

Three-Dimensionally Braided Carbon Fiber–Epoxy Composites, A New Type of Material for Osteosynthesis Devices. I. Mechanical Properties and Moisture Absorption Behavior

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ABSTRACT: In recent years, three-dimensionally (3D) braided composites have attracted a great deal of attention because of their high-impact damage tolerance and fatigue life, superior fracture toughness, and so forth, and have been used in aeronautics, military, and transportation. These advantages make them strong candidates for osteosynthesis devices. In this study, 3D braided carbon fiber–epoxy (C_{3D}/EP) composites were produced via a simple vacuum impregnation technique. The load-deflection curve, mechanical properties, and influence of fiber volume fraction, braiding angle, and axial reinforcing fibers were examined to determine their suitability for internal fixation devices. It is found that the C_{3D}/EP composites have excellent toughness and do not show brittleness when fractured because of their relatively high void content. The flexural, shear, and impact strengths of the C_{3D}/EP composites are excellent. It was shown that a C_{3D}/EP composite with a stiffness similar to load-bearing bones can be made while maintaining enough strength. It is concluded that a relatively higher void content and braiding angle is more suitable for the C_{3D}/EP composites from the viewpoint of requirements of fracture fixation materials. The moisture absorption behavior and changes in mechanical properties caused by moisture uptake were evaluated. Results show that absorbed moisture slightly decreases mechanical properties of the C_{3D}/EP composites. Contrary to the unreinforced epoxy, the moisture absorption behavior of the C_{3D}/EP composites cannot be described with Fick's law of diffusion, probably because of the presence of voids and/or 3D fiber structure. The exact mechanisms should be proposed in further investigations. © 2002 Wiley Periodicals, Inc. *J Appl Polym Sci* 85: 1031–1039, 2002

Key words: three-dimensionally (3D) braided; carbon fiber; composites; mechanical properties; moisture absorption

INTRODUCTION

The present osteosynthesis devices made of metals were found to evoke allergic reactions because of the

release of metal ions caused by corrosion¹ or particles caused by friction and wear,² and lead to osteoporosis owing to their much higher modulus than the surrounding load-bearing bones. The disadvantages of conventional metallic fracture fixation devices have encouraged research into absorbable devices³ made of bioabsorbable polymers such as poly(lactic acid) (PLA), polyglycolide (PGA), their copolymers (PGA/PLA), polydioxanone (PDS), poly(β -hydroxy butyric acid) (PHBA), and others. The

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use of high-modulus fiber-reinforced bioabsorbable composite materials is a promising alternative for osteosynthesis devices in view of their high strength and fatigue life.⁴ However, several crucial factors that limit the application of these osteosynthesis devices made of bioabsorbable materials and their composites are high cost, lack effective methods to avoid sterile sinuses because of the release of acid compounds during degradation,⁵ and are difficult to precisely control the rate of degradation. Hence, bioabsorbable materials and their composites cannot totally replace the corresponding metals at the present time, particularly in China (the production of bioabsorbable polymer has not yet been industrialized). Given this situation, fiber-reinforced nonabsorbable polymer composites may be the best alternative to metal osteosynthesis devices on the basis of their low cost, tailorable mechanical properties, high environmental resistance, good biocompatibility, and others.

Continuous and chopped fiber-reinforced nonabsorbable polymer composites were applied for fixation of human fractures.^{6–8} However, delamination (for the former) and relatively low mechanical performance (for the latter) make them unsuitable for orthopedic implants. Three-dimensionally (3D) braided fiber-reinforced composites may be the most suitable materials for osteosynthesis devices because of their high-impact damage tolerance and fatigue life, superior fracture toughness, potentially less expensive manufacturing, reduced material wastage, and so forth.^{9,10} Nevertheless, there are no reported studies on 3D fiber-reinforced polymer composites used as osteosynthesis devices.

Because of its controllable viscosity and changeable curing conditions, epoxy resin can easily be reinforced with 3D braided, woven, stitched, or knitted fibers. 3D carbon fiber-reinforced epoxy resin (hereafter as referred to as C_{3D}/EP) composites were used to manufacture aircraft components, boat hulls, airframe spars, I-beams, etc., on account of their excellent mechanical properties.¹⁰ Even though many of their mechanical properties (compression, tension, flexural, and fatigue) were studied,^{11–13} their durability under wet conditions was not investigated extensively. In fact, this issue is of vital importance because the C_{3D}/EP composites may be exposed to moisture environments.

