

Research Article

Liangpeng Yuan, Nadzirah Zainordin*, Norshakila Muhamad Rawai and Guanggong Zong

Study on the fracture toughness of wood fiber reinforced high-density polyethylene composites

<https://doi.org/10.1515/epoly-2026-0038>

Received June 24, 2026; accepted August 12, 2026;

published online September 24, 2026

Abstract: The fracture toughness of WPE significantly influences its service life and safety, particularly under sudden impact. This study examines the dynamic fracture properties of WPE with varying wood fiber (WF) contents through low-speed impact tests and digital image correlation (DIC) analysis. The results show that wood fiber plays a dual role: it increases the likelihood of brittle fracture while simultaneously enhancing resistance to rapid crack advance. The addition of WF enables the WPE composite material to withstand higher impact forces and absorb more impact energy during the initial impact stage (0–1 ms). The initial peak force of WPE8 in 80 % wood fiber specimens was optimal, and the crack propagation length under 10 J impact was 9.20 mm. The analysis of mode I stress intensity factors (SIFs) confirms this duality. Under increasing impact energy, all WPE composites exhibit rising mode I SIF values, with WPE8 reaching $2.32 \text{ MPa m}^{1/2}$ at 10 J – 4.7, exhibiting a relatively high flexural strength (52 MPa) and modulus (3.2 MPa).

Keywords: wood plastic composite; high-density polyethylene; wood fiber; dynamic fracture toughness; digital image correlation

1 Introduction

Polymeric materials find extensive applications in production and daily life. To further improve material performances and expand their application scope, reinforcing fibers represented

by carbon fibers are commonly incorporated into the matrix [1, 2]. As the philosophy of green sustainable development gains growing recognition, natural materials (including natural fibers) are widely employed as reinforcing phases for polymer matrix composites [3–5]. Differences in the variety and loading content of natural fibers can impart tailored comprehensive performances to the composites [6–8], and the composite materials prepared from the above-mentioned lignocellulosic fibers, thermoplastic resins and other additives are called wood-plastic composites (WPC) [9, 10]. It is easy to shape and does not require paint for modification. It is resistant to insects and is not easily deformed [11, 12]. These characteristics have made WPC widely used in the field of architecture, landscaping, and furniture [13]. In recent years, by regulating the amount of biomass fibers, interface modification, and the length-to-diameter ratio (L/D) of fibers, WPC with different mechanical properties has been prepared [14–16]. To further reduce costs and raise fiber incorporation fractions, Xu et al. revealed the preparation process and molding mechanism of WPC with high wood fiber content from the aspects of rheology and physics [17, 18]. Zhou et al. revealed the effect of increasing wood fiber content on the improvement of the flexural modulus of WPC, which mainly depends on the continuous plastic crust structure on the surface of the WPC [19]. However, the increase in wood fiber content poses great challenges to the interfacial bonding performance between fiber and Matrix [20, 21]. The increase in wood fiber content is prone to fiber aggregation, which causes material defects, deformation, and fracture when subjected to long-term load [22]. In addition, the increase in wood fiber content disrupts the continuous long-chain structure of HDPE, increases the rigidity and brittleness of the material, and is prone to brittle fracture when subjected to impact stress [23]. The dynamic fracture toughness of WPC is a decisive parameter governing their service life and operational safety. Accordingly, exploring the evolution of dynamic fracture toughness of WPC with varying fiber loadings bears significant theoretical and engineering significance [24].

Traditional research on dynamic fractures mainly focuses on macroscopic overall mechanical indicators and fracture characterization, and cannot continuously and visually detect the entire process of dynamic fractures. After the introduction of high-speed DIC, the entire process of

*Corresponding author: Nadzirah Zainordin, School of Architecture and Built Environment, UCSI, Kuala Lumpur, 56000, Malaysia; and Faculty of Built Environment, Universiti Malaysia Sarawak, Kota Samarahan, 94300, Malaysia, E-mail: Nadzirah@ucsiuniversity.edu.my

Liangpeng Yuan and Norshakila Muhamad Rawai, School of Architecture and Built Environment, UCSI, Kuala Lumpur, 56000, Malaysia, E-mail: 1002370271@ucsiuniversity.edu.my (L. Yuan), Norshakila@ucsiuniversity.edu.my (N. Muhamad Rawai)

Guanggong Zong, Art and Design Institute, Yangzhou University, Yangzhou, 225009, China, E-mail: ggong@yzu.edu.cn

dynamic fracture can be visualized in a full-field, transient and continuous manner, making up for the shortcoming that traditional methods cannot capture the transient mesoscopic evolution. In this work, high-density polyethylene (HDPE) featuring superior chemical stability and excellent processability, and abundantly available wood fibers, were utilized to fabricate wood fiber reinforced high-density polyethylene (WPE) composites, and the addition amounts of wood fibers are 0, 20, 50 and 80 wt%. The specimens were tested using a low-speed drop impact machine. During the testing process, DIC was used to collect image data on the dynamic fracture process of WPE affected by the addition amount of wood fiber, specifically involving the analysis of drop impact performance, history and ratio of crack propagation, stress intensity factor, and surface morphology. It attempts to reveal the mechanism of the effect of wood fiber content on damaged WPE during impact fracture and explores the development path of the preparation of WPE composites with high-filled fibers.

2 Materials and methods

2.1 Materials

- (1) high-density polyethylene (HDPE): The raw material is white and granular, with a model of 5000S, a density of $0.949\text{--}0.953\text{ g/cm}^3$, and a melt index of $0.8\text{--}1.1\text{ g/10 min}$ at 190°C . It was purchased from Petro China Daqing Petrochemical Co., Ltd.
- (2) Wood fiber (WF): The 2-mm thick poplar veneer is crushed using a grinder and screened through a 60–80 mesh metal sieve to obtain uniformly shaped poplar powders. The poplar veneer was purchased from Jinan Yuanfang Wood Trading Company.
- (3) Maleic anhydride grafted polyethylene (MAPE): Used for improving the interfacial compatibility between HDPE and wood fiber, with a grafting rate of nearly 1 % and a melt index of $0.7\text{--}0.9\text{ g/10 min}$ at 190°C . It was purchased from Shanghai Rzhisheng New Technology Development Co., Ltd.
- (4) Polyethylene wax (PW): Used as a lubricant for the extrusion of WPE materials during granulation, purchased from Shandong Qilu Petrochemical Engineering Co. Ltd, Zibo.

2.2 Preparation of test pieces

Place the wood fibers in an oven, dry them at 65°C for 48 h until they are dried, and keep them for later use. According

to Table 1, use an electronic balance to weigh the corresponding weight of raw materials and add them to the mixer for pre-stirring. Add the stirred raw materials to the twin-screw granulator for granulation. The processing parameters of granulation are shown in Table 2. According to the ratios of wood fiber addition to the total amount of HDPE, wood fiber, and MAPE (0, 20, 50, and 80 %), each group of specimens was named as WPE0, WPE2, WPE5, and WPE8.

