Reinforcing Effects of UHMWPE Fiber on the Mechanical Properties of Woods

Wendong Shen and Jian Li*

Three layers of wood-based composites of planed lumber-UHMWPE-veneer structure were prepared using polyurethane (PUR) as the resin matrix. The effects of ultrahigh molecular weight polyethylene (UHMWPE) fiber on the wood's bending performance, tensile properties, and other mechanical properties, such as shear resistance to the agglutination interface, were investigated. Chemical constituents of debonded fibers were characterized by infrared spectroscopy (FTIR). The results show that PUR could feasibly be used to manufacture UHMWPE fiber/wood composites. UHMWPE fiber played an important role in the wood destruction process and improved the flexural performance of the lumber. This positive effect was closely related to the thickness of veneer. When fiber was within the load-bearing strength range, there was a positive correlation between the tensile strength and the bonding distance. Meanwhile, the reinforcing effect of UHMWPE fiber strongly affects the performance of the bonding interface under shear.

Keywords: UHMWPE fiber; Three-layered wood-based composites; Mechanical properties; PUR

Contact information: Key Laboratory of Bio-based Material Science and Technology of Ministry of Education, Northeast Forestry University, 26 Hexing Road, Harbin 150040, P. R. China;
** Corresponding author: nefulijian@163.com*

INTRODUCTION

In recent years, earthquakes in China have caused serious harm to human beings. Such events have raised concern also in the timber and building industries. Such natural disasters have also promoted the application of large spans of wood in houses, bridges, sports venues, and other large buildings. Under normal circumstances, wood must be very thick to prevent it from deforming. This increases the weight and amount of wood required in construction. However, the appearance and successful application of Fiber Reinforced Plastics (FRP) in various fields has provided potential designs for lightweight wood structures. Research regarding the use of carbon fiber (Trimble 1999; Dourado *et al.* 2012) and Kevlar® fiber (Ou *et al.* 2010) in woody material engineering has gradually developed. Ultrahigh molecular weight polyethylene (UHMWPE) fiber, which is composed of carbon and hydrogen, has excellent mechanical properties. It is the third generation of high-energy fiber, after carbon fiber and Kevlar® fiber, but its interfacial adhesion to polymer matrices is weak. Some modifications with plasma have attempted to change its surface morphology, internal cross-linking (Valenza *et al.* 2004; Kusano *et al.* 2011), and optical radiation (Enomoto *et al.* 2010; Li *et al.* 2011) properties. Research regarding UHMWPE is still limited to laboratory research due to its high cost. The study of resin matrices containing UHMWPE fiber has a great potential for new developments, since the technology is mature and the implementation cost is low (Ziaee and Palmese 1999; Park and Jin 2001). Polyurethane (PUR) was the first resin to be used as a matrix in

UHMWPE composite materials because it has a high peel strength, good chemical stability, and good resistance to low temperature, parameters widely required in structural, glued, laminated timber. Thus, the common use of PUR resin makes the enhancement of wooden material possible. No research regarding enhanced UHMWPE fiber wood-based composites has been reported. In this study, PUR was chosen as the resin matrix, and three layers of wood composite materials of the planed lumber-UHMWPE-Veneer structure were prepared. The reinforcing effects of UHMWPE fiber addition on the mechanical properties of various wood composites were investigated.

EXPERIMENTAL

Materials and Equipment

Sawn *Betula costata* timber with a moisture content of around 10 was collected from the Mount MaoEr experimental forest farm of Northeast Forestry University. Specimens of 3-mm *Populus ussuriensis* veneer, also of around 10% moisture content were obtained from Xuzhou Shenghe Wood Co., Ltd.. UHMWPE fiber (600d/276f, filament number 1~5d) was obtained from the Special Fiber Technology Development Co., Ltd.. Polyurethane resin (PUR, 2000-5000 Mpa.s) was offered by the Harbin Chengfeng Adhesive Co., Ltd..

Testing was carried out using a small, self-made cold press, UTM-1T-PL. The IR 560 Fourier Transform infrared spectrometer used in this experiment was purchased from the Nicolet Company, USA.

Bending Test

When wood is bent under a transverse load, the convex direction is under a tensile stress and typically breaks first. In order to explore the feasibility of using UHMWPE fiber to enhance wood and to investigate the effects of filaments and PUR on the bonding properties, layers of wood composite materials of the planed lumber-UHMWPE-Veneer structure were prepared. Filaments were prestressed to reach a state of tension in order to realize their role as a strength enhancer before loading. As shown in Fig. 1, UHMWPE fiber was placed between planed and lumber veneers under pressure. The filaments were therefore in a state of equilibrium stress when loading was done.

