COMPRESSIVE MECHANICS AND FAILURE MECHANISM FOR UHMWPE FIBER REINFORCED COMPOSITE LAMINATES UNDER HYGROTHERMAL ENVIRONMENT

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Keywords: UHMWPE composite, Hygrothermal aging, SHPB

ABSTRACT

Quasi-static and high strain rate compressive mechanics and failure behaviors of hygrothermal treated ultra-high molecular weight polyethylene (UHMWPE)/polyurethane composite were studied in this paper. Firstly, the UHMWPE composites were treated under hygrothermal environment for 12 days and 24 days. The out-of-plane compressions were then performed on the dry/wet state specimens at quasi-static states (0.001/s) and high strain rate states (1000-3000/s). The split Hopkinson pressure bar (SHPB) was adopted in the dynamic tests. Stress balance at both ends of the specimen was verified and waveform shapers were used to smooth and control the incident pulse. Failure modes of specimens conducted at quasi-static compression and dynamic compression were found to be different. Results show that the out-of-plane compressive stress of UHMWPE composites has strain rate sensitivity at high strain rate. The hygrothermal treatment improves the high strain rate peak stress while decreases the quasi-static compressive strength.

1 INTRODUCTION

In recent years, ultra-high molecular weight polyethylene (UHMWPE) fiber reinforced composite materials are increasingly used in weapon equipment and security fields. UHMWPE fibers were first developed around the 1970s. It has high oriented straight chain structure, small density and good chemical and weather resistance. UHMWPE composites, with small density and excellent anti-ballistic performance, are gaining more researches on its mechanical and ballistic properties[1-4].

Many efforts have been made to investigate the compressive behavior of the UHMWPE composite[5-11]. J.P. Attwood[5] has studied the quasi-static out-of-plane compression properties of six grades UHMWPE composites. Compressive strength was found to be dictated by fiber tensile fracture because of the existence of "shear-lag". M.R. O'Masta[6] identified two classes of defect of the [0/90] UHMWPE composite. The split Hopkinson pressure bar (SHPB) was usually used to study the dynamic behavior of fiber/matrix composites[7-11]. Khubab Shaker[10] investigated the high strain rate compression properties of Dyneema H62, Dyneema H5T and UHMWPE/aramid hybrid composite. Peak stress of the composite was found to increase with higher strain rate and UHMWPE/aramid hybrid composites had better energy absorption properties than the pure UHMWPE composites. The energy absorption properties of composite materials were also affected by material density and panel thickness. SHI[11] studied the dynamic energy absorption of three kind of ply-angle UHMWPE composite, and found that laminated angle had little effects on the dynamic energy absorption at higher strain rates.

Some researchers have studied the moisture and temperature effects on the dynamic compression properties of resin matrix composites[12-14]. Woldesenbet[12] studied the moisture effects on the high strain rate compression of IM7/8551-7 graphite/epoxy composite. They concluded two factors that affected the performance of the material due to moisture absorption: the matrix plasticization and the fiber / matrix delamination. A. HAQUE[13] investigated the effects of moisture and temperature on 2-Glass–Vinyl Ester Woven Composites. It was found that the compression failure strengths at high strain rates decreased under both moisture and high temperature. Matrix cracking was the main failure mode. S.N. Wosu[14] studied the effects of moisture, temperature and the combination of these two factors on the IM7/8551-7 graphite/epoxy composite. They found that the combined effect on the damage process was more apparent.

In this paper, the effects of hygrothermal treatment on the out-of-plane compressive behaviors of UHMWPE composites were investigated. Both quasi-static compression and high strain rate compression were conducted by a MTS machine and a SHPB facility, respectively. Moisture absorption and its effects on the composite compressive properties were studied.

2 EXPERIMENTAL WORK

2.1 Materials and Specimen Geometry

The material studied in this paper was UHMWPE fiber reinforced composite. UHMWPE fibers, coated with polyurethane, were stacked by 0/90 and then kept at pressure of 15MPa, temperature below120 ℃ for about 30 minutes. Each ply had a thickness of about 0.13mm and the mass fraction of the polyurethane matrix was about 15%. The quasi-static compressive specimens of 10 × 10 × 10mm cubes, and the dynamic compressive specimens of $\Phi \times h$ = 12 × 4mm cylinders were cut from a UHMWPE fiber laminated plate of 10mm thickness by water-jet method. For the dynamic compressive specimens, Φ was the in-plane direction while h was the through thickness direction. The basic material description is listed in Table1.

