Long Term Creep Assessment of Room-temperature Cured Epoxy Adhesive by Time-stress Superposition and Fractional Rheological Model

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Received: 5.6.2018, Final version: 15.8.2018

Abstract:
The creep behavior of a new type epoxy resin adhesive which is room-temperature cured and used for reinforcing engineering structures was studied. The tensile strength of the adhesive has reached the desired values for the structural adhesive used for bonding concrete as the base material with steel. The short-term creep tests were conducted under four different stress levels. The generalized curve for reference stress was obtained by utilizing the time-stress equivalent principle. Moreover, compared with traditional Burgers model, an improved fractional KBurgers model obtained by replacing the Newton derivative with the fractional derivative element (Abel component) in the traditional Burgers model can capture the creep behavior of this epoxy adhesive with high precision in the condition of the room-temperature and tensile stress of 36 MPa.

Key words:
Epoxy resin adhesive, creep, time-stress equivalence principle, KBurgers model

1 INTRODUCTION

Epoxy resin adhesive is widely used in civil engineering structures and other engineering applications because of its excellent comprehensive performance and good bonding to the surface of materials. The long-term behavior of the structural adhesive has a great impact on the engineering structures which have a design life of several decades or even a hundred years [1]. Therefore, the long-term behavior of the structural adhesive in the certain condition needs to be studied. Obviously, it is impossible to estimate the long-term property according to the method listed in the standard, because it will cost at least several months or even several years. It has been proved that the high temperature and high stress can accelerate the creep rate of materials. In recent decades, temperature, load and physical aging attracted lots of attention were considered to be the main factors of great effect on the creep [2–6] and some accelerated methods developed to assess the long-term creep behavior of epoxy adhesive were mainly the utilization of time-temperature equivalence principle and time-temperature-stress equivalence principle [7–14].

In the past decades, extensive efforts have been devoted to understanding the principle of time-temperature equivalence applied to predict the long-term performance of epoxy adhesive in a short time [15, 16]. Nevertheless, the creep behavior of adhesive was found to be very sensitive to small change in temperature and sometimes in order to obtain data in the certain temperature, tests need to be operated at extremely low and high temperature which cannot be readily realized in the laboratory [17, 18]. On the contrary, it is easier to control and realize the extremely low and high stress in the laboratory. According to the time-temperature-stress equivalence principle, the generalized curve of reference temperature and stress level can be constructed by the short-term creep curve shifted along the time scale. Luo et al. had proved that the time-stress equivalence principle can be deduced from time-temperature-stress equivalence and verified it by experiments [14]. The validity and practicability of the time-stress equivalence principle focused on accelerating the creep behavior of materials were indicated by considerable research [19–21]. Except for temperature and stress, the physical aging, such as hydrothermal aging

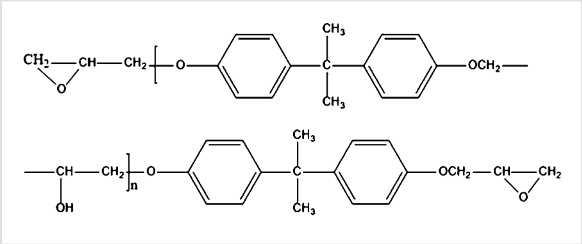

Figure 1: The general formula of E51.

Appearance	Viscosity (40℃)	Epoxide number	Organo-chlorine	Volatile content	Inorganic chlorine
Canary, yellow, transparent, viscous liquid	2.5 Pas	0.48~0.52	0.02	1 %	0.001

Table 1: Performance parameters of E51. Epoxide number and chlorine contents are given in units of equivalent weight/100 g.

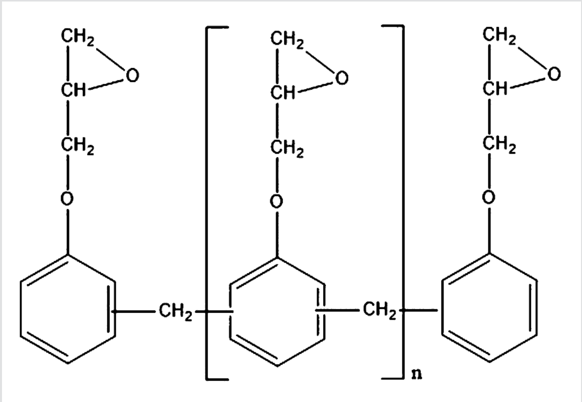

Figure 2: The general formula of F51.

Appearance	Softing point	Epoxide number	Organo-chlorine	Inorganic chlorine	Volatile content (110 ℃, 3h)
Brown, transparent, high viscosity liquid	28℃	0.50	0.02	0.005	≤ 1 %

Table 2: Performance parameters of F51.

and thermal aging, also has a great impact on creep behavior of adhesive [22, 23]. It was proved that, at each aging condition, the strain-time curves obtained at the same stress could be superimposed by shift along the time axis consistent with the time-stress equivalence principle.

The fact that the generalized curve obtained by the methods analyzed above can extend the tests data by several decades were reported in the researches [24–27], but it was far from enough compared with the design life of engineering structure and it is also unrealistic to obtain the creep properties of adhesive for greater range through laboratory. Therefore, it is necessary to develop some techniques and methods to accelerate the characterization of long-term properties. The rheological models which can the offer the functional relationship between mechanical behavior and

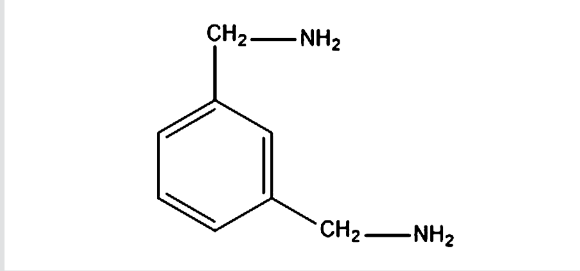

Figure 3: The chemical structure of m-Xylylenediamine (m-XDA).

time of adhesives effectively were seldom used for simulating the generalized curves of adhesive over the past decades. The integer order rheological models, such as Burgers model, modeling only the primary and secondary ranges of the experimental creep curve of adhesives well, were mostly common used in the literature [28–36]. In recent years, the fractional order viscoelastic constitutive models with fewer parameters and well description of the viscoelastic behavior of materials were introduced by some scholars [37–43]. However, there have fewer relevant references about epoxy adhesive simulated by the fractional rheological model. Furthermore, the rheological models are not universally applicable and one kind of material corresponds to a most suitable rheological model under certain environment. Besides, for a new type material, the fractional model should be employed to simulate from simple to complex and chose a model with the highest fitting degree.

