DF1 = 6 and DF2 = 14, was $F_{0.05;6;14} = 2.85$. Since F_calculated > F_table, the null hypothesis (H_0) is rejected, indicating that there is a significant difference among the treatments. A multiple comparison test using the Tukey method revealed that the comparisons between treatments of UTC/E and TC/E-HA1, UTC/E and TC/E-HA2, UTC/E and TC/E-HA3, TC/E and TC/E-HA1, TC/E-HA1 and TC/E-HA3, and TC/E-HA1 and TC/E-HA5 showed significant differences. These statistical outcomes confirm that the combination of carbon surface treatment and optimized HA addition (specifically 1%) yields significantly superior tensile properties compared to other groups.

For Young's modulus, the ANOVA table showed an F-calculated (F_calculated) of 7.10. Meanwhile, the F-table (F_table) at a significance level of $\sigma = 0.05$, with degrees of freedom DF1 = 6 and DF2 = 14, was $F_{0.05;6;14} = 2.85$. Since F_calculated > F_table, the null hypothesis (H_0) is rejected, indicating that there is a significant difference among the treatments. A multiple comparison test using the Tukey method revealed that the comparisons between treatments of UTC/E and TC/E, TC/E and TC/E-HA1, TC/E-HA1 and TC/E-HA3, TC/E-HA1 and TC/E-HA5, TC/E-HA1 and TC/E-HA7, TC/E-HA2 and TC/E-HA7 showed significant difference. This statistical evidence strengthens the claim that HA concentration and fiber treatment are key variables in modulating stiffness.

3.2. Flexural properties

The flexural properties (Figure 7) exhibited a similar trend to the tensile properties (Figure 4), with the TC/E-HA1 composite showing the highest flexural strength of 263.45 MPa and a flexural modulus (bending stiffness) of 19.73 GPa. All TC/E-HA composites demonstrated bending stiffness values that fall within the range of human cortical bone. While the flexural strength of the TC/E-HA1 composite differed significantly from its tensile strength, the flexural modulus remained comparable to the tensile modulus. This consistency in modulus values suggests that stiffness-related mechanical behavior is less sensitive to the testing mode than strength-related behavior, highlighting the stable reinforcement effect of carbon fiber and well-dispersed HA fillers.

As illustrated in Figures 4 and 7, all specimens exhibited higher tensile strength compared to flexural strength. In tensile testing, the load is uniformly distributed across the cross-sectional area, allowing the matrix, fibers, and interfacial bonding to work in unison to resist deformation. This uniform stress distribution enables efficient load transfer, resulting in greater tensile strength. In contrast, flexural testing induces a bending load with maximum stress concentrated on the outermost surfaces. One side experience tensile stress and the other side compressive stress, while the center experiences minimal stress. Consequently, only the outer layers contribute effectively to resisting the applied load, leading to a lower measured flexural strength. Furthermore, the stress gradient in bending increases the sensitivity of the composite to microstructural imperfections such as voids or weak fiber–matrix interfacial bonding, which may not be activated under uniform tensile loading.

The flexural modulus and tensile modulus both primarily depend on the stiffness of the composite's constituent materials (epoxy matrix, carbon fiber, and HA fillers). These intrinsic properties remain relatively consistent across testing modes, which leads to comparable modulus values in tension and bending. The ability of the composite to withstand elastic deformation under applied stress is the basis for both modulus measurements. This similar deformation behavior results in values for the flexural modulus being close to those for the tensile modulus. This comparable stiffness behaviour suggests that the HA content and fiber architecture primarily influence strength rather than stiffness, emphasizing the importance of optimizing filler dispersion to avoid stress localization.

The highest flexural modulus of TC/E-HA1 was still lower than that of previously reported CF/flax/E (~57.4 GPa) [13] and G/flax/E composite with 45° fiber orientation (~30.03 GPa) [15]. Overall, all current composites exhibited lower flexural modulus compared to those prior works [13,15], which suggests greater flexibility. The observed fluctuations in modulus (Figure 7) may be attributed to uneven carbon fiber–epoxy bonding caused by non-uniform HA dispersion, especially at HA concentrations exceeding 1 vol%. These findings suggest that the mechanical flexibility observed here may benefit applications requiring compliance, such as biomedical fixation plates, although it may compromise load-bearing capacity under complex bending conditions.

