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Mechanical Properties of Polyurethane Materials of Different Thicknesses under Impact Loading

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Abstract

To investigate the mechanical response patterns of polyurethane materials with varying thicknesses under impact loading and clarify the influence mechanism of thickness on their impact resistance, dynamic compression tests were conducted on polyurethane specimens with thicknesses of 5 mm, 10 mm, 15 mm, 20 mm, and 25 mm using a Separated Hopkinson Pressed Bar (SHPB) test apparatus under an impact pressure of 0.4 MPa. The study revealed that peak stress initially decreased continuously with increasing thickness, reaching a minimum at 20 mm before slightly rebounding. Peak strain exhibited a monotonically increasing trend with thickness. Elastic modulus decreased significantly with thickness, showing a cumulative reduction of 92.5% within the 5–25 mm thickness range. This study reveals the correlation between thickness and the dynamic mechanical properties of polyurethane materials, providing data support and theoretical reference for selecting polyurethane material thickness in impact-resistant protection engineering.

Keywords

Ultra-high Performance Concrete, Seismic Performance, Low-cycle Repeated Loading, Numerical Simulation.

1. Introduction

Polyurethane materials, as polymer composites with outstanding elasticity, wear resistance, and energy absorption properties, are widely used in building protection, automotive cushioning, aerospace, and other fields, playing a particularly crucial role in impact protection engineering. [1-3] From automotive collision protection systems to impact shielding layers in civil engineering, their core function lies in efficiently and reliably responding to dynamic impact loads. They convert instantaneous kinetic energy into controlled, non-destructive deformation energy, thereby safeguarding primary structures and personnel safety. [4-5] In this process, the material's geometric dimensions-particularly its thickness-serve as a critical structural design parameter. This directly governs the propagation path of stress waves and the deformation modes of the material, thereby decisively influencing the overall performance of the protective system. Systematically investigating the mechanical properties of polyurethane materials with varying thicknesses under impact loads, and elucidating the intrinsic relationship between thickness and impact resistance, holds both theoretical significance and practical engineering value.

In recent years, scholars worldwide have conducted extensive research on the mechanical properties of polyurethane materials. Zhao Hua et al. [6] investigated the strain rate-dependent characteristics of polyurethane elastomers during compressive deformation, considering response features at different compressive strain rates, and established a nonlinear viscoelastic constitutive model for polyurethane elastomers. Liu Gaochong et al. [7] conducted uniaxial compression tests on polyurethane elastomers under quasi-static and dynamic loading conditions. By analyzing the relationship between the strain energy density function form and the experimental curve shape, they proposed a constitutive model for strain rate based on a "trisecant" strain energy formula. Chen et al. [8] investigated the incompressibility and micro-macro viscoelastic effects of polyurethane elastomers through uniaxial tensile, nanoindentation, and macroindentation experiments. NIKOUKALAM et al. [9] investigated strain rate dependence, damage, and hysteresis effects in polyurethane elastomers through cyclic tensile/compressive loading-unloading and relaxation tests at various strain rates within the medium strain rate range.

However, existing research has primarily focused on factors such as hardness and impact velocity affecting the mechanical properties of polyurethane materials. Systematic studies on the influence of thickness on impact mechanical properties remain relatively scarce, and there is no unified understanding of the variation patterns of mechanical parameters under impact loading for materials of different thicknesses. Therefore, this study employs the Superhead Punch Breakdown (SHPB) test method to conduct dynamic compression tests on polyurethane materials of varying thicknesses. By analyzing key mechanical parameters-including stress-strain curves, peak stress, peak strain, and elastic modulus-the influence of thickness on the impact mechanical properties of polyurethane materials is revealed. This provides data support and theoretical reference for optimizing the thickness selection of polyurethane materials in engineering practice.

2. Experimental Materials and Methods

2.1. Experimental Materials

This test employs rigid polyurethane elastomer material, with raw materials consisting of polyether polyol and isocyanate, prepared via the casting molding method. To ensure test validity and comparability, all specimens maintain a density of 1.2 g/cm^3 and a Shore hardness of D60±2. According to the test protocol, specimens with thicknesses of 5 mm, 10 mm, 15 mm, and 20 mm were prepared. The cross-sectional dimensions of all specimens were uniformly set to Φ50 mm, as shown in Fig. 1, to meet the dimensional matching requirements between specimens and compression rods in the SHPB test. Three parallel specimens were prepared for each thickness group to ensure the reliability of the test results.