In this series of articles, a nonabsorbable polymer, epoxy resin, was reinforced with 3D carbon fibers to obtain a new type of material for osteosynthesis devices. The goals of Part I are to prepare different C_{3D}/EP composites with various fiber volume fractions (V_f), to examine their me-

chanical properties and effects of braiding parameters, as well as to determine their durability in moisture condition. The influence of fiber-surface treatment will be presented in the second part of this series of articles. The application of this new type of osteosynthesis devices depends very strongly on their biocompatibility that will be investigated and presented later in this series of articles. The final goal of our studies is to evaluate their suitability for osteosynthesis devices.

EXPERIMENTAL

Materials

A commercial epoxy resin from the Research Institute of Synthesis Materials, Tianjin, China, with a density of 1.80 g cm⁻³ and a viscosity of <1000 cp (25°C) was used and an anhydride curing agent was used at a content of 38% by weight (the biocompatibility of the epoxy has not yet been proven). The medium-strength, epoxy resin-sized carbon fibers with a nominal diameter of 7.5 μm and a density of 1.75 g cm⁻³, supplied by Jilin Carbon Ltd. (Jilin, China), were used as reinforcement. According to the manufacturer, the carbon fibers have the following mechanical properties: tensile strength, 2800 MPa; modulus, 200 GPa; elongation at break, 1.5%. No surface treatment was applied to the fibers. The preforms, 3D four-directional fabrics, were prepared by Tianjin Institute of Textile Science and Technology. Their preparation and structure character were reported earlier.⁹

Preparation of Composites

Because of the low viscosity of the epoxy resin matrix, the C_{3D}/EP composites were not produced by the conventional resin transfer molding (RTM) process; instead, they were prepared by a simple technique, a vacuum impregnation process. Briefly, a 3D braided fabric with a nominal size of 160 × 12 × 2 mm was placed in a mold. Epoxy resin and its curing agent were intimately mixed at room temperature and freed from air bubbles by degassing at 70°C for 30 min in a vacuum oven. The mold containing the 3D braided fabrics was also equilibrated at 70°C prior to resin pouring. The casts were cured at 90°C for 2 h and post-cured at 140°C for 3 h. A constant pressure (0.5 MPa) was maintained during the curing process to obtain regular-shaped C_{3D}/EP composite samples (160 × 12 × 2 mm). The unreinforced epoxy resin samples (ca. 2 mm in thickness) were pre-

pared by the same procedure as that used for the C_{3D}/EP composites. Following manufacture, the composite specimens were assessed by examining the polished cross sections using a Neophot 2 optical microscope.

Moisture Absorption Studies

The fiber volume fraction (V_f) of the C_{3D}/EP composites for moisture absorption studies was kept constant, $46 \pm 1\%$, in the present study.

The specimens were totally immersed in distilled water at $37 \pm 0.5^\circ\text{C}$ to evaluate their moisture absorption behavior. The kinetics of moisture absorption was determined by weighing the specimens at regular time intervals. A TG328-A model balance with a precision of 0.1 mg was used. The moisture content at any time t , M_t , was expressed as:

$$M_t = \frac{m - m_0}{m_0} \times 100\% \quad (1)$$

where m_0 and m are the original dry weight and weight after immersion, respectively:

Measurements

The V_f of the composites was determined by weighing the fibers and the composites. It was calculated using the equation

$$V_f = \frac{W_f/\rho_f}{(W_f/\rho_f) + (W_m/\rho_m)} \quad (2)$$

where W and ρ are the weight and density, respectively. Subscripts f and m represent the fiber and the matrix, respectively. The void content, V_v , of each composite sample, was measured according to ASTM Standard D2734.

The flexural properties of the composites as well as unreinforced samples before and after moisture absorption tests were conducted by three-point flexural tests on a DL-1000B electronic testing machine at a temperature of 25°C . Three-point flexural tests were carried out with a span-to-depth ratio of 16 : 1 at a crosshead speed of 1 mm/min. The flexural strength (σ) and modulus (E) were obtained by the following equations

$$\sigma = \frac{3Pl}{2bh^2} \quad (3)$$

where P is the applied load at the moment of fracture, l is the span length, and b and h are the

width and thickness of the test specimens, respectively, and

$$E = \frac{Pl^3}{4bh^3\delta} \quad (4)$$

where P is the load at a chosen point on the initial linear portion of the load-deflection curve, and δ is the deflection corresponding to the load P .

