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Dynamic thermo-mechanical and impact properties of helical auxetic yarns

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A B S T R A C T

This paper presents an experimental investigation of the dynamic thermo-mechanical and impact properties of helical auxetic yarns (HAYs). A series of thermoplastic polyurethane (TPU) core fibres fabricated using an extrusion process have been wrapped with either ultra-high-molecular-weight polyethylene (UHMWPE) wrap or stainless steel wire wrap to form helical auxetic yarns. Dynamic mechanical analysis (DMA) measurements indicated that the core/wrap diameter ratio and the initial wrap angle influenced significantly the dynamic thermo-mechanical behaviour of HAYs. The impact test results have shown that the fibre property, impact velocity and the initial wrap angle had great effect on the impact response of a HAY. Importantly, in this work it is shown that an optimal wrap angle can be found to give the best combination of stiffness, energy absorption and auxetic performance of HAYs.

1. Introduction

Materials with a negative Poisson's ratio are called auxetic materials [1]. Auxetic materials become wider in tension and narrower in compression. The helical auxetic yarn (HAY) is one type of auxetic material, first proposed by Hook et al. [2]. The HAY comprises an elastomeric core and a stiff helical wrap, see Fig. 1a. When a tensile load is applied the core fibre becomes wider as the wrap fibre straightens out, causing a lateral expansion of the core, and thereby exhibiting a large negative Poisson's ratio as shown in Fig. 1b. Combining two of these primary structures together and arranging them in pairs, an 'out of phase' movement occurs between the paired structures, causing pores to open along their length (Fig. 1c). Multiples of this two-yarn primary system can be incorporated into a textile to offer an uni-directional auxetic fabric. Therefore, such advantages of HAY structures open up a number of possible applications, including body armour [2] and blast mitigation [3] due to its high energy absorption ability. In addition, the HAY may be placed in a composite as a yarn reinforcement and the formed composite is able to exhibit auxetic, low modulus [4] and high modulus [5] behaviours depending on the stiffness of the HAY and matrix. The HAY has been investigated previously in terms of manufacture, auxeticity and static mechanical properties [6–11]. According to the previous studies, the auxetic behaviour can be tailored by selecting the core/wrap diameter ratio, component moduli, the initial wrap angle, and the applied strain.

The basic requirement for body armour and blast mitigation is a material or structure that can absorb energy locally and redistribute that energy fast and effectively at high strain rates [12]. Therefore, low density and high strength fibres may offer better energy absorption and lighter weight in protective fabrics. The ballistic behaviour of high performance fabrics has been investigated experimentally and theoretically in the last two decades [13–22]. The absorption of energy is caused by the deformation of yarns during the impact test. Yarns within fabrics are either broken or deformed as a result of energy absorption. The following parameters have been identified as major factors in influencing the ballistic performance of fabrics: material properties (tensile strength, modulus and elongation of a yarn), fabric structure, number of fabric layers, projectile geometry, impact velocity, boundary conditions (the size of the specimen and means of the fixture) and friction between the projectile and the fabric and the yarns themselves.

It has been suggested previously that the HAY can be woven into technical auxetic textiles and placed in a composite for body armour and blast mitigation applications. However, prior to any fabrics and composites manufacturing, testing and analysis, it is important to understand the dynamic thermo-mechanical

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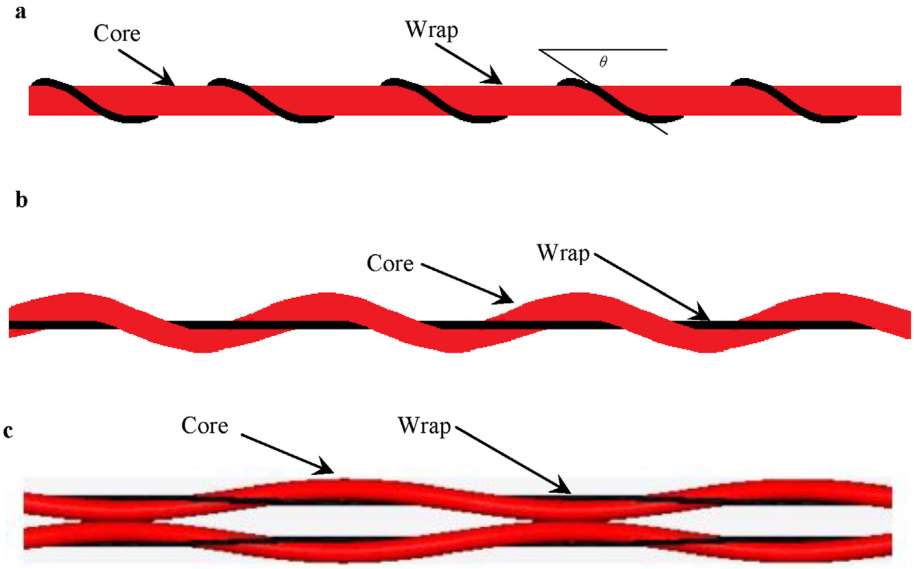

Fig. 1. Schematic of HAY structures: (a) one HAY at zero strain; (b) one HAY at maximum strain; and (c) pores open under tension in a pair of HAYs for textile application (after [11]).

properties and the energy absorption capability of the HAY itself. The energy absorption capability of the HAY is a major factor in its blast mitigation behaviour which may lead to improved safety in an explosion. This paper reports experimental investigations on the dynamic thermo-mechanical behaviour and high strain rate performance of HAYs.

2. Methods

2.1. Fibres and HAYs manufacturing

Elastomeric core fibres were fabricated by extrusion using a Rondol (www.rondol.com) 18 mm diameter bench top single screw extruder (model-Linear 18). Elastollan® TPU-CA85A granules (polyester-based TPU) were purchased from BASF for manufacturing core fibres. Multifilament UHMWPE fibre and monofilament stainless steel wire were purchased from Monofil Technik and employed here as the wrap fibres due to their high strength, high modulus, and differing energy absorbing mechanisms on failure. Accurate diameters of core and wrap fibres were obtained using optical stereo microscope. Helical auxetic yarns were manufactured using a bespoke spinner, described in a previous study [7]. The properties for component fibres and HAYs are shown in Table 1. Three types of monofilament core fibres and two types of wraps were utilised to fabricate HAYs. The Young's moduli of the component fibres (samples A to E) were obtained using the elastic region (0.05–0.25%) [23].

2.2. DMA measurements

DMA measurements for TPU fibres, UHMWPE fibres and HAYs were conducted using a dynamic mechanical analyser (DMA1, Mettler Toledo) in the tensile mode, see Fig. 2. The fibres and HAYs were tested from 25 °C to 125 °C at heating rate of 3 °C × min^{-1} and at 1 Hz frequency. The tensile amplitude of 10 μm was applied for core and wrap fibres, and a larger tensile amplitude of 250 μm was employed for HAYs in order to investigate the influence of the wrap on the thermo-mechanical property of HAYs. A pre-tension of 0.5 N was applied for all the measurements.

Table 1
Measured properties for fibres and HAYs.

