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Uniaxial creep property and viscoelastic–plastic modelling of ethylene tetrafluoroethylene (ETFE) foil

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Abstract Ethylene tetrafluoroethylene (ETFE) foil has been widely used in spatial structures for its light weight and high transparency. This paper studies short- and long-term creep properties of ETFE foil. Two series of short-term creep and recovery tests were performed, in which residual strain was observed. A long-term creep test of ETFE foil was also conducted and lasted about 400 days. A viscoelastic–plastic model was then established to describe short-term creep and recovery behaviour of ETFE foil. This model contains a traditional generalised Kelvin part and an added steady-flow component to represent viscoelastic and viscoplastic behaviour, respectively. The model can fit tests' data well at three stresses and six temperatures. Additionally, time–temperature superposition was adopted to simulate long-term creep behaviour of ETFE foil. Horizontal shifting factors were determined by W.L.F. equation in which transition temperature was simulated by shifting factors. Using this equation, long-term creep behaviours at three temperatures were predicted. The results of the long-term creep test showed that a short-term creep test at identical temperatures was insufficient to predict additional creep behaviour, and the long-term creep test verified horizontal shifting factors which were derived from the time–temperature superposition.

Keywords ETFE foil · Short-term creep property · Viscoelastic–plastic model · Long-term creep property · Time–temperature superposition

1 Introduction

Ethylene tetrafluoroethylene (ETFE) is a co-polymer of polyethylene and tetrafluoroethylene which has received increasing attention from architects and structural engineers. This material is suitable for long-span structures for its light weight, high transparency and environment-friendly characteristics (Robinson-Gayle et al. 2001; Wu et al. 2011; Hu et al. 2014a). Numerous structures have been successfully constructed using ETFE foil,

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such as the Eden Project, a green house in England (2001), and the National Aquatics Centre, a facility constructed for the 29th Olympic Games in Beijing (2008) (LeCuyer 2008).

Mechanical properties of ETFE foil have been investigated by tests and numerical analysis. For instance, De Focatiis and Gubler (2013) compared uniaxial tensile property of ETFE foil from different manufacturers at a range of temperatures and rates, all exhibiting two yield points. Galliot and Luchsinger (2011) analysed uniaxial and biaxial tensile properties of ETFE foil and demonstrated that ETFE foil had similar tensile mechanical properties in uniaxial and biaxial condition before the second yield point. Hu et al. (2014b) performed eight experiments to study the uniaxial cyclic tensile mechanical properties of ETFE foil and found three kinds of cyclic elastic modulus.

The design working life of ETFE structures is generally 5 to 25 years. To avoid the wrinkling of membrane surfaces, ETFE foil should be maintained in tensile condition during its working life. Meanwhile, as a kind of high polymeric material, ETFE foil creeps when tensioned long-term. This creep property of ETFE foil decreases safety performance of structures. Studies on creep behaviour of ETFE foil included short-term creep tests conducted by Kawabata and Moriyama (2006) and Charbonneau et al. (2014). While Kawabata (2007) proposed a viscosity and plastic model for ETFE foil, Charbonneau et al. (2014) presented a constitutive modelling on integral form. However, these studies primarily focused on short-term creep tests lasting several days with additional numerical simulation. Modelling of the recoverability and long-term creep property of ETFE foil is still unclear.

In the research of creep property of polymers, viscoelastic creep behaviour can be described by the superposition integral-form proposed by Boltzmann and the modified superposition principle proposed by Leaderman (Lakes 2009). To consider the nonlinearity of stress and temperature, Schapery (1969) established single-integral constitutive equations from thermodynamic theories. These equations were applied to modelling time-dependent behaviour of plastics and polypropylene (Sakai and Somiya 2011; Tscharnuter et al. 2012; Hao et al. 2014). Also, Liu et al. (2008) and Cheng et al. (2011) suggested practical methods to determine the constitutive formulation and used rigorous statistical techniques to analyse relationships among parameters.

While the viscoelastic or viscoplastic model of polymeric materials can fit data from short-term creep tests, prediction of long-term creep behaviour often lacks precision. To address this problem, Williams et al. (1955) found a relationship between the relaxation time and reference temperature, and established the W.L.F. equations. Nakano (2013), Xu et al. (2013) and Saprunov et al. (2014) showed the applicability of time–temperature superposition to a series of viscoelastic materials. Extending the application of this principle, Qaiser and Price (2011) and Chang et al. (2013) showed the possibility of stress–time superposition and applied it to estimate the creep behaviour of a polycarbonate. Hadid et al. (2014) successfully predicted long-term creep of thermoplastics by a stepped isostress method.

In the present study, a revised creep model is suggested to describe short-term creep and recovery behaviour of ETFE foil, which can distinguish recoverable and unrecoverable creep strains. The time–temperature superposition is adopted to simulate additional creep behaviour, and horizontal shifting factors of ETFE foil are determined by W.L.F. equation. Several long-term creep predictions are made, and a long-term creep test lasting 400 days verifies them.