The shear strength was measured with a DL-1000B electronic testing machine at a crosshead speed of 1 mm/min. The shear strength was measured with the help of a homemade tool, as previously reported.⁹

A X CJ-500 impact tester was used in this work to obtain the impact properties of the composites and epoxy samples. Unnotched $80 \times 12 \times 2$ mm bars were used at a span of 50 mm to measure the impact strength. All moisture-absorbed samples were mechanically tested in the wet stage to reflect the in-service conditions (for example, an implanted device *in vivo*). The immersed unreinforced epoxy and composite samples were removed from distilled water at day 0, 1, 7, 14, 21, 28, and 35, respectively. The removed samples were wiped dry (on the surface) by using filter paper and then immediately measured at ambient temperature to get the flexural strength (σ), modulus (E), shear strength (τ), and impact strength (a_k). The measured bending strength and modulus, shear strength, and impact strength were normalized to their initial values (σ_0 , E_0 , τ_0 , and $a_{k,0}$), respectively. The normalized values, σ/σ_0 , E/E_0 , τ/τ_0 , and $a_k/a_{k,0}$, were added to the corresponding figures to demonstrate the rate of degradation.

A minimum of five specimens was tested for each set of samples and the average values were reported in the present study.

RESULTS AND DISCUSSION

Mechanical Properties

Stress–Strain Behavior

A typical flexural load-deflection curve obtained by three-point flexural tests for a C_{3D}/EP composite ($V_f = 0.46$) is shown in Figure 1(a). As illustrated in Figure 1(a), this composite displays a linear load-deflection relation at initial loadings. A slight yield plateau is followed. The load increases further nonlinearly with increasing deflection after this plateau and gradually de-

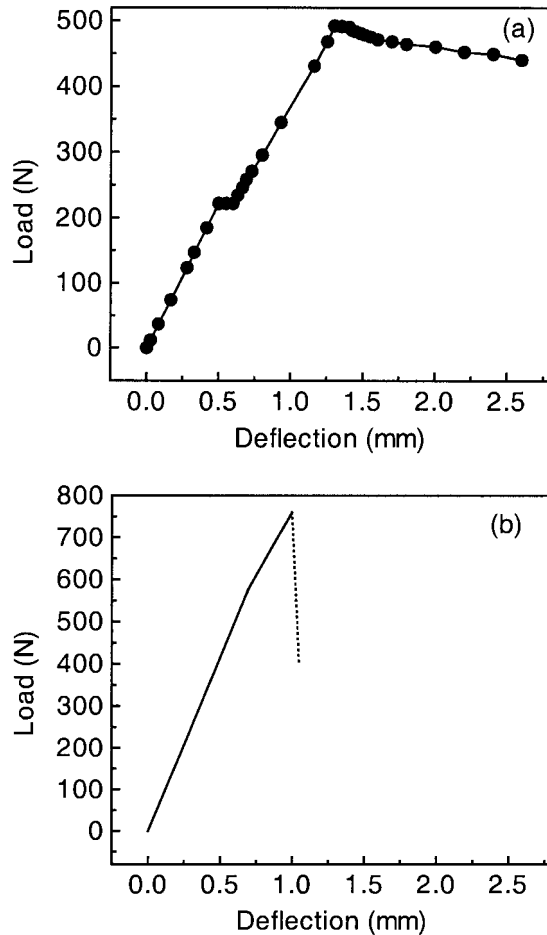


Figure 1 Load-deflection curve of the C_{3D}/EP composites containing 46 vol % fibers. (a) A typical C_{3D}/EP composite prepared in this work ($V_v = 5.5\%$); (b) a C_{3D}/EP composite prepared by RTM technique ($V_v \leq 1\%$).¹⁵

creases after this maximum load. The slow decrease in load after this peak load is in agreement with the noted phenomenon that brittle fracture associated with unreinforced epoxy is not observed for all C_{3D}/EP composite specimens. In all composite specimens, fiber breakage occurs only at the outermost layer in tensile side. On the whole, all tested composite samples still stay integrated; no separation is found, suggesting they are ductile. This behavior is very beneficial to osteosynthesis devices. The good toughness of all the C_{3D}/EP composites with various V_f seems to be in contrast with results obtained by other researchers who found that the failure of 3D epoxy composites were brittle in flexure force,¹⁴ and our earlier results with the C_{3D}/EP composites prepared by RTM process [see Fig. 1(b)].¹⁵ The fact that the only difference between these and our

previously prepared C_{3D}/EP composites is the V_v level indicates that it is the high V_v that changes the failure mode from brittleness to toughness. The details were presented in our earlier article.¹⁵ A similar mechanism has been proposed by Varna et al. for RTM laminates.¹⁶ It can be concluded that a proper amount of voids may be beneficial to a material for osteosynthesis devices.

