UHMWPE Composites Dynamic Property Variation Due to Moisture Ingress and Egress

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Abstract. Ultra-High-Molecular-Weight-Polyethylene (UHMWPE) fibre based composites are extensively used for armour applications. UHMWPE composites are usually processed under optimized conditions. However, the effect of ageing and in particular exposure to environmental moisture may deteriorate the performance of an armour. This study is conducted to understand the dynamic compressive behaviour of three different specimens of UHMWPE composite. Further, the objective of the study is to understand the relative change in the rate-dependent properties of UHMWPE composite as a function of moisture ingress and egress as compared to a fresh dry composite. UHMWPE composite laminate was compression moulded at 138 bar and cylindrical specimens were cut out from the laminate. Specimen types used for dynamic loading in a split Hopkinson pressure bar test were fresh dry, moist and dried specimens. The composite samples attained different strain rates under identical loading conditions as a function of moisture ingress and egress. Fresh dry composite achieved highest strain rates, stress and strain when compared to wet and dried composite. Dry specimens attained 42% and 29% higher stresses as compared to the wet and force dried specimen, respectively, indicating the importance of keeping UHMWPE composites away from moisture. Moisture egress enhanced dynamic performance by 18%. Although peak stress improved as a function of moisture egress, the loss in stress as compared to dry composite indicates an irrecoverable loss. The damage behaviour was identical in the form of delamination. However, the delamination initiates at a lower strain rate as a function of moisture ingress. Removal of moisture enhanced the composite properties but could not bring the performance of the composite equivalent to an initially dry composite, which indicates the need for the development of proper guidelines for the storage and usage of personal body armour.

1. INTRODUCTION

Defence and law enforcement personnel work in challenging environments. Particularly, extreme weather conditions add to the difficulties. Their fibre reinforced composite armours, vital to protecting against ballistic threats, also get subjected to those working environmental conditions. Generally, atmospheric temperature variation is within the acceptable range of polymer matrix properties, as far as their functionality for body armour applications is concerned. However, moisture concentration may vary the properties of the composite material system. Both polymers and fibres may interact with moisture at both macroscopic or microscopic level depending on their hydrophobic or hydrophilic nature. Moisture ingress at damage sites may lead to swelling or delamination, even in the case of hydrophobic composites [1][2].

UHMWPE fibre-reinforced polymer composites are the most widely used in personal body armour applications [3]. Thus, these composites are susceptible to temperature change, moisture and other liquid attacks. Water ingress is a major structural integrity degrading phenomenon for composite material. Allred and Roylance [4], studied Kevlar composite and reported a loss of 14%, 35% and 27% in stiffness, strength and elongation as a function of moisture ingress. The decline in properties was attributed to the degraded matrix and weakening of interface and tendency of fibre to fail as a function of moisture absorption. A similar loss in properties as a function of moisture is reported in the known literature for glass/epoxy, carbon/epoxy and kevlar/epoxy composites [5].

Mechanical response of UHMWPE fibre-reinforced composite materials is rate sensitive. Split-Hopkinson pressure bar (SHPB) is used to test materials under high strain rate load conditions. Thus, SHPB test becomes vital in determining the performance of UHMWPE composites [6]. Shaker et al. [7] tested UHMWPE fibre-reinforced polymer composites at strain-rates up to 8000 /s using the SHPB test.

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Authors determined that out-of-plane compressive strength was around 800 MPa. Zhu et al. [6] studied the effects of moisture absorption on out-of-plane compressive strength of UHMWPE composites at various strain rates. The moisture absorption decreased strength at both low and high strain rates. In another study on the effect of moisture ingress in UHMWPE composites, it was revealed that high strain rate performance of compression moulded UHMWPE composites diminishes along with lower rates of loading for identical incident impact energy [8].

Composite panel serving as a personal protection gear may encounter minor damage while in operations. These minor damage sites may allow moisture ingress and hence can be the cause of property deterioration. Though moisture ingress is bound to affect composite performance, egress of moisture may further complicate the scenario. Therefore, a systematic study is required to study the effect of water ingress and egress on high strain rate properties of UHMWPE fibre-reinforced composites. The UHMWPE composite specimens were kept in a potable water container, for 24 hours. The composite specimens were then tested in out-of-plane compression direction at high strain rates using a split Hopkinson pressure bar (SHPB) apparatus. To study the effect of moisture egress, composite specimens were oven-dried followed by high strain rate loading on SHPB. High strain rate compression tests were performed on three different sets of composite specimens derived from a single composite laminate. The three types of specimens tested under high strain rate loading were, fresh dry compression moulded UHMWPE composites, moisture ingressed and moisture egressed specimens. Dynamic properties including peak stress, peak strain and toughness were evaluated for all type of composite specimens.

