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Comparison of MC nylon-based composites reinforced with two different three-dimensionally braided fabrics

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In recent decades, three-dimensionally (3D) braided composites have attracted a great deal of attention because of their high impact damage tolerance, long fatigue life, superior fracture toughness, and so forth, and have been used in aeronautics, military applications, and transportation [1–3]. These advantages make them suitable for orthopaedic applications. Epoxy resin is the most widely used matrix material for 3D composites. Indeed, epoxy resin is a high-strength material and some epoxy resin products have been used in clinics for many decades in vascular grafts, pacemakers, and dental products [4, 5]. However, thermoplastics have found more medical applications such as orthopaedic implants, catheters, prosthetics, etc. [6, 7] due to their excellent biocompatibility, good processibility, high chemical stability, and so forth. Likewise, thermoplastic-based composites are expected to show better performance in orthopaedics when compared to their thermoset counterparts. Though discontinuous fiber-reinforced thermoplastic composites have been made, it is hard to prepare continuous fiber- and 3D fabric-reinforced thermoplastic composites due to the difficult processability. In most cases, resin transfer molding (RTM) is being employed to make thermoset-based 3D composites like epoxy, unsaturated polyester, etc., but RTM is not being used to prepare 3D thermoplastic-based composites because almost no thermoplastic can meet the stringent requirements to the rheological nature. Our preliminary investigation, however, indicates that it is possible to make such thermoplastic-based 3D composites as monomer casting (MC) nylon and poly(methyl methacrylate) by means of RTM by taking advantage of the low viscosity of their monomers.

In this study, MC nylon was chosen as the thermoplastic matrix. Two fibers, carbon—an inorganic fiber and Kevlar—an organic fiber were selected to prepare 3D fabric-reinforced MC nylon composites.

Typical parameters of the fibers used in this work are listed in Table I. The preforms, 3D four-directional fabrics with a braiding angle of 16° were prepared by the Nanjing Fibreglass R&D Institute, Nanjing, China. An RTM-aided vacuum solution impregnation plus *in situ* anionic polymerization technique was employed to prepare the three-dimensionally braided carbon- and Kevlar-reinforced MC nylon (denoted as C_{3D}/MC and K_{3D}/MC, respectively) composites. The preparation procedures were similar to that described in reference [8] except that a higher pressure was applied for the 3D fabrics. The fiber volume fraction (V_f) of the composites used in the present study was kept at 30% and 40%.

Flexural properties, shear and impact strengths were tested in this study. The three-point bending test and shear strength measurement were described previously [9]. Load-deflection curves were recorded during flexural tests. The impact test was conducted using an XCJ-500 Impact Tester (pendulum type). Notched specimens were used for the impact test. The sample dimensions were 80 mm × 12 mm × 2 mm with a support span of 40 mm. The fracture surfaces were observed using an XL30 scanning electron microscope (SEM) after impact testing. All specimens were mechanically tested along the wrap direction. For each experiment, five specimens were tested, and the values were averaged.

The typical flexural load-deflection curves of the C_{3D}/MC and K_{3D}/MC composites ($V_f = 0.30$) are shown in Fig. 1. As illustrated in this figure, the C_{3D}/MC composites exhibit a linear load-deflection relation at initial loadings. Then, a yield plateau occurs. The load increases further linearly with increasing deflection after this plateau. Overall, the load-deflection behavior is linear-elastic until failure due to buckling of the fabrics under the loading nose. In the case of the K_{3D}/MC composites, an initial linear part and a yield are observed. Afterwards, an obvious nonlinear load-deflection curve is noted with a slow increase in load. It is worth noting that, unlike the three-dimensionally braided carbon-epoxy resin (C_{3D}/EP) composites which experienced a brittle fracture [10], no brittle fractures are observed for both C_{3D}/MC and K_{3D}/MC composite specimens, due to the ductility of the matrix material and the higher structural integrity of the 3D fabrics, which prevent the specimens from separating. For all the C_{3D}/MC composite specimens, fiber breakage occurs only at the outermost layer in the tensile side. All tested composite samples still stay integrated and no separation is found, suggesting they are non-brittle in nature. For the K_{3D}/MC composite specimens, no fiber breakage is

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TABLE I Properties of fibers used in this study

Materials	Type	Tensile strength (MPa)	Tensile modulus (GPa)	Density (kg m^{-3})	Strain at break (%)
Carbon	T300	3530	230	1760	1.5
Kevlar	Kevlar49	3260	102	1440	2.7

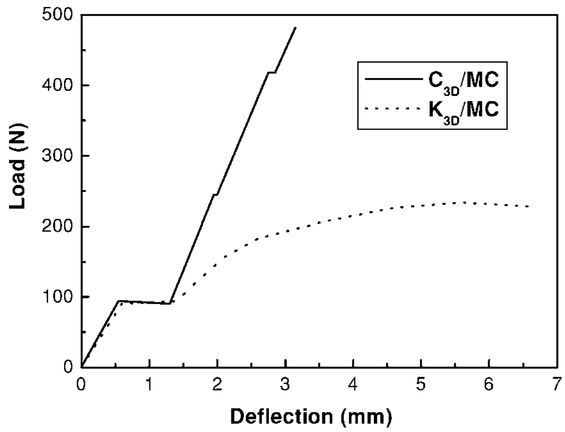

Figure 1 Load-deflection behavior of the 3D MC nylon composites.

observed except for an irreversible deformation, indicating a better ductility than the C_{3D}/MC composites.