Figure 2 shows the polished surface of a C_{3D}/EP composite ($V_f = 0.46$). It can be seen from both photos that the fibers are homogeneously distributed and no fiber contact is observed. Moreover, no obvious voids were detected, which suggests that void content in 3D composites cannot be measured precisely by metalloscopy.

Effect of Fiber Volume Fraction

The effects of V_f on mechanical properties, flexural strength and modulus, and shear and impact

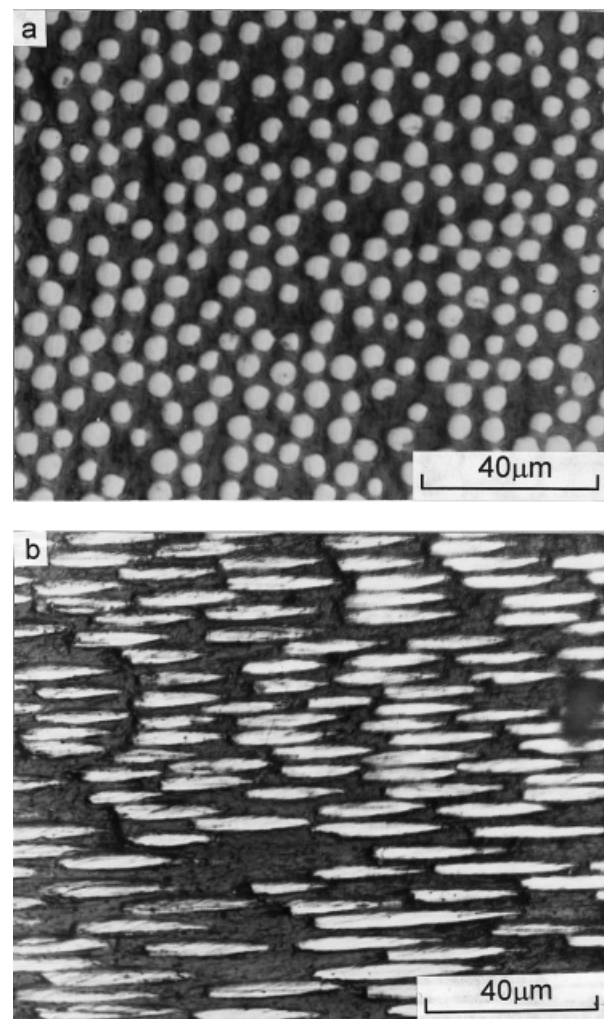


Figure 2 Microstructure of a C_{3D}/EP composite containing 46 vol % fibers: (a) transverse; (b) longitudinal.

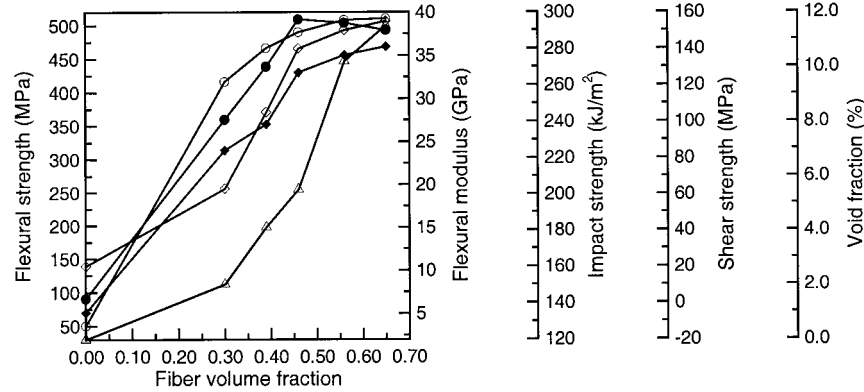


Figure 3 Effects of fiber volume fraction on mechanical properties of the C_{3D}/EP composites (○: Flexural strength; ◆: flexural modulus; ◇: impact strength; ●: shear strength; △: void fraction).

strengths are illustrated in Figure 3. It is shown that below a V_f value of 0.46, all mechanical properties tested in this work increase considerably with the increase in V_f . Above this V_f value, flexural strength and modulus, as well as impact strength, continue to enhance at a slower rate, whereas shear strength exhibits a slight decline. The slight decline in shear strength above 0.46 may be ascribed to the notably increased void content of the composites (see Fig. 3). This result suggests that shear strength is more sensitive to porosity within a 3D braided composite in comparison with flexural strength, modulus, and impact properties, which agrees well with previous results for C_{3D}/PLA composites.⁹