The use of woven carbon fiber in the composite contributes to partially isotropic mechanical behavior. Unlike unidirectional fibers, woven fabrics enable more uniform stress distribution and enhance resistance to bending deformation. During flexural loading, the outermost layers experience the greatest tensile and compressive stresses. The bidirectional structure of woven fibers improves the composite's ability to resist these stresses, as demonstrated by the superior flexural strength of the TC/E-HA1 composite (263.45 MPa). Therefore, the combination of woven reinforcement and low HA content provides synergistic benefits in terms of both strength and toughness under bending.

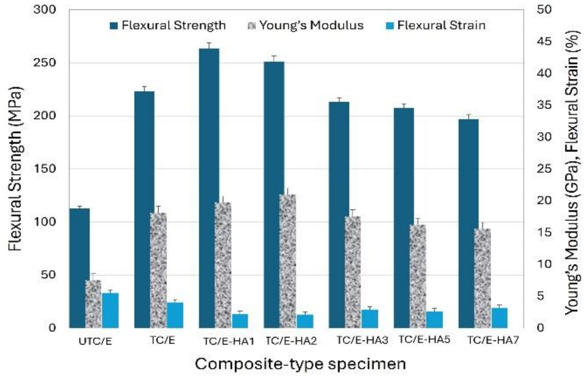

Fig. 7: Flexural strength, flexural modulus, and flexural strain of C/E-HA composite-type specimens

Furthermore, Figure 8 illustrates the bending test results, where the initiation points of first failure varied across different composite compositions (see circles). Both UTC/E and TC/E curves showed plastic deformation before failure. However, this behavior was absent in all surface-treated carbon fiber composites (TC/E-HA). Despite the increased flexural strength and stiffness, these TC/E-HA composites still exhibited brittle failure, as evidenced by the absence of plastic deformation. This brittle behavior, even at improved strength levels, indicates that while interfacial bonding has been enhanced, the ductility of the epoxy matrix remains a critical limiting factor. The brittle nature of the matrix under bending highlights the need for future strategies to improve energy absorption capabilities.

Optical microscopy analysis following the bending tests confirmed that none of the specimens experienced complete fracture. The cracks, observed along the tensile surface, propagated in a straight path that is consistent with brittle failure. As shown in Figure 9, the composites demonstrated excellent interfacial bonding between carbon fiber and epoxy, indicating successful fabrication. Delamination was evident in UTC/E specimens (Figure 9a), while the use of treated carbon fiber reduced delamination severity in TC/E-HA composites (Figs. 9b to 9d). However, increasing HA content led to more pronounced delamination, particularly in specimens with higher HA levels (Figs. 9g and 9h). This behavior confirms that the brittleness of the composite is primarily due to the epoxy matrix. The worsening delamination with higher HA suggests that filler clustering introduces microstructural weaknesses.

As mentioned earlier, at low HA concentrations such as 1 vol%, microparticles are evenly distributed within the epoxy matrix and enhance stress transfer between matrix and fiber. This distribution improves both flexural strength and modulus. Optical micrographs (Figure 9) confirm

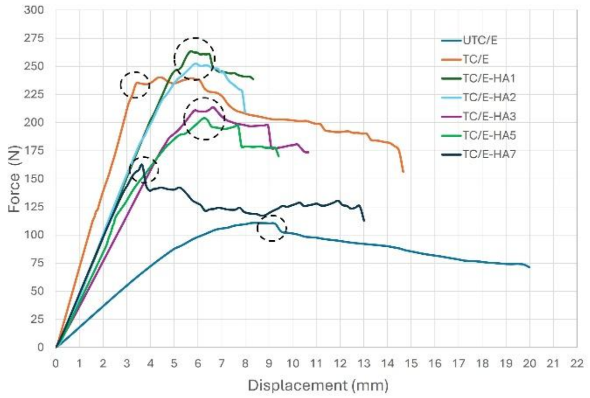

Fig. 8: Bending test results of C/E-HA composite-type specimens

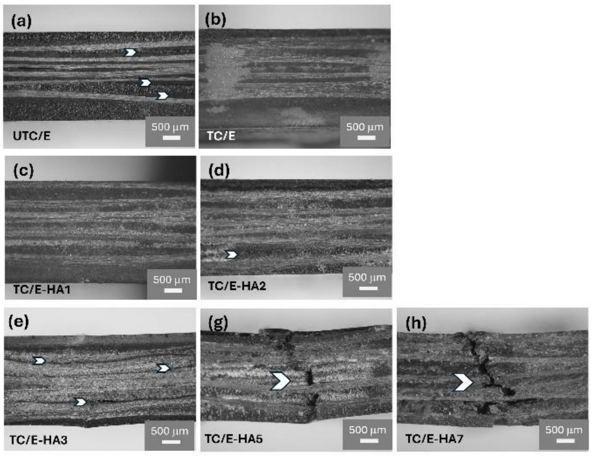

Fig. 9: Optical micrographs of bending test of C/E-HA composite-type specimens obtained from side view. White arrows indicate the delamination

minimal particle clustering at this concentration, resulting in a homogeneous structure that supports efficient load transfer. In contrast, higher HA contents above 1 vol% show clear sign of agglomeration, forming stress concentration zones that disrupt matrix integrity. This phenomenon was particularly evident in TC/E-HA5 and TC/E-HA7 composites, where decreased flexural performance correlated with poor filler dispersion and localized failures along the fiber–matrix interface.