In this paper, a new kind of room-temperature cured epoxy resin adhesive used for engineering structures was fabricated and studied. The formula of adhesives was simple without modification and the adhesives can be cured at room-temperature with high performance. The short-term creep experiments of this new type adhesive were conducted at four different stress levels. The generalized curves for the 36 MPa of creep behavior at room-temperature obtained by time-stress equivalence principle were fitted well by an improved fractional rheological model (KBurgers model). The objective of this research is to analyze the creep behavior of this new type adhesive and, especially, to establish the functional relationship between the strain and time by an improved fractional rheological model. Moreover, it has shed light on the role of the fractional rheological model on the creep behavior research and structure analysis of structural adhesive.

2 EXPERIMENTAL PROCEDURE

2.1 MATERIALS

A commercial epoxy resin with a brand name of E51 was chosen, and purchased from Xing-chen Chemicals Co., Ltd. (Wuxi, China). Performance parameters are shown in Table 1. The general formula of E51 is shown in Figure 1.

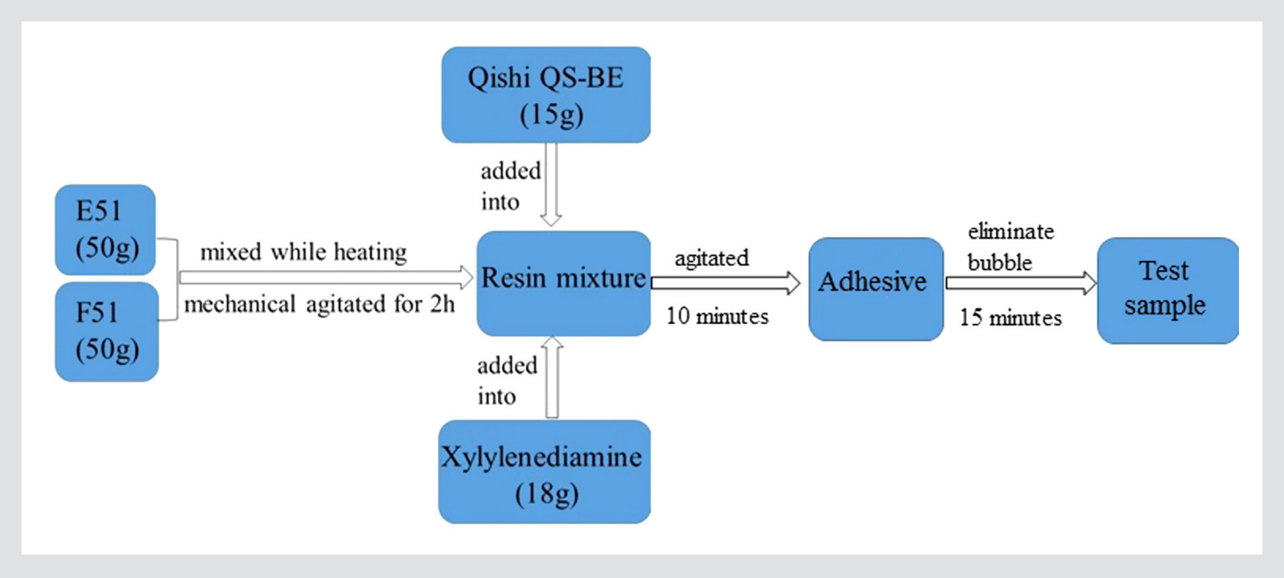

Figure 4: Flowchart of sample preparation.

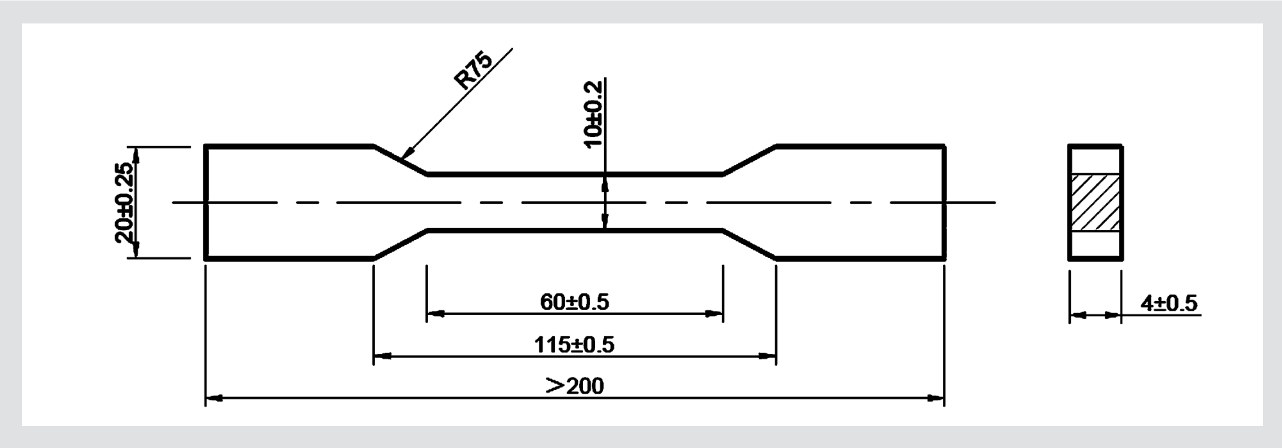

Figure 5: Dimensions of the test sample (mm).