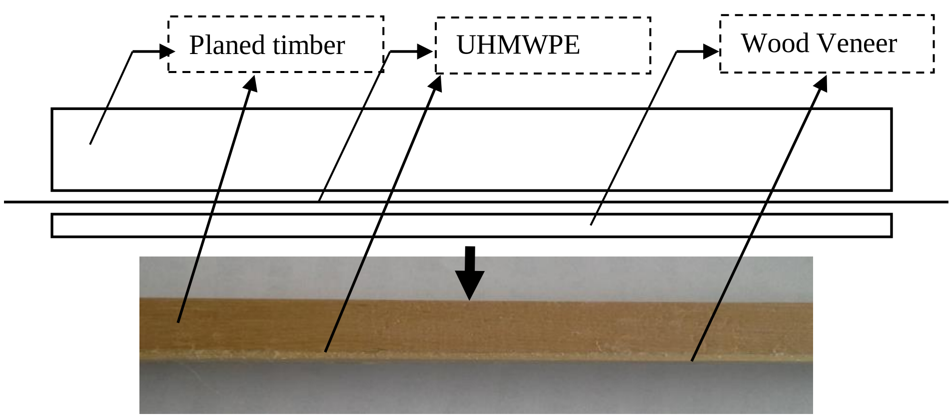

Fig. 1. Diagram of the three layers of the composite structure

The bonding pressure was 10 kgF/cm^2 and curing time was 4 h under adhesive content of $250g/m^2$ and a constant pressure. The sample was allowed to cure for 7 d after the pressure was relieved.

When wood is subjected to a flexural load, the part closer to the convex curved vertex experiences a bigger tensile force and can easily be destroyed. Thus, the thickness of the veneer impacts the reinforcing effect of UHMWPE fibers. In order to compare the effects of different veneer thicknesses and to improve the structure of the composite, a planing treatment was carried out on one side of each of the three layers of compound veneer. The obtained thickness was 1 mm, and samples of these were labelled as type II. The veneer specimen without planing was labelled as type I. The common specimen without UHMWPE fibers was designated as a control for comparisons. The reinforcing effect of UHMWPE fiber would be observed before the wood sustained damage. In order to avoid damaging the wood before the fiber provided any reinforcing effects, the thickness of the specimen was decreased, and a measure was taken to increase the span to improve the bending deflection of the specimen. According to GBT1936.1-2009, the cross-sectional size of the specimen was 20 mm×14 mm (width×thickness), with a span of 290 mm.

Tensile Testing

The tensile strength, tensile fracture strain, and effective bond distance of composites are the factors enhanced by UHMWPE fiber addition. In order to investigate the effect of the effective bond length of UHMWPE fiber in this composite structure, the specimens used for tensile testing were made according to Fig. 2. Each fiber bundle contained approximately 70 fibers. To ensure that the filaments were in a state of tension, a certain pre-stress was added before loading.

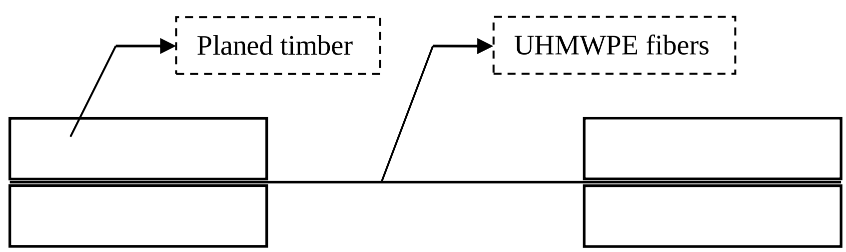

Fig. 2. Diagram of extending specimen

The size of each piece of planed lumber was 20 mm×5 mm. The length of the left side was 60 mm. To measure the effective bond length, the length of the right side was set to 11, 17, 31, and 60 mm, respectively. Gluing, curing, and maintenance parameters were the same as in bending test specimen, with a tensile speed of 10 mm/min.