The extruded WPE particles were further crushed using a grinder to obtain uniform particles. Using a metal mold with a size of $150 \times 200 \times 14\text{ mm}$ and a shape of quadrate. The same weight of HDPE and WPE particles were weighed and placed in the mold. After covering the demolding paper and the thermally conductive steel plate, they were treated at 180°C for hot pressing. The pressure was applied at 1.2 MPa for 8 min. During the hot-pressing process, release the pressure 2-3 times for exhaust treatment to avoid material defects caused by residual water vapor. Subsequently, the mold was taken out and placed in a cold press until it was cooled and shaped, followed by demolding treatment to obtain a plate-shaped specimen with uniform thickness and smooth surface. The preparation process and main detection contents are shown in Figure 1.

2.3 Test methods

2.3.1 Sample density measurement

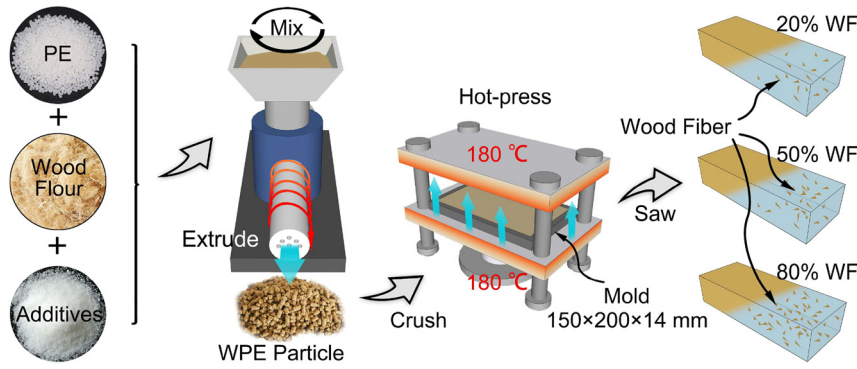
The WPE specimens with different formulations were cut into 5 sample pieces with a size of $20 \times 20 \times 14\text{ mm}$, and the density of each group of specimens was measured by the overflow method. The steps are as follows: (1) Weigh the sample pieces using an electronic balance with an accuracy of 0.001 g . (2) Pour an appropriate amount of distilled water into the measuring cylinder. (3) The sample pieces of each group were immersed in distilled water in turn, and the volume of the WPE sample pieces was converted according to the change of the scale of the measuring cylinder. (4) Calculate the density of each sample piece based on its volume and weight, and take the average value.

Table 1: WPE formula with different wood fiber contents (g).

No.	HDPE	WF	MAPE	PW
WPE0	1,000	0	0	0
WPE2	1,520	400	480	240
WPE5	920	1,000	480	240
WPE8	320	1,600	480	240

Table 2: Processing temperature of WPE granulation.

Temperature of different heating sections (°C)								Feeding speed (kg h ⁻¹)	Extrusion speed (rpm)
1	2	3	4	5	6	7	Nose		
150	160	170	180	180	180	170	170	3	55

**Figure 1:** Preparation process of WPE specimens.

2.3.2 Determination of dynamic elastic modulus and Poisson's ratio

The dynamic elastic modulus and Poisson's ratio of different types of WPE materials were measured in a non-destructive manner using a UMS-100 ultrasonic echo test system. The measurement system applied a longitudinal wave to the WPE material through the Teclab #L-5-3 (5 MHz) ultrasonic transducer and applied a transverse wave to the WPE material through the Teclab #L-5-3 (5 MHz) ultrasonic transducer, with five repeated samples in each group. Subsequently, the data processing software UMSOFT V5.0 was used to determine the longitudinal and transverse wave velocities inside the WPE material, while the elastic modulus (E_d) and Poisson's ratio (ν_d) of the WPE material can be calculated using formulas (1) and (2), respectively. By measuring the longitudinal and transverse wave velocities in the solid, the elastic modulus (E_d) and Poisson's ratio (ν_d) of the solid material can be obtained using the above equations. The specific calculation formula is as follows:

$$E_d = \frac{(3Q^2 - 4)\rho C_s^2}{Q^2 - 1} \quad (1)$$

$$\nu_d = \frac{Q^2 - 2}{2(Q^2 - 1)} \quad (2)$$

2.3.3 Test of dynamic fracture toughness

(1) Preparation of test pieces

Different WPE materials were cut into $64 \times 28 \times 14$ mm for the test of dynamic fracture performance. A 1-mm blade was used to cut a notch with a depth of 13–14 mm in the middle of the specimen, and a 0.5-mm blade was further used to process an initial notch with a depth of 1 mm at the top of the gap. After spraying the surface of the test pieces with white self-spraying paint, an oily black marking pen was used to draw speckles on the surface of the test pieces, and the cross of the speckles was strictly avoided during the drawing process. The size and style of the specimen are shown in Figure 2, which also depicts the coordinate system of the crack tip for dynamic parameter determination and with a 25×25 mm² dashed box representing the region of interest (ROI).

(2) Experimental setup and program test

According to ASTM D7136-2005, the Instron CEAST 9350 testing machine was used to conduct low-speed drop hammer impact on the test pieces, and five repeated samples in each group. The diameters of the loading roll punch and the backup roll were 8 mm and 4 mm respectively, and the impact energy was set to 10 J, 20 J, and 30 J. There are random speckle patterns on the surface of the specimen. The surface deformation of the specimen during the fracture process was captured by using high-speed imaging technology. As shown in Figure 3, the surface of the specimen was illuminated with a high-power flash lamp, and the deformation of speckles during the whole fracture process was recorded by the Photron Fastcam SA-Z high-speed camera. The whole process from the impact head first contacting the surface of

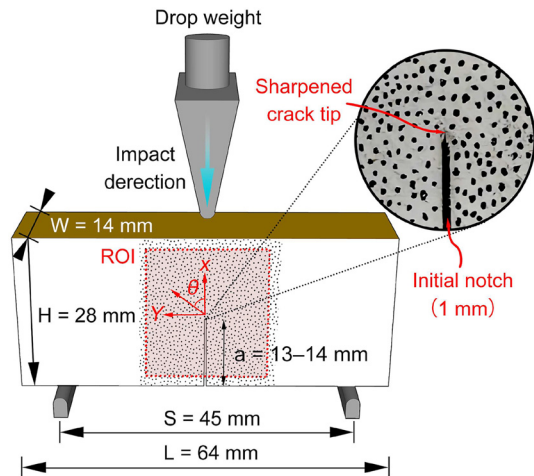


Figure 2: The pattern of dynamic fracture of the WPE specimens.

the specimen to the final damage of the specimen was recorded at a speed of 100,000 frames per second. Other specimens were tested while maintaining the same frame frequency. The speckles of the un-deformed state, the deformed state, and the subsequent deformed state are paired and correlated in turn. Therefore, two displacement components (u , v) on the specimen surface can be evaluated.

(3) Performance analysis of drop hammer impact test

By adjusting the loading weight of the Instron CEAST 9350 testing machine, dynamic fracture performance tests were conducted on specimens with different impact strengths (10 J, 20 J, 30 J). Through the experimental data collector, the data of impact energies, impact strengths, and impact displacements of each group of specimens with the change of impact fracture time were obtained.