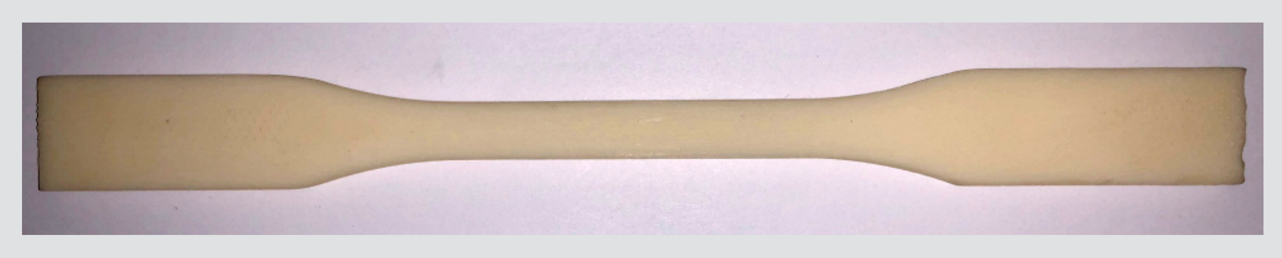

Figure 6: The physical map of the test sample.

A commercial novolac epoxy resin with a brand name of F51 was used and purchased from Xing-chen Chemicals Co., Ltd. (Wuxi, China). Performance parameters are shown in Table 2. The general formula of F51 is shown in Figure 2. Qishi QS-BE was chosen as toughening agent and purchased from Beijing Jingdao Qishi Materials Sci & Tech Co., Ltd. (Beijing, China). m-Xylylenediamine (m-XDA) was chosen as a hardener and purchased from Xiamen Grandachem Co., Ltd. (Xiamen, China). It is crystalline liquid at room-temperature and the chemical structure is shown in Figure 3.

2.2 SAMPLE PREPARATION

As shown in Figure 4, 50 g E51 and 50 g F51 were mixed and mechanical agitated for 2 hours. Then 15 g Qishi BE and 18 g m-XDA was added to the resin mixture agitated for 10 minutes and placed in a vacuum box to eliminate bubble for 15 minutes. At last, the epoxy adhesive was poured into the mold prepared before and cured at room temperature for 7 days. The test samples (shown in Figures 5 and 6), according to the standard of ASTM D2990 were all poured simultaneously and cured in the

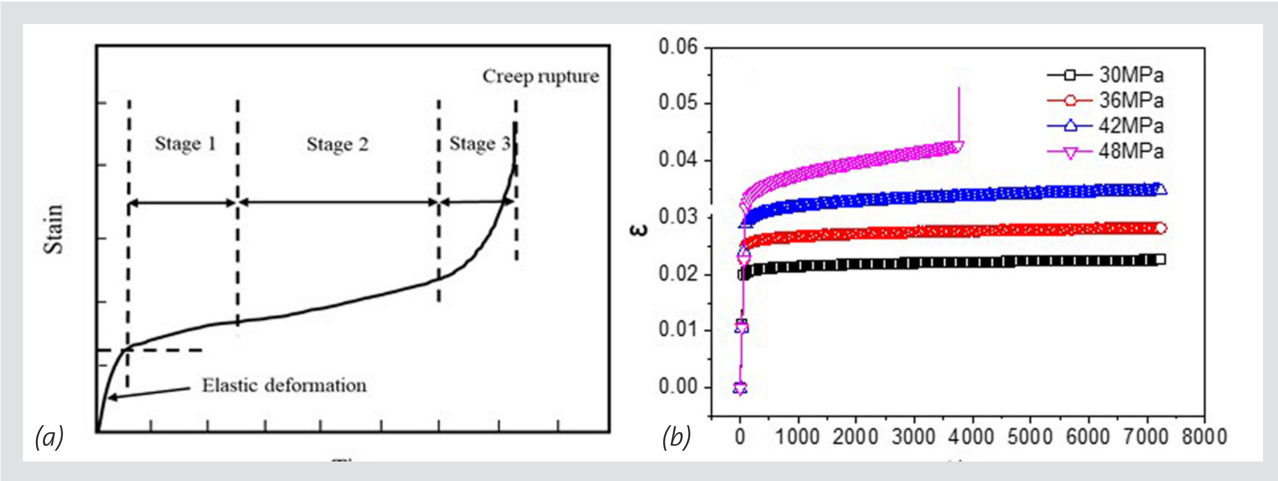

Figure 7: Standard creep curve of viscoelastic materials (a) and strain-time curves under different loads (b).

same conditions [44]. The cross-linking degree of the samples was 87.25 % measured by Soxhlet Extraction after cured for 7 days at room temperature. The whole process of adhesive fabrication must be controlled within the preliminary gel time (40 minutes) measured by wire drawing test.

2.3 TESTING

According to the standard of ASTM D2990 and "Technical code for safety appraisal of engineering structural strengthening materials" (GB50728-2011, China) considering the significance of the long-term behavior and tensile property of adhesive used in the engineering structure, tensile creep tests of this new type adhesive were chosen to be studied in the follow experiments. The test machine was an electronic universal testing machine produced by Meitesi Industry System Co., Ltd. (China). As a new type of material, the tensile strength of the epoxy adhesive samples was first tested by the method consulted the national standards. The strain rate of tensile was set to 0.05 mm/s. In the tensile test, the clamping length of the test sample was fixed. The cross-section area of the middle part of the sample was small and the length occupied the vast majority of the clamping length. Considering the existence of the necking phenomenon, it can be considered that all the deformation occurred in the middle of the sample. During the tensile test, the strain was obtained by the deformation of the middle part of the sample divided by the effective length of 60 mm.

