

Experimental Studies on Viscoelasticity of Film Materials in Laminated Glass Sheets

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ABSTRACT

Polyvinyl butyral (PVB) film and SentryGlas® Plus (SGP) film have been widely used in automotive windshield and architecture curtain serving as protective interlayer materials. Viscoelasticity is the unique property of such film materials, which can contribute to improving impact resistance and energy absorbing characteristics of laminated glass. In this study, the uniaxial tensile creep and stress relaxation tests are conducted to investigate the viscoelasticity of PVB and SGP films used in laminated glass. Firstly, tensile creep and stress relaxation tests of PVB film (0.76mm) and SGP film with three thickness (0.89mm, 1.14mm and 1.52mm) are conducted using Instron universal testing machine to obtain creep and stress relaxation curves. Afterwards, both viscoelastic models (Burgers model, Maxwell-Weichert model) and empirical equations (Findley power law, Kohlrausch equation) are applied to simulate the creep and stress relaxation results. The simulating results from both models and empirical equations are in good agreement with the creep and relaxation experimental results. Furthermore, an additional effort is carried out to analyze the influence of material properties on parameters of viscoelastic models and empirical equations. Results may provide basic experimental data and theoretical support to explore energy absorbing characteristics and safety design of laminated glass.

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INTRODUCTION

Polyvinyl butyral (PVB) film and SentryGlas® Plus (SGP) film serve as preferred interlayer materials for current automotive windshield[1] and architecture curtain[2], with excellent adhesive property, optical clarity, toughness and flexibility[3, 4, 5]. The mechanical behavior including impact resistance and energy absorption characteristics is highly dependent on the interlayer materials mainly due to its viscoelasticity[6, 7]. Therefore, the investigation on viscoelastic behavior of interlayer materials is a hot topic of current research.

Several experimental studies have been carried out to investigate the mechanical behavior of PVB interlayer. Xu[8, 9] and Liu[3] have investigated the compressive behavior of PVB under quasi-static and dynamic loadings, and set up its constitutive relations. However, the interlayer film shows tensile deformation in the process of laminated glass being impacted[10]. Thus, Liu[3], Chen[11] and Iwasaki[12] conducted uniaxial tensile experiments of PVB materials at low strain rates, and established corresponding constitutive models to describe its mechanical behavior. Uniaxial tensile experiments of PVB and its rate dependent constitutive behavior at high strain rates range from 118s^{-1} to 3768s^{-1} have also been studied by Iwasaki[12] and Yang[10].

In fact, the viscoelastic model can describe the mechanical properties of interlayer materials well[13]. Liu[14] and Hooper[15] studied the dynamic viscoelasticity of PVB interlayer based on Dynamic Mechanical Analysis (DMA) at various temperature, heating rate and vibration frequencies. Constitutive behavior of PVB was analyzed

based on Generalized Maxwell model and Fractional Derivative Maxwell model. Zhang et al.[16] studied the dynamic tensile response of a transparent polyurethane interlayer using DMA, Instron testing system and low impedance Split Hopkinson Tension Bar (SHTN) under different strain rate and temperature, and employed thermal-viscoelastic Zhu-Wang-Tang (ZWT) constitutive model to describe its dynamic tensile response. Long term viscoelastic behavior of interlayer materials as creep and stress relaxation have also been explored. Charitidis et al.[17] conducted compression creep experiments of carbon nanotube/polyvinyl butyral composites, and revealed that a higher loading rate results in a greater primary creep deformation and leads to an increase of the total creep deformation. Froli et al.[18, 19] conducted compression shear tests of PVB in laminated safety glass to investigate its shear viscoelastic properties, as creep and relaxation. Serafinavičius et al.[20] carried out bending creep tests of laminated glass with PVB, Ethyl Vinyl Acetate (EVA) and SGP interlayers at different temperature.

However, few research focus on the creep and stress relaxation characteristics under uniaxial tensile tests to investigate the viscoelasticity of interlayer films, which is particularly important to understand the tensile viscoelasticity of interlayer films. In this study, the uniaxial tensile creep and stress relaxation tests are carried out to explore the viscoelasticity of PVB and SGP films. Afterwards, both viscoelastic models and empirical equations are introduced to model

the creep and stress relaxation curves. Finally, an attempt is carried out to study the influence of material properties on parameters of creep and stress relaxation models.