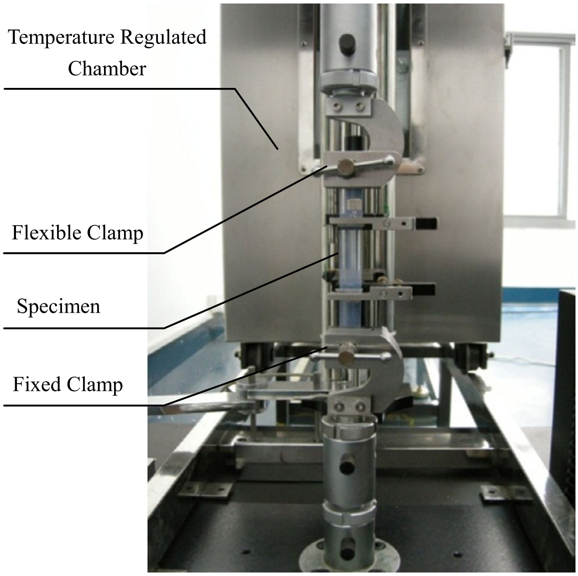


Fig. 1 Equipment for short-term tests. This figure describes the equipment for all short-term creep and recovery tests. Positions of specimens and clamps are shown at the front of temperature regulated chamber to highlight them. During the test, the specimens and clamps are positioned in the temperature-regulated chamber

2 Material and methods

2.1 Short-term creep and recovery tests

In the tests, ETFE foils were all produced by Asahi Glass Company. The thickness of these ETFE foils was identical at 250 μm, which is widely used in structures. The linear expansion coefficient of this material is about 0.001 %/°C. Stress and temperature were the two major factors being controlled in the creep tests.

Two series of short-term creep and recovery tests of ETFE foil were performed at different stresses and various temperatures. Specimens were cut into rectangular shape with a length and width of 150 mm and 15 mm, respectively. In the length direction, specimens were fixed by clamps on two sides, and deformations of the core 100 mm between clamps were recorded. During the tests, specimens were placed in a temperature-regulated chamber to maintain a constant environmental condition. Equipment required for these tests was a microcomputer electronic testing machine as shown in Fig. 1. The accuracy of recorded deformations in the machine was ±0.001 mm and the accuracy of the force was ±2.5 N.

In these short-term creep and recovery tests, specimens were first tensioned to creep stress σ_c by a loading rate of 1.8 MPa/s, enabling the loading process be performed in a short time. Then, creep tests began and lasted for 24 hours. During creep tests, the stress of specimens was kept constant. After 24 creep hours, the stress decreased to zero through an unloading rate of 1.8 MPa/s. When the stress reached zero at the end of the unloading process, recovery tests started. The stress was maintained at zero in the recovery tests. Recovery tests were also performed for 24 hours. All deformations of specimens during the whole processes were recorded by the microcomputer electronic testing machine.

Short-term creep and recovery tests for three representative stress levels were performed at 23 °C. These stresses were 3, 6 and 9 MPa, which are commonly used in ETFE structures. Additionally, six short-term creep and recovery tests were performed at different temperatures. The temperatures used in these tests were 23, 28, 35, 41, 46 and 51 °C. These temperatures are common environmental temperatures for ETFE structures. Also, they are

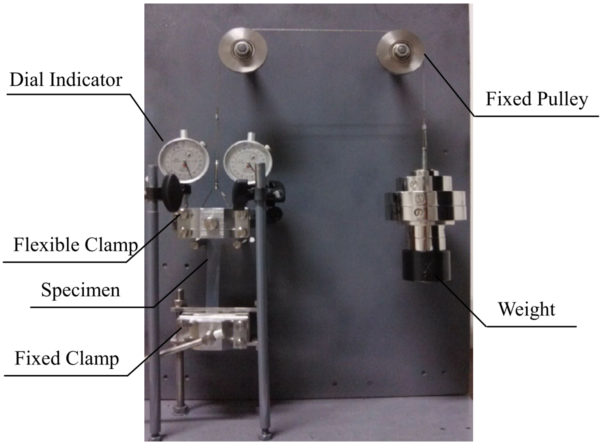


Fig. 2 Equipment for long-term test. This figure describes the equipment for long-term creep test. Positions of specimens and clamps are displayed. During the test, the weight generates a constant stress and the dial indicators record creep deformation. Fluctuation of temperature during the test is also recorded.

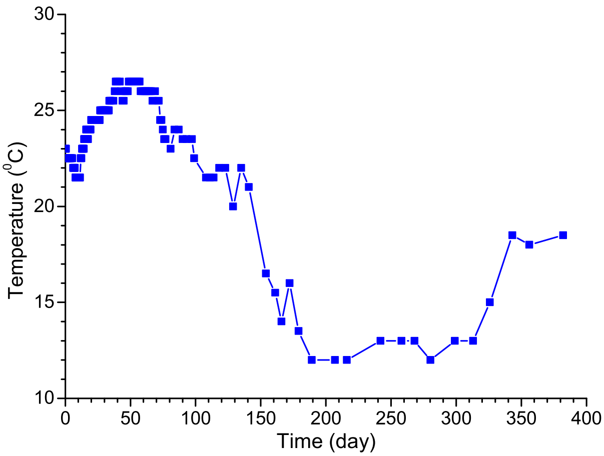


Fig. 3 Temperature in the long-term test. This figure describes the fluctuation of temperature in the long-term creep test. The figure is a time versus temperature plot. Time is in days, and temperature is in degrees Celsius. Fluctuation of temperature ranges from 12 to 26.5 °C. The average temperature is approximately 20 °C

determined by considering predicted long-term creep behaviour of ETFE foil over several decades. The stresses for these creep tests at different temperatures were identical at 6 MPa.