After cured for 7 days, the tensile strength of the epoxy resin adhesive was 55 MPa and the elongation at break was 3.77 %. They all reached the requirements of the national standard, in which, the desired value of class A adhesive used for bonding steel with concrete were that the tensile strength is more than 35 MPa and the elongation at break is more than 1.2 %. As it is difficult to observe the creep behavior at low stress in the short term creep test, four different stress levels were selected (30, 36, 42, and 48 MPa), which varied from 54 to 87 % of the tensile strength of the epoxy adhesive, in the creep tests with static tensile mode. The rate of the extension was set to 2 mm/min and the test time was settled to 7200 s.

	30 MPa	36 MPa	42 MPa	48 MPa
Steady creep rate	$1.44 \cdot 10^{-7}$	$1.89 \cdot 10^{-7}$	$3.65 \cdot 10^{-7}$	$1.69 \cdot 10^{-6}$

Table 3: Steady creep rate of materials under different stresses.

3 RESULTS AND DISCUSSIONS

3.1 SHORT-TERM CREEP BEHAVIOR

Figure 7a shows a standard creep curve of viscoelastic materials. At the beginning of loading, the first period with very short length and fast growth deformation is the elastic deformation stage and the creep period appear rapidly as follows. Generally, there are three stages in the creep period: (1) Primary creep stage corresponding to the decrease of creep rate $\Delta\epsilon/\Delta t$ with time (stage 1 in Figure 7a), (2) steady creep stage corresponding to constant creep rate (stage 2 in Figure 7a), and (3) accelerated creep stage corresponding to the increase of creep rate with time (stage 3 in Figure 7a). The experimental result that the strain increased at each stress level shown in Figure 7b illustrated that this new kind of epoxy adhesive was a typical viscoelastic material. It can be seen that the elastic deformation appeared in the initial period (< 100 s) when the load was exerted immediately and the creep behavior of epoxy adhesive mainly had previous two stages as the load was lower (30, 36, and 42 MPa). In the primary creep stage, the creep strain increased rapidly with the increase of time and in the steady creep stage, the longest period in the whole creep behavior, the change of strain tended to be gentle with the increase of the time of exerted stress. The rate of steady creep stage was the slope of the fitting line obtained by linear fitting of the steady creep curve and was listed in Table 3. As shown in Figure 4 and the Table 3, at each stress level the rate of steady creep

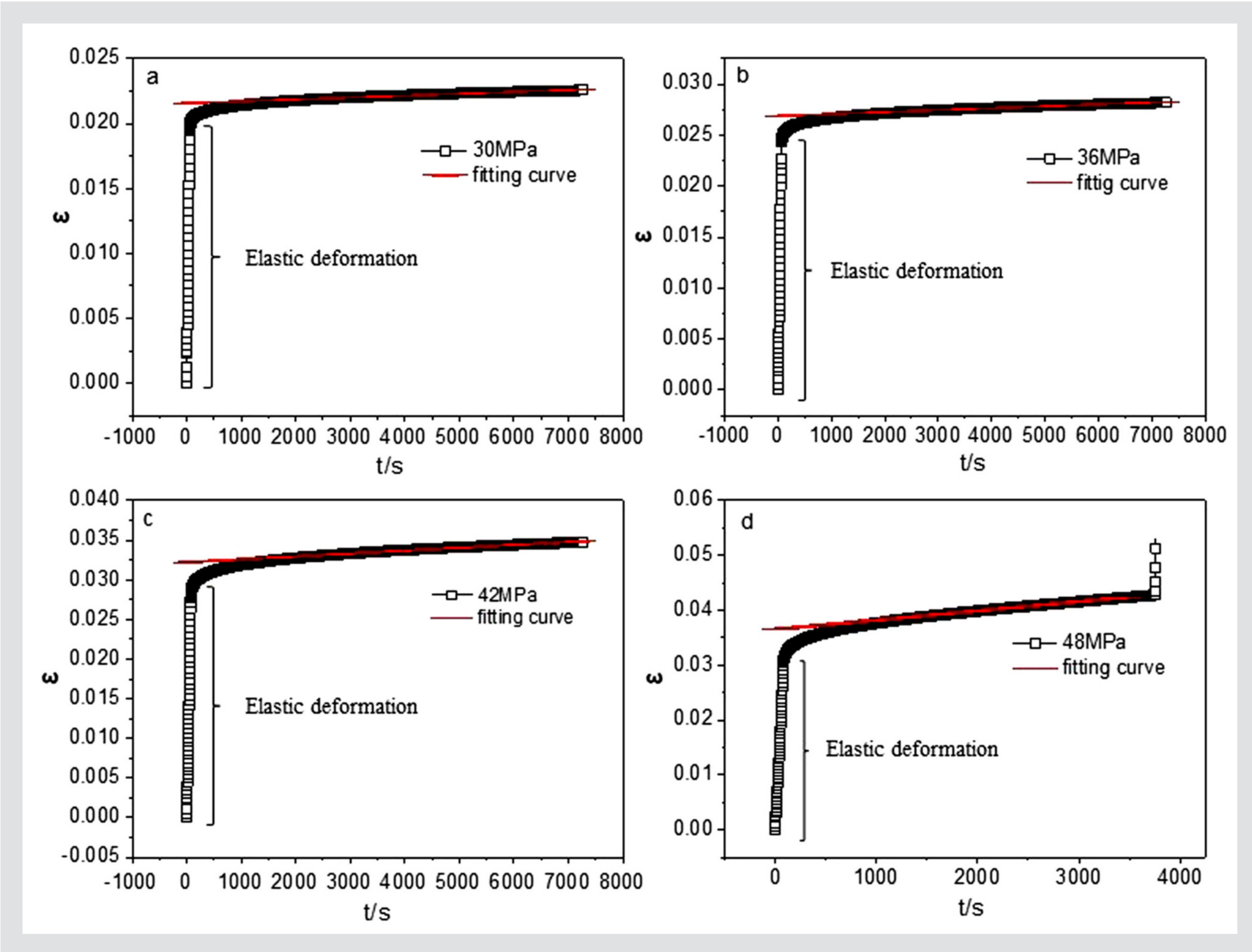

Figure 8: Linear fitting diagram of steady creep state under different stress levels.