2. EXPERIMENTS

2.1 Materials and Specimen

UHMWPE composite laminate was fabricated using a high-pressure compression moulding machine. 16 layers of a commercial grade of Spectra Shield (Grade: SR-3124, by Honeywell Inc., USA) were compression moulded at a pressure of 138 bar and 115 ˚C, respectively. The areal density of the resulting composite was 4.01 ksm. Cylindrical specimens having 10 mm diameter were cut from the flat composite laminate using rota broach machining.

Three different types of composite specimens were used for experimental works. After machining, first set of specimens was weighted on a digital weighing scale and then kept in an oven at 65 ˚C and 700 mm of Hg for 24 hours, to measure if there was any moisture in the specimen. The temperature could not be increased beyond 65 ˚C, as the UHMWPE fibre/matrix interface may degrade at further higher temperatures. There was no change in the specimen weight before and after oven drying, specifying initial moisture-free specimens, being moulded at 115 ˚C. This set of specimens was treated as dry specimen and the same is supposed to unveil the exact UHMWPE composite response. Another set of specimens was placed in potable water for 24 hours in a clean room with the top edge of the specimen at least 100 mm below the surface of the water and with at least 50 mm clearance around the specimen, at 21 ˚C. Wetting time was kept much higher than NIJ 0101.06 standard to expose the property loss as a function of moisture ingestion, whereas the rest of the protocol was kept in conjunction with NIJ standards [9]. The high strain rate testing was performed on the wet composite specimens within one hour of removal of specimens from the water container. Before testing, the specimens were wiped and weighed on a digital balance. This set of the specimen was used to evaluate the performance of moisture ingressed UHMWPE composite. Another set of wet samples was kept for drying in an oven at 65 ˚C and 700 mm of Hg for 24 hours. Drying in oven brought down the weight of composite specimens to their original weight. These dried specimens served as the third set of composite specimens. The motive of this study is to reveal the high strain rate behaviour of the composite under dynamic high strain rate loading, to mimic the real-life threat of ballistic impact. Study of dried specimens was also conducted to reveal the composite behaviour as a function of moisture removal.

2.2 Test setup

A split Hopkinson pressure bar (SHPB) setup was designed and developed in-house for the high strain compressive loading of composite specimens. The SHPB setup typically comprises of a gas propelled striker bar, an incident bar, transmission bar, a suitable momentum trap and a signal conditioner amplifier in association with a data acquisition system as shown in Figure 1. Key specifications of bar material used in SHPB apparatus are given in Table 1. The specimen is kept in between the flat ground surface of Titanium incident and transmission bar. The high strain rate loading is induced in the specimen as a function of the impact of striker bar onto the incident bar. The striker bar is propelled by Nitrogen gas pressure. A suitable pulse shaper, natural rubber (Linatex) in this case is placed in between the striker

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bar and incident bar to minimize high-frequency oscillations and to control the rise time of the incident pulse. The elastic stress wave travelling thorough the incident bar is picked up in the form of strain induced in the bar and is recorded by the strain gauge mounted at the mid-section of the bar. On reaching the incident bar/specimen interface, partially the stress wave is reflected and rest of the wave travels through the specimen into the transmission bar. The reflected and transmitted waves were recorded to give reflected and transmitted strains, respectively.

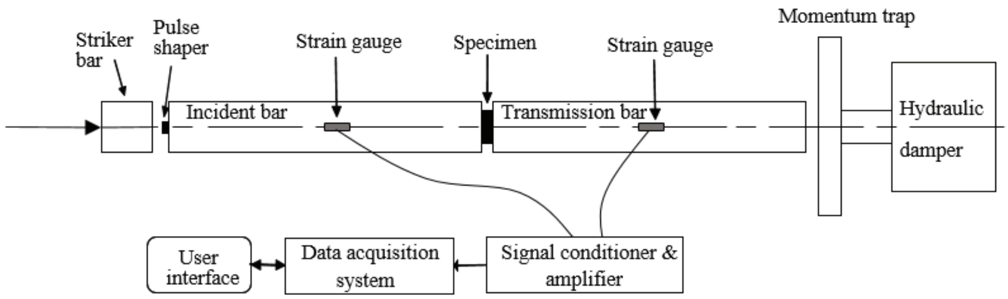

Figure 1. Basic arrangement of compressive split Hopkinson pressure bar test apparatus

