Effect of Temperature on the Uniaxial Tensile Properties of Wood Plastic Composites: Experimental Investigation and Numerical Analysis

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Seven groups of uniaxial tensile experiments on wood plastic composites with a High Density Polyethylene (HDPE) matrix at different temperatures were completed in this paper. The test temperatures ranged from -60 °C to 60 °C, with a temperature difference of 20 °C for each group. All samples exhibited tensile brittle fracture. The test results showed that the tensile strength of the specimens decreased continuously with increasing temperature. Taking 0 °C as the reference temperature, the ultimate strength of the sample at -60 °C was 1.63 times that at 0 °C. When the temperature was 60 °C, this value was 0.41. Then, it can be calculated that the ratio of the strength of the sample at -60 °C to that at 60 °C was approximately 3.93, and the corresponding ratio of the elastic modulus was approximately 4.52. This shows that the mechanical properties of WPC are sensitive to changes in temperature. The variation coefficient of the average strength and elastic modulus of WPC for different specimens at different temperatures was less than 0.17, showing good stability due to the small dispersion of mechanical properties among different samples at any specific temperature.

DOI: 10.15376/biores.19.3.4547-4554

Keywords: Uniaxial tensile test; Different temperatures; Mechanical property; Coefficient of variation

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INTRODUCTION

Wood plastic composites (WPCs) are environmentally friendly biomass composite materials made of thermosetting or thermoplastic plastics (such as polyethylene, polypropylene, polyvinyl chloride, *etc*.) instead of resin adhesive, combined with waste plant fibers such as wood flour, rice husk, straw, and different additives (Rowell 2007). In recent years, the output of WPCs has been rising (Zhao *et al*. 2022), and their application range has been increasing, including indoor and outdoor decoration, garden architecture, automobile fields, packaging and transportation, aerospace, and other areas of life (Zhao *et al*. 2021a,b). Research on the mechanical properties of WPCs has mainly included the following aspects: the development of production equipment and manufacturing technology; the effects of the proportion of wood plastic materials, types of raw materials, and additives on the density, mechanical properties, and stability of WPCs; and the improvement of the mechanical properties of WPCs by fiber materials such as carbon fiber, glass fiber, basalt fiber, polyester fiber, and mineral cotton. However, there are few reports on the mechanical properties of WPCs at different temperatures. Haider *et al*. (2009) found that the heat deflection temperature of WPCs made of thermosets was better than those made of thermoplastics by measuring the tensile strength, creep, and thermal expansion at higher temperatures. The effects of cyclic temperature on the mechanical properties of wood flour (50% and 70%) polypropylene wood plastic composites were studied by Lee *et al*. (2011). They concluded that at a temperature below -10 °C, the stiffness and strength of WPCs are higher than those at higher temperatures, as WPCs are in the glassy state. Tamrakar *et al*. (2011) studied the effects of time and temperature on the mechanical properties of extruded wood polypropylene composites and found that the elastic modulus and fracture modulus decreased with increasing temperature.

The samples were prepared by a two-step forming process, and uniaxial tensile tests of WPC with an HDPE matrix at different temperatures were completed. The variation laws of ultimate strength and elastic modulus with different temperatures were analyzed, and a calculation model was established to predict the mechanical behavior of WPCs at high and low temperatures. This study provides a theoretical basis for the bearing capacity design of WPC under different temperature conditions.

EXPERIMENTAL

Materials

The WPC used in this paper was prepared by a two-step extrusion process after mixing 30% High Density Polyethylene (HDPE), 50% poplar powder (wood powder of 60 mesh), 15% calcium carbonate, and lubricant. Granulation was carried out using a parallel twin-screw extruder, and then the particles were extruded in the temp of about 140 to160 °C. The sample was made with reference to ASTM D-143 (2014). The specific test piece size is shown in Fig. 1. The width of the effective part was 9.5 mm (b=9.5 mm), and the relevant thickness was 5 mm (*t*=5 mm).