2.2 Long-term creep test

To evaluate additional creep behaviour of ETFE foil, a long-term creep test was performed for 400 days. The shape and dimension of specimen used in this test were identical to those described in Sect. 2.1. The equipment designed for this test is shown in Fig. 2. As illustrated, the equipment employed weights to generate a constant stress and two dial indicators to record deformation of specimen at the middle 100 mm. The accuracy of the dial indicators was ±0.001 mm, and the creep stress in this test was 6 MPa with an accuracy of ±0.01 MPa.

The loading process in this test was finished in 4 seconds to ensure similar strain rate as that in short-term creep tests, which has a significant effect on creep coefficients. And then, the stress was maintained at a constant level in the creep time. The fluctuation of temperature, which also has a great effect on creep behaviour, was recorded and is shown in Fig. 3. As illustrated, the temperature during the whole test fluctuated around an average of

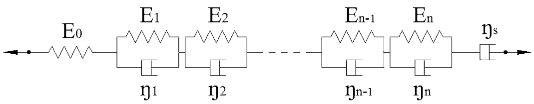


Fig. 4 Physical model. This figure describes the physical model for the revised creep equations of ETFE foil. The physical model comprises a spring, multi-Kelvin and a dashpot. This physical model represents the physical relevancy of the viscoelastic–plastic model

20 °C with the maximum temperature at 26.5 °C and the minimum at 12 °C. The temperature during the first half (in summer) is higher than that during the second half (in winter).

3 Theory and calculation

3.1 Viscoelastic–plastic model

Schapery's nonlinear constitutive equation, which has been widely adopted to describe viscoelastic behaviour of polymers, can be simplified into the following form (Schapery 1969):

$$\varepsilon(t) = g_0 D_0 \sigma + g_1 g_2 \Delta D(\psi)\sigma \tag{1}$$

where t represents time, $\varepsilon(t)$ is the strain, σ is the stress, D_0 is the initial value of compliance, and $\Delta D(\psi)$ is the transient component. In this equation, ψ represents the reduced-time and is defined by:

$$\psi = \int_0^t \frac{dt'}{a} \tag{2}$$

where g_0, g_1, g_2 and a are coefficients relating to stress and temperature.

Traditionally, a generalised Kelvin model is adopted to obtain an expression of $\Delta D(\psi)$. This expression can fit the creep data of material but cannot simulate the recovery property. Therefore, the generalised Kelvin model is modified in this section to simulate the creep and recovery property of ETFE foil. The revised model uses generalised Kelvin model to represent viscoelastic behaviour of ETFE foil and adds a steady-flow component to represent viscoplastic behaviour. Then, the constitutive equation (1) is rewritten as Eqs. (3a), (3b), and the physical model for ETFE foil is shown in Fig. 4:

$$\varepsilon_c(t) = \varepsilon_o + \varepsilon_{ve}(t) + \varepsilon_{vp}(t) \tag{3a}$$

$$\varepsilon_c(t) = \left[g_0 D_0 + g_1 g_2 \sum_{r=1}^{N} D_r \left(1 - e^{-\frac{\psi}{\tau_r}}\right) + g_1 g_2 D_s \psi^n \right] \sigma \tag{3b}$$

where ε_0 is the initial strain, $\varepsilon_{ve}(t)$ is the viscoelastic creep strain, $\varepsilon_{vp}(t)$ is the viscoplastic creep strain, N is the number of generalised Kelvin components, D_r is coefficient in the Kelvin model, τ_r is the retarded time in the generalised Kelvin model, D_s is the coefficient for the dashpot, and n is a material constant in the dashpot.

The first term on the right side of Eq. (3b) is the initial compliance. This term is simplified as a spring in the physical model and can recover immediately after the removal of load. The second term of Eq. (3b) is a part of the transient component of compliance. This term is represented by the generalised Kelvin model and can fully recover over a given time. The last term of Eq. (3b) is the revised power law. This term is simplified as a dashpot in the physical model and represents the unrecoverable strain of ETFE foil. This unrecoverable strain, which is different from the classic plastic strain, also increases during the creep time as shown in tests.

The revised model, as written in Eqs. (3a), (3b), contains both viscoelastic and viscoplastic components. So, it can be called viscoelastic–plastic model. One of the most significant characteristics of this model is that it can distinguish the recoverability of creep strains, using a viscoelastic component to represent those strains that are recoverable and a viscoplastic component to represent unrecoverable ones.

