Static and dynamic mechanical behavior and constitutive model of polyvinyl chloride elastomers for design processes of soft polymer materials

Jingfa Lei1,2, Yan Xuan1, Tao Liu1,2, Feiya Duan1, Hong Sun1,2 and Zhan Wei1

Abstract
Soft polymer materials are often used in shock absorption, cushioning, and so on. During the design and development process, determining the mechanical behavior and constitutive properties under static and dynamic loads is important to improve product performance. This study aims to analyze the static mechanical performance of polyvinyl chloride elastomers with different Shore hardness levels. Static and dynamic mechanical performance experiments with loading strain rates of 0.1, 1650, 2000, and 2700 s⁻¹ were performed in polyvinyl chloride elastomers (57A, 52A, and 47A) using an electronic dynamic and static fatigue tester and an improved Split Hopkinson pressure bar. Microstructures were observed by scanning electron microscopy. Results showed that the addition of plasticizers to polyvinyl chloride promoted the crystallization of the polymer. The presence of plasticizer in the crystal also reduced crystallization. The material plasticity, elastic modulus, yield stress, and flow stress increase with increasing hardness/strain rate, whereas the hardness decreases. The mechanical behavior of polyvinyl chloride elastomers under static and dynamic loads exhibited superelastic and viscoelastic characteristics, respectively. The Mooney–Rivlin, Neo–Hookean, and Yeoh models were selected for the superelastic constitutive model, whereas the Zhu–Wang–Tang model was used for the viscoelastic one. Finally, the applicability of the model was explained. This study can provide theoretical model and method support for the design and development of soft polymer materials.

Keywords
Polyvinyl chloride, strain rate, Split Hopkinson pressure bar, constitutive

Date received: 5 October 2019; accepted: 8 April 2020
Handling Editor: James Baldwin

Introduction
Soft polymers, such as polyvinyl chloride (PVC) elastomers, are widely used in military,1 automobile,2 marine,1 aviation,4 electronic,5 and other industries (e.g. car crash dummies test,6 aviation bearing buffer packaging,7 domestic water pipes,8 etc.) due to their low production cost, light weight, good impact resistance, and other advantages. In the abovementioned fields, components or materials are often subject to static and dynamic loads. Engineers and technical professionals have developed process optimization and micro-organization analysis for polymer products. During the preparation of materials, the increase in the plasticizer content will promote the crystallization of the polymer,9,10 resulting in changes in the

1School of Mechanical and Electrical Engineering, Anhui Jianzhu University, Hefei, China
2Anhui Education Department Key Laboratory of Intelligent Manufacturing of Construction Machinery, Hefei, China

Corresponding author:
Tao Liu, School of Mechanical and Electrical Engineering, Anhui Jianzhu University, Hefei 230601, China.
Email: tao.liu@ahjzu.edu.cn; liutao19841015@163.com

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
microstructure of the polymer, which indefinitely affects the static and dynamic mechanical properties of the material; hence, studying the relationship between the static and dynamic mechanical performance and micro-organization analysis will be of great importance to the design and development of polymer materials.

In recent years, test devices, such as universal testing machines and Split Hopkinson pressure bars (SHPBs), have been used to test the static and dynamic performance of polycarbonate/methyl acrylate blend, polyester matrix, polyurethane elastomer, three-dimensional (3D) printing polymer, polytetrafluoroethylene, gelatin, polyuria, and other polymer materials. High-speed camera, scanning electron microscope (SEM), high/low temperature environment box and other devices and digital image technology, remanufacturing assembly technology, pulse shaping technology, and so on are used to analyze the impact deformation, microstructure evolution, and damage mechanism of polymer materials. Experiment on static and dynamic mechanical performance found that (1) the elastic modulus and yield strength of polymers exhibit a significant strain rate effect; (2) the stress–strain curves under quasi-static and dynamic conditions are susceptible to temperature (i.e. the lower the temperature is, the greater the deviation will be); (3) the compression behavior at high strain rate is aligned with the Zhu–Wang–Tang (ZWT) constitutive model, which indefinitely affects the static and dynamic mechanical properties of the material.