Sample	Type	TPU core diameter (μm)	UHMWPE wrap diameter (μm) (±27 μm)	Stainless steel wrap diameter (μm) (±0.3 μm)	Initial wrap angle (°)	Young's modulus (MPa)
A	Core Fibre	394.5 ± 23.8	–	–	–	12.5 ± 2.2
B	Core Fibre	683.6 ± 30.5	–	–	–	14.7 ± 3.6
C	Core Fibre	1302.1 ± 23.4	–	–	–	14.8 ± 1.4
D	Multi-filament Wrap	–	370	–	–	23,000 ± 3000
E	Wire Wrap	–	–	139.8	–	43,000 ± 1700
F	Helical auxetic yarn	394.5 ± 23.8	370	–	30.3 ± 1.6	–
G	Helical auxetic yarn	683.6 ± 30.5	370	–	30.8 ± 1.9	–
H	Helical auxetic yarn	1302.1 ± 23.4	370	–	12.5 ± 1.5	–
I	Helical auxetic yarn	1302.1 ± 23.4	370	–	20.6 ± 1.2	–
J	Helical auxetic yarn	1302.1 ± 23.4	370	–	30.9 ± 1.4	–
K	Helical auxetic yarn	1302.1 ± 23.4	370	–	40.7 ± 1.9	–
L	Helical auxetic yarn	1302.1 ± 23.4	–	139.8	19.8 ± 1.1	–
M	Helical auxetic yarn	1302.1 ± 23.4	–	139.8	31.4 ± 1.5	–
N	Helical auxetic yarn	1302.1 ± 23.4	–	139.8	40.5 ± 1.3	–

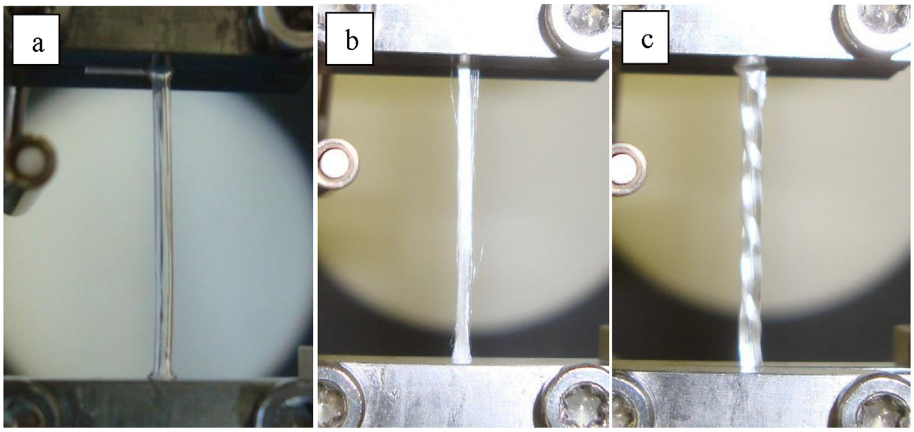

Fig. 2. Sample clamping for DMA test: (a) TPU core fibre (sample C); (b) UHMWPE wrap (sample D); and (c) HAY (sample J).

2.3. *Impact measurements*

High rate tensile impact tests of fibres and HAYs were performed at ambient temperature according to ISO 8256 Method A [24] using a CEST 9350 (INSTRON) drop tower impact system. The total mass of the impactor used was 11.49 kg. One impact energy level (323.21 J) was employed for testing samples C, D, H, I, J and K. Three impact energy levels were applied (35.91, 143.65 and 323.21 J) for testing sample J. The impact energy was adjusted by the initial impact velocity. Three initial velocities were employed: 2.5 m × s^{-1}, 5 m × s^{-1}, 7.5 m × s^{-1}. The sampling frequency was set at 500 kHz for testing all the samples. The force, impact velocity, deformation and energy versus time were automatically computed by the drop tower's internal data acquisition system. The specimen gauge length is taken as the distance between the grips and it has been set as 30 mm for fibres and HAYs.

Fig. 3a–c shows a typical sample clamping process for TPU core fibre, UHMWPE wrap and HAYs respectively. Repeat measurements were performed for each sample type: five repeat tests for TPU core fibre (sample C), five repeat tests for UHMWPE wrap (sample D), and five repeats tests for each type of HAY (samples H, I, J and K). In an attempt to understand the influence of the wrapping process and the wrap angle on the impact property of HAYs, two additional combinations of fibres were set up for impact testing, see Fig. 3d and e. Fig. 3d presents the impact tests carried out by having TPU core and UHMWPE wrap fibres clamped tightly next to each other with the same gauge length (30 mm). Fig. 3e shows a wrap fibre was taken off from a 30 mm HAY with a 40° initial wrap angle and clamped next to the core fibre which was taken from the same HAY, thus allowing for the longer initial length of the yarn but without enabling the auxetic mechanism. The energy absorption capability of HAYs was evaluated in three circumstances: (1) when the wrap fibre is broken, (2) when the core fibre is broken, and (3) when the core fibre is unbroken.

The peak force and absorbed energy were selected as parameters to analyse the impact performance of fibres and HAYs. The

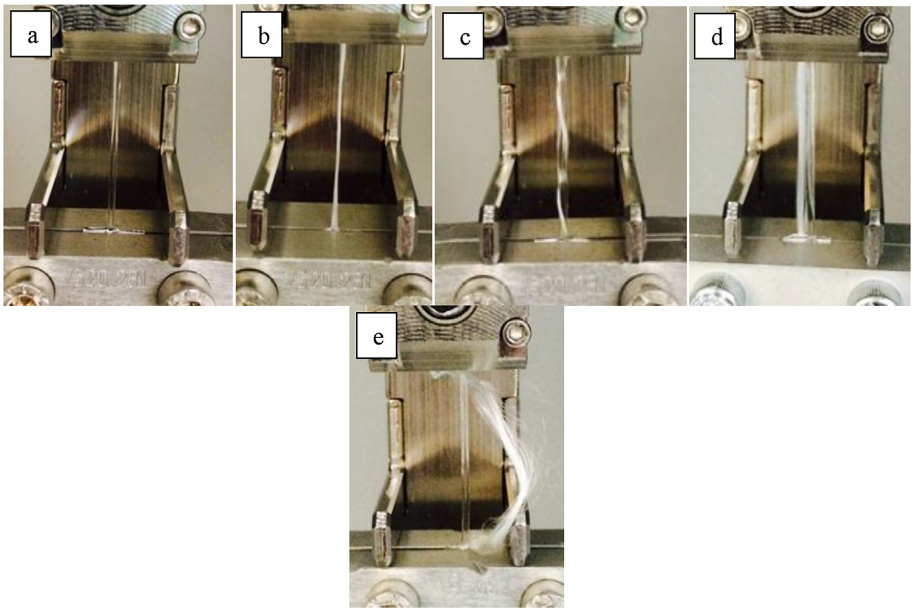

Fig. 3. Sample clamping for impact test: (a) TPU core fibre (sample C); (b) UHMWPE wrap (sample D); (c) HAY (sample H); (d) tight TPU core (sample C) and tight UHMWPE wrap (sample D); and (e) tight TPU core (sample C) and unwrapped UHMWPE wrap (unwrapped from sample K − 40°).