Composite Density	Resin Mass Fraction	Ply Thickness	T_g	Tension Strength	Tension Modulus	Short-beam Shear Strength
0.95g/cm^3	0.1-0.15	0.13±0.02mm	118 ℃	541MPa	28.5GPa	6.65MPa

Table 1 Material description of the $[0/90]_n$ UHMWPE/ polyurethane composites

2.2 Environmental Conditioning

Specimens were firstly kept in a heating oven to reach the engineering dry condition until the daily mass loss less than 0.02%. Heating temperature was set at 50 ℃ which is below the composite glass transition temperature T_g = 118 ℃. Subsequently, the dry specimens were put in a beaker of distilled water and the beaker was at kept in a 70 ℃ water bath for 24 days. Five specimens were numbered and taken out regularly for weighing using an OHAUS analytical balance. Wet, hot specimens were cooled for a short time to reach the room temperature and surface water was removed before weighing. Moisture absorption rate of the composite under hygrothermal environment is calculated according to formula (1)

$$W_t = \frac{M_t - M_0}{M_0} \times 100 \tag{1}$$

where, W_t, M_t and M_0 represent the moisture absorption rate, weight of the hygrothermal treated specimens and weight of the dry specimens, respectively. Average moisture absorption rate of the numbered five specimens was regarded as the moisture absorption rate of the UHMWPE composite.

2.3 Compressive Experiments

Both quasi-static compression and dynamic compression were conducted for the UHMWPE composite in out-of-plane direction. The quasi-static compressive tests were carried out on an MTS E45 testing machine at strain rate 0.001/s. Cross head displacement of the machine was recorded for strain calculation and normal stress σ_n and normal strain ε_n were calculated for analysis. The high strain rate dynamic compressive tests were carried out on a split Hopkinson pressure bar (SHPB) experimental facility in Ship Structure and Strength Laboratory of Naval University of Engineering. Schematic of the SHPB equipment is shown in Fig. 1. The material of the SHPB facility bars are 60Si2Mn and had density of 7850 kg/m^3, elastic modulus of 206GPa. The 20 mm-diameter striking, incident and transmission bar had lengths of 300, 2000 and 1500mm, respectively. Bar wave velocity $c = \sqrt{E/\rho}$ = 5123m/s was verified by experiments. Strain gauges with sensitivity of 2.13 were attached to the incident and transmission bar. Lengths of the strain gauges to the specimen/bar contact surfaces were approximately 1000 and 745 mm for gauges on the incident bar and transmission bar, respectively. The strain signals were measured using a DH5960 dynamic strain tester (sampling rate 20MHz) by half bridge connection to the strain gauges. During the test, the speed of the bullet was controlled by adjusting the driving pressure in the range of 0.2 - 0.45MPa. Annealed copper disks with thickness of 1mm and diameters ranging from 8 – 14mm were used to smooth and control the incident pulse[15,16]. Molybdenum disulfide was used at the specimen/bar contact surface to reduce the friction. At least three dry specimens and three wet specimens were carried out respectively for each driving pressure.

The SHPB experiment is based on the no-dispersion one-dimensional stress wave theory and dynamic stress equilibrium assumption in the specimen. A parameter R was considered to evaluate the stress equilibrium[17]

$$R(t)=\left|\frac{\Delta\sigma(t)}{\sigma_{avg}(t)}\right|=2\left|\frac{F_1-F_2}{F_1+F_2}\right| \tag{2}$$

where, F_1, F_2 represent the specimen axial force history in the incident bar/specimen end and transmission bar/specimen end, respectively, and can be calculate according to formula(3)

$$\begin{aligned} F_1 &= AE(\varepsilon_i+\varepsilon_r) \\ F_2 &= AE\varepsilon_t \end{aligned} \tag{3}$$

Fig. 2 shows a typical pulse received from the incident bar and transmission bar and the equilibrium parameter calculated according to formula(2), indicating that the specimen was in dynamic stress equilibrium from 5-130μs. Thus, the strain rate, engineering strain and engineering stress of the specimen can be calculated according to formula(4)

$$\begin{aligned} \dot{\varepsilon}(t) &= \frac{2c_0}{L}\varepsilon_r(t) \\ \varepsilon(t) &= \frac{2c_0}{L}\int_0^t \varepsilon_r(t)d\tau \\ \sigma(t) &= \frac{S_BE}{S_s}\varepsilon_t(t) \end{aligned} \tag{4}$$

where, c_0 is the longitudinal wave velocity in the bar, S_B, E are the cross sectional area and elastic modulus of the bar, L and S_S are the length and cross sectional area of the specimen.