Comparable studies have emphasized the importance of fiber orientation and uniform filler distribution in optimizing flexural performance. While unidirectional fibers can achieve high flexural strength, they often result in lower modulus compared to woven fibers that offer more balanced properties due to multi-directional reinforcement [36)]. In line with this, the present composite design uses woven carbon fabric and microparticle HA to achieve a compromise between strength and stiffness. The effectiveness of this design depends on preventing HA agglomeration, which would otherwise reduce the reinforcement effect and create local stress concentrations. Epoxy resin is known for its high stiffness and strength but has low ductility, making it vulnerable to brittle fracture under mechanical loading. This inherent brittleness limits the resin's capacity to absorb energy, especially during bending where both tensile and compressive stress are involved. In the TC/E-HA composites, the epoxy matrix is the main load-bearing component. Its limited ductility contributes directly to the brittle behavior observed during flexural testing. This condition emphasizes the need for future matrix modifications to enhance energy absorption and toughness.

3.3. Hardness

Table 3 presents the Shore-D hardness values of all C/E-HA composite specimens. The surface treatment of carbon fibers slightly increased the composite's hardness, and the addition of HA further improved this property. The increase can be explained by the higher density of HA (3.156 g/cm³) compared to that of epoxy (1.2 g/cm³), as observed in previous research on HA/PMMA composites [37)]. This increase in hardness with HA addition can be attributed not only to the high density of HA but also to its inherent stiffness and ceramic nature, which enhances surface resistance to localized deformation under Shore-D indenter pressure [38)].

Shore-D hardness testing is commonly used to evaluate the surface resistance of hard rubbers, rigid plastics, and polymer composites. A previous study on Kevlar/E-glass/epoxy composites with 1% SiC particles reported a Shore-D hardness of 85 [39)], which is higher than the Shore-D hardness of 65 recorded for TC/E-HA1 in this study. Our unpublished results with other types of synthetic fibers support these findings. Compared to inorganic reinforcements such as SiC, the relatively lower Shore-D hardness of HA-based composites may result from differences in particle morphology and interfacial bonding strength. While HA is more bioactive, it is less rigid than fillers like SiC. This trade-off reflects a balance between mechanical robustness and biocompatibility.

In contrast, the hardness of human bone is typically expressed in Vickers hardness units, ranging from 50 to 100 HV [33,40)]. Hardness is one of the most important physical properties of bone. However, studies investigating the hardness of composites for external bone plate applications are still rare. In this study, it was not feasible to use a micro-Vickers hardness test due to the composite configuration. A prior study, [13)] evaluated the hardness of a CF/flax/epoxy composite using Rockwell E (HRE) scale and reported a value of 73.43 HRE. Since Shore-D and HRE are based on different indentation mechanisms, direct conversion to Vickers hardness is not applicable. Nevertheless, the Shore-D values obtained here indicate moderate surface resistance, which is appropriate for materials in contact with bone tissue.

The Shore-D hardness values observed in this study, which range from 65 to 74, demonstrate that TC/E-HA composites provide adequate surface hardness for wear

Table 3: Hardness of C/E-HA composite-type specimens

Composite specimen	Shore-D Hardness (Shore-D)
UTC/E	59.0
TC/E	61.0
TC/E-HA1	65.0
TC/E-HA2	67.0
TC/E-HA3	71.0
TC/E-HA5	73.8
TC/E-HA7	74.0

resistance in biomedical applications. Although direct conversion from Shore-D to Vickers hardness is not possible, these values suggest that TC/E-HA composites offer mechanical compatibility with bone hardness. This compatibility may help reduce stress shielding and enhance the material's biocompatibility for external fixation use.

3.4. General finding for potential external fixation bone plate

This study represents a preliminary investigation into the mechanical behavior of composites designed to approximate the properties of human cortical bone. The materials used in fabricating the C/E-HA hybrid composites were carefully selected for their biocompatibility. Carbon fiber and epoxy have previously been confirmed as biocompatible through in vivo testing [13]. Hydroxyapatite (HA), a well-established bioceramic, is inherently biocompatible due to its chemical structure, which closely resembles the mineral component of bone. Therefore, incorporating HA into the composite matrix can enhance its bioactivity and potential for biomedical applications [41].