Data in Figure 3 demonstrate that our C_{3D}/EP composites (except $V_f = 0.30$) exhibit higher flexural strength than that of the ultra-high-strength carbon fiber-reinforced liquid crystalline polymer (LCP/CF) composite prepared by Kettunen et al.,¹⁷ who reported that the flexural strength of their LCP/CF composite was higher than the yield strength of some metals used in orthopedic applications, and its elastic modulus was quite close to the corresponding value of cortical bone (see Table I).¹⁷ From the data in Table I, we can say that the flexural, shear, and impact strengths of the C_{3D}/EP composites are high enough, and the modulus value is very close to that of the load-bearing bones (1–30 GPa). It can be expected that applications of the C_{3D}/EP composites will help to alleviate the osteoporosis associated with metal osteosynthesis devices.

Effect of Braiding Angle

Braiding angle and fiber volume fraction are thought to be two important factors in determin-

ing the properties of 3D composites.¹⁸ Comparison of the strength of the C_{3D}/EP composites at the same level of V_f but with various braiding angles are presented in Table II. It should be stated that it is difficult to obtain completely identical V_f and V_v for the C_{3D}/EP composites with different braiding angles. Anyhow, the difference in V_v for these four composites is negligibly small. Therefore, data from Table II can demonstrate that the flexural strength and modulus decrease with increasing braiding angle, which is inconsistent with that reported by other investigators,¹⁸ and that predicted by a theoretical model.¹⁹ It is found from Table II that the flexural modulus seems to be more sensitive to the variation of braiding angle in comparison to flexural strength. An ideal material for osteosynthesis devices

Table I Mechanical Properties of Some Orthopedic Implant Materials, LCP/CF Composite, Cortical Bone, and Our C_{3D}/EP Composites

Materials	Flexural Strength (MPa)	Flexural Modulus (GPa)
Cortical bone	180	20
Ti-Al-V	380	120
Stainless steel	280	200
Co-Cr	480	240
LCP/CF	450	40
C_{3D}/EP		
$V_f = 0.30$	416	24
$V_f = 0.39$	466	27
$V_f = 0.46$	490	33
$V_f = 0.56$	508	35
$V_f = 0.65$	510	36

Table II Effect of Braiding Angle on Mechanical Properties of the C_{3D}/EP Composites ($V_f = 0.46$)

Sample No.	Braiding Angle (°)	Flexural Strength (MPa)	Flexural Modulus (GPa)	V_v (%)
1	15	505	41	5.4
2	20	490	33	5.5
3	27	476	29	5.3
4	41	464	22	5.6

should possess a high strength and close modulus to bones; a C_{3D}/EP composite with a higher braiding angle is more preferable (see Table II).

Effect of Axial Reinforcing Fibers

To examine the effect of axial reinforcement on the mechanical properties of the C_{3D}/EP composites, we have produced a C_{3D}/EP composite with 5 vol % axial reinforcing fibers (the total V_f was kept at 46%). Its mechanical properties are presented in Table III. It is demonstrated that the flexural properties decrease when axial fibers are added in fabrics. However, the differences in the observed shear and impact strengths of the composites with and without axial fibers are not statistically significant.

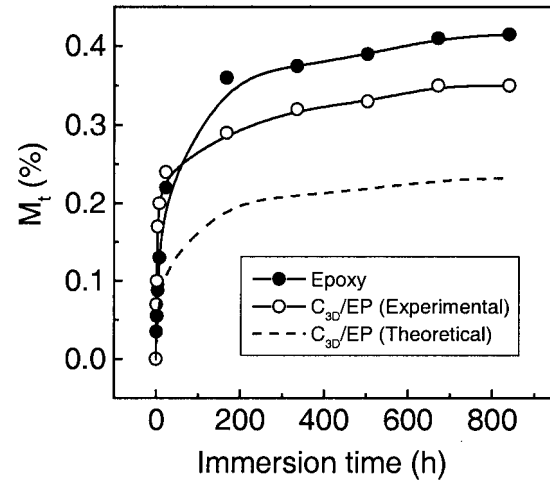
Moisture Absorption Behavior

Moisture Absorption Kinetics

Figure 4 shows the moisture absorption of a C_{3D}/EP composite ($V_f = 0.46$), as well as the unreinforced epoxy. The C_{3D}/EP composite and epoxy exhibit similar M_t versus t curves. The shape of the curves is characteristic of polymer composites.^{20,21} It is seen that the moisture content bursts up during the first day of immersion for