was constant and improved with the increase of load consistent the analysis above. There were three creep stages in the creep curve for 48 MPa and the sample ruptured at 3759 s while the strain was 0.05296.

3.2 TIME-STRESS EQUIVALENCE PRINCIPLE

The higher the stress is, the faster the material creep. As mentioned in the introduction above, the mechanism of the stress acceleration is similar to the creep process of viscoelastic material accelerated by increased temperature. There has a certain equivalent relationship between stress, time and temperature, which has attracted the attention of many researchers and put forward the principle of time-stress equivalence and time-temperature-stress equivalence principle [45–47]. From the time-temperature-stress equivalence principle, the effect of the stress levels on the free volume of the materials is as follows [14]:

$$f = f_o + \alpha_T(T - T_o) + \alpha_\sigma(\sigma - \sigma_o) \tag{1}$$

where α_T is the thermal expansion coefficient of free volume fraction, α_σ the stress expansion coefficient of free volume fraction, f_T the free volume fraction of material at the reference temperature T_o and reference stress σ_o. It is assumed that there is a temperature-stress joint shift factor $\Phi_{T\sigma}$ which makes:

$$\eta(T,\sigma) = \eta(T_o,\sigma_o)\Phi_{T_\sigma} \tag{2}$$

by the equation of Doolittle

$$\eta = a\,exp(b/f) \tag{3}$$

where *a* and *b* are constants. According to Equations 2 and 3, it can be obtained as follows [14]:

$$\begin{aligned} log\Phi_{T_\sigma} &= \frac{-b}{2.303 f_o}\left[\frac{\alpha_T(T-T_o)+\alpha_\sigma(\sigma-\sigma_o)}{f_o+\alpha_T(T-T_o)+\alpha_\sigma(\sigma-\sigma_o)}\right] \\ &= -C_1\left[\frac{C_3(T-T_o)+C_2(\sigma-\sigma_o)}{C_2C_3+C_3(T-T_o)+C_2(\sigma-\sigma_o)}\right] \end{aligned} \tag{4}$$

where $C_1 = b/2.303f_o$, $C_2 = f_o/\alpha_T$, and $C_3 = f_o/\alpha_\sigma$. If there is no change of stress $\sigma - \sigma_o = 0$, Equation 4 degenerates into the WLF equation. If the reference temperature is selected as the experiment temperature T_o, that is $T - T_o = 0$. Equation 4 degenerates to the stress shift factor which ex-

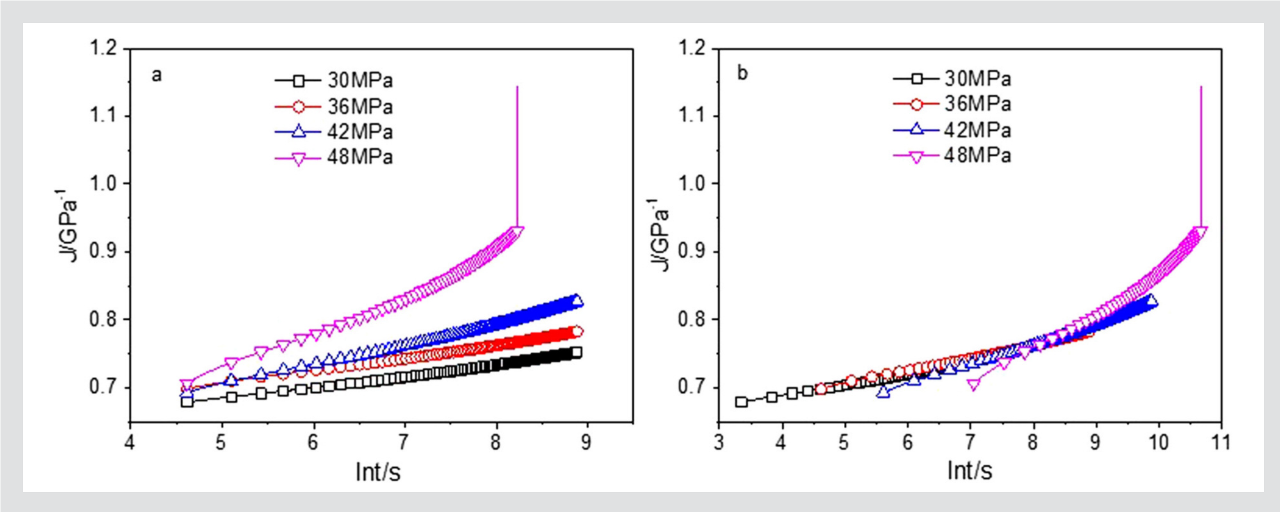

Figure 9: Creep compliance-time curves under different stresses (a) and master curve for 36 MPa (b).

presses as follow [14]:

$$log\Phi_{T_\sigma} = \frac{-b}{2.303 f_o}\left[\frac{(\sigma-\sigma_o)}{f_o/\alpha_\sigma+(\sigma-\sigma_o)}\right] = -C_1\left[\frac{(\sigma-\sigma_o)}{C_3+(\sigma-\sigma_o)}\right] \quad (5)$$