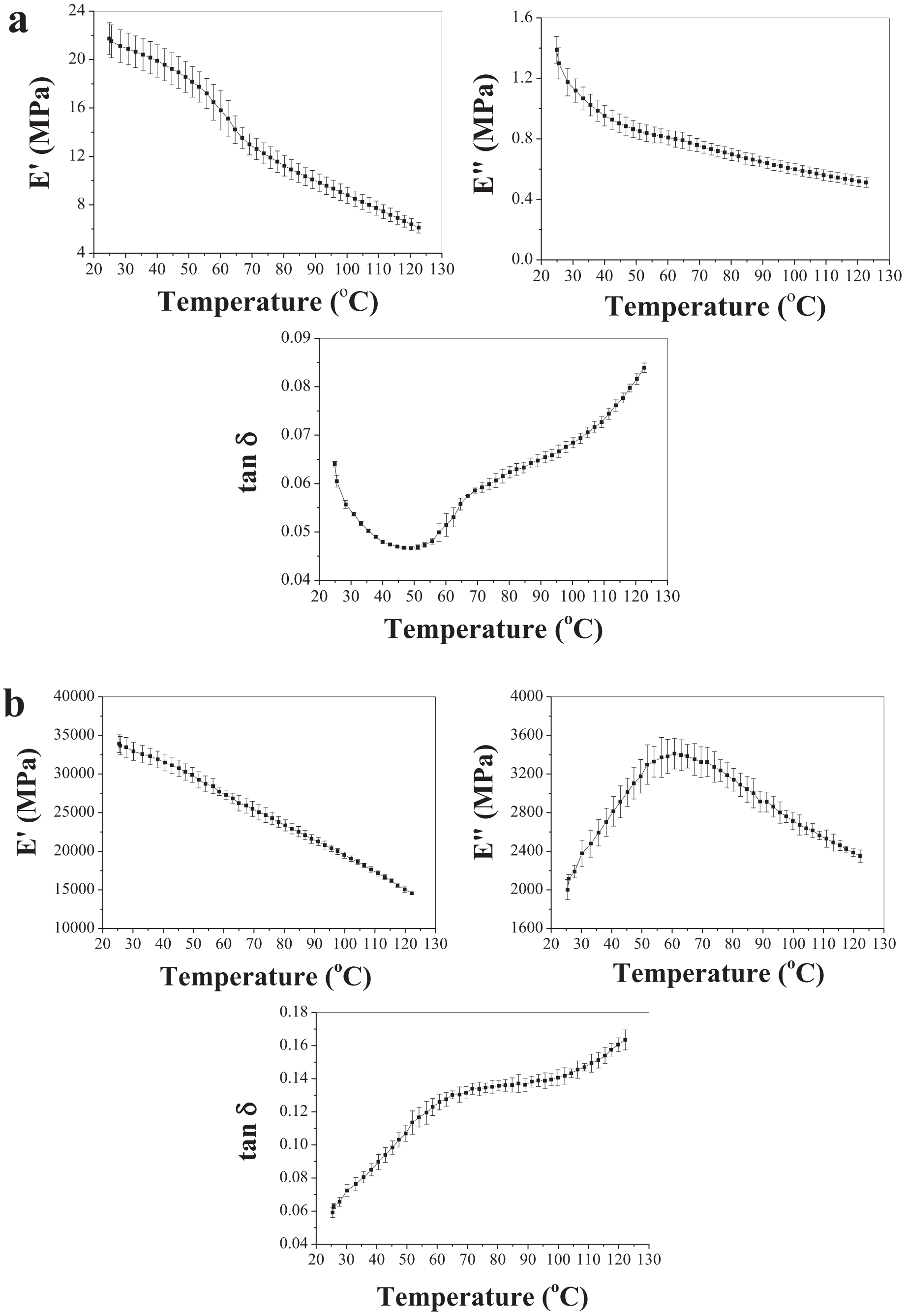

Fig. 4. (a) Dynamic storage modulus (E'), dynamic loss modulus (E'') and loss tangent (tan δ) as a function of temperature (25 °C–125 °C) for TPU core fibre (sample C); (b) Dynamic storage modulus (E'), dynamic loss modulus (E'') and loss tangent (tan δ) as a function of temperature (25 °C–125 °C) for UHMWPE wrap fibre (sample D).

impact energy is the total amount of energy available from the impact tester. The absorbed energy is the total amount of energy absorbed by the specimen in an impact test. The absorbed energy was obtained using the integral area of the force-displacement curve for every measurement.

3. Results and discussion

3.1. DMA measurements

Fig. 4a illustrates the dynamic mechanical behaviour of the TPU core fibre, which was tested from 25 °C to 125 °C. The dynamic storage modulus measures the stored energy, representing the elastic portion; and the dynamic loss modulus measures the energy dissipated as heat, representing the viscous portion. Damping is a measure of how well a material can dissipate energy and is reported as the loss modulus to storage modulus ratio (the tangent of the phase angle). Overall, the dynamic storage modulus of TPU core fibre decreases as a function of temperature as the TPU fibre is softening with an increase of temperature. A weak variation is observed in the tan δ (phase angle) curve due to the glass transition of polyester within TPU fibre, thereby a sharp decrease in the dynamic storage modulus occurs between 50 °C to 80 °C. Fig. 4b shows the dynamic mechanical behaviour of UHMWPE fibre. The

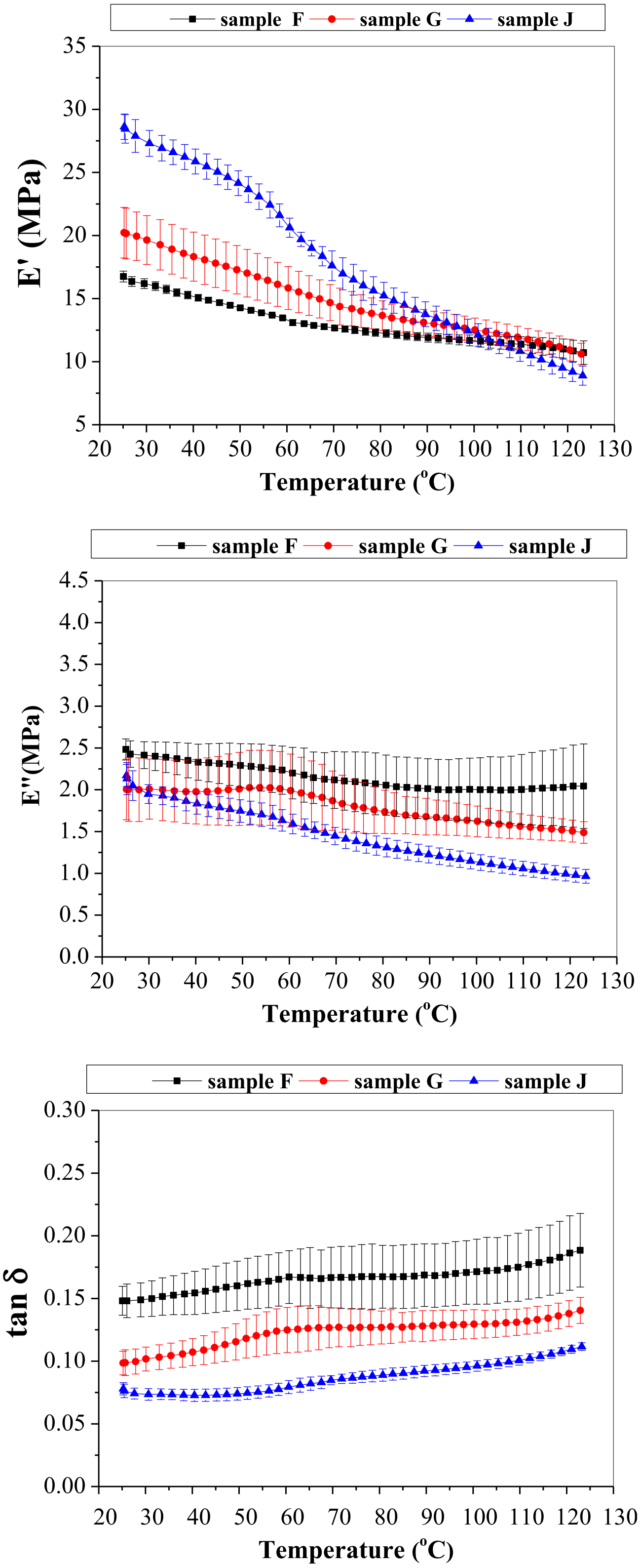

Fig. 5. Dynamic storage modulus (E'), dynamic loss modulus (E'') and loss tangent (tan δ) as a function of temperature (25 °C–125 °C) for HAYs: samples F, G and J.