(4) Evaluation of crack propagation rate and propagation history

The initial frame of crack generation was determined by comparing the stress diagrams, and the stress diagram of the whole process was selected at an interval of 10 frames (ten-thousandths of a second), as shown in Figure 4. By using Photoshop software, with the width of the specimen as the reference value, it was determined that the image of the time-varying stress field was consistent with the actual ratio of sample size. The curve measurement tool in Photoshop software is used to measure along the crack edge of the specimen from the starting point to the crack tip, and the corresponding statistics of the instantaneous propagation history of cracks in each frame of the stress field images were completed. Based on this data, the calculation of crack propagation rate was completed. The real-time crack propagation rate on the surface of WPE material (V) is:

$$V = \frac{L}{t_{i+1} - t_i} \quad (3)$$

(5) DIC analysis and evaluation

DIC, also known as Digital Speckle Correlation, is a non-contact image measurement technology that applies computer vision technology. The basic principle is to obtain the displacement vector of the same pixel in the speckle image before and after the deformation of the object surface by tracking or matching the position information of the same pixel, and then obtain the full field displacement of the entire sample surface from place to place. The principle is shown in Figure 5. Firstly, there needs to be a random speckle pattern on the imaging surface of the sample block under test, which can reflect the deformation. Then, during the testing process, the speckle distribution on the surface of the specimen after loading and deformation is recorded and stored in a computer. Finally, the displacement field information on the surface of the specimen is obtained using

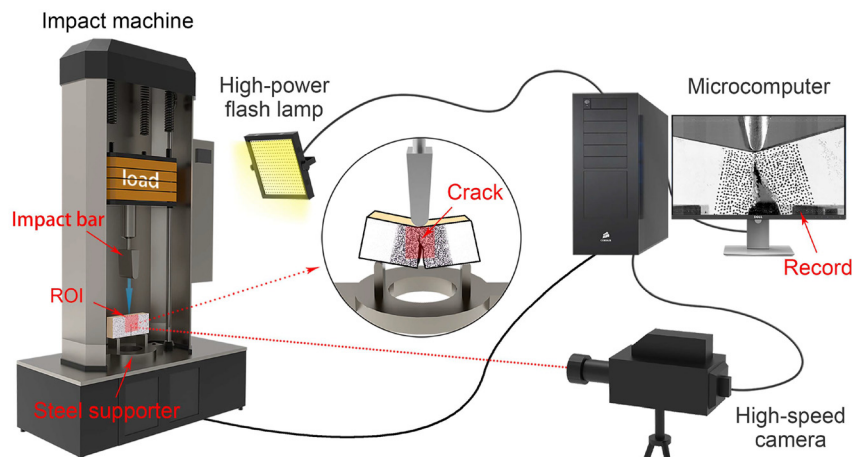


Figure 3: Dynamic fracture test process of WPE specimens.

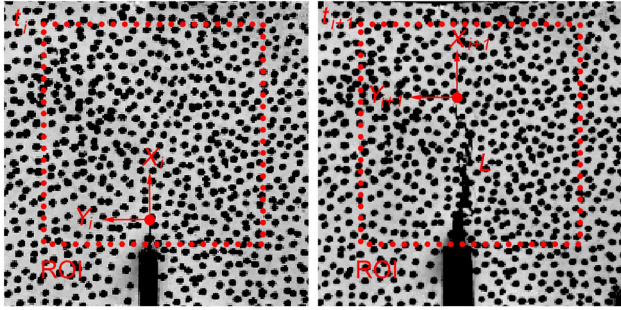


Figure 4: The propagation process of the crack tip of the initial notch on the surface of the WPE specimens.

relevant mathematical algorithms using the Vic-2D 6 image analysis software (Correlated Solutions, Inc., SC, USA). Figure 6 is representative speckle images and stress field images.

By performing the analysis of multi-point least squares on the orthogonal displacement data of the crack tip extracted from each photo, the real-time mode I and mode II stress intensity factors (SIFs) of the material can be solved, and the influence history of mode I and mode II SIFs of the sample pieces during the entire dynamic fracture process can be finally obtained. The asymptotic expression for the control of the orthogonal displacement field (u, v) near the crack tip of the initial notch in the sample pieces before cracking can be expressed as:

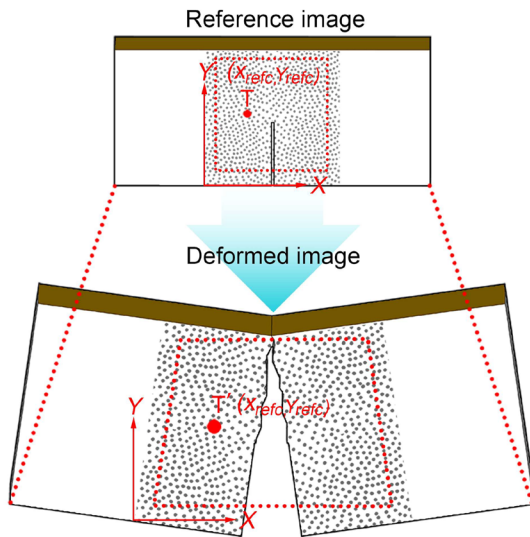


Figure 5: The reference speckle pattern and the deformed speckle pattern of WPE specimens.

$$\begin{aligned} \begin{Bmatrix} u(r, \theta) \\ v(r, \theta) \end{Bmatrix} &= \sum_{n=1}^N \frac{(K_I^d)_n}{2\mu} \frac{r^{n/2}}{\sqrt{2\pi}} \\ &\times \begin{Bmatrix} k \cos \frac{n}{2}\theta - \frac{n}{2} \cos \left(\frac{n}{2} - 2 \right) \theta + \left\{ \frac{n}{2} + (-1)^n \right\} \cos \frac{n}{2}\theta \\ k \sin \frac{n}{2}\theta + \frac{n}{2} \sin \left(\frac{n}{2} - 2 \right) \theta - \left\{ \frac{n}{2} + (-1)^n \right\} \sin \frac{n}{2}\theta \end{Bmatrix} \\ &+ \sum_{n=1}^N \frac{(K_{II}^d)_n}{2\mu} \frac{r^{n/2}}{\sqrt{2\pi}} \begin{Bmatrix} k \sin \frac{n}{2}\theta - \frac{n}{2} \sin \left(\frac{n}{2} - 2 \right) \theta + \left\{ \frac{n}{2} + (-1)^n \right\} \sin \frac{n}{2}\theta \\ -k \cos \frac{n}{2}\theta - \frac{n}{2} \cos \left(\frac{n}{2} - 2 \right) \theta + \left\{ \frac{n}{2} - (-1)^n \right\} \cos \frac{n}{2}\theta \end{Bmatrix} \\ &+ \begin{Bmatrix} Pr \cos \theta + Qr \sin \theta + u_{0x} \\ Pr \cos \theta + Qr \sin \theta + v_{0y} \end{Bmatrix} \end{aligned} \quad (4)$$