At present, scholars have carried out research on static and dynamic mechanical properties in combination with PVC elastomer materials. However, there are few studies on the effects of different composition ratios on material hardness, microstructure, and static and dynamic mechanical properties during the development of materials. This study aims to reveal the influence of the microstructure of PVC elastomers of different Shore hardness and the changes in the hardness on the static and dynamic mechanical performance of PVC elastomers. The ratio of plasticizer composition is varied in three PVC elastomer materials with three different Shore hardness values under the load rates of 0.1, 1650, 2000, and 2700 s\(^{-1}\). The effects of plasticizer on Shore hardness, microstructure of PVC elastomers, and static and dynamic mechanical performances are further expounded through microstructure analysis. Finally, the static and dynamic constitutive models of the material are constructed.

### Experimental materials

The experimental materials in this article are modified PVC elastomers with three different plasticizer parts (98 parts, 105 parts, and 112 parts). The rubber–plastic Shore A hardness tester (model: 20076069, Shanghai Yueming Scientific Instrument Co., Ltd.) was used to measure the Shore hardness of the three PVC elastomers (57A, 52A, and 47A). This parameter was used to distinguish PVC elastomers. The proportion of each component in the preparation process is shown in Table 1. The specific preparation process is as follows: first, PVC, a plasticizer (dioctyl phthalate (DOP)), and a composite thermal stabilizer (dibutyltin disilicate) were initially mixed. The materials were then cut and stirred at 500 r/min for 40 min to obtain the mixture. A small vacuum pump was used to defoam and obtain spare materials. After preheating, the spare material was poured into a hot mold and processed on a flat vulcanization machine (XLB-400*400*2, Shanghai Qicai Hydraulic Machinery Co., Ltd.) at 180°C for 70–90 min. After molding the material, the product was obtained through cooling and demolding.

The size of the quasi-static compression specimen was determined to be Φ29 mm × 12.5 mm according to “ISO 7743: 2007”; the size of the dynamic compression test specimen was Φ8 mm × 2 mm.

### Experimental device and method

#### Quasi-static compression experiment

The quasi-static compression properties of PVC elastomers were measured at room temperature (25°C) by the INSTRON0-E3000 electronic dynamic and static fatigue tester (Figure 1(a)). The sample was placed between the base and the bottom head. An extensometer was then added during the experiment (Figure 1(b)).

During the quasi-static compression experiment with a strain rate of 0.1 s\(^{-1}\), the loading rate of the testing machine was 75 mm/min, and the maximum strain was 0.3. The time–load (\(F\)) and time–displacement (\(\Delta L\)) were measured and recorded during the compression. Three sets of loading experiments were performed for each Shore hardness PVC elastomer, and the average of the load and displacement data at

| Shore hardness (A) | Polyvinyl chloride | Diocetyl phthalate | Dibutyltin disilicate |
|-------------------|-------------------|-------------------|-------------------|
| 57                | 100               | 98                | 5.6               |
| 52                | 100               | 105               | 5.6               |
| 47                | 100               | 112               | 5.6               |
the same time was calculated. According to formula (1), it is converted into stress and strain data. The stress–strain curve was then obtained

\[
\sigma = \frac{F}{A}, \quad \varepsilon = \frac{\Delta L}{L_0}
\]  

(1)

In the formula, \(\sigma\) is the stress, \(A\) is the cross-sectional area of the sample, and \(\varepsilon\) is the strain.

**Dynamic compression experiment**

The dynamic compression experiment of PVC elastomers was performed using an improved SHPB experimental device with a diameter of 14.5 mm (Figure 2). The improved SHPB was operated by the launching, bar (impact, incident, transmission, and absorption bars), test (strain and ultradynamic strain gauges and data acquisition systems), and damping systems.

The bar system is composed of a hard, solid aluminum rod with an elastic modulus of 210 GPa, density of 7.83 g/cm³, and wave speed of about 5200 m/s. The length of the impact bar is 200 mm, the length of the incident and transmission bars is 1000 mm, and the length of the absorption bar is 300 mm. Resistive and semiconductor strain gauges (the sensitivity factor of the latter is 55 times that of the former) were used in the test system. The resistive strain gauge was used to collect incident wave signals on the incident bar, and the semiconductor strain gauge was used to

![Figure 1. INSTRON0-E3000 electronic dynamic and static fatigue tester.](image)

![Figure 2. Schematic of the SHPB experimental device.](image)
collect weak transmission signals on the transmission bar.

The PVC elastomer’s cylindrical sample was clamped between the incident and transmission bars. A thin layer of Vaseline was applied on the surface to reduce the friction effects on the sample. The coated paper was used as a reshaper, which was placed at the end of the incident bar without holding the sample, to extend the rising front of the incident wave and eliminate the dispersion effect. The stress–strain curves of the sample under different strain rates (1650, 2000, and 2700 s\(^{-1}\)) were obtained according to constant strain rate loading method in the Hopkinson pressure bar experiment (i.e. by adjusting the speed of the bullet).

