Research on Dynamic Compression Testing of Silicone Rubber under Different Temperatures

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Abstract. For study the mechanical characteristic of silicone rubber under impact loading, the Uniaxial compression tests of silicone rubber under different strain rates (1×10³/s~6×10³/s) and temperatures (233K~373K) were carried out with test device using the split Hopkinson pressure bar which has a controllers of temperature. The dynamic stress-strain curves and related dynamic mechanical parameters of silicone rubber were generated. The results show that the dynamic compressive strength of silicone rubber at different temperatures has the characteristics of the strain rate strengthening, which increases along with the raise in strain rate. Under dynamic condition, the stress-strain curve at 263K shows the characteristic of transition to "glass state".

Keywords: Silicone rubber; SHPB; Temperature effect; Strain rate effect

1. Introduction
Silicone rubber is a straight chain polymer with Si-O as the main chain and univalent organic group as the side group. It gets the advantages of small change in elastic modulus, low temperature of transition to glass, and steady mechanical behavior in a wide temperature range. It plays an important role in vibration isolation and cushioning components. With the change of temperature and strain rate, silicone rubber can also present three different mechanical forms: viscous flow state, rubber state and glass state. It is of great social and economic value to research the dynamic physical properties of silicone rubber at different temperatures.

For the application of split Hopkinson rod in soft materials, many scholars have carried out relevant research [1-6]. The silicone rubber has strong sensitivity of strain rate; The polymer exhibits typical viscoelastic properties at high strain rate. Lu [7-9] applied incident wave shaping technology in the experiment to ensure the stress balance and constant loading of strain rate in the sample, monitored the stress balance at both ends of the sample using quartz crystal, and measured the weak transmission signal. Sasso m et al. [10] carried out uniaxial relaxation tests at room temperature to study the viscoelastic behavior of fluorosilicone rubber, and used the generalized Maxwell model to describe stress relaxation. Ward [11] studied the relationship between strain rate and strength of polymer, and proposed Eyring thermovisco- plasticity theory. The model described the relationship between material stress and material dynamic yield stress, temperature, activation energy, activation volume, and strain energy. Qin [12] established a Maxwell distribution order constitutive model based on the stage mechanical performance of silicone rubber under different strain rate. SHPB technology was utilized to carry out the impact mechanical properties experiment of silicone rubber to verify the model. Many researchers have done in-depth research on the static mechanical properties of some rubber polymers at different temperatures through numerous of materials creep and stress relaxation tests, but there are relatively few studies on the dynamic mechanical properties under different strain.
rates and temperatures.

The test sample is a kind of modified silicone rubber, which is made of silicone rubber, adding reinforcing filler, damping filler, curing agent and so on. For understanding the response characteristics of this kind of silicone rubber under dynamic loading with high strain rate, the compression experiments were carried out at 233K-373K using the SHPB device in the laboratory.

2. Experimental Procedures

2.1. Dynamic Testing of SHPB Method

The experiment was conducted on the separated Hopkinson pressure bar experimental device of engineering center of Nanjing University of technology. The physical diagram of the experimental device is shown in figure 1. Because rubber is soft, the transmission signal is very small under loading of low strain rate, and the strain gauge of semiconductor has the advantages of high sensitivity and high signal-to-noise ratio, which is suitable for measuring weak strain signal. Therefore, in the experiment, semiconductor strain gauge is used instead of traditional strain gauge to measure signal of transmission wave.

For decreasing the influence of the friction force, Vaseline was applied on both ends of the rubber for lubrication. In temperature control, considering the low conductivity for heat of the rubber, for the sake of make the specimen reach the required test temperature, it is necessary to wait for tens of minutes for dynamic impact after the temperature of the temperature control box is stable. The strain gauge of the transmission rod is attached 1 m away from the interface between the rod and the specimen, and the heat source has no effect on the signal of it, and the modulus of the aluminum rod has no change in the temperature range of 233k-373k, so the effect of the gradient field of temperature on the propagation of wave can also be ignored.

Figure 1. Experimental device.