It is established that carbon fiber-polymer composites dominate high-performance applications because of their high strength and stiffness. However, high stiffness is not an advantage in the orthopedic field where a modulus matching the host bones is favored. Kevlar fiber composites, on the other hand, are believed to show low modulus, good ductility, and high damage tolerance. As shown in Table II, the C_{3D}/EP composites [10] do show high flexural strength and modulus. Nevertheless, the flexural strength and modulus of the C_{3D}/MC composites are not as high as those of the C_{3D}/EP composites because of the weaker matrix (the flexural strengths of epoxy and MC nylon are 98 and 78 MPa, respectively), as well as a weaker interface (because the difference in matrix strength contributes to a slight difference in strength and modulus between the two composites). Compared to the C_{3D}/MC composites, the K_{3D}/MC composites show lower flexural strength and modulus as a result of the low strength and modulus of the Kevlar fiber. A comparison to cortical

TABLE II A comparison among cortical bone, typical medical metals, and the 3D composites

Materials	Flexural strength (MPa)	Flexural modulus (GPa)
Cortical bone	180	≤17
Ti-Al-V	380	120
Stainless steel	280	200
Co-Cr	480	240
C_{3D}/EP ($V_f = 0.40$)	756	47
C_{3D}/MC $V_f = 0.30$	395	21
$V_f = 0.40$	451	30
K_{3D}/MC $V_f = 0.30$	205	14
$V_f = 0.40$	243	19

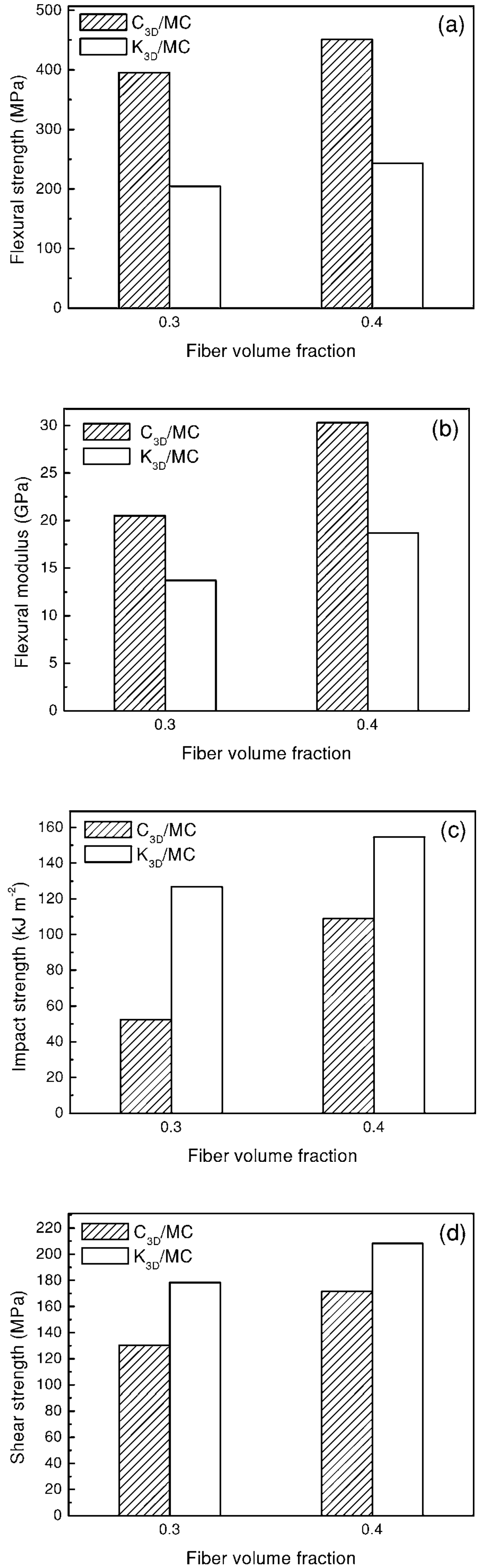

Figure 2 Mechanical properties of the 3D MC nylon-based composites: (a) flexural strength, (b) flexural modulus, (c) impact strength and (d) shear strength.