The SHPB experimental device should meet the one-dimensional (1D) strain and uniformity assumptions.\(^3\) The 1D stress wave theory can be used to process the data obtained by the experiment and determine the strain rate \(e_t(t)\), strain \(e_r(t)\), and stress \(\sigma(t)\) of the sample materials

\[
\begin{align*}
\dot{e}(t) &= \frac{c}{L_0}(e_i - e_r - e_t) \\
\dot{e}(t) &= \frac{c}{L_0} \int_0^t (e_i - e_r - e_t) dt \\
\sigma(t) &= \frac{A}{2A_0} E(e_i + e_r + e_t)
\end{align*}
\]

where \(e_i\), \(e_r\), and \(e_t\) are the measured incident, reflected, and transmitted waves, respectively; \(c\), \(E\), and \(A\) are the elastic wave velocity, elasticity modulus, and sectional area, respectively; \(A_0\) is the area of the sample; and \(L_0\) is the length of the sample.

**Experiment results and analysis**

**Quasi-static stress–strain curve analysis of PVC elastomers**

The stress–strain curves of PVC elastomers with three types of Shore hardness (57A, 52A, 47A) at low strain rates (0.1 s\(^{-1}\)) are shown in Figure 3.

Figure 3 shows that during the loading process of PVC elastomer at a strain rate of 0.1 s\(^{-1}\), the stress–strain curve shows the upper concave nonlinearity of rubber and other polymer materials (i.e. the hardening phenomenon of stress increases with increasing strain). In quasi-static deformation, the tangent modulus is small and slowly increases in the initial stage. The modulus rapidly increases until 30% of the strain reaches the maximum values of 9.30, 15.45, and 15.48 MPa for the respective Shore hardness with increasing strain. The tangent modulus change table is shown in Table 2. After unloading, the analysis showed that the change in the sample size before and after the experiment is less than 1.5%, indicating that the PVC elastomers possess significant superelastic characteristics.

**Dynamic stress–strain curve analysis of PVC elastomers**

The experimental data of the dynamic compression of PVC elastomers were processed to obtain the stress–strain curves of PVC elastomers with different Shore hardness values at different strain rates (Figure 4(a)–(c)).

The stress–strain curve of the three PVC elastomers under high strain rate loading conditions demonstrates nonlinear characteristics and can be divided into two stages of elasticity and plasticity. The PVC elastomers in the elastic stage presents a typical high polymer viscoelastic characteristic; the elastic modulus, yield stress, and flow stress increase with increasing strain rate, thereby exhibiting a certain strain rate sensitivity.

When the strain is 0.1, the corresponding point is connected to the origin and the \(E_g\) of Young’s modulus is characterized with the slope or the secant modulus. The corresponding point when \(\sigma_s = 0.1\) was compared with increasing load strain rate to illustrate the strain rate effect of PVC elastomers. When the Shore hardness values are 47A, 52A, and 57A, \(\sigma_s\) increases from 2.09 to 4.28 MPa, from 2.67 to 8.27 MPa, and from 10.02 to 20.67 MPa, respectively. In addition, the secant moduli of the PVC elastomers increase with increasing strain rate from 20.9, 26.7, and 10.02 MPa at 1650 s\(^{-1}\) to 42.8, 82.7, and 206.7 MPa at 2700 s\(^{-1}\).

Figure 5 presents the stress–strain curves of the three PVC elastomers.

Figure 5(a)–(c) shows that the changes in Shore hardness directly affect the dynamic mechanical performance of PVC elastomers; at the same strain rate level,
the elastic modulus, yield stress, and flow stress of the PVC elastomers increase with increasing Shore hardness.

**Table 2.** Change in the tangent modulus of three PVC elastomers.

| Shore hardness | 0.025 | 0.05  | 0.075 | 0.1  | 0.125 | 0.15  | 0.175 | 0.2  | 0.225 | 0.25  | 0.275 | 0.3  |
|----------------|-------|-------|-------|------|-------|-------|-------|------|-------|-------|-------|------|
| 57A            | 3.78  | 4.29  | 4.82  | 5.43 | 6.10  | 6.92  | 7.83  | 8.93 | 10.20 | 11.73 | 13.54 | 15.48|
| 52A            | 3.40  | 4.26  | 4.01  | 4.51 | 6.09  | 6.50  | 7.29  | 8.78 | 9.93  | 11.72 | 12.30 | 15.45|
| 47A            | 1.32  | 2.78  | 2.96  | 3.21 | 4.02  | 5.29  | 6.03  | 6.40 | 6.75  | 8.01  | 9.03  | 9.30 |

**Figure 4.** Dynamic stress–strain curves of PVC elastomers with three Shore hardness levels: (a) 47A, (b) 52A, and (c) 57A.