Shear Resistance Test

The damage rate of wood and the shear strength are two important indices when evaluating the influence of UHMWPE fiber on the bonding interface conditions. Evaluations were made according to changes in the shear resistance performance of the agglutination interface. Specimens were made and tested according to the structural, glued, laminated timber testing standard JAS112-2006. The gluing, curing, and maintenance parameters were the same as in bending test specimen, with a shear speed of 5 mm/min.

FTIR Analysis

Using the KBr method, samples of debonded UHMWPE fiber and untreated fiber were separately made. Infrared analysis was then carried out *via* the application of a Nicolet 560 spectrometer (Nicolet Co., USA). The chemical constitutions of the debonded UHMWPE and common fiber were characterized by a Fourier transform infrared spectrometer (FTIR) with a resolution of 4 cm^{-1} and a scan index of 32.

RESULTS AND DISCUSSION

The Effect of added UHMWPE Fiber on the Bending Performance

The effect of added UHMWPE fiber on the bending load and the destruction behavior are shown in Table 1. According to calculations, the bending load of specimens I and II increased by 18.2% and 34.4% compared to the control specimen, respectively. It was shown that the ability of the wood to resist bending load increased after it was reinforced by UHMWPE fiber. This shows that UHMWPE fiber can also be used to further enhance wood after carbon fiber and aramid fiber are added. These results show potential for more significant application of UHMWPE fiber in wood materials. The effect of added UHMWPE fiber was more obvious in Specimen II, because the thickness of the veneer in the structures was an important factor affecting the load-bearing capacity. Reducing veneer thickness is one of the key factors in improving the effect of UHMWPE fiber.

Table 1. Bending Performance of Three Kinds of Specimens

Type	Bending load			Deflection		
	Mean value / N	Standard deviation / N	Coefficient of variation /%	Mean value / mm	Standard deviation / mm	Coefficient of variation /%
Control Specimen	1417	124.63	8.80	12.18	3.26	26.76
Specimen Ⅰ	1676	112.85	6.73	13.5	1.60	11.85
Specimen Ⅱ	1819	111.43	6.12	17.7	1.92	10.85

Note: each test was repeated by using 15 specimens.

As shown in Fig. 3, after reaching the maximum strength, the bending load-deflection curve of the control specimen declined immediately. This occurred at only a third of the maximum bending load, indicating that the control lumber would not be suitable for such an application. The curves of specimens I and II are “peak of arc shape” after changing bending load deflection curve model (Karbhari *et al.* 1997). And the bending load gradually declined after reaching the maximum strength. When the bending deflection was several times than that of the control specimen, the remaining bending load was also half of the maximum strength. Specimens I and II had the characteristics of ideal structural materials, such as they had high modulus at the beginning of loading, and they achieved high limiting strength. Then the specimens continued to carry load with further increases in strain, up to the point of breakage. The interfacial bonding between

UHMWPE fiber, PUR, and wood fibers is relatively ideal, which may present a certain hybrid effect (Tissington *et al.* 1991; Li *et al.* 1999). The inclusion of UHMWPE fiber not only improved the bending properties of composites, but it also significantly improved the bending deflection (Fig. 3). Damage bending deflection measurement results of three specimens showed increases for specimens I and II by 8.3% and 50%, respectively, compared to the control specimen. This showed that the wood fracture toughness and the ability to absorb damage energy had been improved; thereby the damage of the wooden parts had been delayed significantly, and the bending properties of the wood had been improved.

Compared to material without UHMWPE fiber, the wood composite materials with three layers of structure (planed lumber-UHMWPE fiber-Veneer) are expected to be safer, and they can provide more time for the person in an earthquake disaster region to escape, and they can also provide reference for load-bearing materials to be used in the earthquake-resistant buildings.