Among them,

$$k = \frac{3 - \nu_d}{1 + \nu_d}$$

$$u = \frac{C_s^2}{\rho}$$

Where, (θ) is the real-time polar coordinates established at the crack tip, k and μ are the in-plane stress and shear modulus, ρ and θ are the parameters of rigid body rotation, u_{0x} and v_{0y} are the rigid body displacement along x-axis and y-axis, respectively. In the main terms of equation (4), when $n = 1$, K_I^d and K_{II}^d respectively represent the mode I and mode II dynamic stress intensity factors during the dynamic fracture process of the WPE sample pieces. Once the crack begins to propagate, the asymptotic expression for the control of the orthogonal displacement field (u, v) during the stable propagation stage is:

$$\begin{aligned} \begin{Bmatrix} u(r, \theta) \\ v(r, \theta) \end{Bmatrix} &= \sum_{n=1}^N \frac{(K_I^d)_n B_I(V)}{2\mu} \sqrt{\frac{2}{\pi}} (n+1) \\ &\times \begin{Bmatrix} r_1^{n/2} \cos \frac{n}{2}\theta_1 - h(n) r_2^{n/2} \cos \frac{n}{2}\theta_2 \\ -\beta_1 r_1^{n/2} \sin \frac{n}{2}\theta_1 + \frac{h(n)}{\beta_2} r_2^{n/2} \sin \frac{n}{2}\theta_2 \end{Bmatrix} \\ &+ \sum_{n=1}^N \frac{(K_{II}^d)_n B_{II}(V)}{2\mu} \sqrt{\frac{2}{\pi}} (n+1) \\ &\times \begin{Bmatrix} r_1^{n/2} \sin \frac{n}{2}\theta_1 - h(\bar{n}) r_2^{n/2} \sin \frac{n}{2}\theta_2 \\ \beta_1 r_1^{n/2} \cos \frac{n}{2}\theta_1 + \frac{h(\bar{n})}{\beta_2} r_2^{n/2} \cos \frac{n}{2}\theta_2 \end{Bmatrix} \\ &+ \begin{Bmatrix} Pr \cos \theta + Qr \sin \theta + u_{0x} \\ Pr \cos \theta + Qr \sin \theta + v_{0y} \end{Bmatrix} \end{aligned} \quad (5)$$

Among them,

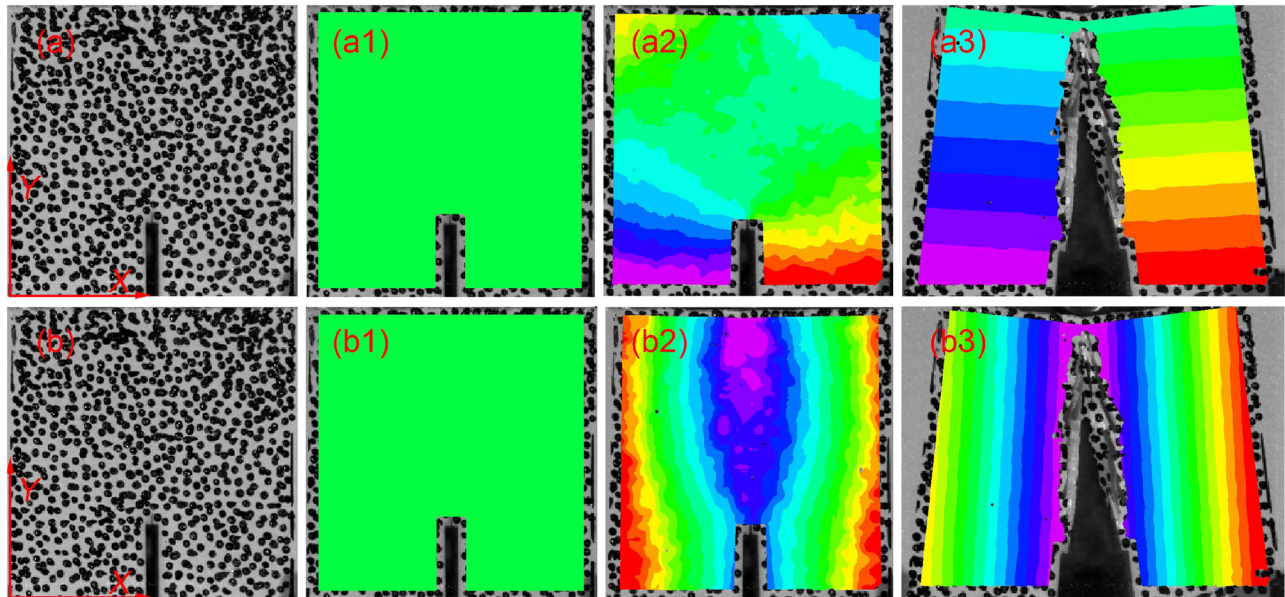


Figure 6: Stress field distribution diagram. (a) WPE0 speckle and displacement field pattern; (b) WPE2 speckle and crack propagation pattern.

$$r_m = \sqrt{x^2 + \beta_m^2 y^2}, \theta_m = \tan^{-1}\left(\frac{\beta_m y}{x}\right), m = 1, 2$$

$$\beta_1 = \sqrt{1 - \left(\frac{V}{C_L}\right)^2}, \beta_2 = \sqrt{1 - \left(\frac{V}{C_S}\right)^2}, B_I(V) = \frac{1 + \beta_2^2}{D}, B_{II}(V) = \frac{2\beta_2}{D},$$

$$D = 4\beta_1\beta_2 - (1 + \beta_2^2)^2$$

$$h(n) = \begin{cases} \frac{2\beta_1\beta_2}{1 + \beta_2^2} & \text{for odd } n \\ \frac{1 + \beta_2^2}{2} & \text{for even } n \end{cases} \quad \text{and } h(\bar{n}) = h(n + 1)$$

In the equation, (x, y) is the Cartesian coordinate system established for the real-time crack tip propagation. Similarly, in the main terms of equation (5), when $n = 1$, K_I^d and K_{II}^d respectively represent the mode I and mode II dynamic SIFs during the dynamic fracture process of the WPE sample pieces.

2.3.4 Surface micro-topography

The sample is frozen with liquid nitrogen and rapidly brittle fractured, and the sample pieces were fixed on the sample stage with conductive adhesive for gold spraying. Then the microstructure of the cross-section was observed using a FEI Quantum 200 scanning electron microscope under an accelerating voltage of 30 kV.

3 Results and discussion

3.1 Dynamic elastic modulus and Poisson's ratio

The density, number of transverse waves, number of longitudinal waves, elastic modulus, and Poisson's ratio of different WPE materials were obtained by drainage method and ultrasonic echo method (Table 3). Based on the above data, according to Formulas (4) and (5), the mode I and mode II SIFs of different WPE materials before and after the propagation of the initial notch under 3P-END impact loading conditions can be calculated by self-programming.

3.2 Analysis of dynamic impact performance

The force-time curves of WPE materials with different wood fiber contents are shown in Figure 7 (a1), (a2), and (a3). The trend of force-time curves of WPE specimens with different wood fiber contents is similar under the impact energies of 10, 20, and 30 J, and there are two stages of peak forces. As the content of wood fiber increases, the occurrence of the initial peak force gradually advances. At the maximum impact energy of 30 J, the generation time of the initial peak force tends to converge. However, the maximum peak force reached by the WPE8 specimen at the earliest time under three different impact energies indicates that the introduction of wood fiber effectively enhances the rigidity of the WPE material. In the initial stage of the specimen's impact

Table 3: Performance parameters determined by ultrasonic echo method for WPE specimens with different wood fiber.