**Analysis of the microstructure of PVC elastomers**

The glass transition temperature ($T_g$) of a common PVC is above 80°C (i.e. typical plastic material at normal temperature). A control phase is required by the elastomer among PVC molecules; hence, the material cannot be used as a thermoplastic elastomer. The control phases for the PVC elastomers in this work were obtained by adding plasticizers to change the polymerization, the proportion of crystalline phase composition of molecular chain groups, and the entanglement points between irregular molecular chains.

The samples after the brittle fracture of liquid nitrogen were first subjected to a 20-min gold evaporation treatment to reveal the static and dynamic mechanical properties of PVC elastomers with different Shore hardness values at the microscopic level. The microstructure of the sample was tested using ZEISS EV018 SEM (Figure 6).
Figure 6(a)–(c) shows the microstructure diagrams of the PVC elastomer materials with different Shore hardness levels. In Figure 6(a), few plasticizers can be observed in the composition, along with a tight chain crystallization structure. With increasing plasticizer amount, the number of chain structures decreases (Figure 6(b)), and a large number of coarse grains and very few fine grains are distributed in the structure. In Figure 6(c) and (d), a large number of coarse grains with few fine grains are distributed in the structure; as the amount of plasticizer increases, the coarse grains are further refined into fine grains and the number of grains increases.

In material preparation, when plasticizers are added, plasticizer molecules will be inserted in the middle of the molecular chain of PVC resin, thereby increasing the activity of the molecular chain and decreasing the crystallization and the entanglement among the molecular chains, and promoting the crystallization of PVC molecules to increase the plasticity of the PVC elastomers. Therefore, the material hardness, strength, and mold reduction decrease with increasing amount of plasticizer, resulting in the decrease in the PVC elastomers’ static and dynamic mechanical performances.

Constitutive model

Superelastic constitutive model

Three typical superelastic constitutive models, namely, Mooney–Rivlin, Neo–Hookean, and Yeoh models, were selected to describe the behavior of the materials and the superelastic characteristics of PVC elastomers in the quasi-static mechanical experiments. The strain

---

**Figure 5.** Stress–strain curves of PVC elastomers with different Shore hardness: (a) 1650 s\(^{-1}\), (b) 2000 s\(^{-1}\), and (c) 2700 s\(^{-1}\).
energy function determination of superelastic materials can be represented by a statistical model based on the molecular chain network and a continuum mechanics model based on the phenomenological theory. The latter is more commonly used than the former; the strain energy density function of which can be expressed in the form of strain invariant or main elongation

\[ W = W(I_1, I_2, I_3) \quad \text{or} \quad W = W(\lambda_1, \lambda_2, \lambda_3) \]  

(3)

where \( I_1, I_2, \) and \( I_3 \) are the first, second, and third strain invariants, respectively; and \( \lambda_1, \lambda_2, \) and \( \lambda_3 \) are the respective elongations.

The Cauchy principal stress corresponding to the principal stretching ratio \( \lambda_i \) can be represented by \( \sigma_i \), then

\[ \sigma_i = \lambda_i \frac{\partial W}{\partial \lambda_i} - p, \quad i = 1, 2, 3 \]  

(4)

In formula (4), \( P \) is a Lagrangian multiplier to be determined, which can be determined by boundary conditions. Nominal stress \( P_i = \sigma_i / \lambda_i \). If \( \lambda_1 = \lambda \) be the elongation in the compression direction. For uniaxial compressive load, there are zero stress components in the other two directions, \( \lambda_2 \lambda_3 = \lambda^{-1} \), that is, \( \lambda_2 = \lambda_3 = \lambda^{-1/2} \).