The coefficients in Eqs. (3a), (3b) are determined by creep and recovery tests. In the process of creep coefficients calculation, the creep behaviour is assumed to be a sum of the viscoelastic and viscoplastic creep, while recovery behaviour is assumed to be the inverse process of the viscoelastic creep, in which no viscoplastic creep strain occurs.

To simplify the calculation of the creep coefficients in Eqs. (3a), (3b), let $\tau_r = 10^r$, $a = 1$, and $N = 5$. Because all specimens were tensioned under an identical stress rate, g_2 can also be taken as 1. Thus, the creep and recovery behaviours can be represented by Eq. (4) and Eq. (5), respectively:

- For $0 \le t \le T$ (creep behaviour),

$$\varepsilon_c(t) = \left[g_0 D_0 + \sum_{r=1}^{5} g_1 D_r \left(1 - e^{-\frac{t}{10^r}}\right) + g_1 D_s t^n \right] \sigma_c; \tag{4}$$

- For $T < t \le 2T$ (recovery behaviour),

$$\varepsilon_r(t) = \left[\varepsilon_c(T) - g_0 D_0 - \sum_{r=1}^{5} g_1 D_r \left(1 - e^{-\frac{(t-T)}{10^r}}\right) \right] \sigma_c, \tag{5}$$

where T is the cycle of creep and recovery behaviours, $T = 24$ h in all short-term creep and recovery tests in this paper.

3.2 Time–temperature superposition

To predict long-term creep behaviour of polymeric materials, W.L.F. equation, as shown in Eq. (6), established a relationship between relaxation time and reference temperature (Williams et al. 1955), which has developed as the time–temperature superposition. The time–temperature superposition indicates that long-term creep behaviour can be predicted through shifting creep curves at different temperatures to form one master creep curve at reference temperature:

$$\log a_t = \frac{-17.44(T - T_{tran})}{51.6 + T - T_{tran}} \tag{6}$$

where T_{tran} is the transition temperature of material, and $\log a_T$ is the horizontal shifting factor from temperature T to the transition temperature T_{tran}. The unit of these temperatures is Kelvin.

On the basis of this principle, long-term creep behaviour of ETFE foil, a kind of polymeric material, is simulated by the horizontal shifting process. The creep curves at different temperatures obtained from short-term creep and recovery tests in Sect. 2.1 were used.

Notwithstanding, the application of W.L.F. equation calls for the transition temperature of a material before determining those shifting factors, and the transition temperature of ETFE foil varies among products from different manufactures and production processes. In other words, the transition temperature is always inaccurate or even unknown for special materials in engineering. Therefore, it is determined by a practical approach in this section.

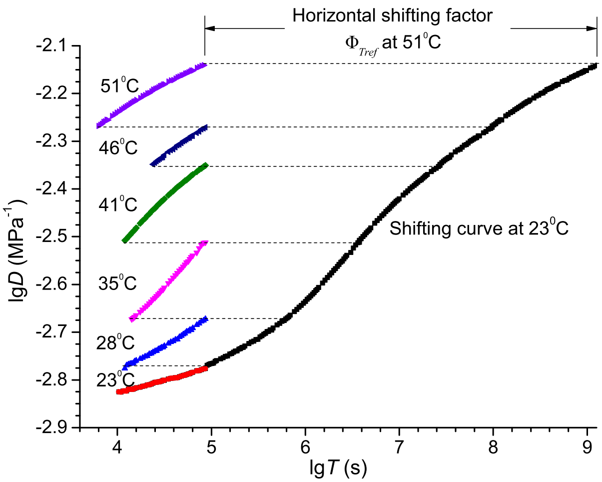


Fig. 5 Horizontal shifting process. This figure describes the horizontal shifting process of time–temperature superposition. The figure is the log T versus log D plot where T is time and D is compliance. Time is in seconds, and compliance is in MPa^{-1}. *Curves* for six temperatures before shifting and the *master curve* after shifting are all plotted. As an example, the method for determining horizontal shifting factors, $\Phi_{T_{ref}}$, is shown for 51 °C

To begin with, the shifting factors are initially determined by the horizontal shifting process basing on the similarity of creep curves' shape. The detailed method of this horizontal shifting process is shown in Fig. 5, where D is compliance, and T is time. As illustrated in Fig. 5, only the curve at the reference temperature (23 °C) needs no shifting. The curves at other temperatures are all shifted according to the temperature. Specifically, a curve at a higher temperature is shifted with its initial part following the end of a prior curve which is at a lower temperature. The distance of the horizontal shifting in each curve is called the horizontal shifting factor at the reference temperature, which is represented as $\Phi_{T_{ref}}$.

Then, the obtained shifting factors and W.L.F. equation are adopted to calculate the transition temperature of ETFE foil in the range from 20 to 50 °C, the common environmental temperatures for ETFE structures. W.L.F. equation is rewritten as Eq. (7):

$$\log a_T = \log a_{T_{ref}} + \Phi_{T_{ref}} = \frac{-17.44(T - T_{tran})}{51.6 + T - T_{tran}} \tag{7}$$

where $\log a_{T_{ref}}$ is the horizontal shifting factor from the reference temperature T_{ref} to the transition temperature T_{tran}.