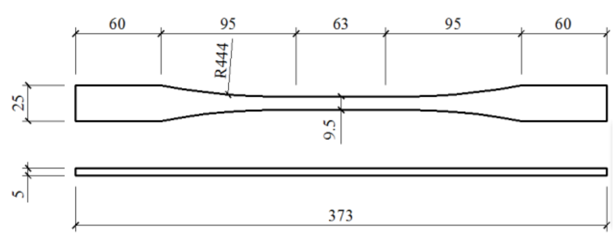
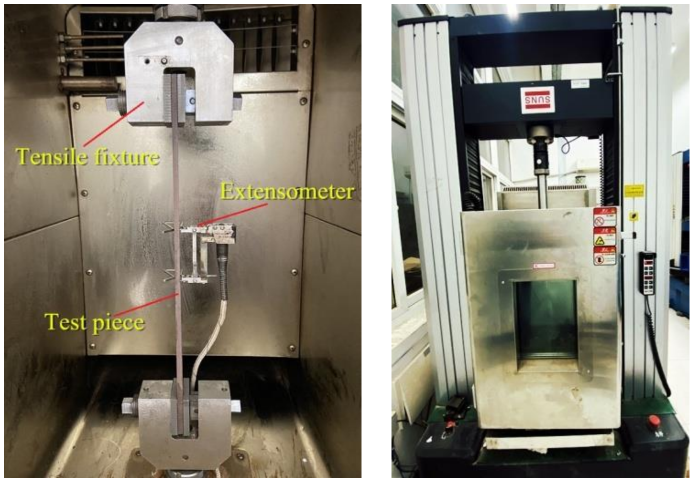


Fig. 1. Specimen size

Testing Device and Scheme

As shown in Fig. 2, the test was carried out on a 50 kN high- and low-temperature universal creep testing machine (model UTM5504GD). A high-temperature extensometer (model 7462-050M-075M, manufactured by Epsilon) with a gauge distance of 50 mm and a measurement range of 7.5 mm was arranged in the middle of the sample to measure the deformation of the test sample. The compiled H-L temperature testing box (model WGDY-7350L) was used for temperature control. The trial was started after the sample was kept constant in the environmental chamber for 30 min (Xi and Zhao 2022), and the temperature of the sample was completely stable. Additionally, during the process of temperature rise and fall and constant temperature, the upper fixture maintained a relaxed state, allowing the specimen to expand and contract to prevent temperature stress due to temperature changes. The loading mode of the tensile test was crossbeam displacement control, and the loading speed was 0.5 mm/min (Ning *et al*. 2021). The load and extensometer data were recorded in real-time by a computer, and the recording frequency was 1 Hz.

The test conditions included 7 groups of temperatures: -60, -40, -20, 0, 20, 40, and 60 °C. Each group contained 3 specimens, making a total of 21 tensile samples in the aggregates.



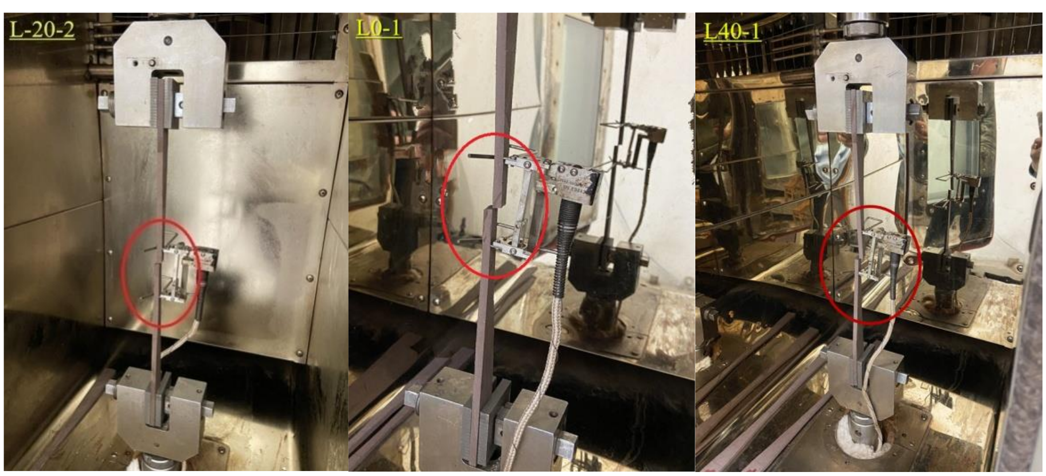
(a) **(b)**

Fig. 2. Testing device. (a) Sample installation; (b) Appearance of the testing machine

RESULTS AND DISCUSSION

Failure

The typical failure mode of the unidirectional tensile test of the WPC specimens at different temperatures is shown in Fig. 3. The fracture of the specimens at all temperatures occurs at the effective part, which is the minimum cross-sectional area of the specimen. The fracture surfaces are neat and flat, almost perpendicular to the tensile axis of the specimens. Brittle fracture occurred in all samples, and the failure mode of the samples was independent of the temperature of the test pieces.



