Mechanical properties of metal and polymeric viscoelastic materials and their applications

Kai Kang
Costal Engineering, School of Civil Engineering, Tianjin University; No.135, Yaguan Road, Jinan District, Tianjin

k_842606106@tju.edu.cn

Abstract. Nowadays, with the wide application of metals and polymeric materials, how to describe the property of viscoelastic material and how to apply them in engineering has become more and more critical. Due to the lack of insight into the mechanical properties of viscoelastic materials, many scholars have done a lot of experiments in studying the behavior of viscoelastic materials. Axial tensile tests were conducted on specimens to derive different mechanical behaviors of metals, polymers, and other materials at different temperatures and loading rates. Metal can generally be divided into elastic and plastic parts, while polymeric materials have the phases of the linear elastic region, drawing region, and oriented molecular strength region. This paper also shows a test conducted by Argon, Ali S., and M. I. Bessonov of four different kinds of polymers at different circumstances of temperature. After that, the paper shows the application of viscoelastic materials as CLD in damping and some engineering problems caused by the mechanical properties of viscoelastic materials. Currently, research on viscoelasticity should mainly focus on the application of Finite Element Methods and the acquisition of more experimental data to establish a complete theoretical system.

Keywords. Mechanical properties, metal, polymeric materials, damping design

1. Introduction
Viscoelasticity is a property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. In terms of microstructure, viscosity results from the diffusion of atoms or molecules inside an amorphous material. At the same time, elasticity is mainly the result of bond stretching inside a crystal material. Nowadays, with the wide application of metals and polymeric materials, how to describe the property of viscoelastic material and how to apply them in engineering has become more and more critical. This paper is mainly based on previous theories and researches. It summarises the basic models and the exact mechanical properties and behavior of viscoelastic materials to the application in engineering. The problems of the steel and concrete due to the viscoelasticity property will be discussed in this paper.

2. Models
2.1. Spring model
Hooke model is the model that follows Hooke's law. Hooke's law is named after 17th-century British physicist Robert Hooke. In 1676, the law is stated for the first time by Robert Hooke. [2].

In general, the spring model corresponds to the elastic deformation. When a force is employed on elastic material, the material will be stretched or compressed, which implies the break points in the stress-time curve.

The stress in the spring model is given by

\[ \sigma = E \times \varepsilon \]

E represents elastic modulus.

2.2. Shock absorber model

The shock absorber model is used to describe viscous material when it begins to deform. The deformation of the absorber model will not react instantly, and it will not reverse spontaneously. We call this phenomenon viscous sliding.

The stress in the shock absorber model is given by

\[ \sigma = \eta \times \frac{d\varepsilon}{dt} \]

\( \eta \) represents fluid viscosity.

2.3. Maxwell model & Voigt-Kelvin model

Maxwell model and Voigt-Kelvin model are used to describe the viscoelastic material. Maxwell model combines the shock absorber and spring in series, and the Voigt-Kelvin model combines them in parallel.
J.A. Epaarachchi represented the Maxwell model's conceptions and dynamic behaviors and Kelvin-Voigt model in Creep and Fatigue in Polymer Matrix Composites. The Maxwell model is one of the simplest idealizations of characteristics of the viscoelastic material shown in Fig. 2.[2]

![Maxwell model](image1)

**Figure 3.** Maxwell model and the stress-time curve

The Kelvin-Voigt model is shown in Fig. 3
In the Maxwell model, For the mechanical properties of polymeric materials, the deformation of elastic materials is instant while the viscous sliding is not. after unloading, the deformation of elastic materials is reverse immediately, whereas the viscous sliding is not reversible.[1]
In the Voigt-Kelvin model, to adapt to the property of rubber tires, the deformation of the system demands the deformation elastically and viciously; after unloading, the elastic element removes the deformation and causes the sliding inversion.[1]
However, The actual behavior of the various types of polymer is more complicated than both the Maxwell model and Voigt-Kelvin model[2]. Moreover, in most cases, we combine models as mentioned earlier to describe a more complex property. An example is shown in Fig. 5