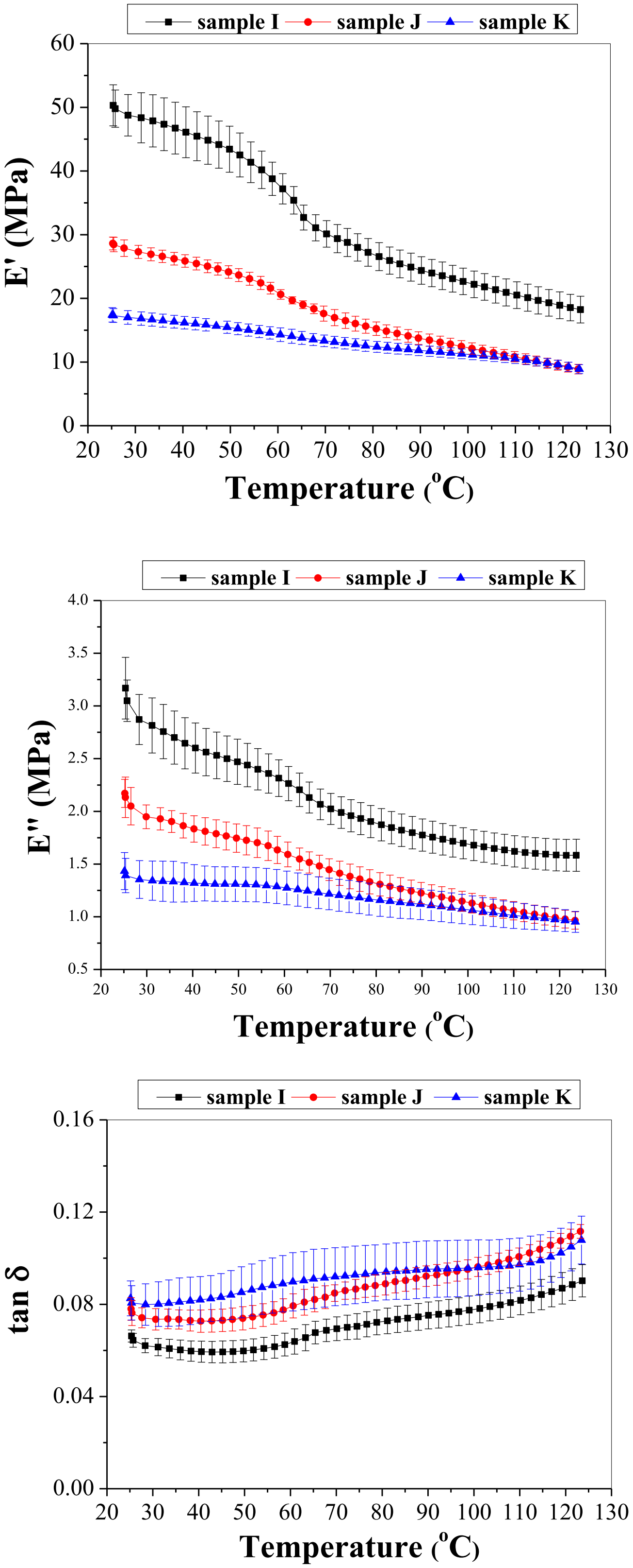

Fig. 6. Dynamic storage modulus (E'), dynamic loss modulus (E'') and loss tangent (tan δ) as a function of temperature (25 °C–125 °C) for HAYs: samples I, J and K.

dynamic storage modulus of UHMWPE fibre decreases with an increase of temperature due to the softening effect and the increase of molecular mobility in the fibre. The peak at approx 60 °C is attributed to a portion of polymeric segments in the crystal phase beginning to melt [25]. Overall, the dynamic storage modulus of UHMWPE fibre was observed to be much higher than that of TPU core fibre due to its higher stiffness. Therefore, UHMWPE fibre has been selected as the wrap for manufacturing the HAY since it could enhance the auxetic behaviour of a HAY.

Fig. 5 shows the dynamic mechanical behaviour of HAYs (samples F, G and J) with a constant wrap angle (30°) and various core/wrap diameter ratio. The results show that a larger core/wrap diameter ratio leads to a higher dynamic storage modulus. Since the same UHMWPE wrap was employed to manufacture samples F, G and J, the diameter of the core fibre therefore plays a significant role in determining the overall storage moduli of HAYs. A sharp decrease in the dynamic storage modulus curve at 60 °C is mainly caused by the glass transition of polyester as observed previously in the dynamic storage modulus curve of TPU core fibre. The effect becomes more obviously for HAYs with a larger core/wrap diameter ratio.

Fig. 6 shows the dynamic mechanical behaviour of HAYs of the same core/wrap diameter ratio (samples I, J and K) as a function of the initial wrap angle (20°, 30°, 40°). The figure indicates that the dynamic storage and loss moduli of HAYs increase with a decrease of the initial wrap angle. The HAY manufactured with a lower initial wrap angle has a higher starting dynamic storage modulus. The overall dynamic storage moduli of HAYs are increased in comparison with TPU core fibre due to the contribution of UHMWPE wrap. It is also interesting to note that the gradient of the dynamic storage modulus curve of HAYs decreases with an increase of the initial wrap angle. This phenomenon is attributed to the wrap fibre tending to straighten, thus contributing more to the overall dynamic storage moduli of HAYs when a lower initial wrap angle was applied. As UHMWPE wrap could not become completely straight under 250 μm tensile amplitude, the initial and overall dynamic storage moduli of HAYs are much lower than the values of UHMWPE wrap.

Fig. 7 presents the dynamic mechanical behaviour of samples L, M and N with a constant core/wrap diameter ratio (TPU core and stainless steel wrap) and various initial wrap angles. The results demonstrate that HAYs manufactured with a lower initial wrap angle have higher starting storage modulus and overall storage moduli. This behaviour agrees well with DMA results for HAYs fabricated with UHMWPE wrap at a constant core/wrap diameter ratio. It is also interesting to note that the overall dynamic storage moduli of HAYs manufactured with stainless steel wrap are higher than those yarns fabricated with UHMWPE wrap. Therefore, a stiffer wrap would offer a higher modulus HAY when a constant initial wrap angle is applied.