$\log a_{T_{ref}}$ and T_{tran} are determined by the least squares estimation method, and they are -4.263 and 280 K (7 °C), respectively. In this way, the relationship between the shifting factors and temperatures, namely W.L.F. equation, can be plotted in Fig. 6. Master creep curves at different reference temperatures can also be determined accurately by Eq. (6).

4 Results and discussion

4.1 Results and simulation of short-term creep tests

The results of short-term creep and recovery tests at different stresses are shown in Fig. 7 using the coordinates of strain (y-axis) versus time (x-axis). As illustrated, the residual strain of specimens in the recovery tests is large, especially under high creep stresses. The viscoplastic deformation, as a part of creep strain, becomes significant along with the increase in stress.

To better consider this viscoplastic creep strain, which cannot be fully described by the traditional generalised Kelvin model, the viscoelastic–plastic model, which is introduced in

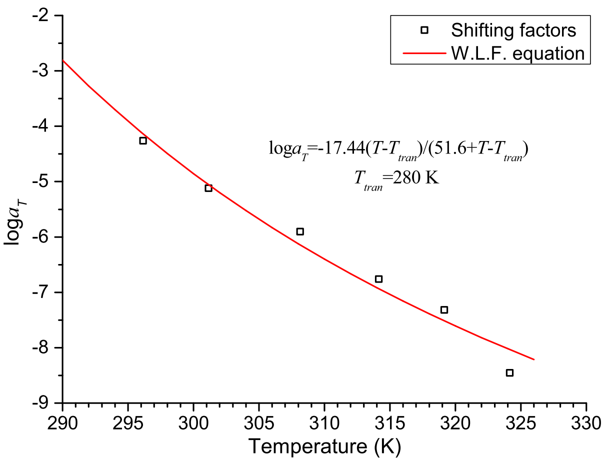


Fig. 6 Horizontal shifting factor. This figure describes the relationship between temperature and shifting factors. Shifting factors ranging from 290 to 325 K are illustrated, and W.L.F. equation is shown. The figure is a temperature versus shifting factor plot. Temperature is in degrees Kelvin

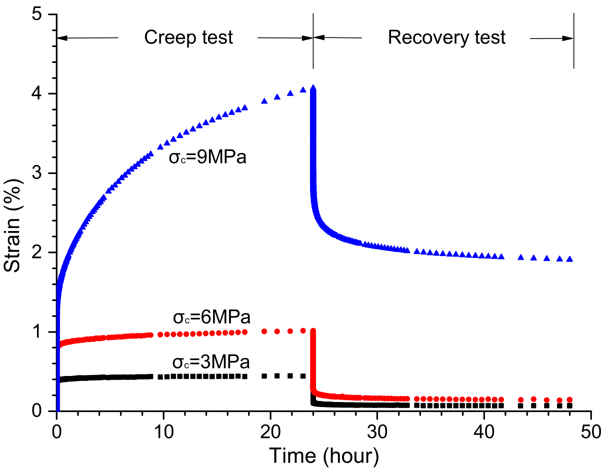


Fig. 7 Creep and recovery curves. This figure describes creep and recovery behaviour of ETFE foil for three different stress levels: 3, 6 and 9 MPa. Creep and recovery tests are conducted over 24 hours. The figure is a time versus strain plot. Time is in hours, and strain is in %. Residual strain is observable in these three tests

Table 1 Creep compliance coefficients for three different stresses. This table shows the creep compliance coefficients of ETFE foil for three different stresses. These coefficients were used in viscoelastic–plastic modelling of ETFE foil and were obtained from short-term creep and recovery tests

Stress	3 MPa	6 MPa	9 MPa
$g_0 D_0$	1.156E-3	1.171E-3	1.205E-3
$g_1 D_1$	6.085E-5	6.330E-5	1.146E-4
$g_1 D_2$	3.895E-5	4.767E-5	1.658E-4
$g_1 D_3$	5.742E-5	7.837E-5	3.600E-4
$g_1 D_4$	5.020E-5	8.295E-5	4.045E-4
$g_1 D_5$	4.986E-5	6.204E-5	3.237E-4
$g_1 D_s$	1.371E-6	1.383E-6	1.991E-6
n	0.3621	0.4345	0.6099

Sect. 3.1, is used to simulate the tests' data. The least squares estimation method is adopted to calculate the coefficients in Eq. (4) and Eq. (5). The creep coefficients of three creep and recovery tests under different stresses are obtained and listed in Table 1.