Fig. 1 Polyurethane Specimen

2.2. Test Setup

The test employed a Separated Hopkinson Pressure Bar (SHPB) apparatus, primarily comprising an emitter, incident bar, transmission bar, absorber bar, data acquisition system, and control system, as illustrated in Fig. 2. The incident bar, transmission bar, and absorber bar were all fabricated from 40Cr alloy steel with a diameter of 50 mm and lengths of 2000 mm, 1500 mm, and 1000 mm, respectively. The data acquisition system employs a high-speed strain gauge and oscilloscope, with a sampling frequency set at 1 MHz to accurately capture the dynamic response signals of the specimen under high strain rates. During testing, the impact load intensity is controlled by adjusting the air pressure in the emitter. For this experiment, an impact air pressure of 0.4 MPa was selected.

(a)Overview of the Hopkinson bar (b)Displacement limiting device for the incident bar

Fig. 2 SHPB Impact Test System

2.3. Test Principle and Procedure

The SHPB technique is based on two fundamental assumptions: the one-dimensional stress assumption (also known as the plane assumption) and the assumption of short-term uniform loading deformation. Under the one-dimensional stress assumption, the strain rate $\dot{\varepsilon}(t)$, strain $\sigma(t)$, and stress $\varepsilon(t)$ of the specimen can be directly determined using one-dimensional stress wave theory.

$$\dot{\varepsilon}(t)=\frac{C}{l_0}\left(\varepsilon_I-\varepsilon_R-\varepsilon_T\right) \tag{1}$$

$$\varepsilon(t)=\frac{C}{l_0}\int_0^t\left(\varepsilon_I-\varepsilon_R-\varepsilon_T\right)dt \tag{2}$$

$$\sigma(t)=\frac{A}{2A_0}E\cdot\left(\varepsilon_I+\varepsilon_R+\varepsilon_T\right) \tag{3}$$

The dynamic stress-strain relationship of the specimen can then be obtained. The stress and strain in the equation are engineering stress and engineering strain, both defined with compression as positive. Based on the assumption of uniform deformation of the specimen, we have $\varepsilon_I+\varepsilon_R=\varepsilon_T$. Substituting this into the above equation yields a simpler form:

$$\dot{\varepsilon}(t)=-\frac{2C}{l_0}\varepsilon_R \tag{4}$$

$$\varepsilon(t)=-\frac{2C}{l_0}\int_0^t\varepsilon_R dt \tag{5}$$

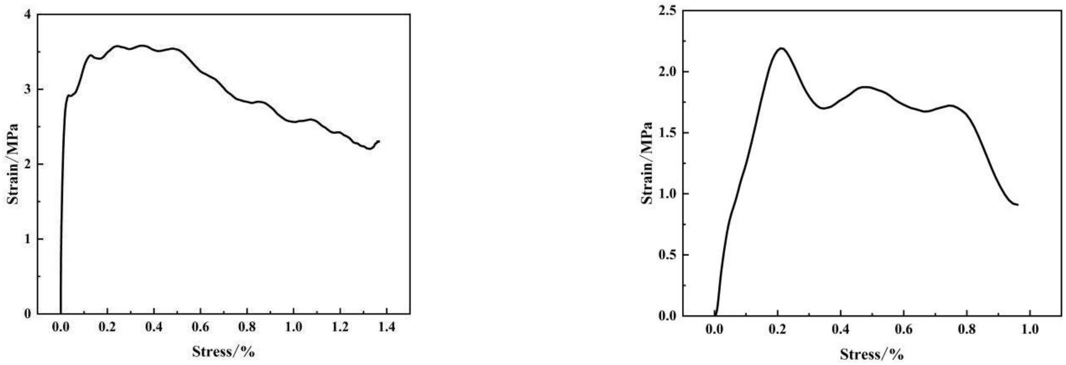
$$\sigma(t) = \frac{A}{A_0} E \cdot \varepsilon_T \tag{6}$$

Test procedure is as follows: (1) Specimen preparation: Measure dimensions and weigh polyurethane specimens of varying thicknesses to ensure dimensional accuracy and consistency; (2) Installation and calibration: Position specimens precisely between the incident rod and transmission rod, adjust the coaxiality of the pressure rod to ensure tight contact between the specimen and pressure rod; (3) Parameter Setup: Configure impact pressure according to the test protocol and calibrate the data acquisition system to ensure proper equipment operation; (4) Impact Testing: Activate the firing mechanism to complete a single impact test, recording incident, reflected, and transmitted wave signals; (5) Repeat Testing: Conduct three parallel tests for each thickness and impact pressure combination. Discard outlier data and calculate the average as the final test result.