On the basis of the basic hypothesis of SHPB test technology, the stress-strain at both ends of the specimen tends to balance gradually after the stress wave is propagated and reflected repeatedly. The stress of the specimen can be figured out by the strain $\varepsilon(t)$, stress wave $\sigma(t)$ and strain rate $\dot{\varepsilon}(t)$. The strength of silicone rubber is low, and the error of test results obtained by two wave method is large, so the three wave method is used to process the test data.

$$\varepsilon(t) = \frac{C_0}{L_s} \left[ \varepsilon_s(t) - \varepsilon_i(t) - \dot{\varepsilon}_s(t) \right]$$

(1)
\[ \varepsilon(t) = \frac{C_0}{L_S} \int_0^t [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] \, dt \]  
(2)

\[ \sigma(t) = \frac{EA}{2A_s} [\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)] \]  
(3)

Where \( A \) and \( A_s \) are the cross-sectional areas of the compression bar and the sample; \( E, \ C_0 \) is the elastic modulus and the longitudinal wave speed of the pressure bar respectively; \( L_S \) is the length of the specimen; \( \varepsilon_i(t), \varepsilon_r(t), \varepsilon_t(t) \) is the incident strain, reflection strain and transmission strain of \( t \) at a certain time; \( T \) is the duration of stress wave.

### 2.2. Materials and Sample Preparation

The diameter of specimen as shown in figure 2 used in this experiment is \( \Phi 10 \) mm, and the average thickness is 2.48 mm. The wave velocity in silicone rubber is very low, even for the very thin sample, the time needed for wave propagation in the sample is relatively long. Only when the loading wave is reflected exceed three times can the stress balance in the sample be achieved. For a long time, the sample is in the condition of non-uniform stress. At this time, the assumption of stress uniformity often used in data processing is no longer tenable, which is the premise of split Hopkinson pressure bar. Therefore, for silicone rubber, the traditional SHPB technology can not obtain accurate and reliable experimental results, so the incident wave shaping technology is needed. In this experiment, rubber was used as plastic sheet, with the diameter of \( \Phi 4-\Phi 8 \) mm and the thickness of 0.5-2 mm.

![Figure 2. Specimen.](image1)

![Figure 3. Typical raw signal waveform.](image2)

### 3. Results and Discussion

#### 3.1. Dynamic Testing

In the experiment, by adjusting the loading conditions properly, all the experiments have obtained the loading of approximate constant strain rate. Figure 3 is a typical original signal waveform diagram during dynamic loading, in which the first channel records the incident signal and the reflection signal in the incident rod, and the second channel records the transmission signal of silicone rubber in the transmission rod. It can be seen from figure 3 that the incident pulse is significantly different from the traditional rectangular steep incident pulse waveform: the incident wave is loaded by bullets directly in the traditional SHPB experimental technology. The incident wave is an adjustable square wave. The rise time of the incident wave is very short, so it is difficult to effectively control the strain rate during loading, especially to obtain the constant strain rate. The wave shape obtained by the shaping technique has a long rising time and the rising front is gentle, which ensures that the internal stress of
the silicone rubber is even before it is not damaged and the stress at both ends reaches equilibrium; The loading curves of constant strain rate are obtained by different size of the shaper.

Figure 4. True stress-strain curves of silicon rubber at 4 different strain rates at a certain temperature.

Figure 4 shows the stress-strain curves of silicone rubber under different ambient temperatures. Figures 4(a)-(e) show that the strength of the material increases obviously with the raise of strain rate, but decreases with the raise of temperature, which shows the correlation with temperature and strain rate. At different temperatures, the maximum strain of silicone rubber is not more than 70%. When the
test temperature changes from normal temperature to high temperature, the maximum stress slightly decreases. When the test temperature is low, the maximum stress is completely different from that at normal temperature and high temperature, about twice of the latter. At room temperature and high temperature, after yielding, the stress decreases slightly with the raise of strain, resulting in the so-called "strain softening" phenomenon.

It can be observed in figure 4(a) that the curve of stress-strain has an obvious elastic-plastic boundary at low temperature, and the deformation at high strain rate can be divided into following periods: the first stage is the rising stage, at which time the material can be approximately linear elastic; The second stage is the nonlinear transformation stage, in which the yield transformation of silicone rubber is similar to that of elastic-plastic material, and then the material continues to maintain the bearing capacity when the strain increases greatly; In the final stage, the strain of the material no longer increases, but decreases sharply with the stress, which is a typical unloading process. The peak stress of silicone rubber at low temperature is obviously higher, and the theoretical model can be described by the thermoviscoplastic model of metal.