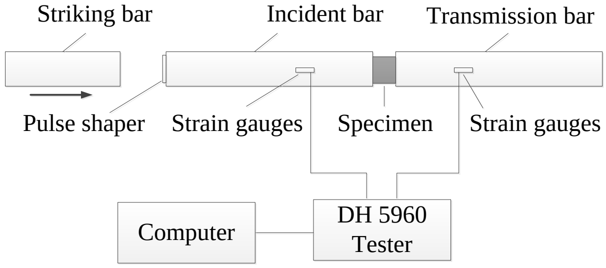
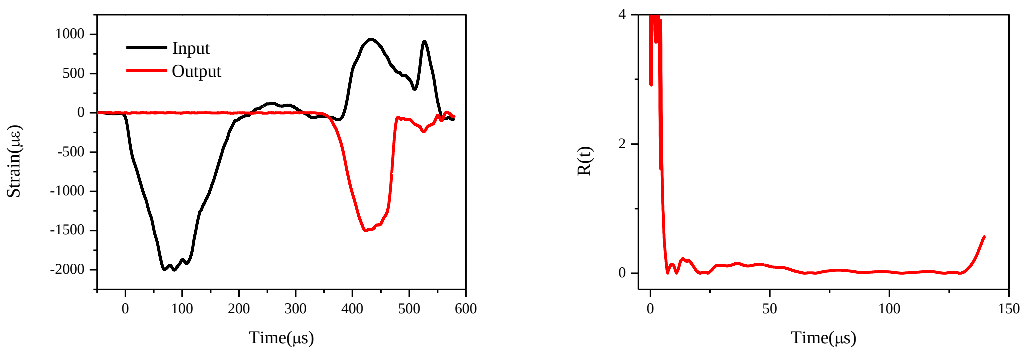


Fig. 1 Schematic of the SHPB equipment



(a) (b)

Fig. 2 (a) A typical pulse received from the incident bar and transmission bar and (b)Force equilibrium parameter in the specimen

3 RESULTS AND DISCUSSIONS

3.1 Moisture Absorption

Moisture absorption rate of the hygrothermal treated UHMWPE material is shown in Fig. 3.The moisture absorption rate rises proportionally to the square root of the time initially and then reaches two plateaus of 1.92% and 2.47% at the day 6 and the day 12, respectively. The moisture absorption process may be explained as follows. Moisture firstly diffused through the composite matrix and occupied the inner defects, reaching the first plateau. Then the inconsistent swelling of the fibers and matrix caused cracks in the fiber/matrix interface and the original cracks expanded as well. Moisture diffused into these cracks and then reached the second plateau.

The DMA tests results of the dry and 24 days hygrothermal treated UHMWPE composites (labled as wet 24 days) are shown in Fig. 4. Hygrothermal treatment seems to decrease the storage modulus and to decrease the glass transition temperature T_g from 118 ℃ to about 115 ℃ (peak tan delta values). The decrease of T_g may indicate the plasticization of the specimen matrix because plasticization usually degrades the glass transition temperature[18,19]. Plasticization also leads to lower buckling stress of composite materials and this is consistent with the quasi-static compression results described later.