(a) **(b)** **(c)**

Fig. 3. Failure mode

Test Results

The uniaxial tensile experimental test results of the WPCs at different temperatures are shown in Table 1. In the table, '*L*' indicates that the test piece is a tensile test sample, followed by -60, -40, -20, 0, 20, 40, and 60 indicating the test temperature in Celsius, and 1, 2, and 3 are the test piece numbers of each group. σ_{tu} is the ultimate strength of the specimen, calculated as $\sigma_{tu}= F_{tu}/ (b \times t)$. ε_{tu} is the ultimate strain, obtained by dividing the deformation measured by the extensometer by the gauge distance. E is the modulus of elasticity, calculated as $E= \sigma/\varepsilon$. It can be seen from the table that as the temperature was increased from -60 °C to 60 °C, the ultimate strength and elastic modulus of the WPC continued to decrease.

Table 1. Uniaxial Tensile Test Results of the WPC

Temperature T (°C)	Number	Stress σ_{tu} (MPa)	Strain ε_{cu} (%)	Elastic Modulus E (MPa)
-60	L-60−1	32.71	0.084	9584
	L-60−2	24.72	0.163	7383
	L-60−3	29.55	0.106	7317
-40	L-40−1	24.17	0.092	6763
	L-40−2	27.65	0.088	8047
	L-40−3	27.73	0.062	8071
-20	L-20−1	24.51	0.097	6753
	L-20−2	24.44	0.103	6944
	L-20−3	20.25	0.091	7253
0	L0−1	18.24	0.112	6076
	L0−2	21.03	0.119	5953
	L0−3	14.18	0.098	5826
20	L20−1	15.15	0.115	4992
	L20−2	16.67	0.129	5345
	L20−3	15.66	0.127	4753
40	L40−1	13.01	0.143	3749
	L40−2	10.19	0.151	2884
	L40−3	13.26	0.145	4456
60	L60−1	6.90	0.250	1410
	L60−2	6.87	0.218	1846
	L60−3	8.35	0.222	2110

The unidirectional tensile stress–strain relationships of WPC under different temperature conditions are shown in Fig. 4. When the temperature was lower than 0 °C, the entire tensile stress–strain curve was characterized by a linear elastic relationship, with no significant elastic–plastic stage. When the temperature was higher than 0 °C, as the strength reached a certain proportion of the ultimate strength, the curve transitioned from the linear elastic stage to the nonlinear stage, exhibiting elastic–plastic characteristics. The strength at this turning point is defined as the proportional limit, and the ratio of the proportional limit to the ultimate strength decreased with increasing temperature.

The elastic modulus of WPC also decreased with the increase in temperature, while the ultimate strain increased in contrast. This is because the polyolefin in WPC softens with the increase in temperature, resulting in WPC exhibiting viscoelastic mechanical properties at high temperatures (above 0 °C). In other words, as the temperature increases, the ductility of WPC increases while the stiffness decreases.

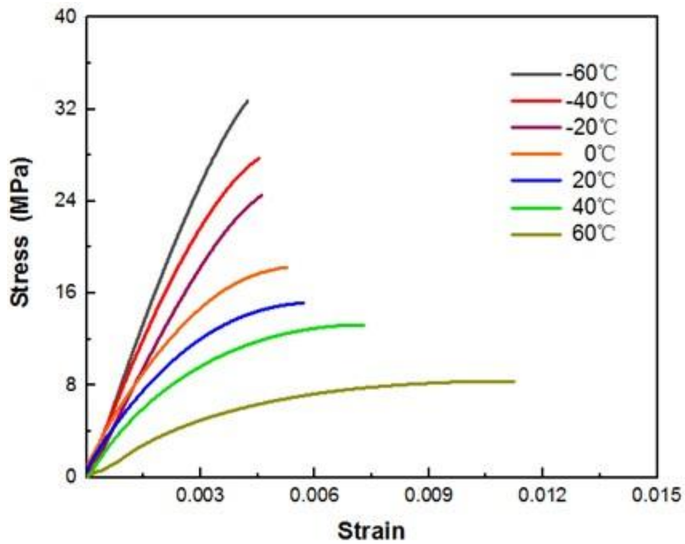


Fig. 4. Tensile stress–strain relationship of the test results

Parameter Analysis

The mean values of mechanical parameters of WPC under different temperatures are shown in Table 2. The coefficient of variation of strength varied from 0.04 (20 °C) to 0.15 (0 °C). The coefficient of variation of the elastic modulus was smallest at 0 °C, at 0.02, and it reached its maximum value of 0.17 at 40 °C. This indicates that the strength and elastic modulus of WPC showed low variability under various temperature conditions, demonstrating the material's good temperature stability.