Under the condition of limited deformation, the deformation of the material can be described by the left Cauchy–Green deformation tensor \( B \), and \( B \) can be expressed by the deformation gradient \( F \) as

\[ B = FF^T \]  

(5)

The deformation gradient \( F \) can be expressed by the main elongation as

\[ F = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} = \begin{bmatrix} \lambda & 0 & 0 \\ 0 & \lambda^{-1/2} & 0 \\ 0 & 0 & \lambda^{-1/2} \end{bmatrix} \]  

(6)

The three strain invariants of \( B \) can be expressed as

---

**Figure 6.** Microstructure of PVC elastomers with different Shore hardness levels: (a) 57A/800X, (b) 52A/800X, (c) 47A/800X, and (d) 47A/1500X.
\[ I_1 = \text{tr}(B) = \lambda^2 + 2\lambda^{-1} \]
\[ I_2 = \frac{1}{2}(I_1^2 - \text{tr}(B^2)) = \lambda^2 + 2\lambda \]
\[ I_3 = \det(B) = 1 \] (7)

Rivlin et al. stated that the relationship between strain energy density function and stress tensor is

\[ \sigma^h = -p^h I + 2 \left[ \frac{\partial W}{\partial I_1} B + \frac{\partial W}{\partial I_2} (I_1 B - B^2) \right] \] (8)

where \( p^h \) is the hydrostatic pressure, \( I \) is the unitary second-order tensor, and \( \sigma^h_{11} = \sigma^h_{22} = \sigma^h_{33} = 0 \) for uniaxial compression experiments. The Cauchy stress in the uniaxial compression state is expressed as

\[ \sigma^h = 2(\lambda^2 - \lambda^{-1}) \left( \frac{\partial W}{\partial I_1} + \frac{1}{\lambda} \frac{\partial W}{\partial I_2} \right) \] (9)

In the continuum mechanics model in the phenomenological theory, the strain energy density function with strain invariant is more common, whereas the strain energy density function expressed by strain invariant is more typical in the polynomial form. The series of strain energy density function can be expressed as

\[ W_R = \sum_{i,j=0}^{\infty} C_{ij}(I_1 - 3)^i(I_2 - 3)^j \] (10)

**Mooney–Rivlin model.** Mooney\(^{32}\) proposed the Mooney–Rivlin model in the form of binomial syllables before the proposal of the strain energy density function in series

\[ W_M = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) \] (11)

This model is used to characterize the mechanical performance of rubber materials in engineering. The mechanical performance of PVC elastomers at low strain rates can be described by this model. By substituting formula (11) into formula (9), then

\[ \sigma^h = 2(\lambda^2 - \lambda^{-1})(C_{10} + \lambda^{-1}C_{01}) \] (12)

where \( C_{10} \) and \( C_{01} \) are the parameters that should be fitted in the model and \( \lambda = 1 - \varepsilon \), in which \( \varepsilon \) is the engineering strain. The relationship between the engineering and Cauchy stresses is expressed as \( \sigma^e = \lambda \sigma^h \). The engineering stress and strain are positive; substituting the two into formula (12) will result in

Table 3. Mooney–Rivlin model fitting parameters.

|          | 47A    | 52A    | 57A    |
|----------|--------|--------|--------|
| \( C_{10} \) | 0.21880 | 0.46406| 0.11210|
| \( C_{01} \) | -0.54714| -0.85645| -0.68300|

**Figure 7.** Experimental and Mooney–Rivlin model fitting curves.

\[ \sigma^e = 2[(1 - \varepsilon) - (1 - \varepsilon)^{-2}][C_{10} + (1 - \varepsilon)^{-1}C_{01}] \] (13)

Table 3 presents the parameter values obtained by fitting the experimental results of the uniaxial compression experiment of PVC elastomers at a low strain rate.

Figure 7 displays the comparison of the experimental and the fitting results of the constitutive model. The curves are in agreement with each other, indicating that the Mooney–Rivlin model can describe the static mechanical behavior of PVC elastomers within a low range of strain rate.

**Neo–Hookean model.** The Neo–Hookean model is the simplest superelastic model, which retains only the first item of the Mooney–Rivlin model, that is

\[ W_N = C_{10}(I_1 - 3) \] (14)

Substituting formula (14) and the engineering stress and strain into formula (9), then

\[ \sigma^e = 2C_{10}[(1 - \varepsilon) - (1 - \varepsilon)^{-2}] \] (15)

The fitting parameters are shown in Table 4, all of which are obtained by fitting the experimental results of the uniaxial compression experiment of PVC elastomers at a low strain rate.
Figure 8 shows the comparison of the experimental and fitting results of the constitutive model. Similar to the previous model, the two curves are in line with each other, indicating that the Neo–Hookean model cannot describe the static mechanical behavior of PVC elastomers within a low range of strain rate.