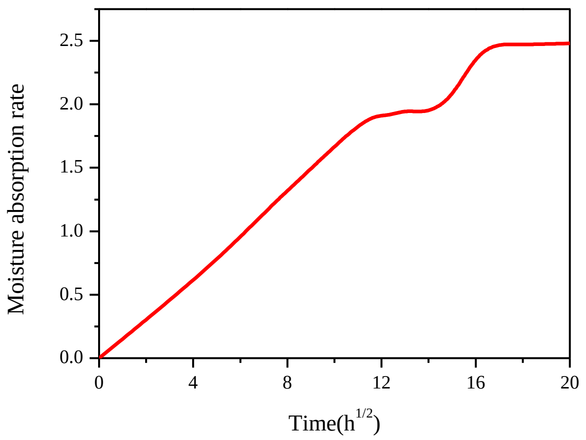


Fig. 3 Moisture absorption curve of the hygrothermal treated specimens

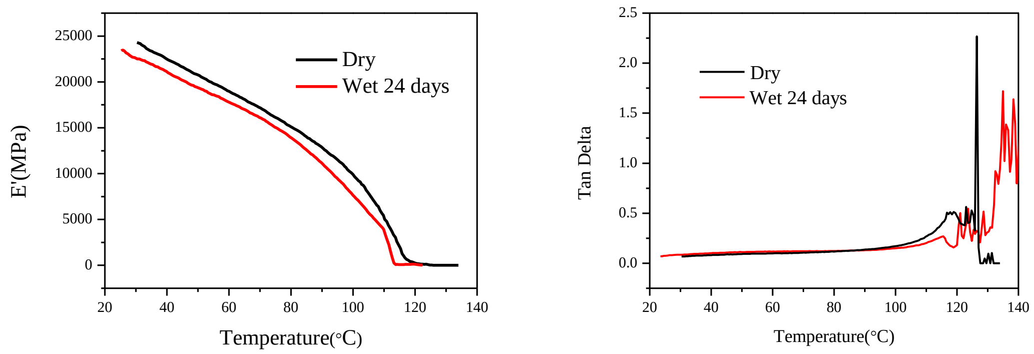


Fig. 4 DMA tests results of the dry/24 days wet specimens

3.2 Quasi-static compression

The out-of-plain quasi-static compressions at strain rate 0.001/s were conducted on the virgin dry samples and 24 days hygrothermal treated samples. The typical compressive stress-strain curves are shown in Fig. 5. Stress had initially increased nonlinearly with strain before 0.15 and then increased linearly until a catastrophic failure occurred with a very loud burst sound and fractured plies ejecting from the edges of the samples. Fibres extruding out transverse to the local fibre direction can be seen over the four side faces of the samples, as shown in Fig. 6. Hygrothermal treatment decreased the compressive strength by about 5% while the compressive modulus remained 4.6GPa.

Attwood[5] and O'Masta[6] have studied the out-of-plane compression behaviour of Dyneema UHMWPE composites. The existence of shear-lag zone was proved at the periphery of specimens. During the quasi-static compression, shear-lag generates tensile stresses along the fibre direction between each 0 ° and 90 ° plies. Lower matrix shear strength, and void-like defects resulting from missing groups of fibres, could degrade the out-of-plane compressive strength[5,6]. The degradation effects of the hygrothermal treatment on compressive strength in our tests thus can be explained as follows. Water absorption usually causes plasticization of the composite matrix, inconsistent swell of matrix and fibres, and expansion of the inner voids. The lower matrix quasi-static shear strength caused by plasticization decreases the compressive strength. Fibre/matrix interface degradation and inner voids expansion also have the same effects on the compressive strength.

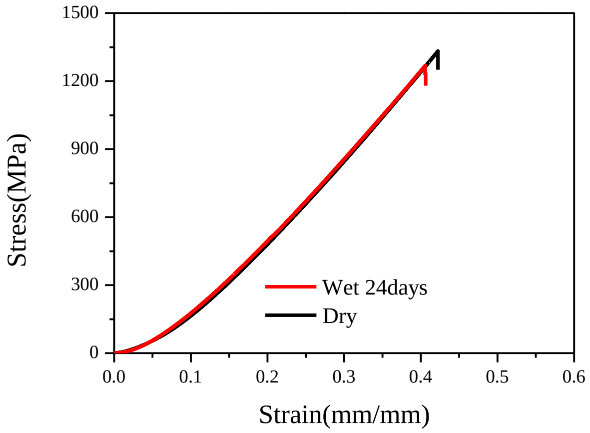


Fig. 5 Quasi-static stress-strain curves of dry/wet composite

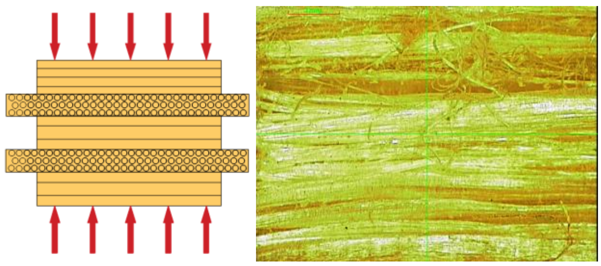


Fig. 6 Optical micrograph of the quasi-static compression specimen

3.3 Dynamic compression

High strain rate compressions were conducted on the virgin dry samples, 12days and 24 days hygrothermal treated samples, respectively. Stress-strain curves of the 12 days hygrothermal treated samples at strain rate 1110/s, 1450/s and 2040/s are shown in Fig. 7. The stress increases with strain until reaching the maximum stress and strain softening occurs at higher strain. Stress plateau was found around the maximum stress for the 2040/s curve. The strain softening and stress plateau may indicate the compression-induced damage such as matrix cracking and delamination[7]. The inner defects and striking-induced damages can not be extended immediately, resulting in the lager loading capacity and striking energy absorption capacity. Thus, maximum stress increases with higher strain rate.