No.	Maximum density ρ_d (kg/m ³)	Longitudinal wave number C_L (m/s)	Transverse wave number C_S (m/s)	Elastic modulus E_d (GPa)	Poisson's ratio ν_d
WPE0	0.953	2,341	986	0.75	0.37
WPE2	0.885	2,154	872	0.53	0.34
WPE5	0.752	1,768	654	0.61	0.25
WPE8	0.767	1,234	487	0.67	0.28

fracture, the presence of more wood fiber has a better crack suppression effect. As the impact strength increases, the generation time of the second peak force of each group of specimens approaches. Although WPE0 specimens generally have higher peak forces under the three impact energies, it can still be observed that as the wood fiber content increases, the peak forces of WPE2, WPE5, and WPE8 gradually increase. In addition, compared with WPE0 specimens, WPE2, WPE5, and WPE8 exhibit greater data fluctuations during the impact fracture stage, which may be attributed to the fact that the introduction of wood fiber breaks the uniform structure of polyethylene materials. The random presence of wood fiber produces varying degrees of crack suppression during the fracture process of the specimen, which in turn requires greater impact force to cause the fracture.

The energy-time curves of WPE with different wood fiber contents are shown in Figure 7 (b1), (b2), and (b3). Under different impact energies, the impact energy of WPE materials exhibits different characteristics with the increase of wood fiber content. Taking the impact energy of 10 J as an example, the maximum energy of the WPE0 specimen reached 9.99 J and stabilized after 7.71 ms. When the wood fiber content reaches 80 %, its maximum impact energy is 1.96J, which is only about 20 % of the maximum energy of the WPE0 specimen. This peak has already been reached at 5.23 ms, which implies that the introduction of wood fiber leads to a decrease in the toughness of WPE materials, thereby absorbing the maximum destructive energy in a shorter period. From Figure 6 (b2), it can be observed that with the increase of wood fiber content, WPE materials absorb greater impact energy at a similar time, indicating that the introduction of wood fiber requires WPE materials to absorb greater impact energy during impact fracture. However, combined with the decreasing trend of impact energy in Figure 6 (b3), it indicates that there is a threshold for the energy absorption effect generated by the increase in wood fiber content.

The displacement-time curves of WPE specimens with different wood fiber contents are shown in Figure 7 (c1), (c2), and (c3). From the figure, it can be seen that as the wood fiber content increases, the impact displacement of WPE

specimens gradually decreases, and the displacement of WPE specimens with 80 % wood fiber content is the least in each group. The above data shows that as the wood fiber content increases, the displacement generated by the fracture gradually decreases, which may be because wood fiber, as a rigid filler, increases the overall stiffness of WPE materials. When subjected to impact, WPE materials with high wood fiber content respond more quickly due to their increased stiffness, leading to their shortest displacement length at failure in a relatively short period.

3.3 Analysis of crack propagation rate and propagation history

The crack propagation rate of WPE materials with different wood fiber contents is shown in Figure 8. From the figure, it can be seen that under the impact energies of 10 J, 20 J, and 30 J, the introduction of wood fiber causes the peak value of the initial notch propagation rate to appear earlier. The crack propagation rates of the WPE2 group and the WPE0 group were similar under three different impact energies. By observing the crack propagation rates of WPE2, WPE5 and WPE8 under three different impact energies, it can be observed that with the increase of wood fiber content, the initial notch propagation rate shows an increasing trend. When the fiber content was 80 % (WPE8), the maximum crack propagation rate at the initial stage (0–10 frames) under three different impact energies, which were 4.61, 10.49, and 6.64 mm/frame, respectively. Compared to the blank specimen in the same group, the initial notch propagation rate was 26, 153, and 16 times that of the WPE0 specimen. Polyethylene resin, as an elastic body, has a certain impact space to withstand damage, and when the impact displacement continues to deepen, it can produce a large bending displacement, thereby delaying the occurrence of fracture failure. Although the addition of wood fibers can retard crack propagation, it simultaneously accelerates the internal stress transfer rate of the composite system. Especially for composites with high wood fiber content, the adverse effect of accelerated crack propagation far outweighs the fiber-induced crack-blocking

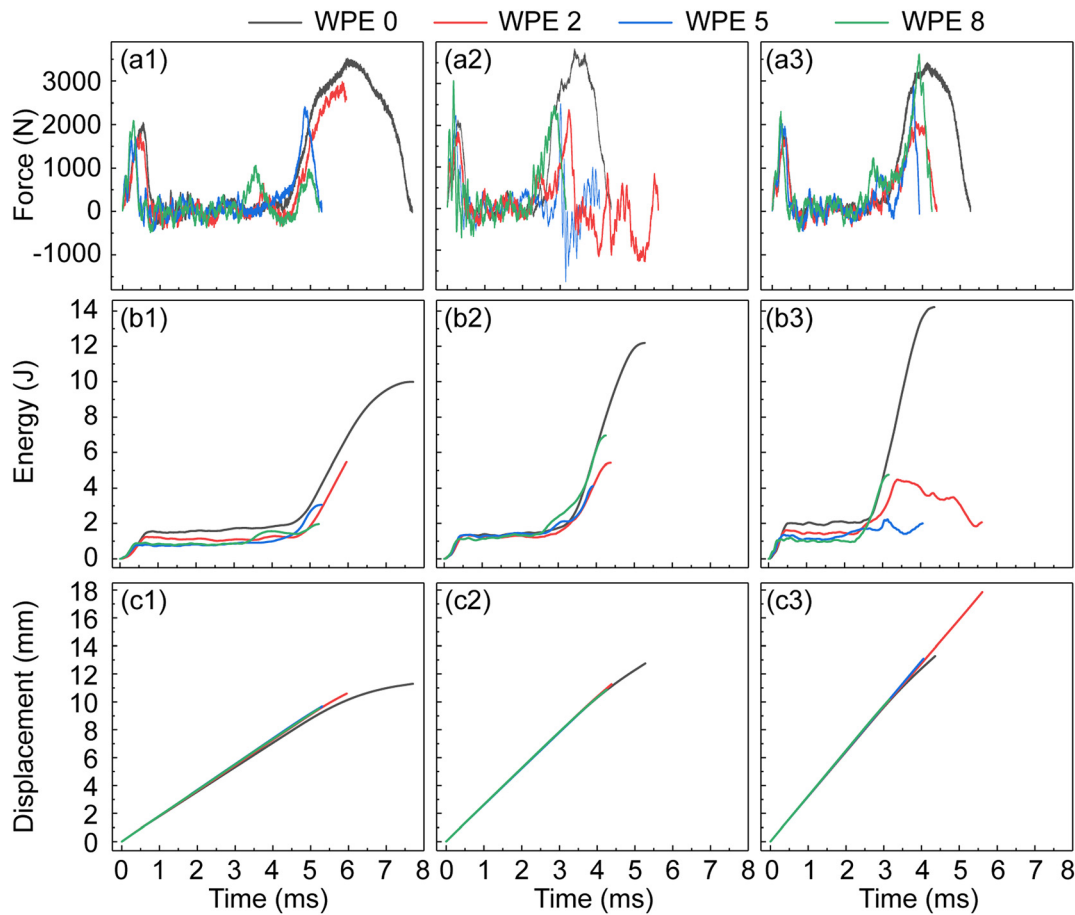


Figure 7: Displacement-time, energy-time, and displacement-time curves of WPE specimens with different wood fiber contents. (a1) (b1) (c1) Impact energy of 10 J; (a2) (b2) (c2) Impact energy of 20 J; (a3) (b3) (c3) Impact energy of 30 J.

effect. This phenomenon arises from abundant weak interfacial layers formed between densely packed fibers at high filler fractions, after stress is transmitted through the wood fiber phase, cracks rapidly propagate along these weak inter-fiber boundaries. Thus, when the specimen is subjected to impact force, although the WPE8 specimen can withstand a greater impact force during the initial notch propagation stage, it also causes material defects, which easily leads to stress concentration at the location where wood fiber agglomerates, thereby increasing the initial notch propagation rate. As the impact energy increases, the greater the impact force causes specimens to generate stress response faster, and the peak of crack propagation rate in each group of specimens gradually advances.