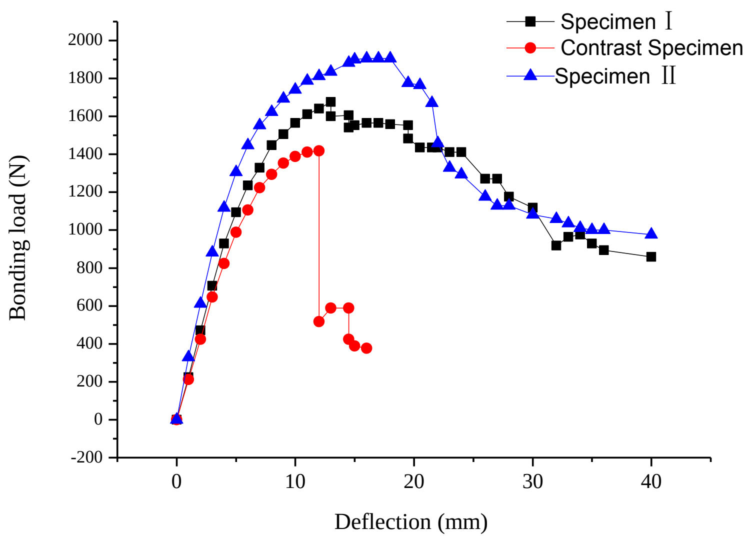

Fig. 3. Bending load-deflection curves of three specimens

The Effect of added UHMWPE Fiber on the Tensile Strength

The effects of bonding length of UHMWPE fiber on the tensile strength were investigated, and the results show that the bonding strength between the fiber and wood was related to the bonding length. Within the scope of tensile strength, the friction of fiber bundle pulling out from the matrix also increased with the increase of the bonding distance. It was characterized by the increase of the cohesive force of the wood fiber bundles. When the bonding length exceeded the bearing tensile strength, fiber bundle fractured, and cohesive force no longer changed (Fig. 4). Within the scope of bearing tensile strength, there was a positive correlation of cohesive force and adhesive distance. The coefficient of determination (R^2) for the fitting was 0.98, as shown in Eq. (1),

$$Y = 5.8X + 48.5 \ (R^2 = 0.98) \quad (1)$$

where *Y* was tensile load (N), and *X* was debonding length (mm). Based on this relationship the effective distance of fiber and timber was calculated to be 45 mm.

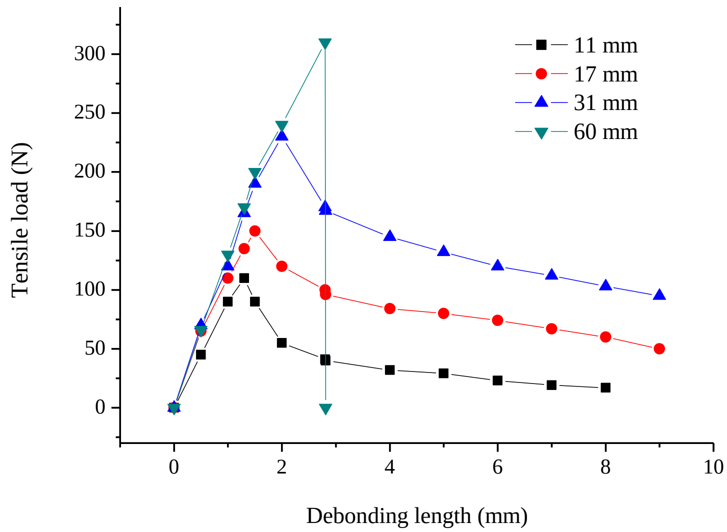

Fig. 4. Tensile load-debonding length curves

As shown in Fig. 4, with the increase of tensile load, UHMWPE fiber exhibited some tensile creep strain, which increased with the debonding distance (Fig. 4). This may have been related to the creep deformation of UHMWPE fiber. As the damaging energy of bonding interface increased, the creep and displacement of UHMWPE fiber increased, until the tensile load reached the maximum value.

The problem was that the poor bonding performance of UHMWPE fiber could not be fully solved by the use of PUR as the matrix. But the cohesive force could be increased by increasing the bonding distance. This provides a train of thought for solving the problem of UHMWPE fiber bonding and the application of UHMWPE fiber in the field of enhanced wood composite materials.

The Effect of Added UHMWPE Fiber on the Shear Resistance of the Bonding Interface

The average shear strength of the specimens without UHMWPE fiber bundle was 13.6 MPa, but the average shear strength of the specimens with UHMWPE fiber bundle was 8.8 MPa, which represents a decrease of 35% in comparison with the former. The average rate of breakage of the specimens with UHMWPE fiber was only 20%, and its broken area was outside of the fiber gathered area (Fig. 5b). This was completely different from the control specimen, which exhibited a continuous destruction form (Fig. 5a), and the average rate of breakage of the control specimen was over 50%. The presence of the UHMWPE fiber influenced the bonding performance between the wood layers because the fiber bundle fiber occupies a certain agglutination area or even increases the thickness of the rubber-like intermediate layer, combined with the surface of the UHMWPE fiber. This gives weaker adhesion performance (Zhamu *et al.* 2007), which renders the bonding performance of the region lower than that of the native wood.