Under different stress levels, the creep compliance of the adhesive satisfy the following equivalent relationship through the conversion time ϵ ($\epsilon = t/\Phi_\sigma$):

$$J(t,\sigma) = J(t/\Phi_\sigma,\sigma_o) = \bar{J}(\epsilon,\sigma_o) \quad (6)$$

where $\bar{J}$ (ϵ, σ_o) is the creep compliance principal curve under the reference stress σ_o. According to the above analysis, the deformation of epoxy adhesive consists of elastic deformation and creep deformation. Thus, the data (> 100 s) was applied in the analysis of creep behavior excluding the influence of the elastic deformation. Figure 9a shows the creep compliance time curve of epoxy resin adhesive under four different stress levels at room temperature. Creep compliance *J* determined as the ratio of the strain to the exerted stress improved with the increase of applied stress. In another word, the creep compliance *J* was strongly stress dependent and the adhesive exhibited nonlinear viscoelastic behavior. The time-stress equivalence was applied to analyze the short term creep behavior of the adhesive based on the data in Figure 9a. σ_o = 36 MPa was taken as a reference stress and the creep compliance curves of 30, 42, and 48 MPa were shifted horizontally to the reference curve, then the master curve of the creep compliance was shown in Figure 9b. It can be seen that the time coordinate axis of the creep curve with 36 MPa extended from 7200 to 59874 s (from 2 to 16.6 h), which effectively saved the test time. The horizontal shift factors were plotted in Figure 10a. According to Equation 5, by fitting the master curve in Figure 10a, the parameters C_1 = - 203.1 and C_2 = 1018. These two parameters were related to the properties of the materials, hence the value of the parameters was sole. At last, Equation 5 can be written as:

$$log\Phi_{T_\sigma} = \frac{203.1\,(\sigma-\sigma_o)}{1018+(\sigma-\sigma_o)} \quad (7)$$

The comparison of the master curve for 36 MPa and experimental curve for 36 MPa were shown in Figure 10b. It can be seen that the two curves coincide with each other well. Through the analysis of this section, by using the time-stress equivalence principle, the time range of creep behavior of the new epoxy adhesive had been effectively extended under the load of 36 MPa. The simulation of the creep curve by rheological models will be more accurate in the follow analysis owing to the extension of the creep curve.

4 RHEOLOGICAL MODEL PREDICTIONS

The time scale of the generalized curve broadened by the time-stress equivalence principle analyzed above is also limited compared with the range of engineering structural design life (usually decades or even hundreds of years). It has been mentioned in the introduction above, the rheological constitutive model is a mathematical model to study the properties of the material change with time and can be used to characterize the relationship between creep properties and time. The traditional Burgers integer order model with four elements (Figure 12) was widely used to describe the creep behavior of adhesives. But the intermediate development process of the system function can not be described very well by the integer derivative which can only describe the state with the specific time. The nonlinear of stress-strain was the most prominent character-

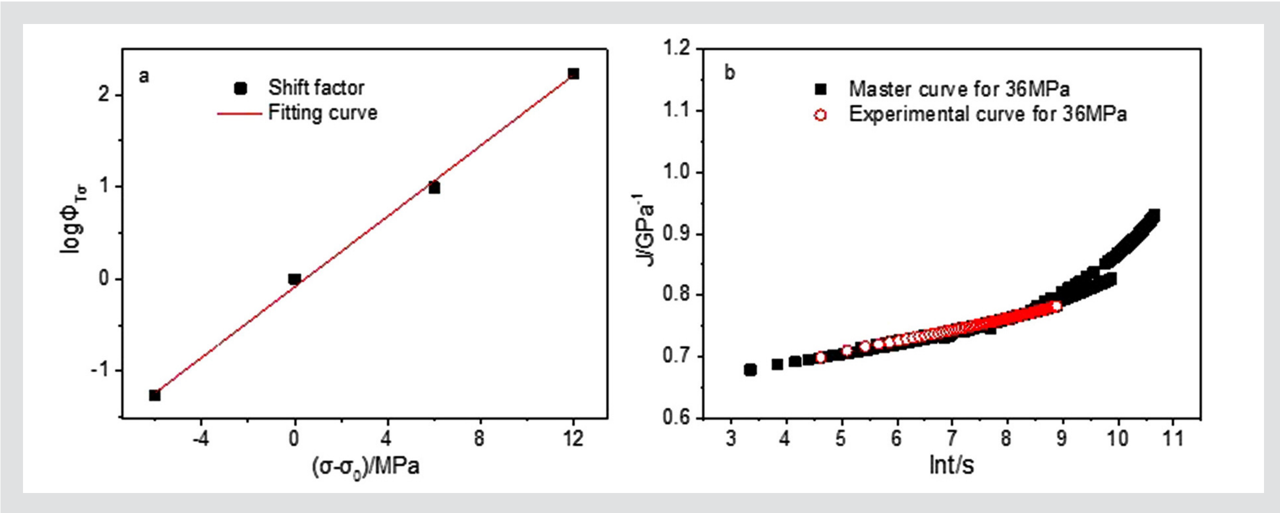

Figure 10: The horizontal shift factors versus the increase of stress (a) and the experimental curve for 36MPa versus master curve for 36 MPa.