3.2. Establishment of Constitutive Model
Zhu-Wang-Tang model is composed of a nonlinear elastic body and two parallel Maxwell bodies. The first Maxwell body represents the viscoelastic response of quasi-static and low strain rate, and the second represents the viscoelastic response of dynamic and high strain rate. The constitutive equation is

$$\sigma = f(\varepsilon) + E_1 \int_0^\tau \varepsilon \exp\left(-\frac{t-\tau}{\theta_1}\right) d\tau + E_2 \int_0^\tau \varepsilon \exp\left(-\frac{t-\tau}{\theta_2}\right) d\tau \quad (4)$$

The strain rate of SHPB experiment in this paper can be considered as constant during the loading process. Under constant strain rate loading, the strain rate is a fixed value, and the integral of equation (4) can be obtained

$$\sigma = E_0 \varepsilon + \alpha \varepsilon^2 + \beta \varepsilon^3 + E_1 \varepsilon \left[1 - \exp\left(-\frac{\varepsilon}{\varepsilon \theta_1}\right)\right] + E_2 \varepsilon \left[1 - \exp\left(-\frac{\varepsilon}{\varepsilon \theta_2}\right)\right] \quad (5)$$

The loading specimen in the compression test of high strain rate is very short, and the response term of low strain rate in equation (5) will only show elasticity without relaxation. In this case, he response term of low strain rate in Zhu-Wang-Tang model can be treated as a linear elastic element, that is, spring with elastic modulus $E_1$.

To sum up, the constitutive model of Zhu Wang Tang under high strain rate can be simplified as follows:

$$\sigma = (E_0 + E_1) \varepsilon + \alpha \varepsilon^2 + \beta \varepsilon^3 + E_2 \varepsilon \left[1 - \exp\left(-\frac{\varepsilon}{\varepsilon \theta_2}\right)\right]$$

For convenience, write formula (6) in the following form:
\[ \sigma = a\varepsilon + b\varepsilon^2 + c\varepsilon^3 + E_2\theta_2 \varepsilon \left[1 - \exp\left(-\frac{\varepsilon}{\varepsilon\theta_2}\right)\right] \]  

(7)

When the model is used to fit the experimental data of 233K and 263K at high strain rates, it is difficult to get satisfactory results. From the preceding analysis, it can be seen that this is because 263K is close to the transition temperature of glass of silicone rubber. Through the attempt, the constitutive model is suitable for normal temperature and high temperature conditions. This paper only gives the fitting stress-strain curve at normal temperature.

The specific fitting process is as follows: select any two stress-strain curves, subtract the two curves to get the relationship between stress difference and strain, and fit the curves to get \(E_2\) and \(\theta_2\). Then, any one of the two stress-strain curves is fitted by equation (7), and the parameters \(a\), \(b\) and \(c\) are obtained. Five parameters of nonlinear viscoelastic constitutive model under high strain rate at room temperature are shown in Table 1.

| \(E_2\) (Mpa) | \(\theta_2\) (\(\mu\)s) | \(a\) (Mpa) | \(b\) (Mpa) | \(c\) (Mpa) |
|---------------|----------------|----------|----------|----------|
| 50.2          | 1.146E-4       | -43.2    | 74.4     | -44.58   |

Table 1. Constitutive model parameters.

Through the model, the curves of experimental and the model are drawn in the same figure, and figure 5 is obtained.

![Figure 5](image)

Figure 5. Comparison of curve between model and experiment

From figure 5, the results show that the model is coincide with the experimental results., which indicate that the model can well represent the viscoelastic mechanical behavior of silicone rubber under one-dimensional compression, which is has a bearing on strain rate. The yield strain of silicone rubber is about 7%. There is a certain deviation between the experimental curve and the predicted curve, which may be because that the failure of the constitutive model to accurately represent the mechanical properties after yielding.

4. Conclusion

In this paper, the experimental research on the dynamic compression mechanical characteristics of silicone rubber under different temperature and high strain rate is designed and carried out by the traditional SHPB experimental system. The real stress-strain curve of the silicone rubber at four strain rate is obtained. According to the real stress-strain curve fitting, the parameters of Zhu-Wang-Tang model of silicone rubber under high strain rate are obtained. The validity of the constitutive model parameters is verified. It finds that the theory and the test are consistent.
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