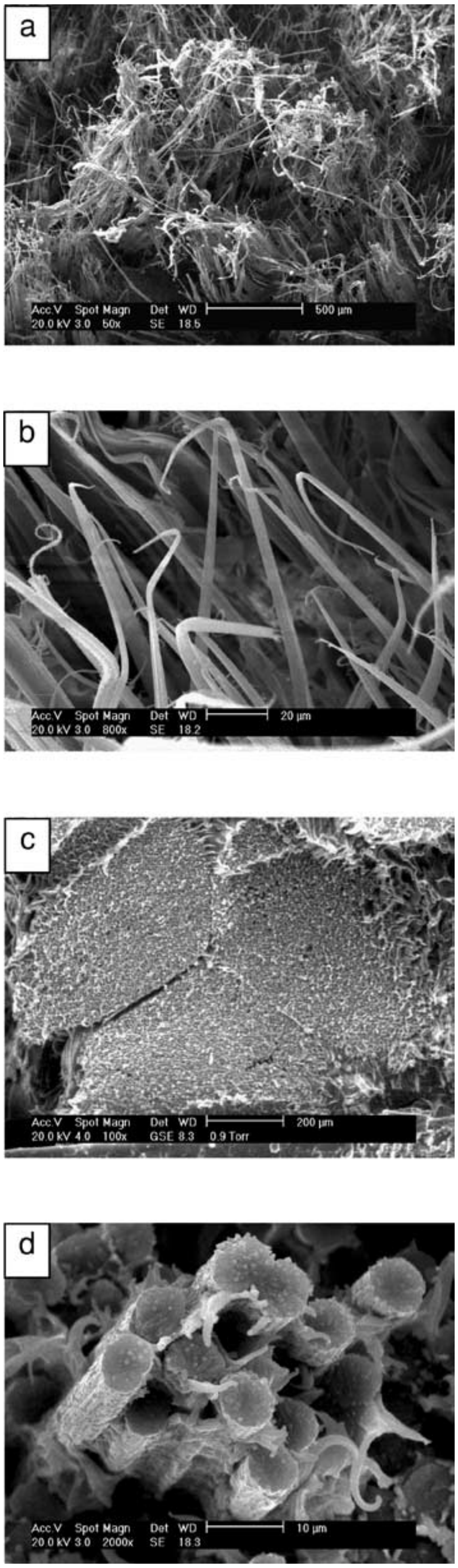

Figure 3 Fracture surfaces of the K_{3D}/MC ((a) and (b)) and C_{3D}/MC ((c) and (d)) composites.

bone [11] and medical metals (also see Table II) suggests that the flexural strength of the C_{3D}/MC composites is higher than the yield strength of some metals used in the orthopaedic field, and the flexural strength of the K_{3D}/MC composites is higher than that of cortical bone though lower than those of metals. It is found that the elastic moduli of the C_{3D}/MC and K_{3D}/MC composites are quite close to the corresponding value of cortical bone, particularly for the K_{3D}/MC composites which have moduli of the same order as that of cortical bone. This result may suggest that the C_{3D}/MC composites show advantages over metals and the C_{3D}/EP composites in terms of their sufficient strength and more importantly, their favorable modulus.

As can be seen from Fig. 2c, the K_{3D}/MC composites offer much higher impact strength than the C_{3D}/MC ones at both 0.3 and 0.4 fiber loadings. This excellent impact property benefits from the good ductility of the Kevlar fibers. As revealed by the impact fracture surfaces (see Fig. 3), Kevlar fibers experience pull-out and a long-term plastic deformation process before eventual break, which consumes a great amount of impact energy, whereas no obvious deformation can be observed among carbon fibers. This result is in agreement with the result of the impact tests and the load-deflection curves. The good ductility of the K_{3D}/MC composites ensure their promise as an orthopaedic material, as well as a promising structural material when good ductility and damage tolerance are required, but high strength and stiffness are not.

Shear strength is critical in internal fixation devices (like bone plates, intramedullary rods, screws, pins), hip, etc. Fig. 2d shows that the K_{3D}/MC composites present higher shear strength than the C_{3D}/MC ones at two fiber loadings, suggesting another advantage of the K_{3D}/MC composites.

Although, at this stage, it is hard to conclude which material is a better candidate from a mechanical property point of view, it is expected that both C_{3D}/MC and K_{3D}/MC composites may find applications in the orthopaedic field. The former may be used in high-load bearing bones and heavy patients while the latter will be suitable for low-load bearing bones and light-weight and active patients like teenagers. Further work should be done to evaluate other properties such as fatigue, wear resistance, moisture absorption, biocompatibility, etc.

In conclusion, the C_{3D}/MC composites show higher flexural strength and modulus but lower impact and shear strengths than the K_{3D}/MC composites. The mechanical properties of the 3D braided MC nylon composites are fiber property dependent. Further changes might be made by adjusting fabric structure, interface conditions, or by fiber hybridization. The properties of MC nylon-based composites may be tailored over a wide range to meet the special demands of different orthopaedic applications.

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