istic of the fractional derivative element, which made up the deficiency of the integer derivative. In this chapter, the integer Burgers model and improved fractional KBurgers model were applied to model the creep behavior of this new adhesive. The Newton dashpot element, as shown in Figure 11a is filled with viscosity liquid and the mathematical relationship is expressed as:

$$\epsilon = \frac{\sigma_o}{\eta} t \rightarrow \sigma_o = \frac{\epsilon}{t}\eta \rightarrow \sigma_o = \dot{\epsilon}\eta \tag{8}$$

where η is the Newtonian viscosity coefficient and $\dot{\epsilon}$ the strain rate. The above formula shows that the strain rate of the Newtonian viscous dashpot is directly proportional to the stress. Fractional derivative element (Abel) is shown in Figure 11b. The main advantage is that the integer derivative can not describe the process of the intermediate development of the system equation well, and its value is not only closely related to the state of the current time but also closely related to the development process of the whole history. Compared with Newton viscosity dashpot, the remarkable characteristic of the fractional derivative element is that its stress-strain relationship is nonlinear. The constitutive equation of it is:

$$\sigma = \eta_a D^r \epsilon(t) = \eta_a \frac{d\epsilon(t)}{dt^r} \qquad (0<r<1) \tag{9}$$

where η_a is the Abelian viscosity coefficient, D a fractional derivative operator, and r the fractional derivative order. When $r = 1$, Equation 9 reduces to Equation 8. In practical problems, the fractional order model had more significances of theoretical and practical application value than the integer order model. The fractional derivative element was used to replace the Newton viscosity dashpot in the Kelvin model of Burgers model, then the KBurgers fractional order model (Figure 11b) was obtained. As we all know, according to the basic constitutive relationship of Hook springs and Newton viscosity dashpot. The constitutive equation of Burgers is as follow:

$$\epsilon(t) = \frac{\sigma}{E_M} + \frac{\sigma}{\eta_M} + \frac{\sigma}{E_K}\left(1 - e^{\frac{-E_K t}{\eta_K}}\right) \tag{10}$$

where η_M, η_K, D_M, and D_K are the viscosity coefficient and spring modulus of spring of Maxwell and Kelvin, respectively. The creep compliance constitutive equation of Burgers model is as follows:

$$J(t) = \frac{1}{E_M} + \frac{1}{\eta_M} + \frac{1}{E_K}\left(1 - e^{\frac{-E_K t}{\eta_K}}\right) \tag{11}$$

The constitutive relationship of the KBurgers model is deduced next. For the Maxwell model

$$\sigma(t) = \frac{E_M \eta_M D}{E_M + \eta_M D}\,\epsilon(t) \tag{12}$$

where D is the differential operator, while for the Kelvin model one has

$$\sigma(t) = \left(E_K + \eta_K D^r\right)\epsilon(t) \tag{13}$$

where D^r is a differential operator, r is fractional order (when $r = 1$, it is integer order). The two parts are connected in series, and the constitutive relationship of the KBurgers model is thus

$$\epsilon(t) = \left[\frac{1}{\eta_M}\frac{1}{D} + \frac{1}{E_M} + \frac{1}{E_K}\frac{1}{\left(1 + Q^{-1}D^r\right)}\right]\sigma(t) \tag{14}$$

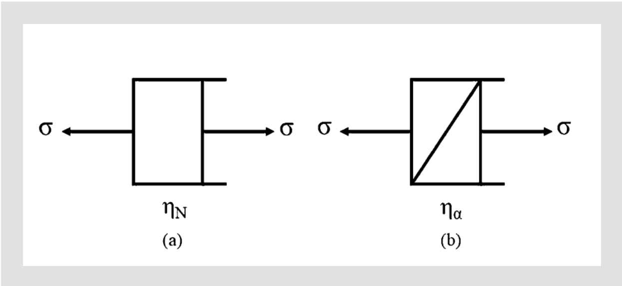

Figure 11: Newton dashpot element (a) and fractional derivative element (Abel).

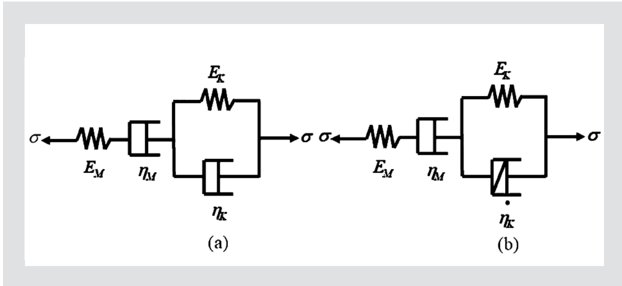

Figure 12: Burgers integer order model (a) and KBurgers fractional order model (b).

where $Q = E_K/\eta_K$ replace the Heaviside unit step function $\Theta(t)$ to Equation 14. For $\Theta(t) = \sigma(t)$, it is indicated that, when $t > 0$, the constant unit stress is applied at both ends of the model. The creep compliance expression of Equation 15 is obtained by a Laplace transformation L,

$$J(t) = Y_o + (Y_\infty - Y_o) L^{-1} \frac{1}{\left(1 + Q^{-1} P^r\right) p} + \frac{1}{\eta_M} L^{-1} P^{-2} \tag{15}$$

Where $Y_\infty = (E_K + E_M)/E_K E_M$ and $Y_o = 1/E_M$. The inverse Laplace transform

$$L^{-1} \frac{1}{\left(1 + Q^{-1} P^r\right) P} = \sum_{n=0}^{\infty} \frac{(-1)^n Q^{n+1} t^{(n+1)r}}{\Gamma\left[(n+1)r + 1\right]} \tag{16}$$

is obtained by the expansion series and retrieved term by term. Equation 15 can thus be further written as follows

$$J(t) = Y_o \left[1 + \left(\frac{Y_\infty}{Y_o} - 1 \right) \sum_{n=0}^{\infty} \frac{(-1)^n Q^{n+1} t^{(n+1)r}}{\Gamma\left[(n+1)r + 1\right]} \right] + \frac{1}{\eta_M} t \tag{17}$$

Equation 17 contains an infinite series and Gamma function, which can be simplified further. Upon adding and subtracting the term $n = -1$ to and from the infinite series, Equation 17 becomes

$$J(t) = Y_\infty - (Y_\infty - Y_o) \sum_{n=0}^{\infty} \frac{\left(-Qt^r\right)^n}{\Gamma(nr + 1)} + \frac{1}{\eta_M} t \tag{18}$$

