A Study on Predicting the Long-term Creep Behavior of Plastics using the Short-term Creep Test

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Abstract: The creep performance of plastics is one of the main criteria for a variety of applications with strict dimensional stability needs, including electrical/electronic parts and various automotive applications. However obtaining or generating accurate creep data is very difficult for both resin suppliers and product designers because the creep property is time dependent, which means it takes over several weeks or even a year time span. Hence a faster and more reliable method of predicting creep behavior of plastics is required when designing plastic products that will encounter long-term loading. This work presents an easy method for predicting the long-term creep behavior of plastics using the short-term creep experimental data. The flexural creep experiments of three plastics, ABS (Acrylonitrile butadiene styrene), PC/ABS (PC and ABS alloy) and LFT (Long fiber reinforced thermoplastics), are performed. For quick and reliable prediction of long-term creep behavior of plastics, time regional power-law model and time-stress modulus are introduced. To analyze the reliability and validity of the proposed method, the creep analyses based on the proposed method are performed. The comparison between the FEA results and the creep tests has shown that the new method can track both primary and secondary creep behavior over a long time. The creep analyses have been carried out by commercial FE Code.

Key words: Creep, Power-law, ABS, PC/ABS, LFT

1. Introduction

In recent years, more and more non-plastic parts in a variety of industries have been made of plastics. Typically plastics as viscoelastic materials have the creep phenomenon, which is a time-stress deformation response to a constant load for a prolonged period of time. In a wide number of applications, including electrical connectors and various automotive applications, short and long term dimensional stability at elevated temperatures is an essential design requirement. Engineers have paid attention to creep analysis for determining the amount of deformation of plastic parts. A characterization of the creep performance of plastics used in such areas is of primary importance. However the creep data of plastics is very difficult to obtain because it is a time consuming job, which means creep test takes over the span of several weeks or a year. It is unreasonable as well as inefficient for a lager number of designers to perform the creep test according to the term of guarantee of developing parts. Hence a fast and reliable method of predicting polymer creep behavior could be a benefit when designing plastic products that will encounter long-term loading.

Many ‘simplified’ uniaxial constitutive relations have been proposed to describe the standard creep curve except for tertiary creep[1-7]. Several creep and/or stress-relaxation studies to predict the viscoelastic properties of polymeric materials have been introduced. B. E. Read[3] presented an analysis of the influence of physical aging on the short- and long-term tensile creep behavior of injection-molded plates of glass-fiber reinforced polypropylene by using exponential function and power law function. The test time was 3 ~ 200 hour. Time-dependent compliance was used but the effect of applied stress was not studied. Carriere[4] studied the short-term (600 sec) creep performance of selected glass-filled semicrystalline and liquid crystalline polymers with a hyperbolic sine and exponential function. It showed that the predicted creep behavior was within ± 10% of the measured data. Meng Deng[5] studied the short- and long-term creep behaviors of ultra-high-molecular-weight polyethylene (UHMWPE). The short-term (30 ~ 120 min) creep test was conducted. Based on short-term creep data, the long-term creep behavior of UHMWPE was predicted using time-temperature superposition and analytical formula. The time-temperature superposition had 90 % of creep deformation of UHMWPE of 1-month creep test (1 MPa at 37 ^{o}C). J. P. Lu[6] carried out creep test on ABS pipes under a constant load at variable temperatures (at nominal 20, 40, 60 and 80 ^{o}C). Three different empirical functions of creep compliance over 2000 ~ 3000 hours were used. It showed that the creep compliance could be provide a means to evaluate the long-term structural properties. Ali E. Akinay[7] carried out the study of prediction of long-term performance of polymeric materials from short-term tests. The test material was a longitudinal polymer liquid crystal (PLC). Experimental creep curves were measured for 2 hours at nine stress levels in the range from 10 to 50 MPa at constant temperature. It provided the capability of using time-stress equivalence for reliable long-term quantitative predictions. Richard D. Sudduth[8] introduced a new unifying mathematical model to describe a definitive relationship between constant strain-rate, creep, and stress-relaxation analysis for viscoelastic polymeric compounds. The polymer used was a high-density polyethylene. This new concept covered all three phases of creep (i.e., primary, secondary, and tertiary). However this was not compared with any experimental creep data.