![Maxwell + Voigt-Kelvin model](image2)

**Figure 4.** Maxwell + Voigt-Kelvin model

3. Behavior of viscoelastic material

3.1. Theories of viscoelastic behavior
Many scholars have made investigations of the property of viscoelasticity. For example, the theory made by Green and Rivlin, who have been proved that the stress tensor of anisotropic material can be expressed as a series of multiple integrals of a symmetric matrix polynomial with the required degree of approximation[4-6]. Another example is the theory shown by Nakada, which is a particular case of the theory of Green and Rivlin for one-dimensional non-linear phenomena, which extended
Boltzmann's superposition principle and expressed the stress as a series of multiple integrals of the strain[5].

### 3.2. The behavior of metals

Fig. 3.1 shows the tensile stress-strain curve of a metal ductile; from the different curves tested by different kinds of metals, we can obtain the different mechanical parameters [1].

As it is shown in Fig. 5, two different regions can be roughly divided. The first region of this curve is the elastic region, where is linear between the stress and the deformation. The second region of this curve is the plastic region. The stress/strain curve shows the characteristic of non-linear behavior; when the sample is unloaded, there is still residual plastic deformation on the sample. At the microstructure of metal materials, due to the displacement of dislocations, there is an irrecoverable flow between lattice atoms; therefore, permanent residual deformation will occur in the specimen. [1]

![Stress/strain curve of a metal](image)

**Figure 5.** Stress/strain curve of a metal

### 3.3. The behavior of Polymers

Polymers are always viscoelastic because they consist out of long molecules which can be entangled with their neighbors.

Fig. 6 shows the tensile stress-strain curve of a thermoplastic polymeric material[1].
The yield stress, $\sigma_y$, corresponds to the peak following the curve.
After yield stress, the neck of the specimen begins to shrink, which is called necking. And the polymer exhibits a phase of drawing, where macromolecular chains begin to realigned along the direction of the load.
When the maximum elongation is reached, it requires larger stress to get higher deformation since it is necessary. In this last part of the curve, macromolecular chains are bond together, and they begin harder to stretch.

3.3.1 TENSILE BEHAVIOR OF DIFFERENT KINDS OF POLYMERS
Different kinds of polymers show different characteristics of mechanical properties. Some kinds of polymers show a yield phenomenon, whereas some kinds of polymers' transitions are smooth. [9]
Argon, Ali S., and M. I. Bessonov have tested four polyimides, and the relationship between stress and strain are shown in Fig. 7
Compared with DFP, H-H, and R-R, Kapton shows a smooth and gradual transition from elastic to plastic behavior, which remains uninfluenced mainly in the entire temperature range. For the three polymers exhibiting a yield phenomenon, the upper yield stresses are slightly different[9]

3.3.2 TENSILE BEHAVIOR AS A FUNCTION OF TEMPERATURE
Argon, Ali S., and M. I. Bessonov also showed the relationship of these four polymerics between the temperature and tensile yield stress. The results are shown in Fig. 8[9]
4. Examples of viscoelastic material & application

4.1. background

With the development and comprehensive application of the Finite Element Method, many engineering problems can be solved by the power of the computational method. However, while finite
element models are applied widely in engineering, such as the design of elastic and inertial properties, damping design still has many potentials to be developed.

4.2. Application of viscoelastic material in constrained layer damping
Typically, the mechanism of damping equipment is that by employing the elastomers in the structure, it enforces the kinetic energy is converted into thermal energy due to the relaxation behavior of the flexible long-chain molecules. The associated damping properties of these viscoelastic materials can be described by rheological and chemical substitute models, accounting for frequency and temperature dependence. [6]
Constrained layer damping is a model of a damping structure represented by Baz A. and Ro J[6]. According to their idea, constrained layer damping (CLD) is a well-developed concept for damping flexural vibrations. In this structure, between the host structure and a stiff face layer, the elastomer is attached as a damping function, shown in Fig. 9 [6]
However, due to the impact of stress rate and temperature, these factors should be considered in this damping structure.