Table 2. Mechanical Properties of WPC

	Temperature (°C)						
	-60	-40	-20	0	20	40	60
σ_{tu}	28.99	26.51	23.07	17.82	15.83	12.15	7.37
SD	4.02	2.44	2.03	3.44	0.77	1.70	0.85
CV	0.11	0.09	0.06	0.15	0.04	0.11	0.09
E	8095	7627	6983	5952	5030	3696	1789
SD	1053	611	206	102	243	642	288
CV	0.13	0.08	0.03	0.02	0.05	0.17	0.16

Note: σ_{tu} refers to ultimate tensile strength, unit: MPa; *E* is the elastic modulus, unit: MPa; *SD* means the standard deviation; *CV* is a dimensionless parameter, which indicates coefficient of variation.

Tensile Strength

The ultimate stress of the WPCs at different temperatures is shown in Fig. 5. The abscissa represents the Kelvin temperature, and the ordinate represents the ultimate strength. The uniaxial tensile strength of the WPC decreased with increasing temperature (Li *et al.* 2022). Based on the tensile strength of the WPC sample at 0 °C, which was σ_{tu} =17.82 MPa, the tensile strengths under different temperatures of -60 °C, -40 °C, -20 °C, 20 °C, 40 °C, and 60 °C were 1.63, 1.49, 1.29, 0.88, 0.68, and 0.41 times that of the WPC at 0 °C, respectively. Different from conventional nonlinear models (Sagar and Sivakumar 2021), the tensile strength decreased linearly with increasing temperature, and the calculation expression of σ_{tu} with temperature was as follows:

$$\sigma_{tu} = -0.18T + 18.82 \quad -60℃ \leq T \leq 60℃ \tag{1}$$

A comparison of the calculated and test results is shown in Fig. 6, and the fitting regression coefficient was $R^2 = 0.99$.

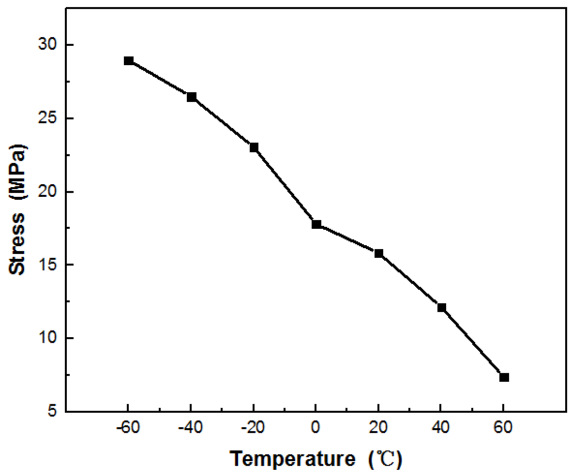


Fig. 5. σ_{tu} variation with temperature

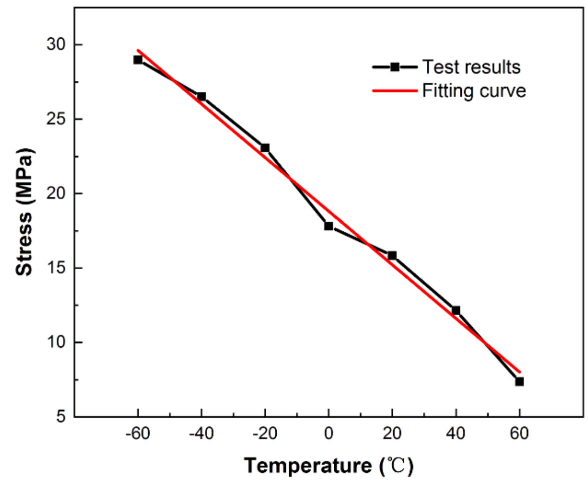


Fig. 6. Fitting results of σ_{tu}

Elastic Modulus

The calculation results of the elastic modulus of the uniaxial tensile trial of the WPCs at different temperatures are shown in Fig. 7. The tensile elastic modulus of the WPC decreased with increasing temperature (Rajkumar *et al*. 2020). Based on the elastic modulus *E* = 5952 MPa at 0 °C, the elastic modulus values at -60, -40, -20, 20, 40, and 60 °C were 1.36, 1.28, 1.17, 0.85, 0.62, and 0.30 times, respectively, that of the WPC at 0 °C. The elastic modulus decreased gradually with increasing temperature with an exponential distribution.