The aim of this study is to present an easy, fast and reliable method of predicting polymer creep behavior from short-term creep test. For this point of view, the time hardening of power-law creep model is chosen due to its simplicity. Nowadays these models are already implemented into the commercial FE analysis codes. The flexural creep experiments[6, 9-12] of three plastics have been investigated in this work. The short-term creep experiments are conducted for several testing conditions. For quick and reliable prediction of long-term creep behavior of plastics, the two new methods, *time regional power-law model* and *time-stress modulus*, are introduced. According to the working fields of plastic parts, the acceptable service life and the criteria of creep time, which are used in classifying the creep behavior, are very different. In this paper, the short-term time is defined as the time, which the secondary creep phase is enough developed. To analyze the reliability and validity of the proposed method, the creep analyses based on the proposed method are performed by using commercial FE code, ABAQUS/Standard. The time-stress modulus is realized by ABAQUS user subroutines, `CREEP` and `USDFLD`. The comparison between the FEA results and the creep tests has shown that the new method can track both primary and secondary creep behavior over a long time.

2. Background

Creep indicates the time-stress change in the dimensions of plastics when subjected to a constant stress. The creep test usually is performed under constant temperature and constant load conditions. The basic result of a creep test is the strain versus time curve shown in Figure 1. There is initial elastic time-independent response. The instantaneous strain is the elastic response to the applied load. Thereafter, the creep curve is divided into three parts: a part of decreasing creep strain rate called *primary* or *transient* creep phase, a part of steady state creep strain rate called *secondary* or *stationary* creep phase and final portion of increasing strain rate called *tertiary* creep phase.

The total creep strain consists of the elastic and inelastic parts of strain.

$$\varepsilon_T = \varepsilon_E + \varepsilon_C$$

Generally the creep strain resulting from a constant load test may be written as a function of stress, time and temperature. It is usually assumed to be separable into each function.

$$\varepsilon_C = f(\sigma, t, T) = f_1(\sigma) \cdot f_2(t) \cdot f_3(T)$$

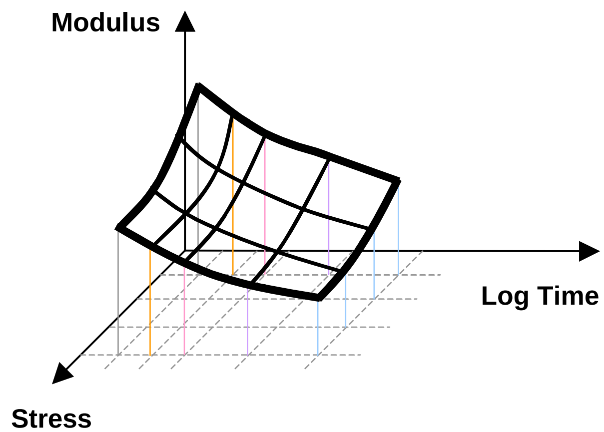


Figure 1. Time-stress modulus coordinates

The following form describes the primary and secondary creep phase.

$$\varepsilon_C = C \exp(-\Delta H / RT)\; t^m \sigma^n \qquad (1)$$

where ΔH is the activation energy, R is the universal gas constant and T is the absolute temperature.

For isothermal conditions, the above creep equation is simplified as

$$\varepsilon_C = B\ t^m \sigma^n \qquad (2)$$

where B, m and n are empirically determined constants.

For varying stress, the creep rate can be calculated from the first derivative of the power-law in Equation 2.

$$\dot{\varepsilon}_C = \frac{d\varepsilon_C}{dt} = mBt^{m-1}\sigma^n \qquad (3)$$

This can be written in a form independent of time if t is eliminated between Equation 2 and Equation 3.

$$\dot{\varepsilon}_C = \frac{d\varepsilon_C}{dt} = \frac{mB^{1/m}\sigma^{n/m}}{\varepsilon_C^{(1-m)/m}} \qquad (4)$$

Equation 3 is usually called *time hardening* model since the hardening phase is modeled using the time parameter and Equation 4 is similarly called *strain hardening* model for the same reason.