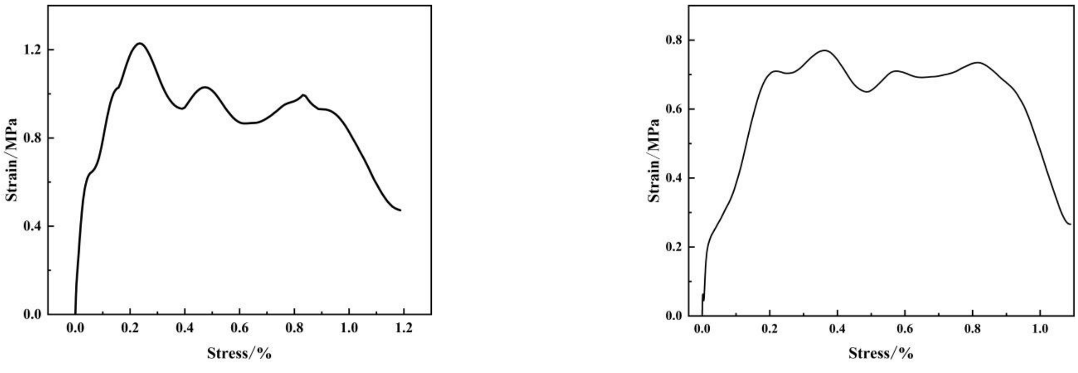
3. Test Results and Analysis

3.1. Stress-Strain Curve Analysis

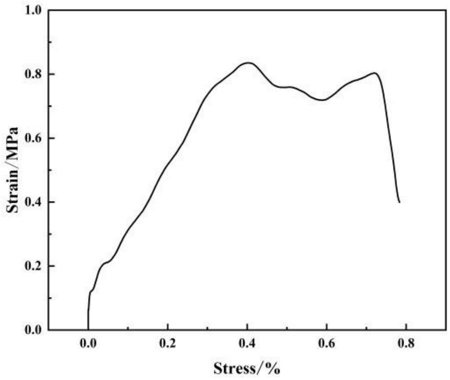
Fig. 3 shows the stress-strain curves of polyurethane materials with different thicknesses under an impact air pressure of 0.4 MPa. The figure reveals that the stress-strain curves of all polyurethane thicknesses exhibit three distinct characteristic stages under impact loading: an elastic stage, a yield plateau stage, and a rapid stress drop stage. During the elastic stage, stress increases linearly with strain, demonstrating elastic deformation characteristics. This stage is relatively brief. Upon entering the yield stage, the rate of stress increase slows significantly while strain increases rapidly. This phase involves extensive micro-pore compression and plastic deformation within the material, representing the primary stage for absorbing impact energy. Once strain reaches a certain threshold, the polyurethane material's load-bearing capacity diminishes, leading to material instability and a sharp decline in the stress curve.



(a)5mm (b)10mm



(c)15mm (d)20mm



(e)25mm

Fig, 3 Dynamic Stress-Strain Curves of Polyurethane at Different Thicknesses

Table 1. Mechanical Properties of Polyurethane at Different Thicknesses

Thickness/mm	Dynamic Peak Stress/MPa	Dynamic Peak Strain/%	Dynamic Elastic Modulus/GPa
5	3.574	0.129	2.771
10	2.186	0.209	1.045
15	1.229	0.235	0.523
20	0.768	0.373	0.206
25	0.835	0.4039	0.207

Fig. 4 shows the variation curve of peak stress with the thickness of polyurethane material. As shown in Fig. 4, peak stress exhibits a trend of continuous decrease followed by a slight rebound as thickness increases. For instance, the peak stress for 5mm-thick material is 3.574 MPa, decreasing to 2.186 MPa at 10mm thickness, further dropping to 1.229 MPa at 15mm, reaching a low of 0.768 MPa at 20mm, and then slightly rebounding to 0.835 MPa at 25mm thickness. From 5 mm to 20 mm thickness, the cumulative decrease in peak stress reached 78.5%. This occurs because stress concentration effects are more pronounced in thinner polyurethane materials, while thicker materials feature longer stress transmission paths and more uniform stress distribution, leading to a decreasing trend in peak stress with increasing thickness. When thickness reaches 20mm, peak stress begins to rise slightly, indicating that 20mm may be one of the critical thicknesses at which stress reduction trends reverse for this density of polyurethane material under impact loading.

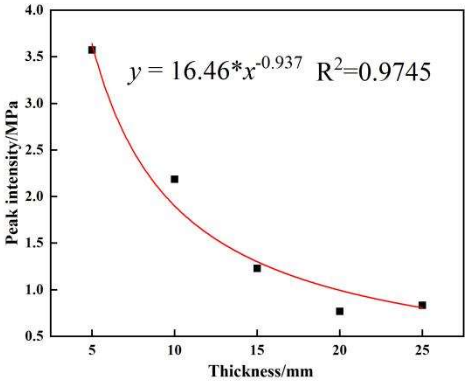


Fig. 4 Peak Stress of Polyurethane at Different Thicknesses

Fig. 5 shows the variation curve of peak strain with the thickness of polyurethane material. As seen in the figure, peak strain exhibits a monotonically increasing trend with increasing thickness. For instance, the peak strain for a 5mm-thick material is 0.129%, increasing to 0.209% at 10mm thickness, 0.235% at 15mm, 0.37282% at 20mm, and further rising to 0.4039% at 25mm. From 5 mm to 25 mm thickness, the cumulative increase in peak strain reached 213.0%. This occurs because thicker specimens undergo longer deformation paths and times during impact, enabling greater plastic deformation through full compression of internal pores, thereby exhibiting higher peak strain values.