Table III Comparisons of Mechanical Properties of the C_{3D}/EP Composites ($V_f = 0.46$) With and Without Axial Reinforcement

C _{3D} /EP Composites	Without Axial Fibers	Containing 5% Axial Fibers
Flexural strength (MPa)	490	467
Flexural modulus (GPa)	33	28
Shear strength (MPa)	280	277
Impact strength (kJ/m ²)	156	153

**Figure 4** Kinetics of moisture absorption for the C_{3D}/EP composite and unreinforced epoxy.

both the reinforced and the unreinforced samples. Between 1 and 7 days, moisture content increases from 0.24 to 0.29% in the case of the unreinforced epoxy, and from 0.22 to 0.36% in the case of the C_{3D}/EP composite. Thereafter, moisture contents of the epoxy and C_{3D}/EP composite continue to increase at a much lower rate and reach only 0.35 and 0.42%, respectively, at the end of 35 days. As expected, the maximum moisture content of the C_{3D}/EP composite is slightly lower than that of the unreinforced epoxy because the carbon fibers in the C_{3D}/EP composite do not uptake water.

Theoretically, the moisture content of the polymer composites, $M_{t,c}$, can be deduced from the corresponding moisture content of the unreinforced matrix material, $M_{t,m}$, through the following equation, assuming carbon fibers do not uptake any moisture²²:

$$M_{t,c} = M_{t,m} \times W_m \quad (5)$$

where W_m is the weight fraction of the matrix material in a composite.

The theoretical result of this C_{3D}/EP composite is depicted in Figure 4 as a dotted line. It is seen that the experimental values of $M_{t,c}$ are obviously higher than the theoretical ones. The percentage differences are in the range of 34 to 48%. These discrepancies may result from the wicking effect of the fiber–matrix interfaces,²³ as well as microcracks within the C_{3D}/EP composites. It is therefore reasonable to predict that the moisture absorption behavior of this composite can be modulated by adjusting the fiber–matrix interfaces through fiber surface treatment, because fiber–

matrix interfaces may influence the wicking effect,²⁴ which will be presented in a later part of this series of articles.

Generally, moisture absorption processes in polymer composites can be described by Fick's second law of diffusion, which can be expressed as:

$$\frac{M_t}{M_\infty} = 1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left\{-\frac{D(2n+1)^2\pi^2 t}{h^2}\right\} \quad (6)$$

where M_t and M_∞ are the moisture content at time t and the equilibrium or maximum moisture content, respectively. D is the diffusion coefficient and h is the sample thickness.

At short times (i.e., the initial absorption), eq. (6) can be reduced to:

$$\frac{M_t}{M_\infty} = \frac{4}{\pi^{1/2}} \left(\frac{Dt}{h^2}\right)^{1/2} \quad (7)$$

Equation (7) can be rewritten as

$$M_t = kt^{1/2} \quad (8)$$

where k is a rate constant relating to the diffusion coefficient.

Figure 5 replots the initial moisture absorption curve of the C_{3D}/EP composite according to eq. (8). As shown in Figure 5, M_t increases linearly with $t^{1/2}$ for the unreinforced epoxy, while a nonlinear relationship is observed between M_t and $t^{1/2}$ for this C_{3D}/EP composite, suggesting the moisture absorption behavior does not obey Fick's law of diffusion. This result is in contrast with those of other investigators for unidirectional polymer composites. Chateauinois and coworkers²⁵ found that water sorption of a glass fiber/epoxy unidirectional composite in distilled water could be satisfactorily described by using Fick's law. It was reported that Fick's diffusion law was applicable to analysis of water desorption and absorption characteristics of carbon fiber-reinforced epoxy resin composites.²⁶ Gopalan and coworkers studied the moisture absorption behavior of E-glass, graphite, and Kevlar-epoxy composites and found the Fickian model was adequate to characterize these composites.²⁷ It is known that water sorption in epoxy composites is a complex phenomenon and many effects such as molecular relaxation and insufficient curing can lead to deviations from Fickian diffusion.²⁸ The deviation from Fickian diffusion for the present C_{3D}/EP composite