3.2. *Tensile impact measurements*

Table 2 summarises the impact properties of the fibres and HAYs as shown in Table 1. The total absorbed energy of HAYs was evaluated at different failure stages: (1) when only the wrap fibre failed and core fibre was left unbroken; (2) when the core and wrap fibres were both broken. Table 2 indicates that UHMWPE fibre (sample D) has the largest peak force and this is attributed to its high strength and modulus. However, being a highly aligned, relatively brittle polymer, UHMWPE fibre has small energy absorption when it breaks in the impact test. The stainless steel wire has the smallest energy absorption among other materials due to it has the highest modulus as demonstrated in Table 1. In comparison with UHMWPE fibre and stainless steel wire, the elastomeric TPU core fibre has lower peak force and higher energy absorption. Meanwhile, it can be noted that broken TPU fibres absorb less energy than unbroken ones; and HAYs tested with unbroken core fibre could absorb more energy than those yarns with broken core fibre. Therefore, consistent and stable ballistic performance of fibres and HAYs are vital when they are woven into technical textiles for body armour and blast mitigation applications. The initial wrap angle has great impact on the absorbed energy of HAYs when the evaluation was considered only up to the failure of the wrap fibre. The results indicate that HAYs manufactured with a higher initial wrap angle

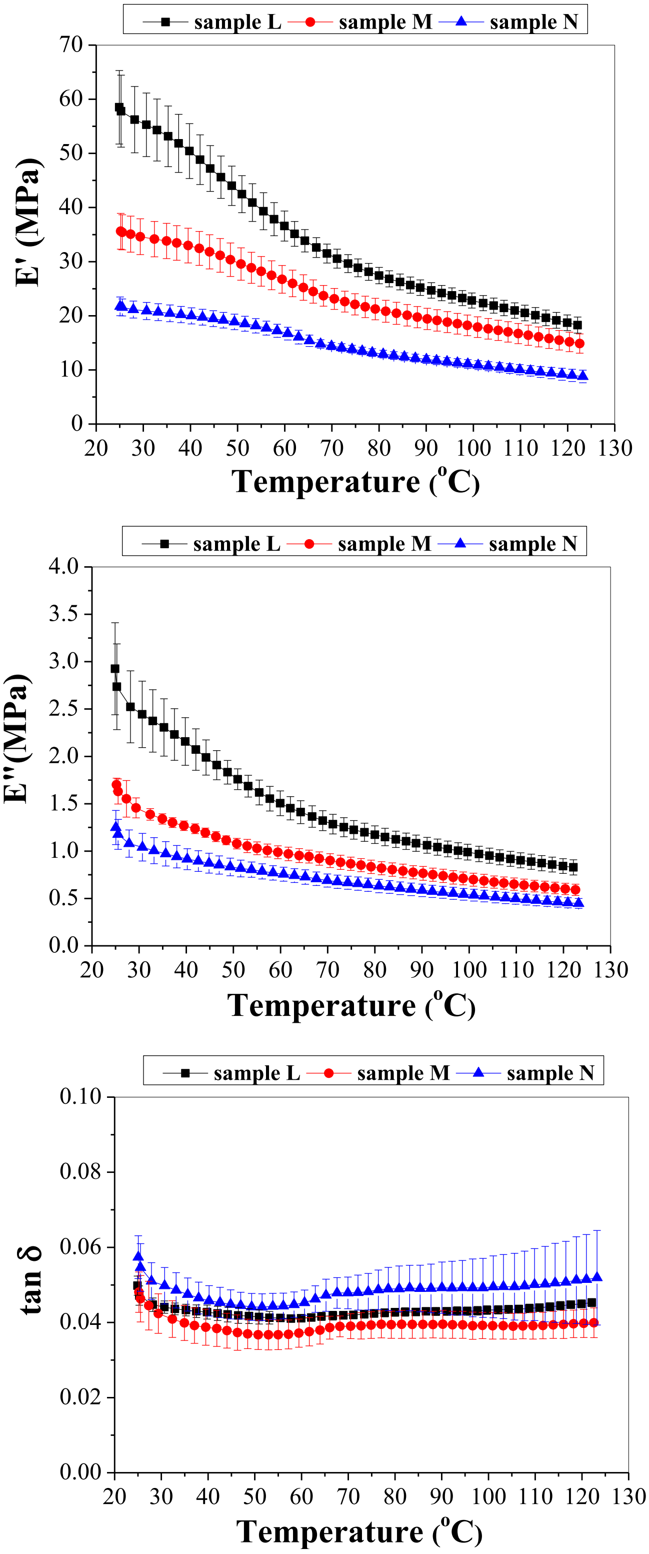

Fig. 7. Dynamic storage modulus (E'), dynamic loss modulus (E'') and loss tangent (tan δ) as a function of temperature (25 °C–125 °C) for HAYs: samples L, M and N.

Table 2
Impact properties of fibres and HAYs (impact velocity: 7.5 m/s).

Sample	Peak force (N)	Break energy (J) (wrap)	Total energy (J) (unbroken core)	Total energy (J) (broken core)
C	42.1 ± 8.4	–	2.28 ± 0.60	1.93 ± 0.04
D	92.5 ± 9.6	0.06 ± 0.007	–	–
H	66.1 ± 10.9	0.08 ± 0.015	2.82 ± 0.08	2.18 ± 0.15
I	71.9 ± 7.5	0.11 ± 0.011	2.81 ± 0.08	1.81 ± 0.5
J	72.1 ± 7.2	0.25 ± 0.031	2.83 ± 0.15	1.61 ± 0.48
K	70.7 ± 10.3	0.30 ± 0.039	2.92 ± 0.25	2.06 ± 0.7
Tight C and tight D (same sample length)	83.3 ± 5.6	0.06 ± 0.009	2.77 ± 0.17	–
Tight C and unwrapped D (40°)	66.2 ± 10.5	0.31 ± 0.02	2.89 ± 0.18	–

are able to absorb more energy due to their wrap fibres having longer travel distance before failure.

Fig. 8 shows force and energy versus time diagram for TPU core and UHMWPE wrap fibres respectively. Five repeat impact tests were performed for TPU core fibre. Two samples were broken and three samples were unbroken as shown in Fig. 8a. These phenomena could be caused by variation in fibre diameter during the manufacturing process. The overall behaviour of five samples does not present any major difference. The time responses of all TPU core fibres do not show any dramatic difference and all the tests start at the same time. As UHMWPE wrap fibre is a rigid material and it breaks much earlier than TPU core fibre, it could absorb as little as 0.06 ± 0.007 J of 323.21 J impact energy in comparison with TPU core fibre as shown in Fig. 8a and b. Fig. 8b indicates small variation occurs in the failure time of UHMWPE fibres, and this behaviour is attributed to their multifilament structures, see inserted picture of one broken wrap fibre in Fig. 8b. The time responses of TPU core and UHMWPE wrap fibres show slight delays in the force-time curve. The delays are caused mainly by longer contact durations between the impactor and the specimens. Therefore, a short flat line is observed at the beginning of every profile. The length of the flat line depends on the contact durations. However, short delays would not have major impact on the peak force and the absorbed energy of fibres.

Fig. 9 shows five repeat impact measurements of HAYs with a 40° initial wrap angle under 7.5 m/s impact velocity. It is interesting to note that the HAY could absorb approximately 0.3 J, which is five times more than UHMWPE wrap. Once the wrap fibre failed in the HAY and the HAY has lost its auxetic effect, the core fibre continued to absorb energy until its failure or not, see inserted pictures in Fig. 9. Fig. 9b presents the force and energy of HAYs until the failure of the core fibres. It indicates that the core fibres of HAYs were broken at different time and resulting variations in energy absorption. It is worth noting that the core fibre of sample three did not break after the impact test and this led to a higher energy absorption for that HAY. Table 2 indicates that HAYs with unbroken core fibre could absorb higher energy than those HAYs had broken core fibre and this is also the case for TPU core fibre.

Fig. 10 compares force and energy as a function of time for individual fibres and HAYs with various wrap angles under 7.5 m/s impact velocity. The results indicate that UHMWPE wrap fibre breaks first and TPU core fibre breaks last, the breakage time of the wrap fibre for HAYs increases with an increase of the initial wrap angle. The HAY fabricated with a higher initial wrap angle takes longer time for its wrap fibre to straighten and break. In addition, HAYs manufactured with a higher initial wrap angle are able to absorb more energy than those HAYs fabricated with a lower initial wrap angle subject to the failure of the wrap fibre as shown in Fig. 10a and Table 2. Previous studies [6,7,9] indicated that the HAY offered a better auxetic performance with a lower initial wrap angle, therefore it is important to balance the auxetic effect and the energy absorption of a HAY in practice. Nevertheless, when the wrap fibre fails and the entire HAY loses its auxetic effect, the core fibre will continue to absorb energy until its failure, see Fig. 10b.