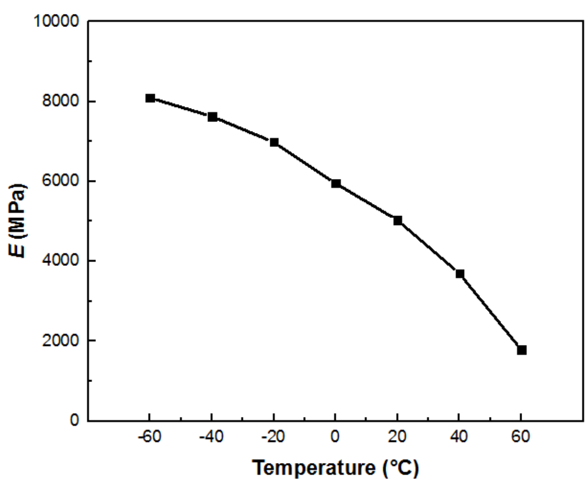


Fig. 7. *E* variation with temperature

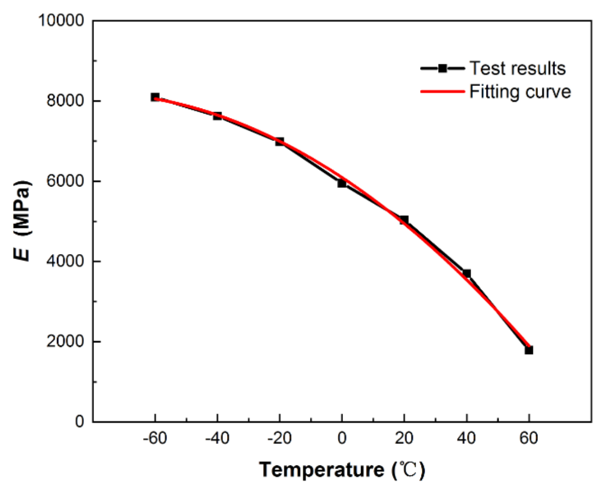


Fig. 8. Fitting results of *E*

The calculation formula of the elastic modulus varying with temperature is as follows. The matching result with the test result is shown in Fig. 8, and the fitting regression coefficient R^2 was 0.99.

$$E = -0.31 \times T^2 - 51.31T - 6092.52 \quad -60℃ \leq T \leq 60℃ \qquad (2)$$

CONCLUSIONS

1. The ultimate tensile strength of a wood-polymer composite (WPC) with a high density polyethylene matrix with 15% poplar wood powder decreased linearly with the increase of temperature, and the regression coefficient of fitting is greater than 0.99. The ultimate strength of WPC at -60 °C was 1.63 times that at 0 °C, while the value at 60 °C was only 0.41, and the maximum strength was 3.93 times the minimum.
2. The elastic modulus also decreased with the increase of temperature, showing a binomial relationship. When the temperature of WPC was -60 °C, the maximum elastic modulus of WPC was 8095 MPa, which was 4.52 times that at 60 °C.
3. The variation coefficient of the average strength of WPC of different specimens at different temperatures ranged between 0.04 and 0.15, while the maximum variation coefficient of the mean elastic modulus was 0.17 and the minimum was only 0.02. This indicates that although WPC is a temperature-sensitive material, the dispersion of mechanical properties among different samples at any specific temperature is small, showing good stability. Therefore, the influence of environmental factors on the mechanical properties of WPC should be considered in the engineering application of WPC.
4. The ultimate strength and elastic modulus of WPC at different temperatures were fitted by first and second-order polynomials, respectively, in this work. The coefficients of determination R^2 of the comparison between the calculation results and the test results are all greater than 0.99, indicating that the mechanical properties of WPC under different temperature conditions can be predicted by simple calculation.

ACKNOWLEDGMENTS

The authors wish to express their gratitude to the National Natural Science Foundation of China (No. 51778300, 52108150), Key Research and Development Project of Jiangsu Province (No. BE2020703), the Natural Science Foundation of Jiangsu Province (No. BK20191390), the six talent peaks project of Jiangsu Province (JZ-017), the Qinglan Project of Jiangsu Province, and the Postgraduate Research & Practice Innovation Program of Jiangsu Province (SJCX20_0277) for financially supporting this study.

Conflict of Interest

The authors confirm that there is no conflict of interest.

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Article submitted: March 15, 2024; Peer review completed: May 5, 2024; Revised version received and accepted: May 9, 2024; Published: May 24, 2024.
DOI: 10.15376/biores.19.3.4547-4554