3. Modeling Approach

3.1 Tracking both primary and secondary creep behavior

Little work has been studied to predicting both primary and secondary creep of plastics. Only one set of creep models for both primary and secondary creep test period is unsuitable for tracking primary and secondary creep behavior because the creep rate is so rapidly changed during the transient time. Hence to predict both primary and secondary creep phase, several sets of time hardening creep parameters should be introduced in this paper. It means the short-term creep test has divided into several time regions. Then each time hardening creep parameters has been calculated using curve fitting for each time region. The time-varying sets of power-law creep parameters have to be prepared in advance for use in creep analysis.

3.2 Time-stress modulus

Typically as a result of creep phenomenon the modulus of plastics is not a constant. When plastics is subjected to a constant load, σ_0 , at some arbitrary time, then creep strain, $\varepsilon(t)$, at any subsequent time, *t*, may be expressed as below:

$$\varepsilon(t) = \frac{1}{E(t)} \cdot \sigma_0 = C(t) \cdot \sigma_0 \tag{5}$$

where $C(t)$ is the viscoelastic creep compliance[3,5,6] and $E(t)$ is the time-stress creep modulus at time t .

$E(t)$ would be rewritten as $E(t,\sigma)$ because the elastic modulus has been changed during creep test time at different applied stresses. It would be called as *time-stress modulus*. The time-stress modulus at some arbitrary time can be adjusted by fitting it to experimental creep data. The surface of time-stress modulus is constructed as shown in Figure 1. This log time-stress surface is very useful to calculate the decrease of the time-stress modulus after a long time. To calculate the time-stress modulus data for long time periods, surface spline method is introduced in this paper.

Surface spline method is a mathematical tool, which is used to find the function of the deflection of an infinite uniform plate, $w(x, y)$, at any point when the vertical deflections, $w_i = w(x_i, y_i)$, are known. This is described as below.

$$\begin{aligned} w(x,y) &= a_0 + a_1 x + a_2 y + \sum_{i=1}^{N} K_i(x,y) P_i \\ K_i(x,y) &= \frac{1}{16\pi} r_i^2 \cdot \ln\left(r_i^2\right) \end{aligned} \tag{6}$$

where $r_i^2 = (x - x_i)^2 + (y - y_i)^2$ and P_i is concentrated load at (x_i, y_i).

Equation 6 is rewritten as a function of creep time, t , and constant stress, σ , as below:

$$E(\ln(t),\sigma) = a_0 + a_1 \ln(t) + a_2\sigma + \sum_{i=1}^{N} K_i(\ln(t),\sigma) P_i \tag{7}$$

Several time-stress modului are adjusted by fitting it to the short-term creep tests. This empirical modulus set of short-term creep test could be called *basic* time-stress modulus set because it has been used as the basic data in predicting the long-term creep behavior of the materials. The basic time-dependent modulus has been expanded using Equation 7 over a long time.

Details for the prediction of the long-term creep in this study as follows.

1. The applied stress levels have been chosen through the instantaneous structural analysis of a plastic structure. The temperature effect did not considered at this time. The four

stress levels were tested. Three samples were tested in each stress level and the data were averaged. The tests lasted 300 hours.

2. The test was divided by six time regions in order to trace the transient behavior between primary and secondary. In this works, the primary creep phase could be considered until 5.0 hour and the transient phase was from 5.0 to 100 hour. After 300 hours, the secondary creep phase was enough progressed in this study. So the last time-varying creep constants of 300-hour creep test did not update for long-term creep analysis above 300 hours.

3. The basic stress-time modulus was adjusted by fitting it to experimental creep data. The stress-time modulus was steadily decreased before tertiary creep behavior.

4. The stress-time modulus was calculated on the base of the basic time-stress surface data, which was used to predict long-term creep behavior of plastics.