THEORETICAL BACKGROUND

Creep Model

Burgers Model

Burgers model or four element model[21, 22] is one of the most widely used numerous viscoelastic creep model to describe the viscoelasticity of polymer materials, consisting of a Maxwell unit and a Kelvin unit connected in series shown in Figure 1. The constitutive formula of Burgers model can be obtained through calculating the strain response under constant applied stress σ as shown in Figure 1. The spring and dashpot in the Maxwell unit are considered as two elements, thus the total strain at time t which is the sum of the three elements, is given below:

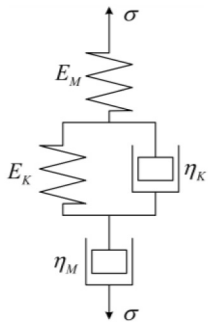


Figure 1. The schematic view of Burgers model.

$$\varepsilon_B = \varepsilon_{M1} + \varepsilon_{M2} + \varepsilon_K \quad (1)$$

where subscript B indicates the parameters associated with the Burgers model and ε_{M1} , ε_{M2} , ε_K represent the strains of Maxwell spring, Maxwell dashpot and Kelvin unit respectively:

$$\varepsilon_{M1} = \frac{\sigma}{E_M} \quad (2)$$

$$\varepsilon_{M2} = \frac{\sigma}{\eta_M} \quad (3)$$

$$\dot{\varepsilon}_K + \frac{E_K}{\eta_K} \varepsilon_K = \frac{\sigma}{\eta_K} \quad (4)$$

where E_M , η_M are the modulus and viscosity of Maxwell unit respectively; E_K , η_K are the modulus and viscosity of Kelvin unit respectively. Then ε_{M1} , ε_{M2} , ε_K can be eliminated to obtain a constitutive equation given below:

$$\sigma + \left(\frac{\eta_M}{E_M} + \frac{\eta_M}{E_K} + \frac{\eta_K}{E_K} \right) \dot{\sigma} + \frac{\eta_M \eta_K}{E_M E_K} \ddot{\sigma} = \eta_M \dot{\varepsilon} + \frac{\eta_M \eta_K}{E_K} \ddot{\varepsilon} \quad (5)$$

Using the initial condition at $t = 0$, the Burgers model to describe creep behavior is obtained as follows:

$$\varepsilon_B = \frac{\sigma_0}{E_M} + \frac{\sigma_0}{E_K} (1 - e^{-t/\tau}) + \frac{\sigma_0}{\eta_M} t \quad (6)$$

where σ_0 is the initial applied stress, the retardation time $\tau = \eta_K / E_K$ is the time taken to yield $(1 - e^{-1})$ of the total deformation of the Kelvin unit.

Findley Power Law

Findley et al. [21] put forward the following empirical power function to describe creep behavior of many polymer materials over a wide range of time with high accuracy:

$$\log(\varepsilon_F - \varepsilon_{F0}) = \log \varepsilon_{F1} + n \log t \quad (7)$$

where subscript F indicates the parameters associated with the Findley power model, n is a constant independent of stress and temperature, and generally less than one. ε_{F0} and ε_{F1} are time-independent and time-dependent strains respectively, which are dependent on stress and material parameters.

Stress Relaxation Model

Kohlrausch Equation

The stretched exponential Kohlrausch equation[23] is an empirical formula which is not a physical model of viscoelastic material, but can accurately express most relaxation curves of viscoelastic materials. The Kohlrausch equation is defined as:

$$\sigma_K = \sigma_\infty + \sigma_1 e^{-(t/\tau)^\beta} \quad (8)$$

where subscript K indicates the parameters associated with the Kohlrausch equation, t and τ are the experimental and relaxation time respectively. Limiting stress σ_∞ , transient stress σ_1 and stretching parameter β are the fitting parameters, wherein the value of β is between 0 and 1.

Maxwell-Weichert Model

Most viscoelastic materials possess at least two main transition, i.e. from glassy state to rubbery state and from rubbery state to liquid state. Maxwell-Weichert or generalized Maxwell model[24] with any number of parallel Maxwell units shown in Figure 2, is a promotion of Maxwell model which just has one relaxation time and cannot describe the stress relaxation of polymer adequately, to describe the relaxation of viscoelastic materials.

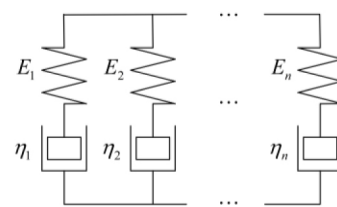


Figure 2. The schematic view of Maxwell-Weichert model.