So it is important for the shear strength to select a reasonable extent of fiber bundle structure and the density of fiber bundle layering.

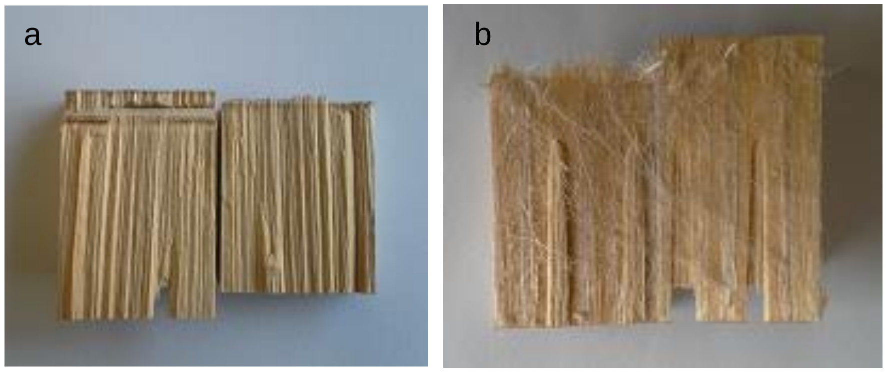

Fig. 5. Image of (a) the control specimen and (b) the fiber reinforced specimen

FTIR Analysis

As shown in Fig. 6, compared with the UHMWPE fiber without any treatment (Fig. 6a), in the spectrum of the debonded UHMWPE fiber (Fig. 6b), there were new bands at 1595, 1409, 1510, 1233, and 1305 cm^{-1}, all of which had obvious peaks. Those were attributed to -NH bending vibration, -C-N- stretching vibration, -COOH stretching vibration/bending vibration, and -O-C(O)- stretching vibration, respectively. The bands at 1409 and 1305 cm^{-1} are the characteristic absorption peaks of polyurethane (Park and Jin 2001). The bands at 1595, 1510, and 1233 cm^{-1} are the characteristic absorption peaks of lignin in wood. The FTIR analysis shows that some wood and PUR were pulled out together with the debonded UHMWPE fibers. It is indicated that PUR can bond UHMWPE fibers with wood strongly, therefore, it is important for UHMWPE fibers to reinforce wood.

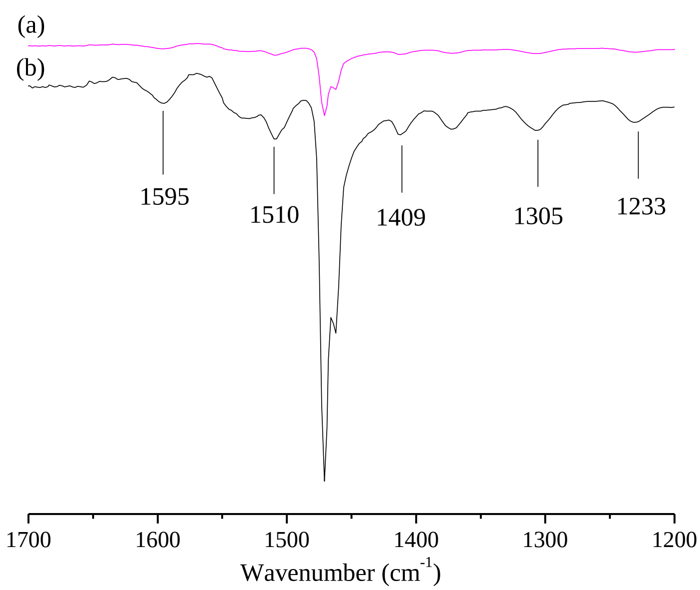

Fig. 6. FTIR spectra of (a) untreated fiber and (b) debonded fiber

CONCLUSIONS

A three-layer structure of wood composite material was successfully prepared from planed lumber, UHMWPE, and wood veneer. According to flexural performance, tensile properties of UHMWPE fiber, agglutination interface shear resistance, and bond properties between PUR and UHMWPE fiber, the feasibility of using UHMWPE fiber as enhancement material for wood was investigated. The conclusions are summarized as follows:

1. Incorporation of aligned UHMWPE fiber into a layered wood structure was able to significantly improve the bending load and bending deflection of the composite.
2. Within the load-bearing strength of the fiber, there was a positive correlation between the tensile strength and bonding length of UHMWPE fiber.
3. UHMWPE fiber reinforcement could reduce the shear resistance within the bonding interface, which provides the basis for the further application of high-strength fiber in wood-based materials.
4. It was feasible to design a three-layer structure of “sawn timber-UHMWPE fiber-veneer”. In such a structure the UHMWPE fiber plays important role in the reinforcement of wood.
5. FTIR analysis was used to reveal information about the distribution of the polyurethane (PUR) adhesive on the UHMWPE fiber after breakage of the layered structure. Such results confirm that PUR is suitable for preparation of a composite of UHMWPE fibers and wood.

ACKNOWLEDGMENTS

The research was supported by the 111 Project from State Administration of Foreign Experts Affairs, the P.R. of China (no. B08016).

REFERENCES CITED

Dourado, N., Pereira, F. A. M., De Moura, M. F. S. F., and Morais, J. J. L. (2012). “Repairing wood beams under bending using carbon-epoxy composites,” *Engineering Structures* 34, 342-350.

Enomoto, I., Katsumura, Y., Kudo, H., and Sekiguchi, M. (2010). “The role of hydroperoxides as a precursor in the radiation-induced graft polymerization of methyl methacrylate to ultra-high molecular weight polyethylene,” *Radiation Physics and Chemistry* 79(6), 718-724.

Karbhari, V. M., Falzon, P. J., and Herzberg, I. (1997). “Energy absorption characteristics of hybrid braided composite tubes,” *Journal of composite materials* 31(12), 1164-1186.

Kusano, Y., Teodoru, S., and Hansen, C. M. (2011). “The physical and chemical properties of plasma treated ultra-high-molecular-weight polyethylene fibers,” *Surface and Coatings Technology* 205(8), 2793-2798.

Li, Y., Xian, X. J., Choy, C. L., Guo, M., and Zhang, Z. (1999). "Compressive and flexural behavior of ultra-high-modulus polyethylene fiber and carbon fiber hybrid composites," *Composites Science and Technology* 59(1), 13-18.

Li, Z., Zhang, W., Wang, X., Mai, Y., and Zhang, Y. (2011). "Surface modification of ultra high molecular weight polyethylene fibers via the sequential photoinduced graft polymerization," *Applied Surface Science* 257(17), 7600-7608.

Ou, R., Zhao, H., Sui, S., Song, Y., and Wang, Q. (2010). "Reinforcing effects of Kevlar fiber on the mechanical properties of wood-flour/high-density-polyethylene composites," *Composites Part A: Applied Science and Manufacturing* 41(9), 1272-1278.

Park, S. J., and Jin, J. S. (2001). "Energetic studies on epoxy-polyurethane interpenetrating polymer networks," *Journal of Applied Polymer Science* 82(3), 775-780.

Park, S. J., and Jin, J. S. (2001). "Energetic studies on epoxy-polyurethane interpenetrating polymer networks," *Journal of Applied Polymer Science* 82(3), 775-780.

Tissington, B., Pollard, G., and Ward, I. M. (1991). "A study of the influence of fiber/resin adhesion on the mechanical behavior of ultra-high-modulus polyethylene fiber composites," *Journal Materials Science* 26, 82-92.

Trimble, B. S. (1999). "Durability and mode-I fracture of fiber-reinforced plastic (FRP)/wood interface bond," Doctoral dissertation, West Virginia University.

Valenza, A., Visco, A. M., Torrisi, L., and Campo, N. (2004). "Characterization of ultra-high-molecular-weight polyethylene (UHMWPE) modified by ion implantation," *Polymer* 45(5), 1707-1715.

Zhamu, A., Wingert, M., Jana, S., Zhong, W. H., and Stone, J. J. (2007). "Treatment of functionalized graphitic nanofibers (GNFs) and the adhesion of GNFs-reinforced-epoxy with ultra high molecular weight polyethylene fiber," *Composites Part A: Applied Science and Manufacturing* 38(3), 699-709.

Ziaee, S., and Palmese, G. R. (1999). "Effects of temperature on cure kinetics and mechanical properties of vinyl-ester resins," *Journal of Polymer Science Part B: Polymer Physics* 37(7), 725-744.

Article submitted: January 24, 2014; Peer review completed: August 9, 2014; Revised version received and accepted: August 23, 2014; Published: September 12, 2014.