One-dimensional wave propagation in elastic bars with particle motion in the longitudinal direction was used to establish the mathematical formulations of SHPB. Complete details of the one-dimensional wave propagation and necessary derivations are available in the known literature [10]. High strain rate properties of composite specimens including stress (σ), strain (ε) and strain rate ($\dot{\varepsilon}$) were calculated based on established one-dimensional propagation theory using the following equations,

$$\sigma = \frac{E_b A_b}{A_s} \varepsilon_t(t) \quad (1)$$

$$\varepsilon = \frac{-2C_e}{L_s} \int_0^t \varepsilon_r(t)dt \quad (2)$$

$$\dot{\varepsilon} = \frac{-2C_e}{L_s} \varepsilon_r(t) \quad (3)$$

where L_s is the length of the specimen, A_b and A_s are the cross-sectional area of the bar and specimen, E_b is the modulus of the bars, C_e is the wave velocity in the bar, $\varepsilon_r(t)$ is the reflected strain gauge signal and $\varepsilon_t(t)$ is the transmitted strain gauge signal.

Table 1. Specifications of SHPB Set-up

Bar properties	
Material	Titanium (Ti6Al4V)
Bar Diameter	16 mm
Striker length	240 mm
Incident bar length	1200 mm
Transmission bar length	1200 mm
Density	4430 kg/m3
Modulus of Elasticity	113.8 GPa
Elastic wave speed	5068 m/s

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3. RESULTS AND DISCUSSION

High strain rate testing was performed in out-of-plane compression direction on UHMWPE composites. Three different sets of composite specimens were machined out from a 300 x 300 mm laminate moulded at 138 bar. The three different types of composite specimens tested were, (i) dry, (ii) moisture ingressed, and (iii) moisture egressed, respectively. The freshly moulded composite specimens were kept in potable water for 24 hours. An average increase in the weight of wet specimens was 5.5%. Table 2 depicts the increment in weight of a composite sample as a function of residence in potable water for 24 hours. It may be noted that heating wet composite in an oven at 65 ˚C and 700 mm of Hg for 24 hours expelled all the moisture content and the resulting dried specimens attained the original weight.

Table 2. Weight of UHMWPE specimens as a function of moisture ingress and egress

S. No.	Dry (gms)	Wet (gms)	Dried (gms)
1.	0.3262	0.3441	0.3262
2.	0.3254	0.3422	0.3254
3.	0.3265	0.3446	0.3265
4.	0.3260	0.3444	0.3260
5.	0.3270	0.3452	0.3270
6.	0.3220	0.3400	0.3220

The Nitrogen gas pressure used for propelling the striker bar was varied from 0.5 – 3.0 bar, the resulting striker bar velocity were in the range of 19.7 – 42.5 m/s for dry composite specimens. The gas pressure were varied from 0.5 – 2.0 bar for moisture ingressed and egressed specimens, resulting in maximum striker bar velocity of 37 m/s. Owing to severe macroscopic damage of wet and dried specimens, the higher striker bar velocities were sidestepped.

3.1 High strain rate stress-strain response

Through-the-thickness dynamic compression tests were performed on dry UHMWPE composites within the strain rate regime of 2280 – 4770 /s. Figure 2 (a) unveils the rate-dependent performance of UHMWPE composites under consideration. The composite underwent an insignificant linear elastic region followed by non-linear elastic region till a strain of ~0.035 is attained. The non-linear elastic region was followed by inelastic plateau region, followed by gradual stress decay. This inelastic plateau is the beauty of UHMWPE fibre with a rubber-based matrix which gives the composite a better ballistic resistance, owing to its tendency to retain constant stress with growing strain. Increasing gas pressure from 0.5 – 2.5 bar only resulted in enhanced strain rates with higher peak stress and strain. For the strain rates from 2280 – 4650 /s, all the composite specimens were recovered macroscopically intact. The further higher gas pressure of 3.0 bar resulted in macroscopic damage of the UHMWPE specimen in the form of delamination. Associated with this high rate loading was the peak performance of the composite. Since the composite specimen delaminated at this rate of loading, therefore, there was no need to enhance the rates of loading further. Also, the strain rate of 4770 /s can be treated at limiting strain rate of loading, at which the first sign of macroscopic damage is noted.