The crack propagation history of WPE materials with different wood fiber contents is shown in Figure 9. The initial notch propagation length of WPE0 with an impact energy of 10 J is 0.90 mm. When the wood fiber content increases, the initial notch propagation lengths of WPE2 and WPE5 are 1.48 mm and 1.37 mm, respectively, which are similar to those

of pure polyethylene samples. However, the initial notch propagation length of WPE8 specimens containing 80 % wood fiber increased to 9.20 mm, which is much higher than other samples. This phenomenon indicates that higher wood fiber content increases the brittleness of the material, which is not conducive to WPE materials for bearing instantaneous impact force. The maximum crack propagation lengths of the WPE8 specimens were 18.17 mm (10 J), 15.33 mm (20 J), and 17.52 mm (30 J), respectively, which were the highest values in each group. Although WPE8 specimens have a higher initial notch propagation rate and the shortest impact fracture time, they have the longest crack propagation history. The presence of fibers effectively prolongs the formation of cracks. When the specimen fractures, it is obstructed by rigid wood fiber, resulting in a longer crack propagation path. With the increase in wood fiber content, it may lead to fiber aggregation, Such fiber aggregation may form micro-defects in the material, which can become the starting point of cracks under stress, leading to an increase in the initial notch propagation rate and propagation history.

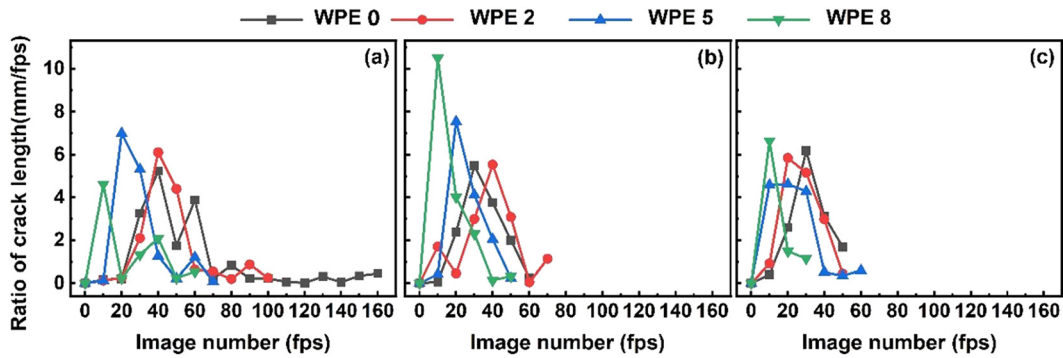


Figure 8: Crack propagation rate of WPE specimens with different wood fiber contents. (a) Impact energy of 10 J; (b) Impact energy of 20 J; (c) Impact energy of 30 J.

3.4 Stress intensity factors analysis

The influence of mode I and mode II SIFs of WPE materials with different wood fiber contents are shown in Figure 10. As shown in Figure 10 (a1), (b1), and (c1), all specimens showed an increasing trend in the mode I SIFs before the onset of the propagation of initial notch ($t-t_i < 0$) and after the onset of the propagation of initial notch ($t-t_i > 0$). The initial frame is defined as the time when the initial notch begins to propagate ($t-t_i = 0$), and frames 0–10 belong to the initial stage. Under the impact energy of 10 J, the influence factor of the WPE8 specimen containing 80 % wood fiber reached $2.32 \text{ MPa m}^{1/2}$ at the 10th frame, which is 4.7 times that of the WPE0 specimen. And reached a peak of $4.88 \text{ MPa m}^{1/2}$ at the 50th frame, which is the maximum value within the group. Based on the data in Figure 9, a higher mode I stress intensity factor indicates an increase in crack propagation resistance. However, a higher mode I stress intensity factor is correlated with a longer crack propagation history, indicating that although the introduction of 80 % wood fiber causes an increase in material brittleness, it has a certain barrier effect on the propagation of crack tips. As the impact energy increases, the WPE specimens with wood fiber have higher

mode I SIFs compared to the WPE0 specimen, further indicating that wood fiber can form a certain resistance at the crack tip through rigid wood fiber during the process of increasing impact capacity.

As shown in Figure 10 (a2), (b2), (c2), although there is a small fluctuation in the values of the mode II SIFs compared to the mode I SIFs, the average values of the SIFs for each group corresponding to different impact energies are 0.047, 0.085, and $0.043 \text{ MPa m}^{1/2}$, respectively. The curve is flat. The failure mode of WPE specimens is still dominated by a cracking mode perpendicular to the stress direction. As the amount of wood fiber added increases, each group of specimens exhibits similar characteristics under different impact energies, and the crack shear propagation mode parallel to the stress direction can be ignored.

3.5 Microscopic morphology of fracture surface

The morphology of the impact fracture surface of WPE materials with different wood fiber contents is shown in Figure 11. Polyethylene is a kind of widely used

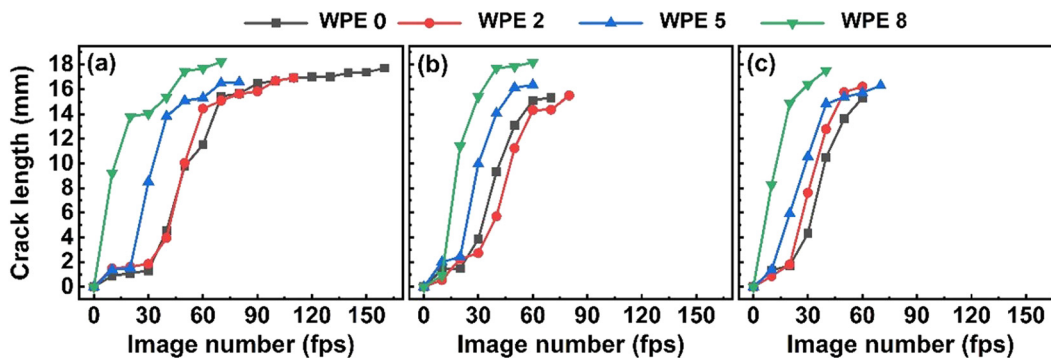


Figure 9: Crack propagation history of WPE specimens with different wood fiber contents. (a) Impact energy of 10 J; (b) Impact energy of 20 J; (c) Impact energy of 30 J.