5. The disadvantage of the viscoelastic property

5.1. Impacts of High temperature on metal
When employed the viscoelastic material, the temperature and stress rate should be well considered since these two factors significantly impact the viscoelastic material.
When R.C is heated, as the temperature goes up, the viscoelastic may have great elongations, which will cause great deformation and destroy the structure.
In a mechanical structure such as a plane engine, while they are working, it will generate much heat. Thus, when engines are overrun, too much heat would cause the metal to have more viscous properties and creep and deform, which will eventually be very dangerous if the viscoelastic property is not considered when designing.
Another example is the application in rockets. The tanks of fuel in the rocket are made of viscoelasticity material. When the rocket is propelled, we need to analyze and evaluate the structural integrity.
Most of the buildings are made of reinforced concrete (R.C), which contains steel. At room temperature, it was strong enough to endure tension and compression. Nevertheless, if there is a fire, greatly heated R.C will suddenly lose rigidity and become viscous. When this happened, the construction will undertake great danger to crush.
By using Eurocode Model, Robert Kowalski gets a series of data when R.C is exposed to fire. The relationship between free thermal elongation of steel and temperature are shown in Fig. 10[8]

![Figure 10. Free thermal elongation of steel](image_url)

5.2. Creep and shrinkage of concrete
Another disadvantage of viscoelastic property is the creep and shrinkage of concrete. Creep of concrete has its source in the hardened cement paste and, at high stresses, also in the failure of the paste-aggregate bond. In order to predict the concrete creep effects, mathematical modeling of creep and shrinkage of concrete.

An essential property of the compliance function of concrete is that it is a function of two variables, the current age, t, and the age at loading t' (Fig. 11)[7], so they both should be considered in the test. Bazant, Zdenek P., and Folker H. Wittmann summarized the new creep law based on solidification theory simplifies the computer creep analysis of structure. However, that is too complicated to demonstrate in this paper.

6. Conclusion
To sum up, this paper focuses on the summarization of the behaviors and application of the viscoelastic materials and lists two examples that the behaviors of viscoelasticity could also have a negative effect in engineering.

In the second part, behaviors of the typical kinds of materials are shown, whereas, take the polymeric materials, for example, some special type of polymer has a totally different mechanical property from the typical one. Therefore, more tests should be made, and more numerical models should be established to consider all of the circumstances. So the main work at present should focus on the development of FEM and establish a series of adaptable models to describe the property of viscoelastic materials such as polymers and rubbers.
7. Reference
[1] M C Tanzi, Silvia F, Gabriele C 2019 Mechanical properties of materials Elsevier BV.
[2] J.A. Epaarachchi 2011 The effect of viscoelasticity on fatigue behaviour of polymer matrix composites (Amsterdam: Elsevier) 492-513
[3] Green A E and Rivlin R S 1957 The mechanics of non-linear materials with memory Archive for rational mechanics and analysis 1-21.
[4] Green, A E, & Rivlin, R S 1959 The mechanics of non-linear materials with memory Archive for rational mechanics and analysis 387-404.
[5] Nakada O 1960 Theory of non-linear responses Journal of the Physical Society of Japan 15(12) 2280-2288.
[6] Baz A and Ro J 1995 Optimum Design and Control of Active Constrained Layer Damping 135-144
[7] Bazant, Zdenek P, and Folker H. Wittmann 1982 Creep and shrinkage in concrete structures (New York: Wiley–Interscience) 12-16
[8] Kowalski R 2017 The Use of Eurocode Model of Reinforcing Steel Behavior at High Temperature for Calculation of Bars Elongation in RC Elements Subjected to Fire Procedia Engineering 193 27-34
[9] Argon A and Bessonov M 1977 Plastic deformation in polyimides, with new implications on the theory of plastic deformation of glassy polymers Philosophical Magazine 35 917-933

Figure 11. Creep isochrones(top), and compliance curves for various ages t’ at loading(bottom)