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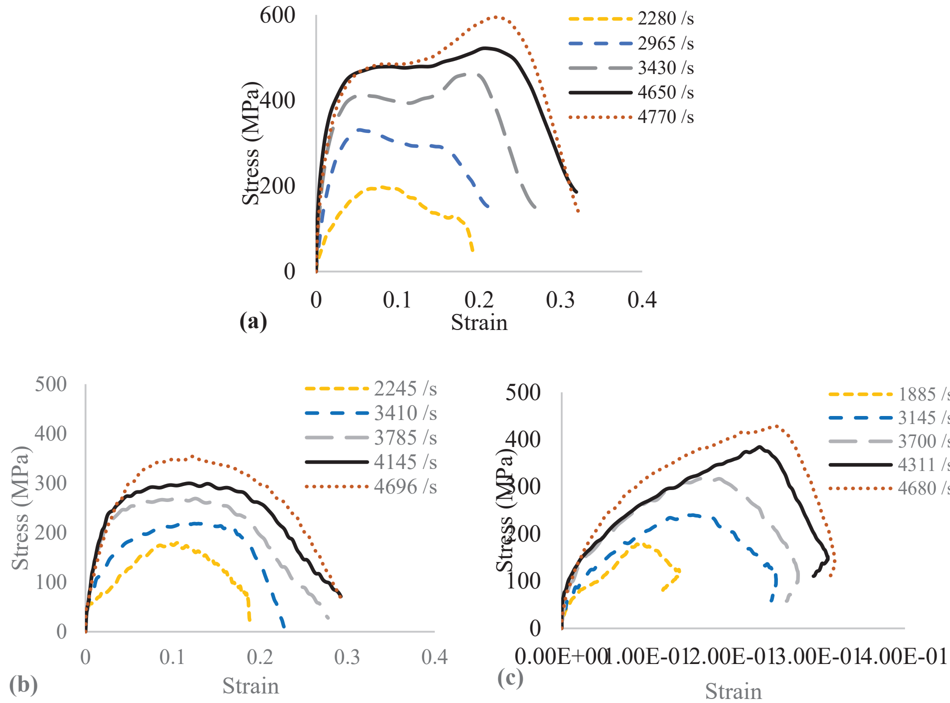

Figure 2. Dynamic stress-strain plots of UHMWPE composites (a) dry, (b) wet, and (c) dried

Figure 2 (b) depicts the high strain rate performance of UHMWPE composites after they were subjected to moisture exposure for 24 hours, resulting in a 5.5% weight gain. At the lowest rate of loading, the total specimen strain attained the values identical to dry specimens; however, the peak stress dropped by 20%, for these wet specimens. For very next rate of loading associated with a gas pressure of 0.8 bar resulting into strain rate of 3410/s, the composite specimen delaminated into two pieces. This early delamination of the specimen is attributed to the moisture residing in the voids and micro-cracks created during moulding and machining of the composite to get the test coupons. It is speculated that the moisture travelled to the interiors of the composite specimen by capillary action within micro-cracks and fibre-matrix interfaces. Reduction in the non-linear elastic stress growth was followed by lower peak stress for all the wet specimens under higher rates of loading. The plateau region shrunk on both ends, thereby decreasing the area under the stress-strain curve, responsible for governing the energy absorption capacity of the composite. This phenomenon of stress reduction is attributed to the plasticization of matrix material resulting in smooth ply movement due to reduced inter-laminar shear strength. However, insignificant loss of total strain is a unique phenomenon, as all other properties like peak stress, the slope of stress growth curve and the area under the stress-strain curve diminished. This unique phenomenon of attaining identical strain value is attributed to moisture expulsion induced deformation of the specimen. The peak stress attained by moist UHMWPE specimen was 353 MPa at a strain rate of 4696 /s. For identical loading conditions due to the gas pressure of 2 bar, a loss of 23% in stress is recorded for moisture ingressed UHMWPE composites.

The moist specimens were oven-dried and tested under identical dynamic loading conditions. Attainment of original specimen weight was a clear indicator of moisture removal from the composite specimens. However, loss in dynamic properties was expected as the space evacuated by moisture in the composite specimens is bound to serve as a site of void/local delamination. Figure 2 (c) shows the dynamic stress growth pattern of dried UHMWPE composite specimens as a function of increasing loading rates associated with a gas pressure of 0.5 – 2.0 bar. An entirely new pattern of the stress-strain curve under dynamic loading was revealed for moisture egressed specimens. All the specimens, irrespective of rates of loading revealed an inelastic stress growth until the stress maxima are attained. Interestingly, for the first time strain rate below 2000 /s was recorded for a gas pressure of 0.5 bar. The increasing rate of loading enhanced not only stress but also the strain to acquire peak stress kept rising. The strain required to attain peak stress increased from 0.1 to 0.25, as a function of rising rates of loading,

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which was limited to 0.035 in previous cases. The peak stress increased from 181 MPa to 428 MPa as strain rates enhanced from 1885 – 4680 /s, in case of the dried composite.