Yeoh model. Yeoh stated that when the strain is large, the second strain invariant exert minimal effect on deformation. This idea resulted in the development of the Yeoh model, which is represented only by the first strain invariant and can be expressed as

$$W_Y = C_{10}(I_1 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 \quad (16)$$

Substituting formula (16) and the engineering stress and strain into formula (9), then

$$\sigma' = 2\left(1 - \varepsilon - (1 - \varepsilon)^{-2}\right)$$

$$\left( C_{10} + 2C_{20}((1 - \varepsilon)^2 + 2(1 - \varepsilon)^{-1} - 3) \right) + 3C_{30}((1 - \varepsilon)^2 + 2(1 - \varepsilon)^{-1} - 3)^2 \quad (17)$$

The fitting parameters are presented in Table 5, all of which are obtained by fitting the experimental results of the uniaxial compression experiment of PVC elastomers at a low strain rate.

Figure 9 shows the comparison of the experimental and fitting results of the constitutive model. The two curves agree with each other; hence, the Yeoh model can describe the static mechanical behavior of PVC elastomers within a low range of strain rate.

ZWT nonlinear viscoelastic model

The dynamic mechanical behavior of high-molecular polymers can be described by the ZWT constitutive model, which consists of a nonlinear spring and two Maxwell units. The schematic of the model is shown in Figure 10, and the constitutive model expression is represented by formula (18)

$$\sigma = E_0\varepsilon + \alpha\varepsilon^2 + \beta\varepsilon^3 + E_1\int_0^t \dot{\varepsilon}\exp\left(-\frac{t - \tau}{\theta_1}\right) d\tau$$

$$+ E_2\int_0^t \dot{\varepsilon}\exp\left(-\frac{t - \tau}{\theta_2}\right) d\tau \quad (18)$$

The first three terms in formula (18) correspond to the nonlinear springs, which describe the nonlinear elastic response of the material; $E_0$, $\alpha$, and $\beta$ are elastic constants. The fourth and fifth terms are the two Maxwell units, which describe the viscoelastic response of the material. The first integral is used to describe the viscoelastic response of the material at low strain rate loading, where $E_1$ and $\theta_1$ are the elastic constant and...
relaxation time, respectively. The second integral is used to describe the viscoelastic response of the material at high strain rate loading, where \( E_2 \) and \( \theta_2 \) are the respective elastic constant and relaxation time. When the material is loaded with a low strain rate, the Maxwell unit corresponding to the high strain rate is always in a relaxed state. When the material is loaded with a high strain rate, the Maxwell unit corresponding to the low strain rate is too late to relax. Therefore, the corresponding model expression can be represented as

\[
\sigma = E_0 \varepsilon + x \varepsilon^2 + \beta \varepsilon^3 + E_1 \int_0^t \varepsilon \exp \left( -\frac{t - \tau}{\theta_1} \right) d\tau \\
\sigma = (E_0 + E_1) \varepsilon + x \varepsilon^2 + \beta \varepsilon^3 + E_2 \int_0^t \varepsilon \exp \left( -\frac{t - \tau}{\theta_2} \right) d\tau
\]

(19)

In this study, the loading rate of the experiment can be approximated as constant strain rate loading; thus, formula (19) can be rewritten as

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

(20)

The experimental data of the PVC elastomers under the high strain rate are fitted based on formula (20). The corresponding fitting parameters are shown in Table 6.

Figure 11 shows the comparison of the experimental and fitting results of the constitutive model. The two curves are in line with each other, indicating that the ZWT constitutive model can describe the dynamic mechanical behavior of PVC elastomers under high strain rate range.

**Discussion**

In this article, an experimental method for the design and development of soft polymer materials is reported. The mechanical response of PVC elastomer is measured at low and high strain rates, and the structural modification mechanism of PVC elastomer by plasticizer is analyzed from the microscopic angle. The mechanical parameters such as elastic modulus, yield stress, and flow stress of PVC elastomer materials are obtained through experiments. The correlation rules between the above parameters and plasticizer content, material hardness, and other parameters are clarified. Finally, the superelastic and viscoelastic characteristics of PVC elastomers are described separately. In the