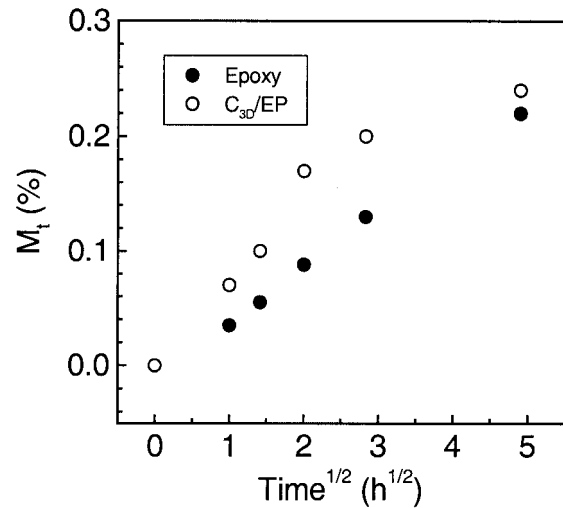


Figure 5 Moisture content as a function of the square root of immersion time (initial part of the moisture absorption curves of Fig. 4 according to eq. (8)).

is probably due to the special fiber architecture of the 3D fabric that alters the diffusion path of water molecules when compared to unidirectional fibers. Another possible explanation may be the relatively high void content because the existence of voids will lead to rather complex water absorption behavior.²⁹ The exact mechanisms will be investigated in depth in further studies.

Changes in Mechanical Properties

The effects of moisture absorption on the flexural properties of a typical C_{3D}/EP composite ($V_f = 0.46$) are illustrated in Figure 6. Included are the normalized values showing the degradation rate. Figure 6 clearly shows that the presence of water reduces the bending strength and modulus for the C_{3D}/EP composites and unreinforced epoxy. The flexural strength suffers a more substantial decrease during the first day of immersion and remains practically stable thereafter. Similar results were reported by Vina et al. for carbon fiber-PEI composite,³⁰ and by Adams et al. for carbon fiber-reinforced epoxies,³¹ suggesting it is a typical trend for polymer composites.

Comparisons of normalized values between the C_{3D}/EP composite and the unreinforced epoxy reveal that there is no great difference in degradation rate between the C_{3D}/EP composite and unreinforced epoxy.

Figure 7 shows the shear strength versus immersion time for a C_{3D}/EP composite ($V_f = 0.46$), along with the unreinforced samples for comparison. This behavior is very similar to the flexural

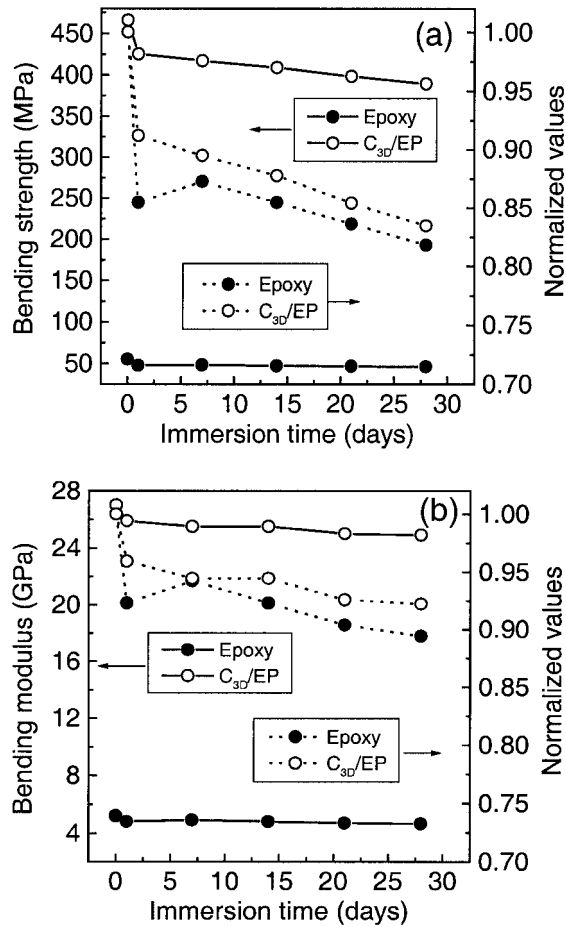


Figure 6 Effects of immersion time on bending strength (a) and modulus (b) for a C_{3D}/EP composite and epoxy.

properties. A rapid degradation within the first day is followed by an approximately stable process. In contrast to the flexural properties, the shear strength of this C_{3D}/EP composite demonstrates a slightly higher decreasing rate in comparison with the epoxy.