3.2 Comparison of high strain rate response of dry, moisture ingressed and moisture egressed composites

Dynamic stress-strain response of dry, moisture ingressed and moisture egressed UHMWPE composites specimens at the loading rates resulting in the first occurrence of physical damage is shown in Figure 3. Freshly moulded specimen attained highest rates of loading at 3 bar of Nitrogen gas pressure resulting in striker bar velocity of 42.5 m/s. Associated with the highest rate of loading were highest peak stress, strain and area under the stress-strain curve. Moisture ingressed specimens could only take striker bar energy associated with 0.5 bar of gas pressure (striker velocity 19.7 m/s) without any damage. Firing at a gas pressure of 0.8 bar (striker velocity 24.7 m/s) onwards resulted in physical damage of the wet specimen. Moisture ingress diminished not only the stress-strain behaviour but also the strain rate dropped due to early physical damage of the composite specimen. Drying by placing the moisture ingressed specimens inside the hot oven assisted in enhancing the performance of composite specimens. Total strain and strain rates for dried composite approached the values close to that of dry composite. However, removal of moisture could not restore all the properties of a composite.

When compared to moisture ingressed composite properties at the first instance of delamination, moisture removal enhanced peak stress, strain and strain rate by 90%, 30% and 37 %, respectively. However, as compared to a fresh dry compression moulded composite, the dynamic composite properties were found significantly lacking, as the peak stress and strain were 28% and 15% lesser for the dried composite specimen. Interestingly, the strain rate could attain the values in the close proximity as that of dry composite. This unique phenomenon of partial strength regain is attributed to moisture removal, but the larger voids created due to moisture removal served as sites of larger local voids. These larger voids are responsible for diminished dynamic composite properties. In the case of wet specimens, dynamic compression of moisture sites increases the area of local delamination. When one moisture site meets another due to dynamic compression, a larger local delamination plane is created and this phenomenon continuous till complete delamination occurs. Hence, the resulting properties of moist specimens are lowest.

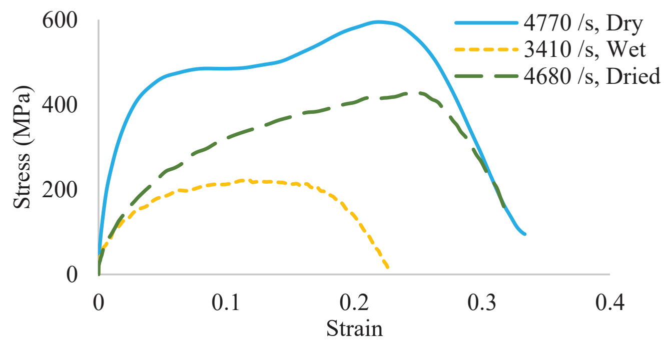

Figure 3. Comparison of dry, wet and dried UHMWPE composite specimens at the loading rates resulting in physical damage of the specimen

3.3 Influence of strain rate on dynamic properties of dry, moisture ingressed and moisture egressed composite

Rate sensitive UHMWPE composites exposed dependence to moisture ingress and egress. Figure 4 depicts the sensitivity of dynamic properties, including peak stress, peak strain and toughness with respect to strain rate for all the three cases. Table 3 presents the variation of stress, strain and toughness as a function of rising strain rates of loading of dry, wet and force dried composite. Irrespective of post-fabrication processing, all the UHMWPE composite specimens exposed increment in peak stress as a function of an increase in the rate of loading. Peak stress enhancement within the experimental regime was noted highest for freshly moulded composites. Increasing rates of loading from 2280 – 4770 /s, resulted in peak stress enhancement by 201% for dry composites. Similarly, for moisture ingressed and egressed composite, the peak stress growth with an increase in loading rates from 2245 – 4696 /s and 1885 – 4680 /s resulted in stress enhancement by 97% and 136%, respectively. However, the slope of stress growth is maximum for dry specimens and worst for moisture ingressed specimens. Removal of

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moisture reduced strain rates at lower loading rates with minor increment in peak stress. Average growth of 20% stress was recorded due to the drying of specimen for the loading rates above 3500 /s. Figure 4 (a) depicts that moisture removal can only help marginally, as the slope of the stress-strain rate curve is negatively impacted when compared to the dry specimen's stress-strain rate growth. The relationship between the strain rate and stress for dry, moisture ingressed and moisture egressed composites can be linearly estimated using Equation 4, 5 and 6.