4. Experiment

4.1 Material

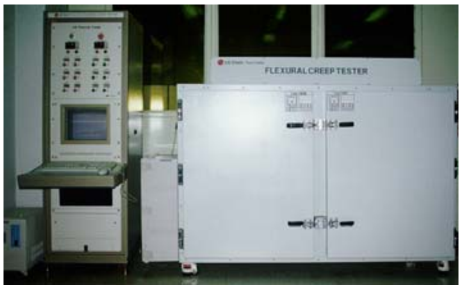
The three different plastics, ABS (Acrylonitrile butadiene styrene), PC/ABS (PC and ABS alloy) and LFT (Long fiber reinforced thermoplastics), have been evaluated. General ABS[6, 13] is thermoplastic resin made from three-dimensional monomer of Acrylonitrile/Butadiene/Styrene. It has a wide range of applications such as electric/electronic parts, automotive parts and so on. PC/ABS alloy is high performance engineering polymer with excellent mechanical properties, high heat resistance, high impact strength, and dimensional stability. LFT has excellent impact resistance plus high stiffness, good property retention at elevated temperatures, high creep resistance, and low warpage and good dimensional stability.

Table 1. Material properties of the plastics used

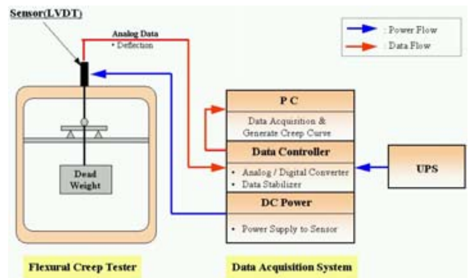
Resins	Tensile Yield Strength MPa (psi)	Elongation @ Break (%)	Flexural Modulus MPa (psi)	Flexural Strength MPa (psi)	Heat Deflection Temperature ^oC (^oF)
	ASTM D 638	ASTM D 638	ASTM D 790	ASTM D 790	ASTM D 648
ABS	50 (7250)	30	2400 (384000)	75 (10900)	87 (189)
PC/ABS	60 (8700)	100	2400 (384000)	88 (12800)	107 (225)
LFT	93 (13500)	3	4900 (711000)	113 (16400)	160 (320)

4.2 Creep Test

The three-point flexural creep tester is used in this work as shown in Figure 2. The creep tester gathers real-time deflection through LVDT (Linear variable differential transformer). The flexural creep tester[9-12] is almost free from the misalignment of applied load and also is less sensitive to fluctuation of temperature compared with the uniaxial tensile tester.



(a) Apparatus of creep tester



(b) Signal flow of creep tester

Figure 2. Flexural creep test system

When the constant load P is applied at the midpoint of the test specimen, the maximum stress in the outer surface of the test specimen occurs at the midpoint. The creep stress in three-point flexural test was calculated by means of the following equation.

$$\sigma_f = 3PL/2bd^2 \tag{8}$$

where σ_f is stress in the outer fibers at midpoint, P is load at a given point, L is support span, b is width of specimen and d is thickness of specimen.

Creep specimens are similar to the traditional tensile and flexural test. The creep specimens used are 12.7×3.2×120 (mm) and the span of support length is 50 mm as shown in Figure 3.

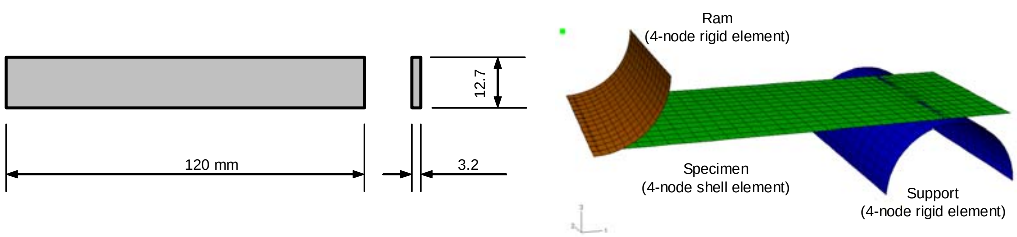


Figure 3. Creep test specimen and half of FE model

The flexural specimens were injection molded. The creep tests are performed at several conditions as listed in Table 2.

Table 2. Creep test conditions of the materials used

Resins	Applied stress (MPa)	Test Temperature (^oC)
ABS	5.61, 11.22, 16.82, 22.43	25, 50
PC/ABS	10.92, 16.37, 21.83, 27.29	50, 80
LFT	5.88, 11.76, 17.63, 23.53	50, 80

5. Results and Discussion

5.1 Comparison for short-term creep tests

5.1.1 Tracking primary and secondary creep phase

Creep parameters of each material are calculated using power-law curve fitting. In order to track both primary and secondary creep behavior, the creep data are divided into six time regions, 0.2, 1, 5, 25, 100 and 300 hours. One example of the time regional power-law curve fitting procedure is shown in Figure 4.