**Table 6. ZWT model fitting parameters.**

| Fitting parameters (MPa) | 1650 s\(^{-1}\) | 2000 s\(^{-1}\) | 2700 s\(^{-1}\) |
|-------------------------|-----------------|-----------------|-----------------|
|                         | 47A  | 52A  | 57A  | 47A  | 52A  | 57A  | 47A  | 52A  | 57A  |
| \( E_0 \)               | 63   | 82   | 73   | 57   | 155  | -230 | 10   | 139  | 336  |
| \( E_1 \)               | 85   | 63   | 61   | 47   | 0    | 508  | 43   | 79   | 0    |
| \( \alpha \)            | -474 | -220 | -500 | -222 | -244 | 1021 | -627 | -591 | 3253 |
| \( \beta \)             | 945  | 9    | 3    | 26   | 71.76| -9698| -2471| 1055 | -20,339|
| \( E_2 \)               | 783  | 256  | 479  | 1010 | 919  | 5361 | 557  | 2184 | 5654 |
| \( \theta_2 \)          | 9.3  | 2.0  | 2.8  | 9    | 1.5  | 1.3  | 2    | 1.1  | 9.4  |
design and development of soft polymer materials, these parameters and characteristics are the key to clarifying the mechanical behavior of materials under impact loading and improving the performance of shock absorption/buffer components in the automotive, aerospace, electronics, and other industries. These factors are very important for material design and development.

Conclusion
In this study, PVC elastomer materials with three Shore hardness levels (57A, 52A, 47A) were obtained by varying the composition ratio of the plasticizers. The static and dynamic mechanical performances of the three materials were studied at strain rates of 0.1, 1650, 2000, and 2700 s⁻¹. Micro-organization observation was conducted, and the superelastic and viscoelastic constitutive models were constructed. The analysis of the experimental results revealed the following:

1. PVC elastomers exhibit obvious strain rate effect. Higher load strain rate signifies a more evident reinforcement effect.
2. The quasi-static mechanical behavior of the PVC elastomers with three Shore hardness levels demonstrates superelastic characteristics. The characteristic error described by the Mooney–Rivlin and Yeoh models is small, whereas that described by the Neo–Hookean model is large. In addition, the error in the viscoelastic characteristics of the dynamic mechanical behavior described by the ZWT constitutive model is small.
3. The Shore hardness and the plasticity of the PVC elastomers decreases and increases, respectively, with increasing amount of plasticizer, resulting in the decrease in the value of the mechanical parameters (i.e. elastic modulus, yield stress, and flow stress).

The conclusions of this study can serve as a reference for further research on the static and dynamic mechanical performances of soft polymer materials. Tests at different ambient temperatures should be performed in high-/low-temperature environmental chamber to investigate the effect of temperature on the static and dynamic mechanical performances of PVC elastomers.

Declaration of conflicting interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the Key Natural Science Research Projects of Anhui Higher Education Institutions (Grant No. KJ2016A145), Natural Science Foundation of Anhui Province (Grant No. 1708085ME130), Anhui Education Department Excellent Young Talent Support Project (Grant No. gxyqZD2019057), Open Fund of State Key Laboratory of Vehicle NVH and Safety Technology (Grant No. NVHSKL-201407), and Anhui Province Key Research and Development Project (Grant No. 1804a09020009).