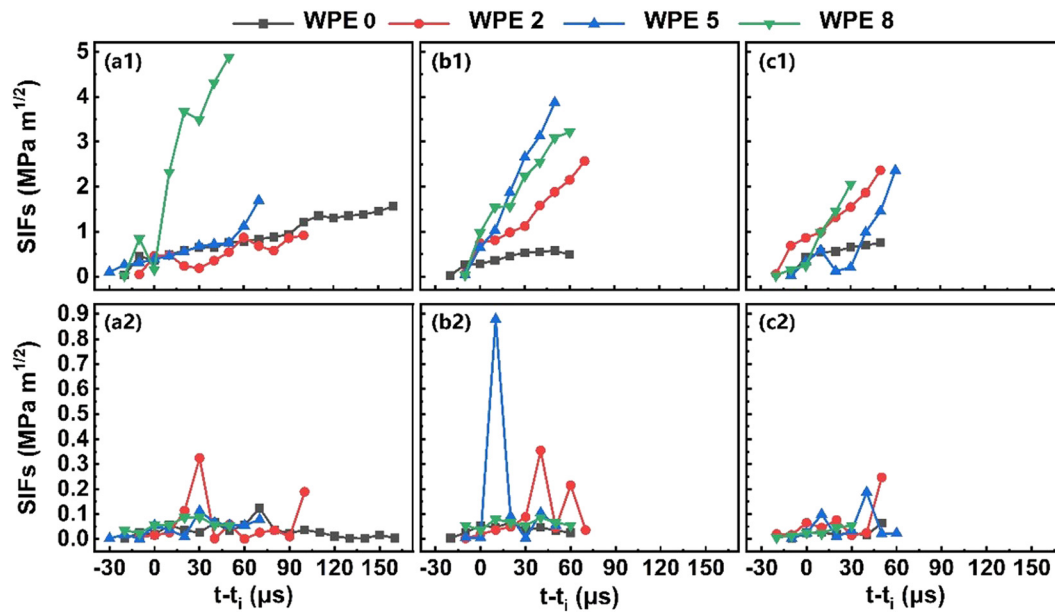


Figure 10: Influence of mode I and mode II SIFs of WPE specimens with different wood fiber contents. (a) Impact energy of 10 J; (b) Impact energy of 20 J; (c) Impact energy of 30 J.

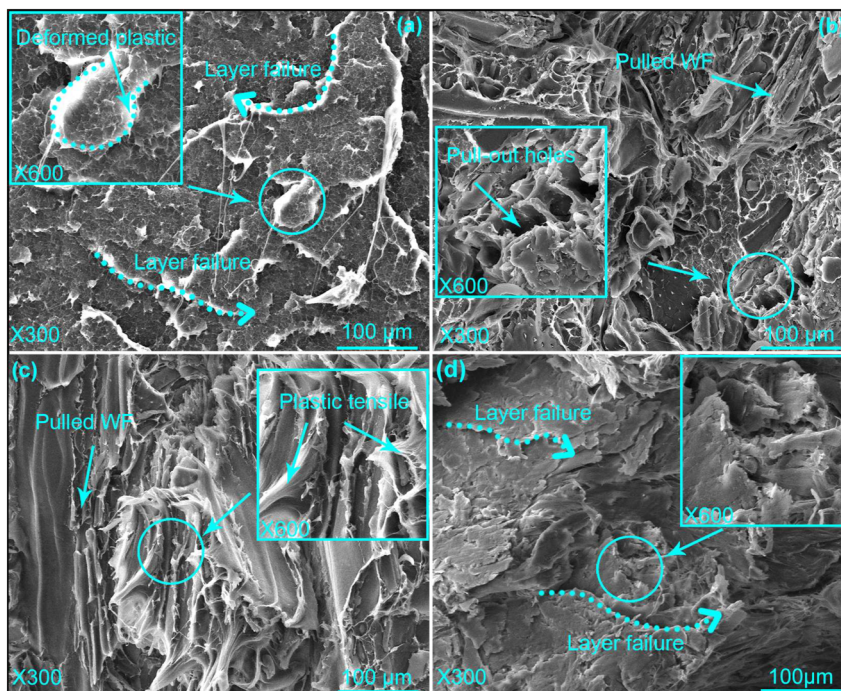


Figure 11: The morphology of impact fracture surface of WPE specimens with different wood fiber contents. (a) WPE0; (b) WPE2; (c) WPE5; (d) WPE8.

thermoplastic polymer. According to the scanning electron microscope images, the fracture surface of PE exhibits typical ductile fractures, characterized by irregular and rough surface morphology, which indicates the plastic deformation that the material undergoes before fracture (Figure 11(a)). In addition, the appearance of filamentous textures in some areas of the plastic matrix further confirms

the plastic deformation, which is caused by the propagation of molecular chains.

The fracture surface of WPE2 specimens with 20 % wood fiber was observed by scanning electron microscopy (Figure 11(b)). The obvious pull-out phenomenon between the PE matrix and wood fiber may be related to interfacial compatibility. The interface between wood fiber and PE is

bridged by MAPE, which can enhance the interfacial bonding performance of the two materials. Nevertheless, tiny voids and fiber-pull-out structures in certain areas can still be observed, which may be related to the uneven distribution of interface modifiers.

From Figure 11(c), it can be seen that WPE5 specimens with 50 % wood fiber exhibit obvious wood fiber particles, displaying a denser distribution than WPE2. Although the particle sizes of wood fiber in the two materials are similar, the distance between wood fiber particles is smaller due to the higher content of wood fiber in WPE5, increasing the interface bonding area. Although both groups of materials were added with the same amount of MAPE, WPE5 exhibited more interfacial failure in certain areas than WPE2, which is possibly due to the stress concentration caused by higher wood fiber content. In addition, the shorter filamentous texture of polyethylene can be observed in the WPE5 specimen than in the WPE0 specimen, which may be related to the reduced plastic deformation ability of the material.

WPE8 specimens with 80 % wood fiber were observed by scanning electron microscopy (Figure 11(d)), compared to the other three groups of specimens, the fracture surface of the WPE8 specimens exhibited more breakages and pores, but no obvious filamentous texture of polyethylene formed by tensile force was observed. This may be because the addition of 80 % wood fiber increases the rigidity of WPE materials, which are mostly brittle during impact fracture. The fiber morphology that is not wrapped by polyethylene resin can be seen locally, which is also prone to causing cracks when the material is subjected to impact loads, resulting in a higher crack propagation rate in the initial stage of impact fracture.

4 Conclusions

This study conducted a detailed investigation into the dynamic mechanical properties of wood fiber/high-density polyethylene (WPE) composites and emphasized the significant role of wood fiber content in shaping the impact performance, fracture behavior and microstructure characteristics of the materials. The conclusions are as follows:

- (1) As the wood fiber content increases, the initial peak force under impact loading shifts forward, indicating a faster material response and greater initial stiffness and the composite material transitions to be harder but more brittle. This behavior was most obvious in the WPE8 samples, the total impact fracture time of WPE8 is the shortest, but the crack propagation process is the longest. At 10 J, the crack propagation length of WPE8 is

9.20 mm, which is much longer than that of other specimens.