The force and energy curves of tight TPU core and wrap fibres are shown in Fig. 11a. The general behaviour of three samples shows no major difference in terms of their force and energy absorption. The wrap fibre breaks at almost same time and absorbs the same amount of energy when the wrap fibre was tested individually as shown in Fig. 11a and Table 2. These phenomena demonstrate that the energy absorption capability of HAYs is enhanced by the wrapping process. Fig. 11b shows three impact tests for having straight core fibre and unwrapped wrap fibre clamped next to each other. The slack wrap fibres were taken off from HAYs with a 40° initial wrap angle. The results indicate that the breakage time for the unwrapped wrap fibre has been delayed almost 2 ms in comparison with straight wrap fibre. This effect leads to larger energy absorption and the energy absorption of the unwrapped wrap is almost five times more than straight wrap fibre as shown in Table 2. In addition, the total energy absorbed by the core fibre and the unwrapped wrap fibre approach the total energy absorption of sample K. This demonstrates that the wrapping process offers additional energy absorption mechanisms in HAYs.

The impact tests were conducted for HAYs under various impact velocities in order to evaluate the influence of the impact velocity on the impact properties of HAYs. Fig. 12 shows the force and energy verse time for HAYs with a 30° initial wrap angle under 2.5, 5 and 7.5 m/s impact velocities respectively. It can be noted that the starting points of force and energy curves were delayed due to a slower velocity and the breakage time for the wrap fibre decreases with increasing impact velocity. In addition, HAYs which were tested at high impact velocity could absorb more energy. Therefore, a high impact velocity could break the wrap fibre earlier and cause the HAY to absorb more energy. It is vital to take these factors into account in designing fabrics which are manufactured from HAYs. The impact velocity has great impact on the impact properties of HAYs, as it will affect the impact performance of HAYs in potential applications for body armour and blast mitigation.

Fig. 13 shows the relationship between DMA and impact properties of samples I, J and K at ambient temperature. The results indicate that the dynamic storage modulus of HAYs decreases as a function of the initial wrap angle; however, the break energy up to the failure of the wrap fibre of HAYs increases as a function of initial wrap angle. It is important to note that in practical HAYs should achieve both high stiffness and energy absorption. The cross point of two curves gives an optimal initial wrap angle of 27° for offering both reasonable high stiffness and energy absorption of HAYs. In

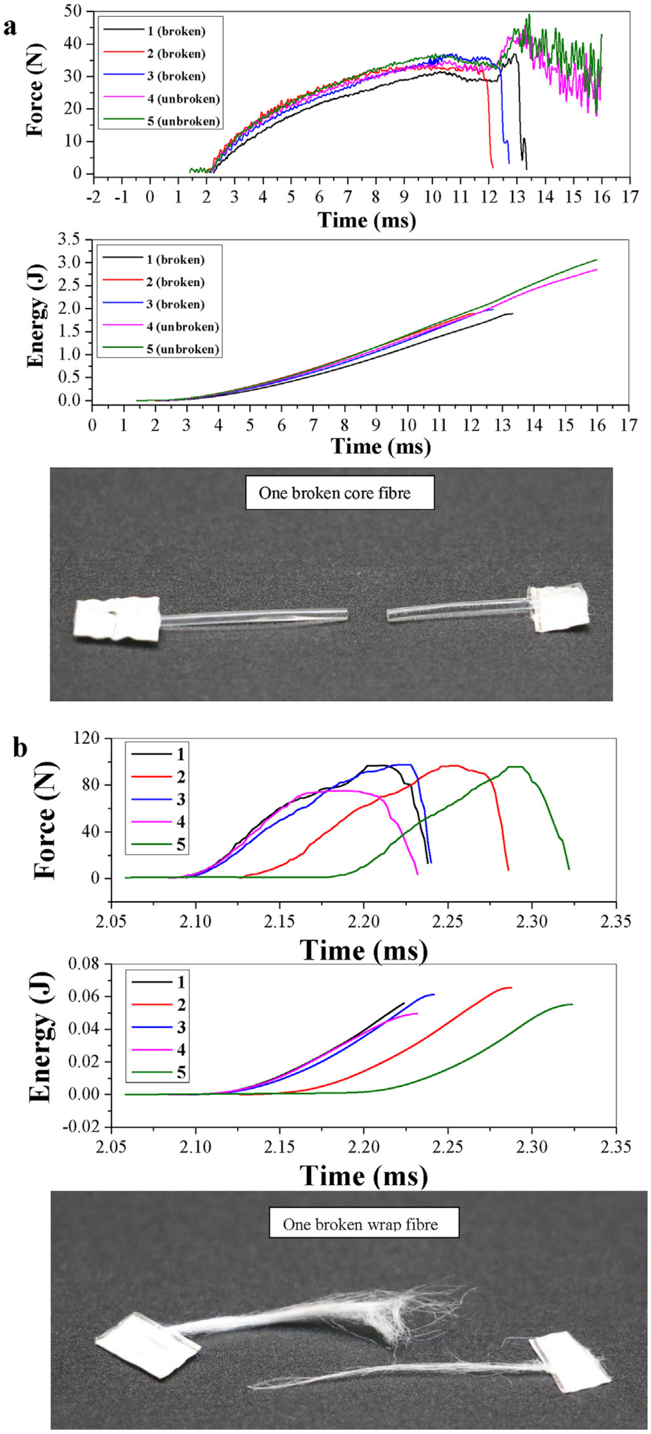

Fig. 8. Force and absorbed energy vs time for (a) broken and unbroken TPU core fibres (five repeat tests); force and absorbed energy vs time for (b) broken UHMWPE wrap fibres (five repeat tests).