Dry: $\text{Stress} = 0.1424\dot{\varepsilon} - 98.557 \quad (R^2 = 0.9509)$ (4)

Wet: $\text{Stress} = 0.0782\dot{\varepsilon} - 23.701 \quad (R^2 = 0.9677)$ (5)

Dried: $\text{Stress} = 0.09\dot{\varepsilon} - 8.1577 \quad (R^2 = 0.9584)$ (6)

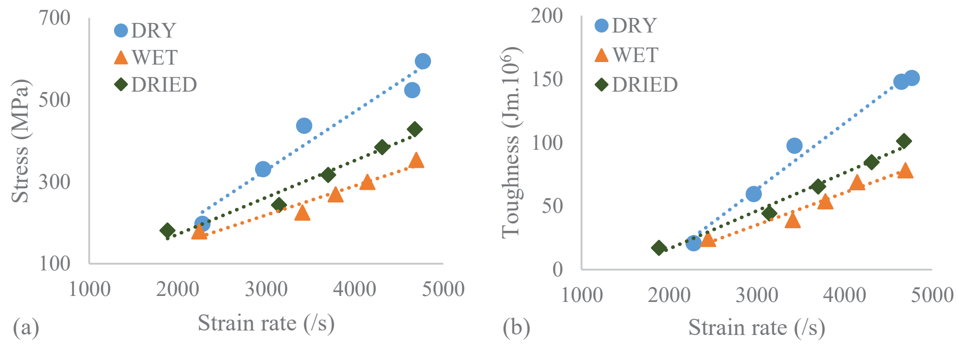

Figure 4. Effect of strain rate on (a) stress and (b) toughness

Table 3. Dynamic compressive properties of UHMWPE composites under different conditions

Specimen condition	strain rate	Max. strain	Stress (MPa)	Toughness $(Jm^3)*10^6$
Dry	2280	0.1976	197	20.78
	2965	0.2335	330	59.68
	3430	0.2940	437	97.54
	4650	0.3625	524	148.1
	4770	0.3758	594	150.84
Wet	2245	0.1906	179	24.2
	3410	0.2450	224	39.09
	3785	0.2900	269	53.97
	4145	0.3406	299	68.85
	4696	0.4000	353	78.22
Force Dried	1885	0.1375	180	17.13
	3145	0.2498	243	44.39
	3700	0.2754	317	65.54
	4311	0.3101	384	84.62
	4680	0.3181	428	101.22

The rate of toughness growth governing the energy absorption ability of UHMWPE composites can be established with respect to strain rate for dry, wet and dried composite using Equation 7, 8 and 9. At lowest rates of loading toughness values were identical for all the composites. As the rate of loading enhanced, dry specimens exposed much higher toughness growth rate. The rate of toughness growth was quite close for wet and dried composites. However, the toughness of dried composite always remained above the wet composites. Increasing rates of loading from 2280 – 4770 /s, resulted in toughness enhancement by 6.25 times for dry composites. Similarly, for moisture ingressed and egressed composite specimens, the toughness growth with an increase in loading rates from 2245 – 4696 /s and 1885 – 4680

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/s resulted in enhancement by 2.2 and 4.9 times, respectively. Just like stress, toughness values also remained approximately 20% higher for dried composites as compared to wet composite at higher rates of loading within the experimental regime.

$$\text{Dry:} \quad \text{Toughness} = 0.0519\dot{\varepsilon} - 92.429 \quad (R^2 = 0.9849) \tag{7}$$

$$\text{Wet:} \quad \text{Toughness} = 0.0254\dot{\varepsilon} - 40.862 \quad (R^2 = 0.9611) \tag{8}$$

$$\text{Dried:} \quad \text{Toughness} = 0.0299\dot{\varepsilon} - 43.365 \quad (R^2 = 0.9813) \tag{9}$$

For all practical purposes, macroscopic damage of ballistic composite can be treated as the limiting condition of loading. As any further loading is bound to result in damage responsible for the loss of personal/material being protected. Peak stresses for dry, wet and dried UHMWPE composites at the dynamic load condition resulting into the first occurrence of macroscopic damage in the form of delamination are shown in Figure 5. The peak stress value falls by 60% due to moisture ingestion. Removal of moisture enhanced peak stress by 90%, as compared to wet composite, but the properties are far lower than initially dry composite. Yet, the results indicate that high-performance composites must be dried at the earliest to enhance the level of protection.