The failure modes of UHMWPE composite at high strain rate compression were quite different from the failure modes of its quasi-static compression, as shown in Fig. 8. Firstly, for specimens conducted around strain rate 1100/s, several layers close to the incident bar delaminated (Fig. 8 (a)).

As strain rate increases, the outer region of the delaminated layers warped up outwards the surface and some fibres and matrix were missing (Fig. 8 (b)). Finally, the periphery delaminated fibres were carbonized and missed at strain rate 2040/s (Fig. 8 (c)). During the high strain rate compression, a small amount of fractured fibres were ejected out from the front delaminated plies and this was inconsistent with the phenomena observed in quasi-static compression, as shown in Fig. 9. High strain rate compression is a transient process during which a large amount of energy is transferred to the specimen, resulting in a temperature rise in the specimens[7]. The outer delaminated fibres will be fractured and carbonized at higher strain rate, resulting in different damage patterns of the specimens.

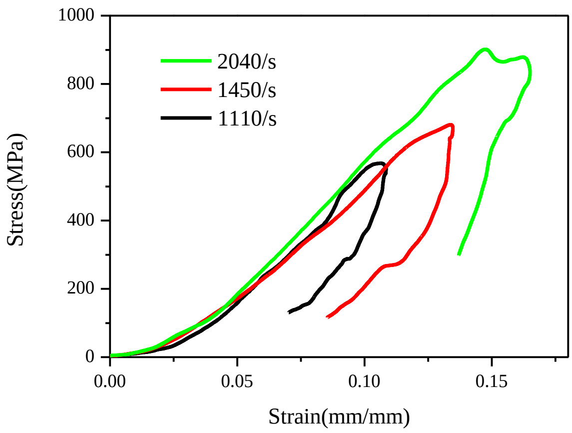
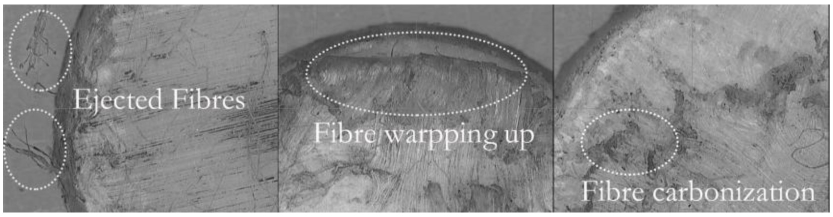
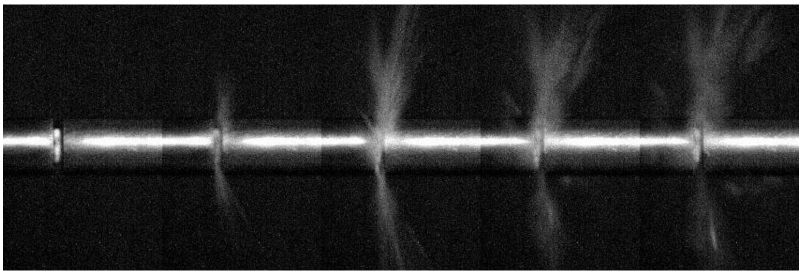


Fig. 7 Stress-strain curves of the 12 days hygrothermal treated specimens



(a) (b) (c)

Fig. 8 Optical micrographs of compressive samples at strain rate (a) 1100/s, (b) 1500/s, (c) 2100/s