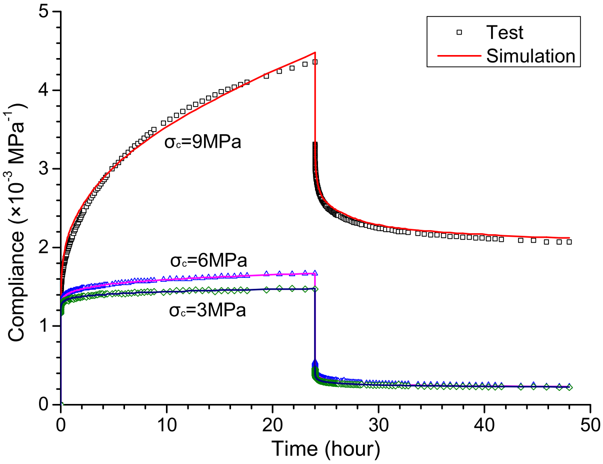


Fig. 8 Comparison of test and simulation results. This figure compares the results of the test and simulation for three different stress levels. Creep and recovery tests are both conducted over 24 hours. The figure is a time versus compliance plot. Time is in hours, and compliance is in $\times 10^{-3}$ MPa^{-1}

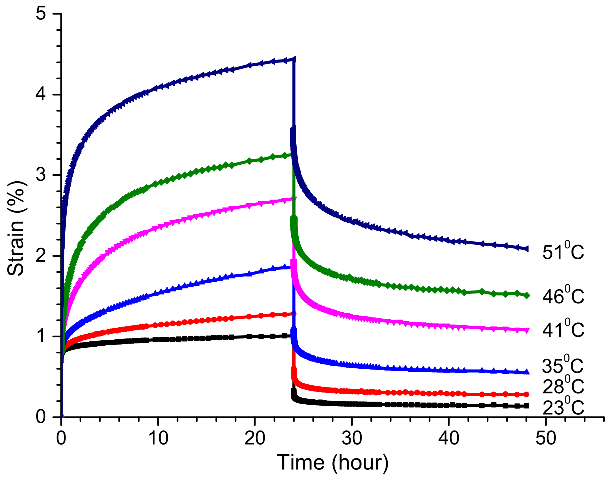


Fig. 9 Creep and recovery curves. This figure describes creep and recovery behaviour of ETFE foil at six different temperature levels: 23, 28, 35, 41, 46, and 51 °C. Creep and recovery tests are conducted over 24 hours. The figure is a time versus strain plot. Time is in hours, and strain is in %. Residual strain is observed in six tests

The results of tests' and simulation curves are plotted in Fig. 8 to evaluate the validity of the viscoelastic–plastic model. This figure shows that tests' curves and simulation curves overlap in a high precision in both creep tests and recovery tests. That means the viscoelastic–plastic model is suitable to describe not only creep behaviour but also recovery behaviour of ETFE foil at three representative stresses.

Also, the results of creep and recovery tests at different temperatures are shown in Fig. 9. As illustrated, unrecoverable deformations are noted. Viscoelastic and viscoplastic deformations both become large with increases in temperature, similar to the effect of stress. The revised model is adopted to simulate these six tests, the coefficients of which are listed in Table 2. A comparison of tests' and simulation curves is given in Fig. 10, which also shows a good fit.

Figures 8 and 10 both exhibit a good precision when the revised model is applied to simulate creep and recovery tests at three stresses and six temperatures. Comparing with the traditional generalised Kelvin model, the viscoelastic–plastic model is more suitable to simulate the creep behaviour of ETFE foil, notably in considering recovery behaviour.

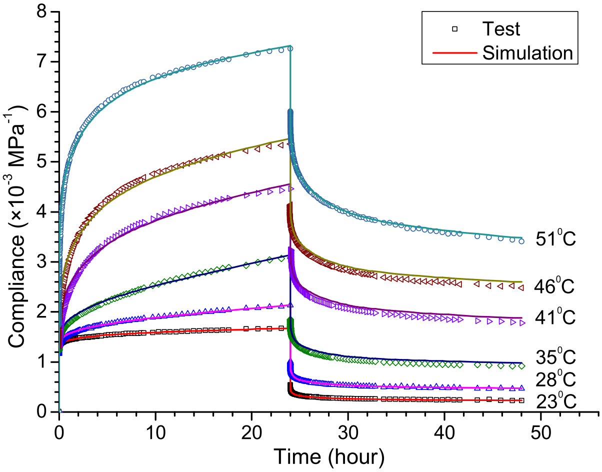


Fig. 10 Comparison of the test and simulation results. This figure compares the results of the test and simulation at six different temperature levels. Creep and recovery tests are conducted over 24 hours. The figure is a time versus compliance plot. Time is in hours, and compliance is in $\times 10^{-3}$ MPa^{-1}

Table 2 Creep compliance coefficients for six different temperatures. This table presents the creep compliance coefficients of ETFE foil for six different temperatures. These coefficients were used in viscoelastic–plastic modelling of ETFE foil and were obtained from short-term creep and recovery tests