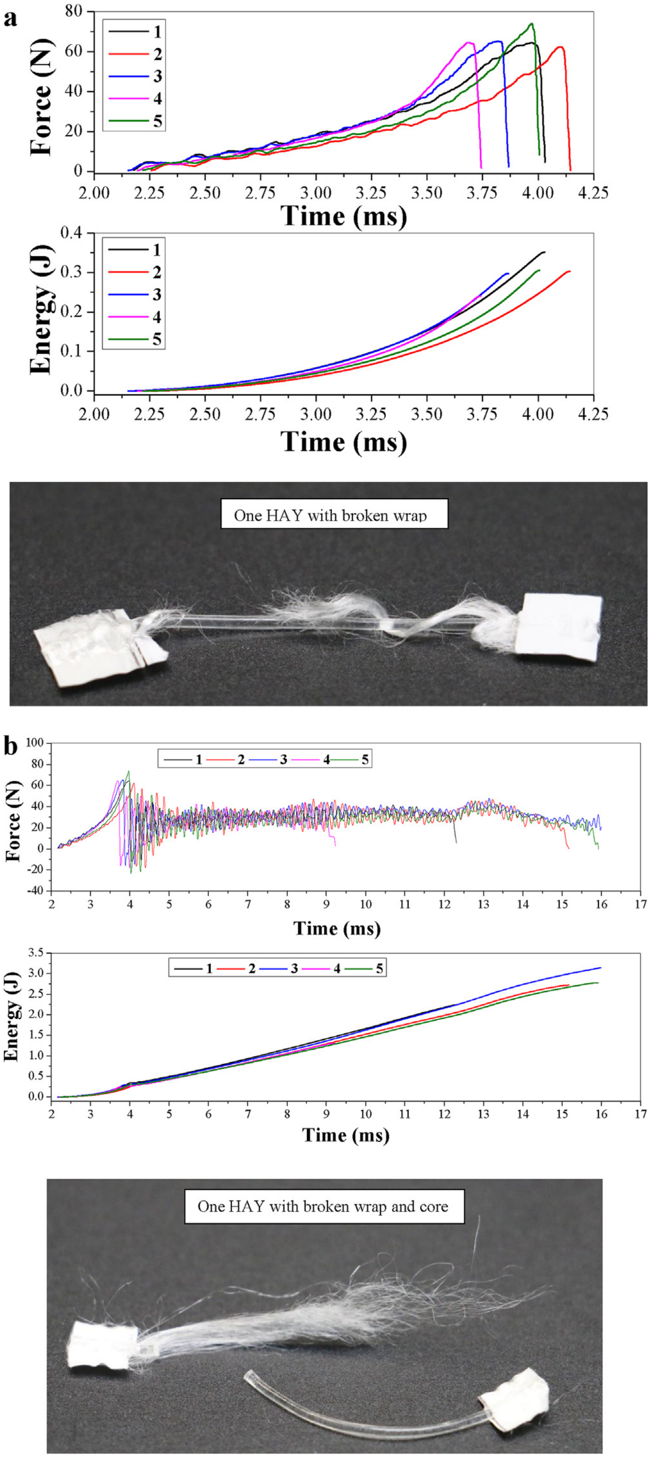

Fig. 9. Force and absorbed energy vs time for HAYs with an initial wrap angle 40° (sample K-five repeat tests): (a) showing the results up to the failure of the wrap fibre, and (b) showing the results of the wrap and core fibres.

addition, a reasonable low 27° initial wrap angle could also offer a good auxetic performance of HAYs.

4. Conclusion

A series of monofilament TPU core fibres were successfully fabricated by extrusion and they have been combined with UHMWPE wrap and stainless steel wrap for manufacturing helical auxetic yarns. The viscoelastic behaviour of HAYs was characterised by DMA measurements. The dynamic storage modulus of TPU core fibre was significantly enhanced by wrapping UHMWPE fibre and stainless steel wire to form a HAY. The core/wrap diameter ratio and the initial wrap angle were found to have great impact on the dynamic mechanical behaviour of HAYs.

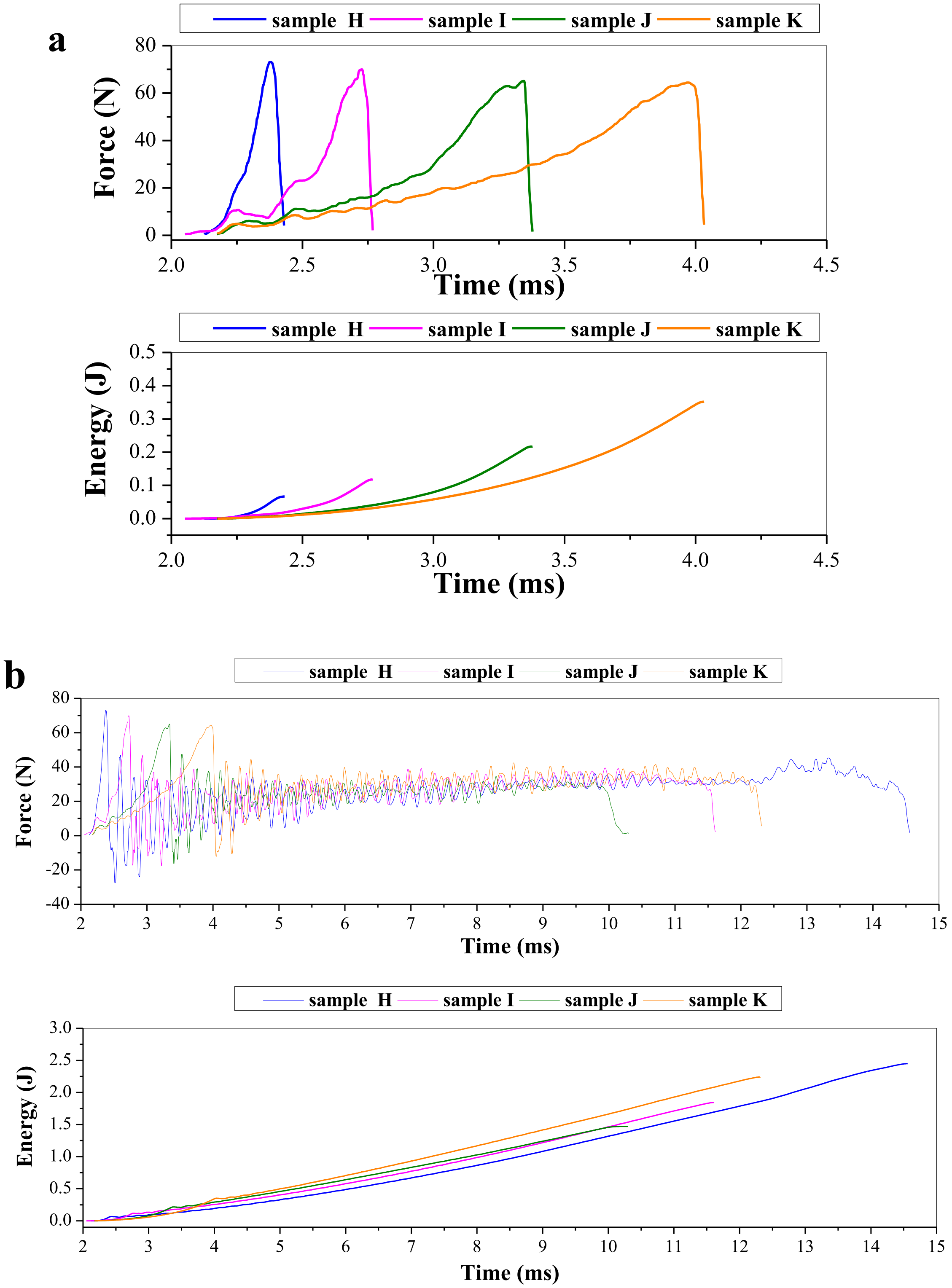

Fig. 10. Force and absorbed energy vs time for HAYs with various initial wrap angles (samples H, I, J and K): (a) showing the results up to the failure of the wrap fibre, and (b) showing the results of the wrap and core fibres.