The variations of impact strength against immersion time for both the reinforced ($V_f = 0.46$) and the unreinforced samples are shown in Figure 8. Similarly, the impact strength of this C_{3D}/EP composite suffers a pronounced decrease during the first day of immersion in distilled water at 37°C. After this time, the decrease in impact strength is minor. In the case of epoxy, a slight increase in impact strength is observed after 1 day of immersion, probably because of the plasticizing effect of absorbed water, which has been found by several investigators.^{32,33} The absence of this phenomenon in the C_{3D}/EP composites is simply due to the fact that the brittle epoxy

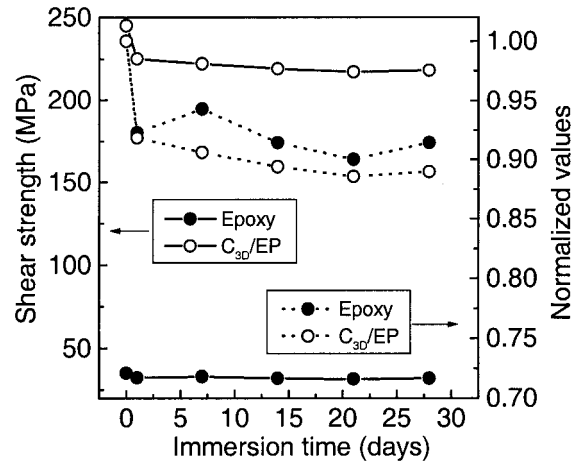


Figure 7 Shear strength versus immersion time for a C_{3D}/EP composite and unreinforced epoxy.

matrix contributes a little to the impact strength of the whole composite. Actually, the epoxy does not show any great decrease in impact strength during the whole immersion test up to 35 days.

The flexural strength and modulus and shear and impact strengths remain, respectively, 84, 92, 89, and 90% of their original values after immersion in water for 35 days. This reduction is minor considering the mechanical tests were performed in the wet state. Furthermore, the loss in the mechanical performance may be reduced by modifying epoxy because the extent of this loss depends considerably on the nature of the polymer in addition to the fiber–matrix interface condition. This behavior makes the C_{3D}/EP composites suitable for osteosynthesis devices because stable

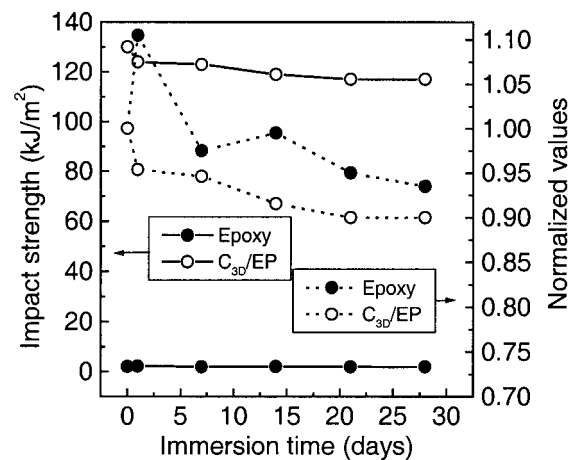


Figure 8 The variations of impact strength against immersion time for a C_{3D}/EP composite and unreinforced epoxy.

fixation cannot be kept if an osteosynthesis device loses its mechanical properties at a higher rate. It is expected that deterioration in mechanical properties will be negligible in further immersion, although the moisture absorption behavior for a longer time is needed in future research.

CONCLUSIONS

1. The load-deflection curve and mechanical evaluation suggest that the C_{3D}/EP composites have excellent toughness, without brittle fracture, because of their relatively high void content.
2. The mechanical properties of the C_{3D}/EP composites are considerably controlled by V_f . In addition, the flexural strength and modulus are a strong function of braiding angle and are related to the presence of axial reinforcement, but the shear and impact strengths are virtually independent of axial-reinforcing fibers. A composite with a modulus similar to load-bearing bones while maintaining a required strength can be obtained by tailoring V_f and fiber structure. It is believed that the C_{3D}/EP composites can be promising materials for fracture fixation devices used in high-load applications in view of their mechanical properties.
3. Unlike the unreinforced epoxy and unidirectional fiber composites, the Fickian model is not applicable to analysis of the moisture absorption of the C_{3D}/EP composites, probably because of the presence of voids and/or their complicated fiber structure.
4. The moisture absorption of the C_{3D}/EP composites decreases their mechanical properties (bending strength and modulus, shear and impact strengths). The decrease in mechanical properties is relatively rapid during the first day of immersion; after that, the mechanical properties are practically stable. Overall, the reduction in mechanical performance is not significant.

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