Temperature	23 °C	28 °C	35 °C	41 °C	46 °C	51 °C
$g_0 D_0$	1.171E-3	1.163E-3	1.234E-3	1.291E-3	1.324E-3	1.738E-3
$g_1 D_1$	6.437E-5	1.142E-4	1.039E-4	1.115E-4	1.171E-4	1.439E-4
$g_1 D_2$	4.603E-5	5.801E-5	1.108E-4	1.289E-4	1.366E-4	1.748E-4
$g_1 D_3$	7.891E-5	1.502E-4	2.392E-4	3.272E-4	3.450E-4	5.682E-4
$g_1 D_4$	8.247E-5	1.515E-4	3.323E-4	5.383E-4	6.365E-4	9.254E-4
$g_1 D_5$	6.198E-5	1.040E-4	2.300E-4	5.183E-4	6.038E-4	1.050E-3
$g_1 D_s$	1.400E-6	6.078E-8	2.826E-8	1.515E-5	8.798E-5	7.046E-4
n	0.4338	0.7818	0.9204	0.4231	0.2966	0.1321

4.2 Prediction of long-term creep behaviour

As an application of time–temperature superposition and short-term creep tests at six temperatures, one master curve at 23 °C was obtained in Sect. 3.2. The shifting curve can predict long-term creep behaviour of ETFE foil over 40 years (10^9 seconds) at the reference temperature of 23 °C, which covers serviceable life of ETFE foil in structures.

Similarly, creep behaviours at 18 and 28 °C are predicted by means of time–temperature superposition. Time of creep prediction in these two temperatures is approximately 5 years (2000 days), which is the generally the design working life of ETFE structures.

The creep curves for these three temperatures are shown in Fig. 11. As illustrated, while the main creep compliance develops in the first year, additional creep compliance develops gradually over a longer time without reaching or maintaining a constant level. This time dependence indicates that the creep behaviour of ETFE foil would not completely halt even after a long period, at least after 5 years.

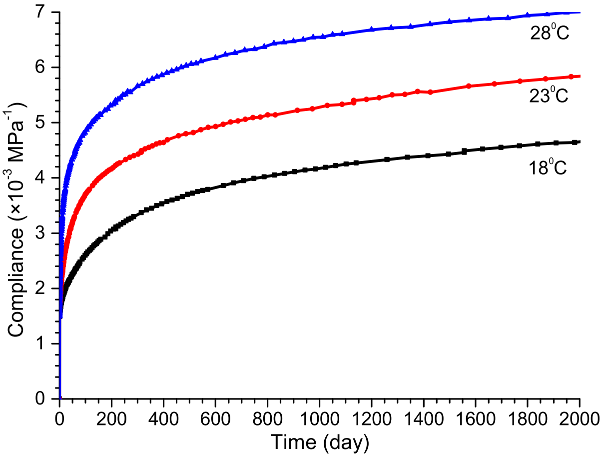


Fig. 11 Prediction of long-term creep behaviour. This figure describes the results of three predictions of long-term creep behaviour. Temperatures in the prediction are 18, 23 and 28 °C. Prediction time is 2000 days. The figure is a time versus compliance plot. Time is in days, and compliance is in $\times 10^{-3}$ MPa^{-1}

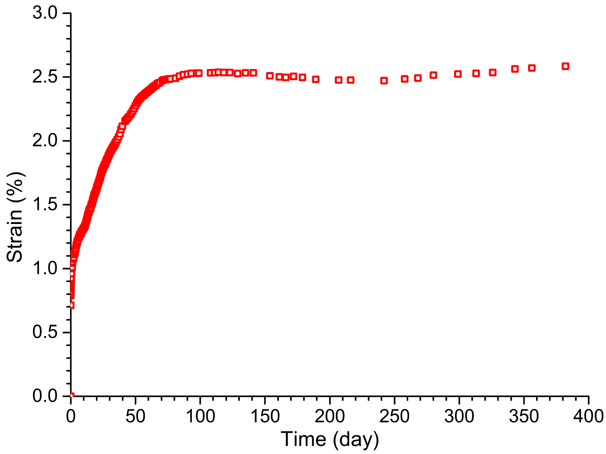


Fig. 12 Long-term creep behaviour. This figure describes long-term creep behaviour of ETFE foil in 400 days. The figure is a time versus strain plot. Time is in days and strain is in %. Slope of creep strain decreases with time, but does not reach zero during the 400 days

4.3 Validity of the long-term creep prediction

The result of the long-term creep test, which was performed for 400 days, is shown in Fig. 12 using the coordinates of strain versus time. As illustrated in Fig. 12, the slope of the creep strain decreases with time, but it does not reach zero after considering thermal deformation caused by temperature fluctuation. That is to say, creep compliance is still developing at the end of test, as predicted in Sect. 4.2.

To examine the long-term creep prediction in Fig. 11, two creep curves are compared in Fig. 13. One creep curve is from the 400 days-long creep test, and the other one is from the prediction given in Sect. 4.2 at a creep temperature of 23 °C. As shown in Fig. 13, the test curve is near to the predicted one at the initial stage from 4.0 to 6.2 in $\log T$, in which the average temperature in creep tests was about 23 °C, but the test curve deviates from prediction from 6.2 to 7.0. This deviation mainly comes from the fluctuation of temperature in the long-term creep test, which has a significant effect on creep behaviour as shown in Fig. 9.