- (2) The analysis of mode I stress intensity factors (SIFs) shows that with the increase of impact energy, all WPE composites exhibit rising mode I SIF values, and WPE8 reaching $2.32 \text{ MPa m}^{1/2}$ at 10 J – 4.7 times higher than WPE0, indicating that high-filled fibers make the composite materials have a stronger ability to resist crack propagation.
- (3) Microstructure observations indicate that with increasing wood fiber content, WPE composites transition from ductile, plastic deformation to rigid, brittle deformation. Moreover, when the fiber content is extremely high, the interfacial interaction is very poor and shows the extreme brittleness of the composites.

This work characterized the mechanical damage of wood-plastic composites (WPCs) via digital image correlation (DIC), and several limitations of the present study should be clarified. Limited loading conditions and fiber modification variables were adopted in the experiments, only surface strain fields of specimens were captured, without dynamic DIC observation under practical service environments such as humidity, heat and low temperature. Further research can expand multi-condition coupling tests and combine microscopic characterizations to supplement the damage mechanism.

Research ethics: Not applicable.

Informed consent: Not applicable.

Author contributions: Conceptualization, Nadzirah Zainordin, Liangpeng Yuan; methodology, Norshakila Muhamad Rawai, Liangpeng Yuan and Guanggong Zong; investigation, Nadzirah Zainordin, Norshakila Muhamad Rawai; writing – original draft preparation, Liangpeng Yuan, Guanggong Zong; software, Guanggong Zong, Liangpeng Yuan; writing – review and editing, Nadzirah Zainordin, Guanggong Zong. All authors have accepted responsibility for the entire content of this manuscript and approved its submission.

Use of Large Language Models, AI and Machine Learning Tools: None declared.

Conflict of interest: The authors state no conflict of interest.

Research funding: None declared.

Data availability: The authors confirm that the data supporting the findings of this study are available within the article.

References

1. Radzuan MAN, Samudin MI, Sereshk VRM, Ma Q, Sulong AB, Foudzi FM, et al. A comprehensive approach for the production of carbon fibre-

- reinforced polylactic acid filaments with enhanced wear and mechanical behaviour. *E-Polymers* 2025;25:20250002.
2. Jin X, Zhang J, Liu C, Gao X, Luo X, Qi S, et al. Influence of stitching parameters on the tensile performance and failure mechanisms of CFRP T-joints. *E-Polymers* 2025;25:20250061.
 3. Hosseini M, Gaff M, Wei Y, Tu C. Engineered bamboo building materials: types, production, and applications. *Forests* 2025;16:662.
 4. Booramurthy D, Jaganathan M, Manickam R. Experimental investigation of properties and aging behavior of pineapple and sisal leaf hybrid fiber-reinforced polymer composites. *E-Polymers* 2023;23.
 5. Hosseini M, Gaff M, Lair J, Hui D, Li H, Hosseini A, et al. Design and analysis of timber-concrete-based civil structures and its applications: a brief review. *Rev Adv Mater Sci* 2023;62:20220321.
 6. Manickam R, Narasimhan LR, Nagarajan S, et al. Influence of filler material on properties of fiber-reinforced polymer composites: a review. *E-Polymers* 2022;22:898–916.
 7. Michalak AJ, Sandak J, Hejna A, Barczewski M. Evaluation of the effectiveness of black tea leaves wastes as phytochemical-rich plant fillers and natural antioxidant in polyethylene. *E-Polymers* 2026;26: 20250099.
 8. Norihan A, Khalina A, Muhammad HMR, et al. Properties of kenaf fiber-reinforced polyamide 6 composites. *E-Polymers* 2024;24:20228112.
 9. Siddiqui NM, Redhwi HH, Andradý LA, Furquan SA, Hussain S. Effect of extensive solar ultra-violet irradiation on the durability of high-density polyethylene- and polypropylene-based wood-plastic composites. *Polymers-Basel* 2024;17:74.
 10. Jiang R, Xu Y, Yang X, Zhang L, Fan Z, Guo X, et al. The effect of colorants on the degradation performance of wood plastic composites. *Wood Res-Slovakia* 2024;69:671–82.
 11. Ghorbani M, Aghmashadi Z, Amininasab S, Abedini R. Effect of different coupling agents on chemical structure and physical properties of vinyl acetate/wood polymer composites. *J Appl Polym Sci* 2019;136:47467.
 12. Chatree H, Chainarong S, Surasit R, et al. Performance of wood-plastic composites manufactured from post-consumer plastics and wood waste under coastal weathering in Thailand. *Fiber Polym* 2022;23: 2679–93.
 13. Teuber L, Osburg V, Toporowski W, Militz H, Krause A. Wood polymer composites and their contribution to cascading utilization. *J Clean Prod* 2016;110:9–15.
 14. Hosseini M, Gaff M, Wei Y, Konvalinka P, Joshua J, Hosseini A, et al. Effect of silane treatment on mechanical performance in Kevlar/jute hybrid composites- an experimental investigation. *E-Polymers* 2026;26: 20250029.
 15. Feng Y, Yuan Z, Sun H, He H, Zhang G. Toughening and reinforcing wood flour/polypropylene composites with high molecular weight polyethylene under elongation flow. *Compos Sci Technol* 2020;200: 108395.
 16. Mollah MZI, Miah MS, Akram MW, Mahmud SH, Faruque MRI, Al-mugren KS. Thermoplastic-polymer matrix composite of banana/betel nut husk fiber reinforcement: physico-mechanical properties evaluation. *E-Polymers* 2024;24:20230158.
 17. Tang W, Xu J, Qi F, Li W, Zhou H, Liu T, et al. Rheological behavior and mechanical properties of ultra-high-filled wood fiber/polypropylene composites using waste wood sawdust and recycled polypropylene as raw materials. *Constr Build Mater* 2022;351:128977.
 18. Xu J, Hao X, Huang S, Chen C, Fan Q, Sun L, et al. Synergistic improvement of mechanical, creep, and dimensional stability in ultra-highly filled wood Fiber/Polyethylene composites using multimodal alloy matrices. *Compos A-Appl S* 2025;193:108830.
 19. Zhou H, Li W, Hao X, Zong G, Yi X, Xu J, et al. Recycling end-of-life WPC products into ultra-high-filled, high-performance wood fiber/ polyethylene composites: a sustainable strategy for clean and cyclic processing in the WPC industry. *J Mater Res Technol* 2022;18: 1–14.
 20. Sriwan K, Chainarong S, Santi K. Effects of natural fiber waste, content, and coupling agent on the physical and mechanical properties of wood species-plastic composites as green materials. *Fiber Polym* 2024;25: 1391–402.
 21. MB, PSS, Suresh S. Influence of fiber length, fiber content and alkali treatment on mechanical properties of natural fiber-reinforced epoxy composites. *Polimery-W* 2019;64:93–9.
 22. Basiji F, Erchiqui F, Koubaa A, Ghasemi I, Baatti A. Impact of fiber morphology and content on the thermal stability, and mechanical performance of maple wood fiber-polypropylene composites. *J Appl Polym Sci* 2025;142:e57211.
 23. Ghanbari A, Madhoushi M, Ashori A. Wood plastic composite panels: influence of the species, formulation variables and blending process on the density and withdrawal strength of fasteners. *J Polym Environ* 2014; 22:260–6.
 24. Khan M, Srivastava SK, Gupta M. A state-of-the-art review on particulate wood polymer composites: processing, properties, and applications. *Polym Test* 2020;89:106721.