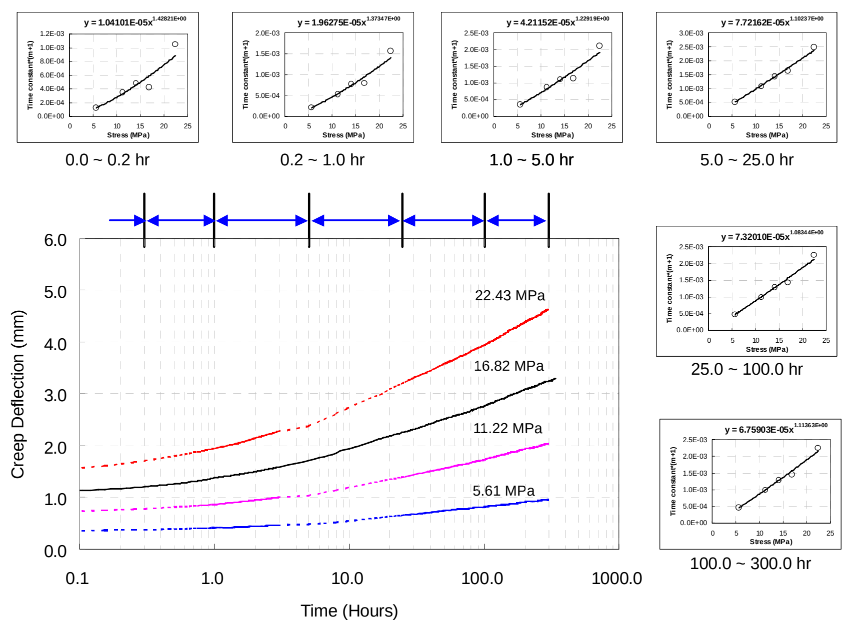


Figure 4. Example of time regional creep parameters for ABS at 50^{o}C

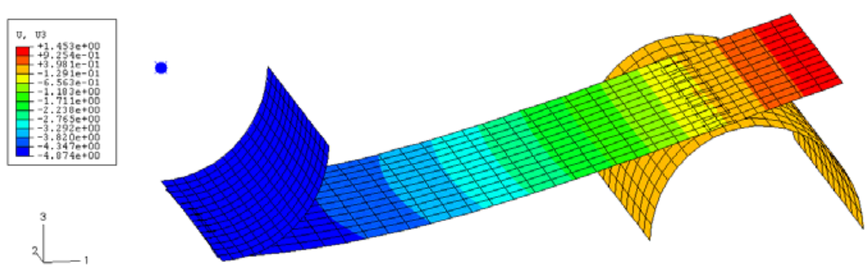
5.1.2 Finding time-stress modulus

The time-stress modulus is adjusted by fitting it to the short-term creep tests. This empirical modulus of short-term creep test could be called *basic* time-stress modulus because it has been used as the basic data in predicting long-term creep behavior of the materials. The basic time-stress modului over 300-hour creep tests of LFT is listed in Table 3.

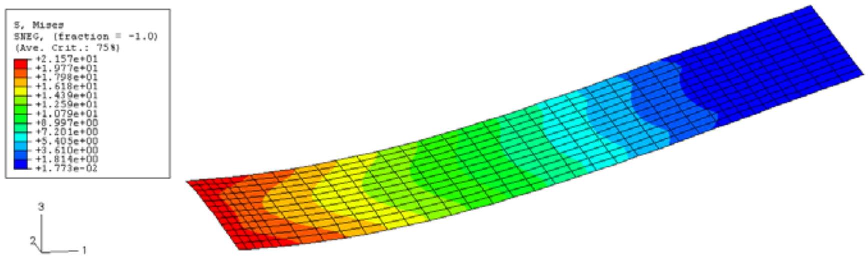
Table 3. Basic time-stress modulus of the 300-hour LFT creep test at 80^{o}C

Stress(MPa) \ Time(hour)	0.1	1	25	150	300
5.88	5400	5100	4900	4600	4470
11.76	4600	4300	4100	4000	3960
17.63	4100	3800	3600	3400	3300
23.52	3500	3150	2950	2800	2735