When $r = 1 - \beta$ with $0 \le \beta \le 1$ the infinite series agrees with the series expansion of the exponential function, Equation 18 is thus more conveniently written as

Model	E_M [GPa]	E_K [GPa]	η_M [GPas]	η_M [GPas]	β	R^2
Burgers	$3.22 \cdot 10^{-3}$	$3.21 \cdot 10^{-3}$	$1.88 \cdot 10^{5}$	$3.46 \cdot 10^{-3}$	/	0.8791
KBurgers	1.386	$1.21 \cdot 10^{3}$	$1.37 \cdot 10^{5}$	$7.62 \cdot 10^{3}$	0.6909	0.9961

Table 4: The fitting parameters of the Burgers and KBurgers model of the master creep curve for 36 MPa.

$$J(t) = Y_\infty - (Y_\infty - Y_o) exp\left(-Qt^{1-\beta}\right) + \frac{1}{\eta_M} t \tag{19}$$

Equation 19 is the creep compliance expression of KBurgers model. If $\beta = 0$, it is the constitutive equation of Burgers model. According to Equation 19, the KBurgers constitutive equation can be obtained as follows

$$\epsilon(t) = \frac{\sigma}{E_M} + \frac{\sigma}{E_K} \left(1 - e^{\frac{E_K}{\eta_K} t^{1-\beta}} \right) + \frac{\sigma}{\eta_M} t \tag{20}$$

The corresponding creep compliance constitutive equation is

$$J(t) = \frac{1}{E_M} + \frac{1}{E_K} \left(1 - e^{\frac{E_K}{\eta_K} t^{1-\beta}} \right) + \frac{1}{\eta_M} t \tag{21}$$

The master curve for 36 MPa in Figure 9b was analyzed by nonlinear fitting with Equations 11 and 21. The results were shown in Figure 13 and the parameters of Burgers model and KBurgers model were listed Table 4. As is visible from Figure 13 and Table 2, the fitting curve from KBurgers model coincided with the experimental creep curve almost completely and the fitting correlation coefficient R^2 was 0.9961, which showed that the KBurgers model can simulate the creep behavior of epoxy resin adhesive with high precision. By comparison, the fitting curve from Burgers model didn't have a great agreement with the master curve and the fitting correlation coefficient R^2 is 0.8791. It was proven that, compared to the integer model, the fractional derivative model can be applied to describe the creep behavior of the epoxy adhesive well under the present conditions.

5 CONCLUSIONS

Creep behavior of a kind of epoxy resin adhesive which was room temperature cured and used for reinforcing engineering structure was investigated in this work. The tensile strength had reached for the desired values of the structural adhesive used for bonding concrete as the base material with steel. The results of creep tests

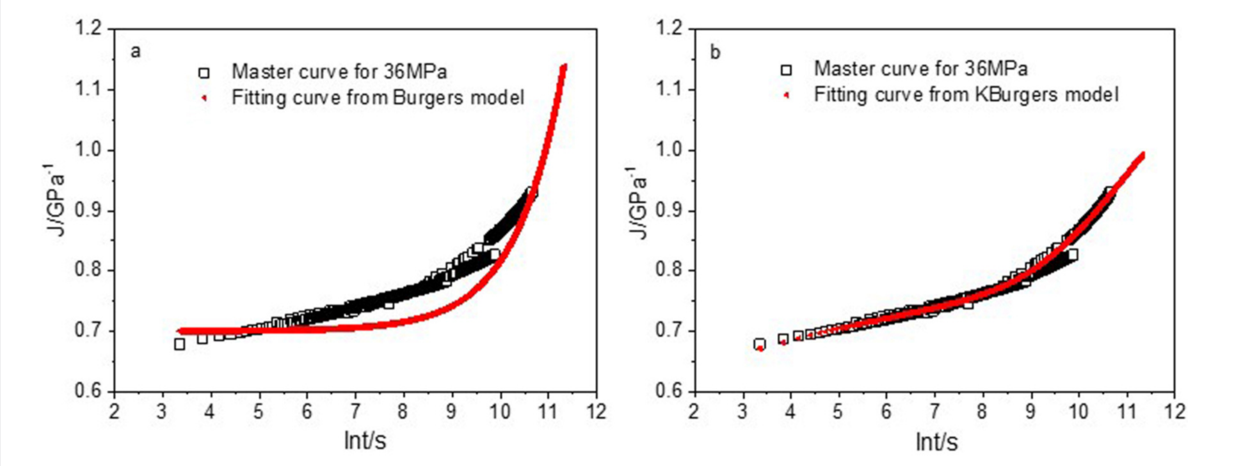

Figure 13: The master creep curve and fitting curve when the stress is 36 MPa: (a) Fitting curve from KBurgers model and (b) fitting curve from KBurgers model.

indicated that the epoxy adhesive was a typical nonlinear viscoelastic material. The generalized curve was obtained by the time-stress equivalence principle in the condition of the room-temperature and tensile stress of 36 MPa. Compared with the Burgers model, the simulation results indicated that the KBurgers model can predict the creep behavior of this new adhesive in the condition of the room-temperature and tensile stress of 36 MPa with high precision. Collectively, the experiments and the model predictions can provide guidance for the various practical applications of the newly developed adhesives in the future. For a new type of material, this study was also an exploratory work, and a lot of work needs to be perfected in the follow-up. For instance, more rheological models, especially fractional order rheological model should be explored which was more suitable for describing this new material in the other conditions.

ACKNOWLEDGEMENTS

This work was supported by the Project of Hunan Provincial Science & Technology Department of P.R. China (NO. 2010GK3110) and the Key Project of the Education Department of Hunan Province of P.R. China (NO. 10A130).

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