Various polymer-based composites have been explored in the literature, including CF/flax/E [13], CF/E [22], glass fiber (GF)/flax/E [15], HA/polyamide (PA)66/GF [42], and CF/nano-HA/E [28]. However, aligning their mechanical characteristics with those of cortical bone remains a significant challenge. Young's modulus is widely recognized as a key mechanical indicator for biocompatibility [43], particularly in the context of external bone fixation plates. According to previous findings, materials with excessively high stiffness can induce stress shielding, which delays bone healing and compromises clinical outcomes [15]. Therefore, selecting materials with stiffness values that closely match those of bone is critical to developing high-performance implants.

Among these studies, the hybrid composite of CF/nano-HA/E [28], shares a nearly identical material composition with the current work, differing primarily in HA particle size. However, Fouad study's [28] in tensile and flexural strength (< 50 MPa) were significantly lower than the values observed in this research. This discrepancy may be attributed to differences in both material processing and surface treatment methods. In Fouad's study, short carbon fibers were treated by heating in an oven at 300 °C for 90 minutes, whereas this study employed a cryogenic surface treatment approach. Additionally, the HA content varied from 0 to 5% in that study. These methodological differences likely contributed to the variation in mechanical performance.

Table 4: Comparative properties of TC/E-HA composites against similar bio-composites

Composite Type	Tensile strength (MPa) / Tensile modulus (GPa)	Flexural strength (MPa) / Flexural modulus (GPa)	Hardness (Shore-D)	References
TC/E-HA1 (1 vol%)	426.76 / **14.98**	263.45 / **19.73**	65	This Study
TC/E-HA7 (7 vol%)	364.00 / **11.24**	221.00 / **15.60**	74	This Study
CF/Flax/E	399.80 / **41.70**	510.60 / **57.40**	~60 (Rockwell E)	13)
GF/Flax/E (45° fibers)	301.87 / **16.51**	499.98 / **30.03**	~62	15)
HA/PMMA	~50.00 / **2.5–2.9**	106–108 / **2.7–2.9**	70–80	37)
Kevlar/E-glass/E-SiC	~300.00	Not reported	~85	39)
CF/nano-HA/E	<50.00	<50.00	Not reported	28)
Cortical Bone	50–150 / **7–25**	7–30	~50–100 (Vickers)	11)

The current study summarizes the mechanical properties of the composites, finding that the Young's modulus values from 11.24 to 14.98 GPa, flexural stiffness values from 14.67 to 21.60 GPa, and tensile strain levels from 2 to 3% for all composites (Figs. 4 and 7, Table 4) are all within the range of values found in human cortical bone [11,12,33]. When compared to metallic bone plates such as stainless steel and titanium alloys, the current composites exhibit significantly greater flexibility. These modulus values are also competitive with other epoxy-based composites reported in the literature [13,15,28]. Despite these favorable characteristics, all TC/E-HA composites in this study demonstrated mechanical strengths that exceed those of cortical bone. This strength disparity suggests the need for further investigation to optimize the composite formulation for clinical use. Nonetheless, the findings indicate that TC/E-HA composites hold substantial potential for development as alternative materials for external bone fixation plates.

4. Conclusion

This study successfully fabricated TC/E-HA composites composed of biocompatible materials, including woven carbon fabric, epoxy, and hydroxyapatite (HA). The HA concentration ranged from 0 to 7 vol%, producing brittle composite behavior, likely due to the inherent brittleness of both HA and epoxy. The TC/E-HA1 composite demonstrated the highest tensile and flexural strengths, which exceeded those of human cortical bone. Notably, the TC/E-HA1 type exhibited a promising combination of mechanical performance and compatibility with bone stiffness, aligning with the requirements for biomedical applications.

In addition, all types of TC/E-HA composites showed Young's modulus, flexural modulus, and tensile strain values within the typical range of cortical bone. These mechanical benchmarks support the potential of these composites to reduce stress shielding effects and ensure sufficient structural integrity in load-bearing applications. Therefore, TC/E-HA composites appear to be strong candidates for external bone fixation plates.

However, the brittleness observed, especially at higher HA concentrations, remains a limitation for clinical applications. Future research should aim to minimize mechanical brittleness by improving HA dispersion and avoiding particle clustering. Modifying the resin system or incorporating hybrid reinforcements could also enhance toughness while maintaining biocompatibility.

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