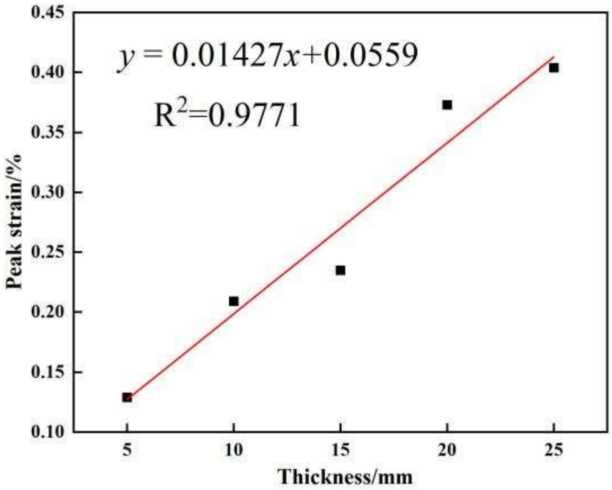


Fig. 5 Peak Strain of Polyurethane at Different Thicknesses

The elastic modulus is a key parameter reflecting a material's capacity for elastic deformation, calculated from the slope of the stress-strain curve during the elastic phase. Fig. 6 shows the variation of elastic modulus with thickness for polyurethane materials. The graph indicates a significant decrease in elastic modulus as thickness increases. For instance, the elastic modulus of a 5mm-thick material is 2770.54 MPa, decreasing to 1045.93 MPa at 10mm thickness, 522.98 MPa at 15mm thickness, 206.00 MPa at 20mm thickness, and slightly varying to 206.73 MPa at 25mm thickness. From 5 mm to 25 mm thickness, the cumulative decrease in elastic modulus reached 92.5%. This occurs because thicker polyurethane materials are prone to developing more micro-defects and voids internally during the molding process. These defects compromise the continuity of the material's internal structure. During elastic deformation, stress transmission is impeded by these voids and defects, leading to a significant reduction in material stiffness. This demonstrates that thickness is the dominant factor influencing the elastic modulus of polyurethane materials.

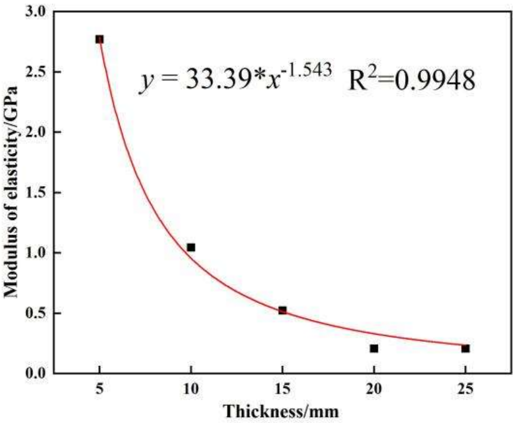


Fig. 6 Elastic Modulus of Polyurethane at Different Thicknesses

4. Conclusion

Through the separated Hopkinson bar test, the mechanical properties of polyurethane materials with varying thicknesses under impact loading were systematically investigated, yielding the following key conclusions:

(1) Under impact loading, thickness is the key factor influencing the dynamic mechanical properties of polyurethane materials. Specifically, the peak stress exhibits a “sustained decrease followed by a slight rebound” pattern with increasing thickness. Within the 5–20 mm thickness range, peak stress decreases significantly. Twenty millimeters represents the critical thickness at which the stress decline trend reverses, after which stress slightly rebounds.

(2) Peak strain exhibits a monotonically increasing trend with thickness. Thicker materials demonstrate superior plastic deformation capacity due to longer deformation paths and more complete pore compression.

(3) The elastic modulus exhibits a pronounced decreasing trend with increasing thickness, with a cumulative reduction of 92.5% within the 5–25 mm thickness range. Increased material thickness leads to greater susceptibility to instability, which is the primary cause of reduced stiffness. The correlation between thickness and the dynamic mechanical properties of polyurethane materials revealed in this study provides direct data support and theoretical reference for selecting appropriate thicknesses of polyurethane materials in impact-resistant protection engineering.

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