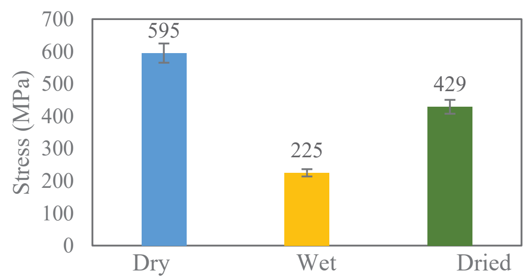

Figure 5. Stress attained by dry, wet and dried UHMWPE composites at dynamic load condition resulting in delamination

3.4 Macroscopic Damage Analysis

Macroscopic images of dry, moisture ingressed and moisture egressed UHMWPE composite specimens following dynamic tests at lowest strain rate and at limiting value of strain rate at which delamination occurs are shown in Figure 5. The dry specimen loaded at 2280/s strain rate experienced minimal macroscopic damage, primarily on both the faces in contact with the incident and transmission bar. All the in-between layers of the specimen revealed negligible damage, as noted in Figure 5(a). At a strain rate of 4770/s, dry specimen delaminated into two pieces. The two delaminated pieces were held together for imaging in Figure 5 (b). Apart from delamination, fibre pull-out and fibre bursting can be noted on the cylindrical surface of the impacted specimen. The delaminated surface of the specimen reveals failure at the lamina level, shown in Figure 5(c). Numerous sites of delamination in between the individual plies were noted with splitted fibre ends. Dynamic loading of moisture ingressed specimen at 2245/s strain rate resulted in more significant damage on both the surfaces in contact with the incident/transmission bar and cylindrical surface, as shown in Figure 5(d). For the very next gas pressure of loading resulting in strain rate of 3410/s, wet specimens showed multiple sites of delamination, as shown in Figure 5(e). Severe surface damage in the form of dislocation of plies, fibre bundle deformation, twist and plies of UHMWPE stuck on the bar surface were noted due to dynamic loading of moist specimens. Interestingly, the delaminated surface of the wet specimen revealed a clear opening in between the UHMWPE plies, as depicted in Figure 5(f). There was minimal damage in the form of UHMWPE ply pulling at all the delamination sites. The phenomenon of easier delamination of wet specimens is attributed to fibre/matrix interface degradation due to plasticization of matrix resulting in lower adhesive strength of the matrix.

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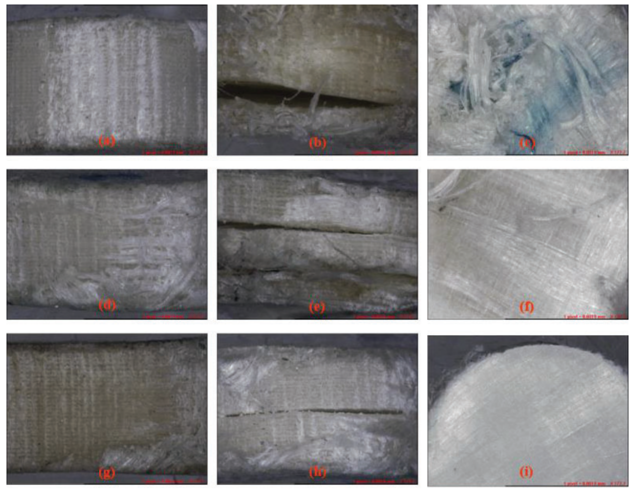

Figure 5. Macroscopic failure of UHMWPE composite (a) dry specimen at 2280/s, (b) dry specimen at 4770/s, (c) delaminated surface of dry specimen at 4770/s, (d) moisture ingressed specimen at 2245/s, (e) moisture ingressed specimen at 3410/s, (f) delaminated surface of moisture ingressed specimen at 3410/s, (g) moisture egressed specimen at 1885/s, (h) moisture egressed specimen at 4680/s, and (i) delaminated surface of moisture ingressed specimen at 4680/s