To minimise the deviation from temperature fluctuation, the long-term creep curve in the test is shifted to an identical temperature of 23 °C according to Eq. (6). Then, the two

Fig. 13 Comparison of two curves. This compares results of the long-term creep curve and prediction curve at 23 °C. The prediction curve deviates from the creep test's curve from 6.2 to 7.0 log T. The figure is an log T versus log D plot, where T is time and D is compliance. Time is in seconds, and compliance is in MPa^{-1}

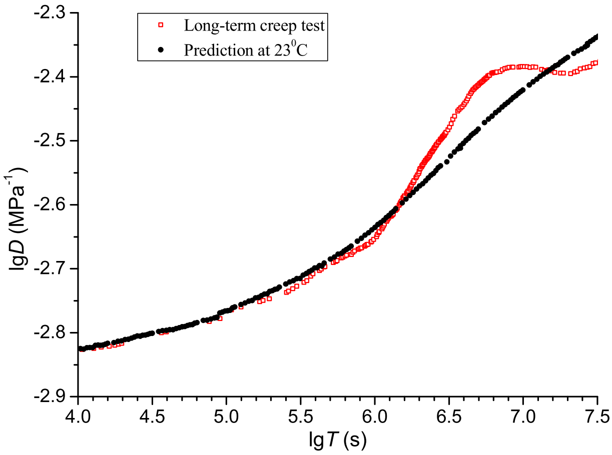
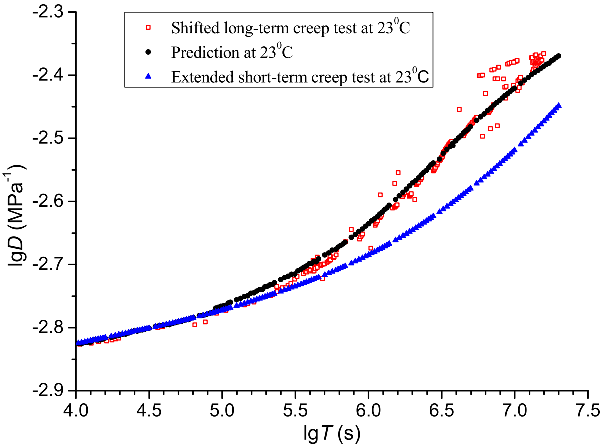


Fig. 14 Comparison of three curves. This figure compares the results of the shifted long-term creep curve, the prediction curve and the extended short-term creep curve, all at 23 °C. The prediction curve and the shifted long-term creep curve are similar. The shifted long-term creep curve and the extended short-term creep curve deviate from 5.0 to 7.2 log T. The figure is an log T versus log D plot, where T is time and D is compliance. Time is in seconds, and compliance is in MPa^{-1}



curves, the shifted long-term creep test curve and the prediction one, are compared in Fig. 14 again, both being at the constant temperature of 23 °C. After horizontal shifting, these two curves overlap over a wider range with less deviation, indicating the precision of prediction in Fig. 11 and the validity of horizontal shifting factors in Eq. (6).

Additionally, the short-term creep curve at 23 °C in Fig. 7 is extended to 400 days to tentatively predict long-term creep behaviour. It is also illustrated in Fig. 14. This figure shows that the short-term extended curve deviates from the long-term creep test from 5.0 to 7.2 in log T, even at identical temperature. This deviation indicates that the short-term creep test at identical temperature is insufficient to predict additional creep behaviour.

Therefore, it is practical to predict long-term creep behaviour of ETFE foil by a series of short-term creep tests at different temperatures according to time–temperature superposition, but this prediction cannot be achieved by short-term creep tests at identical temperature. The horizontal shifting function Eq. (6) is also verified and is valuable in the horizontal shifting process of ETFE foil for creep prediction.

5 Conclusions

The present study suggested a revised creep model to describe short-term creep and recovery behaviour of ETFE foil and a practical approach to predict its long-term creep property.

Short-term creep and recovery tests at three stresses and six temperatures showed that the residual strain was notable in recovery behaviour. Also, this unrecoverable strain became large with the increase of stress and temperature. The generalised Kelvin model was then revised to describe both viscoelastic and viscoplastic creep deformations. This model contained a traditional multi-Kelvin part and a steady-flow component which exhibited good fitting of creep and recovery tests' data.

Long-term creep behaviour of ETFE foil was predicted on the basis of time–temperature superposition. The transition temperature of ETFE foil used in this paper is calculated by the horizontal shifting process of six short-term creep curves at different temperatures, and the horizontal shifting factors were determined from W.L.F. equation. Several predictions of long-term creep behaviour of ETFE foil were also provided. The long-term creep test performed in this study showed that creep compliance had not achieved a constant value in 400 days, indicating the continuous development of compliance during a longer time. Additionally, by comparing long-term creep curves from the test, prediction and short-term extended one, the application of horizontal shifting factors in Eq. (6) is verified and the approach to predict long-term creep behaviour from extend creep curve in short-term is denied.

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