The strain of each unit can be described by spring constants E_i and viscosity η_i , thus the relaxation times τ_i can be determined. The strains of each unit are equal and the total stress σ is the sum of each unit σ_i , which can be described as:

$$\frac{d\varepsilon(t)}{dt} = 0 = \frac{1}{E_1} \frac{d\sigma_1}{dt} + \frac{\sigma_1}{\eta_1} = \frac{1}{E_2} \frac{d\sigma_2}{dt} + \frac{\sigma_2}{\eta_2} = \dots = \frac{1}{E_n} \frac{d\sigma_n}{dt} + \frac{\sigma_n}{\eta_n} \quad (9)$$

and

$$\sigma = \sigma_1 + \sigma_2 + \dots + \sigma_n \quad (10)$$

The integral Eq. (9) is substituted into Eq. (10), then the total stress can be expressed as:

$$\sigma = \sum_{i=1}^n \frac{\sigma(0)_i}{\varepsilon_0} \exp(-t / \tau_i) \quad (11)$$

where t is the experimental time, ε_0 is the constant strain and $\sigma(0)_i$ is the stress on the i th unit at time zero. The Maxwell-Werchert model with three relaxation time is introduced in our study to analyze the stress relaxation procedure, which is given below:

$$\sigma_M = C_1 \exp(-t / \tau_1) + C_2 \exp(-t / \tau_2) + C_3 \exp(-t / \tau_3) \quad (12)$$

where subscript M indicates the parameters associated with the Maxwell Weichert model, C_i are pre-exponential factors dependent on stress and material parameters with $C_1 + C_2 + C_3 = \sigma_0$, and relaxation times τ_i satisfy the relation: $\tau_1 < \tau_2 < \tau_3$.

EXPERIMENTAL DETAILS

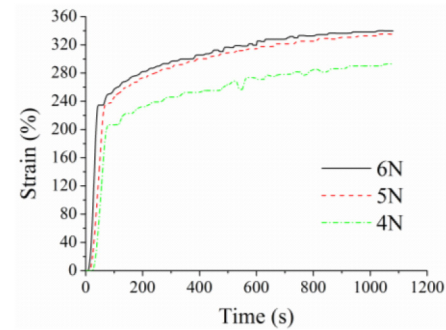
Experimental Setup and Procedure

Uniaxial tensile creep and stress relaxation experiments are conducted using Instron universal testing machine. The dumbbell specimens[25] with gauge length of 33 mm are applied in uniaxial tensile creep and stress relaxation tests. The uniaxial tensile creep and stress relaxation conditions are listed in Table A1 and A2. Each experimental condition is repeated three times and the average values are obtained. In addition, all experiments are carried out in the room temperature (20-25°C) and in the humidity of 20-30%.

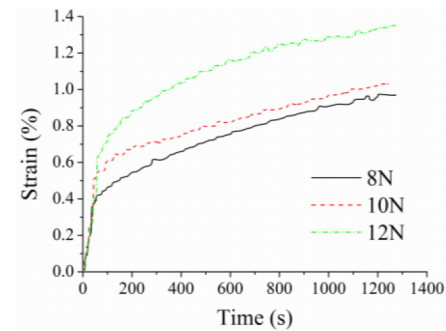
Experimental Results

Figure 3 shows the creep experimental curves of PVB and SGP samples with different thickness under different creep conditions. It can be seen that the curves can be divided into three stages: the first stage is the elastic deformation stage, i.e. the specimens are loaded to certain loads under different loading. In this stage, the slope of SGP film is higher than that of PVB film and the slope of this stage increases with the loading rate, which depicts that the modulus of SGP is higher than PVB and the modulus of viscoelastic materials is affected by the loading rate. The creep begins after the first stage and can be divided into two stages: transient stage and stable stage,

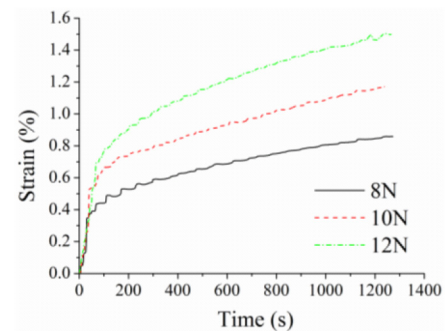
representing the regions of decreasing creep rate and near constant creep rate consistent with previous works[26]. The second stage is the transient stage creep and the duration of this stage is far less than that of the third stage, i.e. stable stage creep. The initial load determines the starting point of creep and the height of the entire curve.



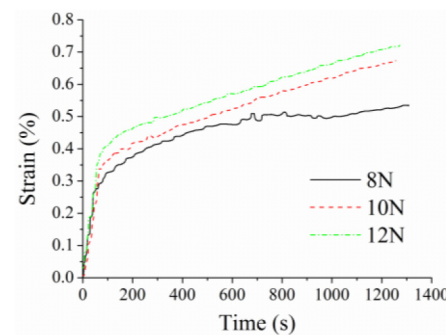
a. PVB-0.76-creep.



b. SGP-0.89-creep.



c. SGP-1.14-creep.



b. SGP-1.52-creep.

Figure 3. The creep experimental curves of PVB and SGP samples with different thickness under different creep conditions.