Moisture removal by oven drying non only enhanced the dynamic strength of composites but also improved the damage resistance as depicted in Figure 5 (g). For identical loading conditions, the strain rate acquired by dried specimens was minimum and the resulting damage was in between that of the dry and wet composite. Dynamic loading at 4680/s strain rate resulted in delamination of the dried composite. However, when compared to wet specimens damage, the delamination was limited to a single plane at the mid-section of the specimen. Numerous sites of fibre bundle pressing and deformation were noted on the surface in contact with the incident/transmission bar, as shown in Figure 5(h). The best outcome of moisture removal was revealed in the form of a clear UHMWPE ply delamination with minimal fibre pull-out on the delaminated surface, as shown in Figure 5(i). There were no sites of local ply damage on this surface, confirming the fact that moisture removal created large voids which served the purpose of delamination plane propagation resulting in ply opening without fibre damage. This type of delamination also confirms the fact that resin starved composites can easily degrade due to residence of foreign fluids and removal of the same may not necessarily bring the properties back to the original state.

5. CONCLUSIONS

Compressive high strain rate studies were carried out on dry, wet and dried UHMWPE composites in the thickness direction. For identical dynamic load conditions, different strain rates were attained by dry, wet and dried composite specimens. Based on compressive high strain rate loading experiments, the following inferences can be drawn:

a. Though UHMWPE composites were conditioned by three different schemes, the dynamic response in terms of peak stress, peak strain and toughness increased with an increase in the rate of loading.
b. For identical dynamic load conditions, a significant reduction in peak stress and toughness for identical strain as a function of moisture ingress confirms that 5.5% moisture retained by the voids and microcavities served as sites of the defect and helped in easy propagation of delamination plane across the UHMWPE plies.
c. Strain values are identical for dry and wet composites under high strain rate load conditions, but the removal of moisture resulted in lowering of strain at high strain rates of loading by 16%. Thus, confirming the fact that removal of moisture will further complicate the issue.
d. Damage studies revealed that matrix in dry composite specimens holds the fibre under dynamic loading whereas, moisture ingress and egress both aids in easy delamination due to reduced interlaminar shear strength.

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e. Peak stress and rate of stress growth were highest for dry composites under dynamic loading conditions, indicating the importance of keeping the UHMWPE composites protected from the influence of moisture.

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References

[1] Tual N. Carrere N. Davies P. Bonnemains T. and Lolive E., Characterization of sea water ageing effects on mechanical properties of carbon/epoxy composites for tidal turbine blades. Compos Part A, 2015; 78; 380–9.
[2] Haque A. and Hossain MK., Effects of Moisture and Temperature on High Strain Rate Behavior of S2-Glass-Vinyl Ester Woven Composites. Jr Compos Mater, 2003; 37; 627–47.
[3] Russell BP. Karthikeyan K. Deshpande VS. and Fleck NA., The high strain rate response of Ultra High Molecular-weight Polyethylene: From fibre to laminate. Int J Impact Eng, 2013; 60; 1–9.
[4] Allred RE. and Roylance DK., Transverse moisture sensitivity of aramid/epoxy composites. Jr Mater Sci, 1983; 18; 652–6.
[5] Sun B. Gu B. and Ding X., Compressive behavior of 3-D angle-interlock woven fabric composites at various strain rates 2005; 24; 447–54.
[6] Zhu L. Li Y. Zhu X. and Zhu Z., Compressive mechanics and failure mechanism for UHMWPE fibre reinforced composite laminates under hygrothermal environment., ICCM Int. Conf. Compos. Mater., China, 20-25 August, 2017.
[7] Shaker K. Jabbar A. Karahan M. Karahan N. and Nawab Y., Study of dynamic compressive behaviour of aramid and ultrahigh molecular weight polyethylene composites using Split Hopkinson Pressure Bar. J Compos Mater, 2017; 51; 81–94.
[8] Chouhan H. Asija N. Ahmed A. and Bhatnagar N. Effect of Moisture on High Strain Rate Performance of UHMWPE Effect of Moisture on High Strain Rate Performance of UHMWPE Fibre Based Composite Fibre Based Composite. Procedia Struct Integr, 2019; 14; 830–38.
[9] Mukasey MB. Sedgwick JL. and Hagy DW., Ballistic Resistance of Body Armour. NIJ Stand. - 0101-16; 2008; 23-45.
[10] Gama BA. Lopatnikov SL. and Gillespie JWJ., Hopkinson bar experimental technique: A critical review. Appl Mech Rev, 2004; 57; 223–50.

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