0.167ms 0.334ms 0.501ms 0.668ms 0.835ms

Fig. 9 The high speed images of specimens at strain rate 1700/s

The compressive stress-strain curves of both dry and wet specimens at dynamic strain rate around 1700/s and 2700/s are shown in Fig. 10. Hygrothermal treatment improves the maximum stress (wet 12 days) and then decreases the maximum stress (wet 24 days) while the corresponding strain were degraded firstly and then improved. The strain softening effects was degraded and then upgraded as well. Fig. 11 shows the maximum stress-strain rate curves of the both dry and wet specimens. Twelve days hygrothermal treatment increased the maximum stress and the improvement was declined in 24 days treatment especially at high strain rate above 2000/s. The fit curves of the maximum stress as a function of strain rate are as follows:

$$
\begin{aligned}
&y = 1455.20756 - 1629.41416 * 0.099943^x && \text{Wet 12 days} \\
&y = 1001.18273 - 2815.61207 * 0.99847^x && \text{Wet 24 days} \\
&y = 865.28809 - 14155.82338 * 0.99693^x && \text{Dry}
\end{aligned}
\tag{5}
$$

The matrix plays an important role in the out-of-plane compression and plasticization of the matrix improves the high strain rate compressive properties while fibre/matrix interface degradation and voids expansion degrades the compressive properties[12]. For the 12 days hygrothermal treated specimens, the effects of plasticization dominate the compressive properties and thus improve the maximum stresses. However, under the treatment of moisture and long-term high temperature, the degradation of fibre/matrix interface and expansion of the inner voids dominates the dynamic compressive properties for 24 days treated specimens. The dynamic compressive properties were then degraded while still stronger than the virgin dry specimens.

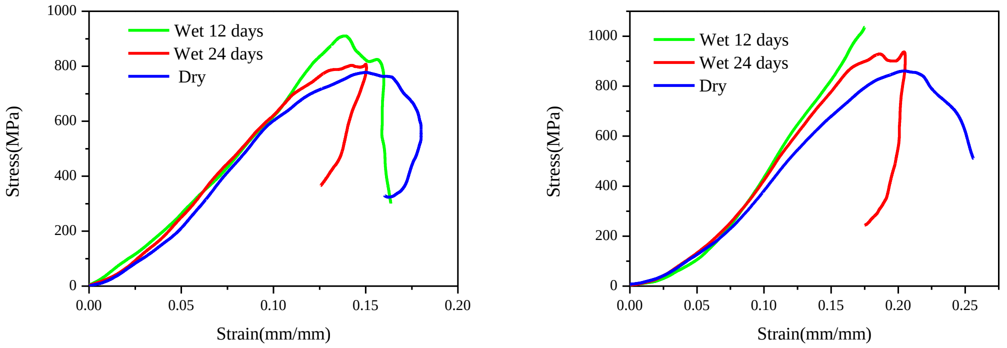


Fig. 10 (a)Stress-strain curves at strain rate 1700/s (b) Stress-strain curves at strain rate 2700/s

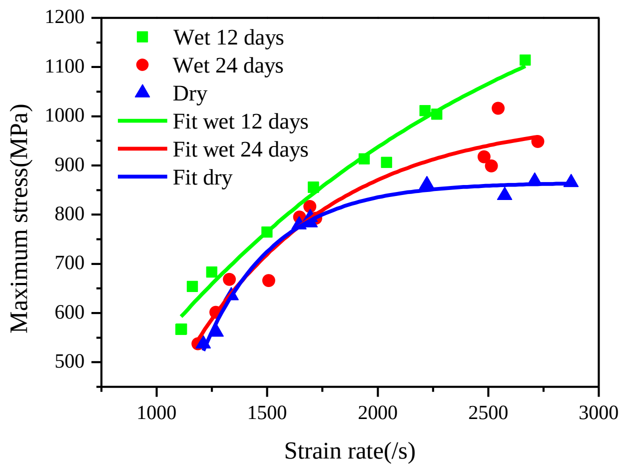


Fig. 11 Effects of hygrothermal treatment on the maximum stress of out-of-plain compression

4 CONCLUSIONS

Hygrothermal treatment reduces the T_g of UHMWPE/ polyurethane composites from 118 ℃ to 115 ℃. Two plateaus of the moisture absorption rate are observed due to the long-term effects of moisture and temperature. Hygrothermal treatment causes plasticization of the composite matrix, inconsistent swell of matrix and fibres, and expansion of the inner voids. Hygrothermal treatment for 24 days degrades the out-of-plane quasi-static compressive strength by 5% and maintains the compressive modulus. The dynamic out-of-plane compressive peak stresses are increased by the 12 days hygrothermal treatment and then degraded by the long-term 24 days treatment. Effects of the matrix plasticization dominate the dynamic compressive properties for the initial 12 days hygrothermal treatment while the fibre/matrix interface degradation and the inner voids expansion play more important roles in the long-term 24 days treatment.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the National Ministries Fund for funding this research.

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