ORCID iD
Yan Xuan https://orcid.org/0000-0001-5650-6033

References
1. Mulliken AD and Boyce MC. Mechanics of the rate-dependent elastic–plastic deformation of glassy polymers from low to high strain rates. Int J Solid Struct 2006; 43: 1331–1356.
2. Hang C, Su E, Yan Q, et al. Experimental investigation on dynamic characteristics of two kinds of rubber engine vibration isolator. J Exp Mech 2019; 34: 157–165.
3. Bernard CA, Bahlouli N, Wagner-Kocher C, et al. Multiscale description and prediction of the thermomechanical behavior of multilayered plasticized PVC under a wide range of strain rate. J Mat Sci 2018; 53: 14834–14849.
4. Wang W, Li W, Liang P, et al. Preparation of car crash dummy skin and its mechanical performance test. J Jilin Univ 2019; 49: 192–198.
5. Du B, Sun X, Xiao M, et al. Advances in thermal performance of polymer-based composites. Trans China Electrotech Soc 2018; 33: 3149–3159.
6. Jha NK, Nackenhorst U, Pawar VS, et al. On the constitutive modelling of fatigue damage in rubber-like materials. Int J Solids Struct 2018; 159: 77–89.
7. Zhang Z, Tian Y, Liu W, et al. Study on the cushioning performance of aviation bearing PDMS buffer packaging pad. Packag Eng 2019; 40: 75–79.
8. Qin G. Research on the influence of different modifiers on the properties of PVC pipe materials. Contemp Chem Ind 2017; 46: 2251–2253.
9. Yang H, Lu S and Xiong C. Research progress on crystallization behavior of polyvinyl chloride. Polynyl Chloride 2003; 4: 1–3.
10. Huang Z, Bao Y, Weng Z, et al. Study on the crystallization behavior of polyvinyl chloride. Polym Mater Sci Eng 1998; 14(4): 79–82.
11. Liu C, Zhu Q, Wei F, et al. An integrated optimization control method for remanufacturing assembly system. J Clean Prod 2019; 248: 119261.
12. Sonia S, Mostapha T, Mourad N, et al. Strain rate effects on the dynamic compressive response and the failure
behavior of polyester matrix. Compos B Eng 2019; 174: 107040.
13. Aisha A, Neelanchali A, Hemant C, et al. Study of polycarbonate based nano-composites at high strain rate impact. Proc Struct Integr 2019; 14: 507–513.
14. Fan JT, Weerheijm J, Sluys LJ, et al. Deformation to fracture evolution of a flexible polymer under split Hopkinson pressure bar loading. Polym Test 2018; 70: 192–196.
15. Duan Y, Du B, Shi X, et al. Quasi-static and dynamic compressive properties and deformation mechanisms of 3D printed polymeric cellular structures with Kelvin cells. Int J Impact Eng 2019; 132: 103300.
16. Rusinek A, Bernier R, Matadi Boumbima R, et al. New devices to capture the temperature effect under dynamic compression and impact perforation of polymers, application to PMMA. Polymer Test 2018; 65: 1–9.
17. Li S, Feng S, Xue Z, et al. Mechanical properties of PTFE at high strain rate. Explosion Shock Waves 2017; 37: 1046–1050.
18. Kun L, Zhilin W, Huilan R, et al. Strain rate sensitive compressive response of gelatine: experimental and constitutive analysis. Polym Test 2017; 64: 254–266.
19. Hao W, Ximin D, Haijun W, et al. Investigating the dynamic mechanical behaviors of polyurea through experimentation and modeling. Def Technol 2019; 15: 875–884.
20. Fan JT, Weerheijm J, Sluys LJ, et al. Compressive response of a glass–polymer system at various strain rates. Mech Mater 2016; 95: 49–59.
21. Fan JT, Weerheijm J, Sluys LJ, et al. Dynamic compressive mechanical response of a soft polymer material. Mater Des 2015; 79: 73–85.
22. Singh SS, Venkitanarayanan P, Kitey R, et al. Dynamic compression behavior of glass filled epoxy composites: Influence of filler shape and exposure to high temperature. Compos B Eng 2019; 164: 103–115.
23. Chen X, Lai J, Chang X-L, et al. Compressive mechanical properties of HTPB propellant at low temperatures and high strain rates. Results Phys 2017; 7: 4079–4084.
24. Zeng HB and Bailly P. Experimental characterization of dynamic behaviour of gelatin-based material using DIC. Polym Test 2017; 63: 298–306.
25. Liu C, Zhu Q, Wei F, et al. A review on remanufacturing assembly management and technology. Int J Adv Manuf Techn 2019; 105: 4797–4808.
26. Liu C, Cai W, Dinolov O, et al. Energy based sustainability evaluation of remanufacturing machining systems. Energy 2018; 150: 670–680.
27. Jiang TZ, Xue P and Butt HSU. Pulse shaper design for dynamic testing of viscoelastic materials using polymeric SHPB. Int J Impact Eng 2015; 79: 45–52.
28. Xu L, Gao G, Zhao Z, et al. Compressive mechanical properties of polyethylene at different strain rates. Explosion Shock Waves 2019; 39: 58–65.
29. Wang B, Hu S and Zhou X. Research of dynamic mechanical behavior and constitutive model of rubber under different temperatures. J Experiment Mech 2007; 22: 1–6.
30. ISO 7743: 2007. Determination of compressive stress and strain properties of vulcanized rubber or thermoplastic rubber. Beijing, China: China Standard Press, 2009.
31. Siviour CL and Jordan JL. High strain rate mechanics of polymers: a review. J Dynam Behav Mater 2016; 2: 15–32.
32. Mooney M. A theory of large elasticity deformation. J Appl Phys 1940; 11: 582.
33. Zhou H, Li S, Xie K, et al. Research on the viscoelastic constitutive model of HTPB propellant over a wide range of strain rates. J Solid Rocket Technol 2017; 40: 325–329.