The impact properties of fibres and HAYs were evaluated using a high rate tensile impact test. The results have shown that the impact velocity has a significant effect on the impact response of the HAY. It is important to take this factor into account when weaving the HAY into fabrics for a range of potential applications. For a given velocity, the energy absorption capacity for HAYs is higher than for a non-wound combination of UHMWPE wrap and TPU core fibres themselves. The initial wrap angle was found to

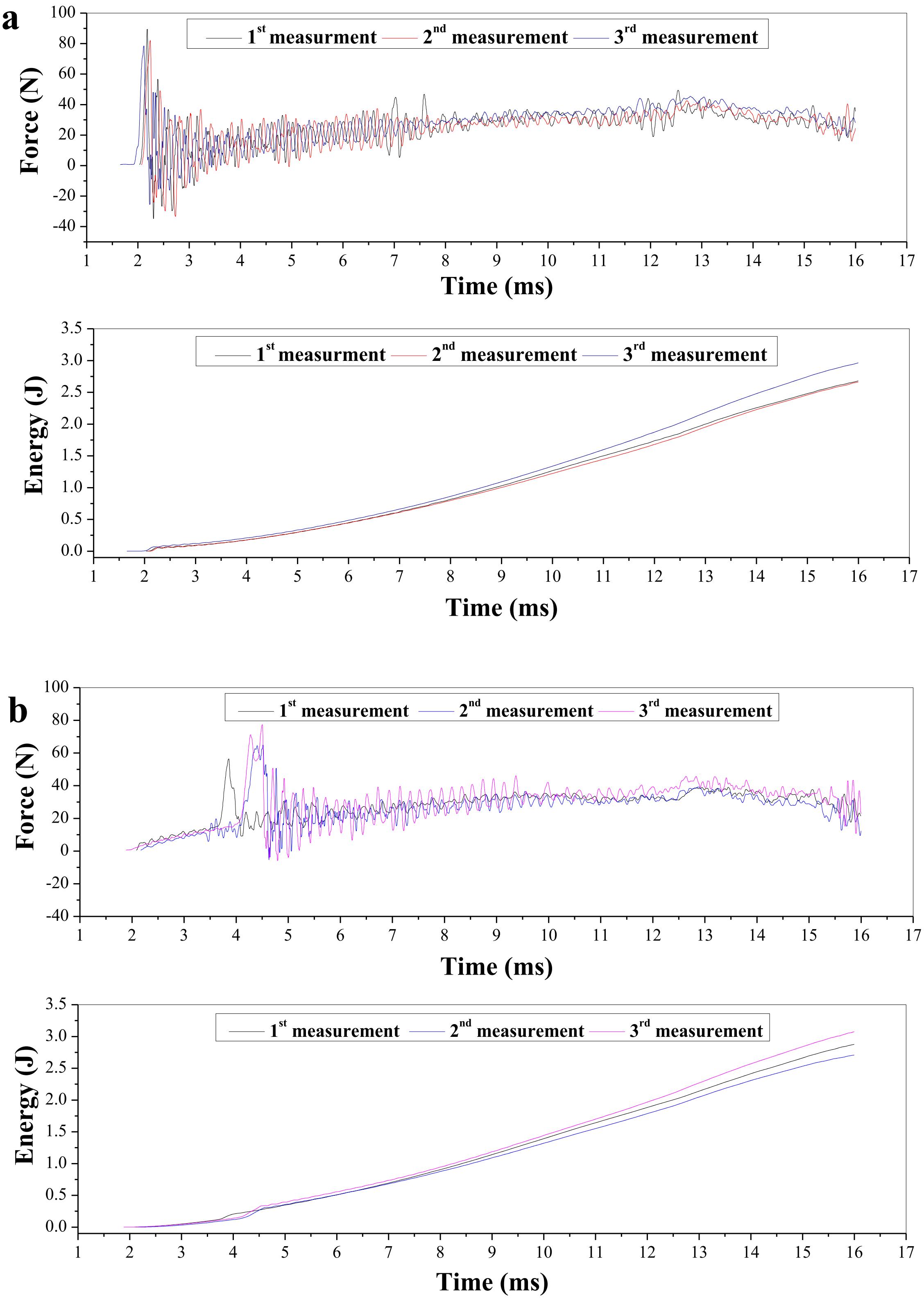

Fig. 11. (a) Force and absorbed energy vs time for tight TPU core fibres and tight UHMWPE wrap fibres; (b) Force and absorbed energy vs time for tight TPU core fibres and unwrapped UHMWPE wrap fibres (they were taken off from HAYs with an initial wrap angle 40°).

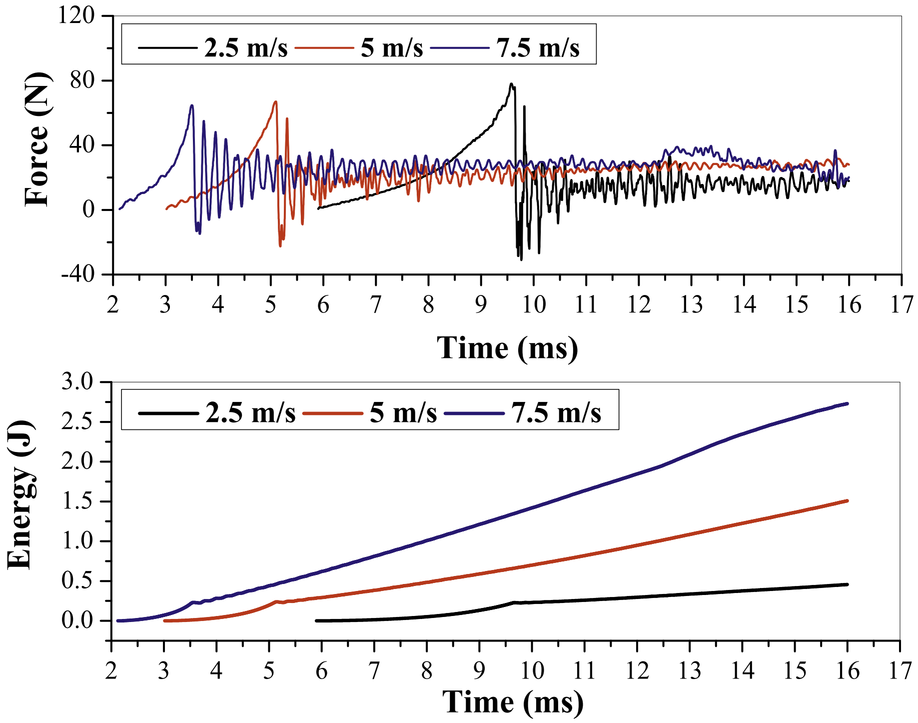

Fig. 12. Force and absorbed energy vs time for HAYs with an initial wrap angle 30° under various impact velocities.

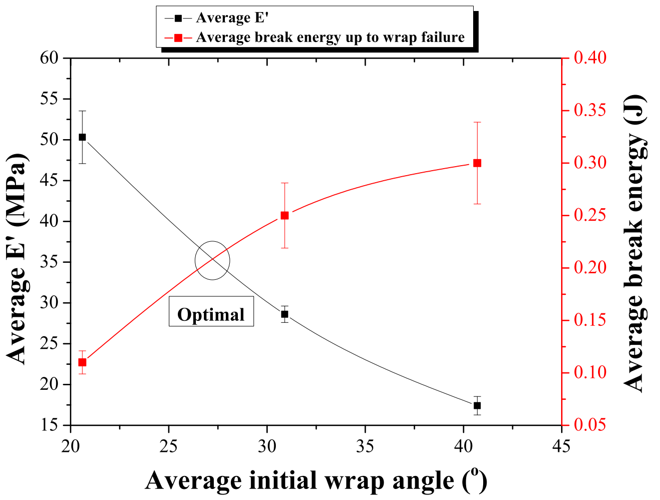

Fig. 13. The relationship between DMA and impact properties of HAYs (samples I, J and K) at ambient temperature.

have great influence on the energy absorption of a HAY when considering the test up to the failure of the wrap and it has little effect on the energy absorption of a HAY once the failure of the core fibre was taken into account. It is important to balance the auxetic effect, the stiffness and the energy absorption of a HAY in practice, as there is competition between the optimum angle for auxeticity (a low value), for stiffness (a low value) and for energy absorption (a high value). An optimal initial wrap angle of 27° has been found to give the best combination of stiffness, energy absorption and auxetic performance of HAYs.

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