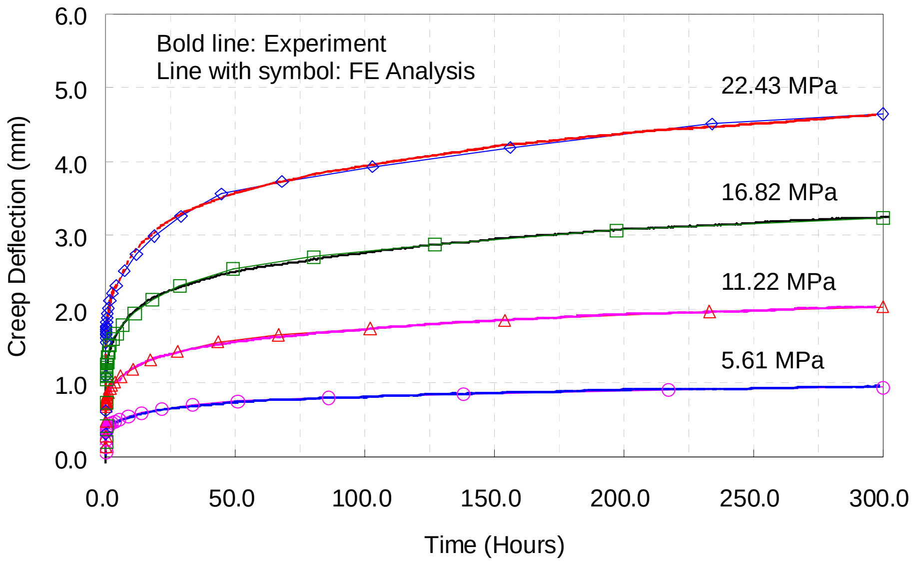
Short-term creep tests and FEA results are compared as shown in Figure 5, 6 and 7. FEA results offer a good accordance with short-term creep test results, as well as the suggested method tracks well both primary and secondary creep phase.



(a) Deflection contour under 22.43 MPa at 300 hours (Max. deflection = -4.874 mm)



(b) Mises stress contour under 22.43 MPa at 300 hours (Max. stress = 21.57 MPa)



(c) Comparison between test and FEA results

Figure 5. ABS 300-hour creep tests and FEA results at 50°C

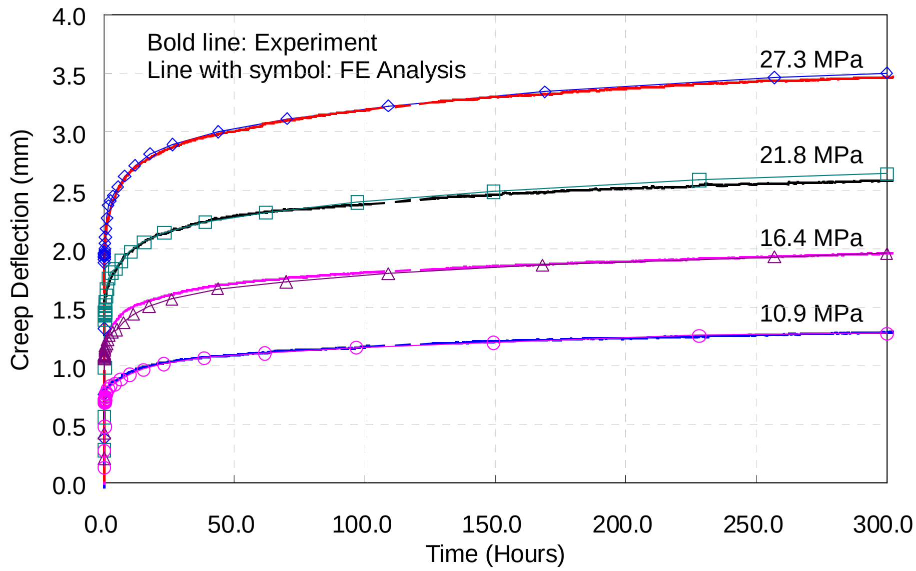


Figure 6. Comparison between PC/ABS creep tests and FEA results at 50°C

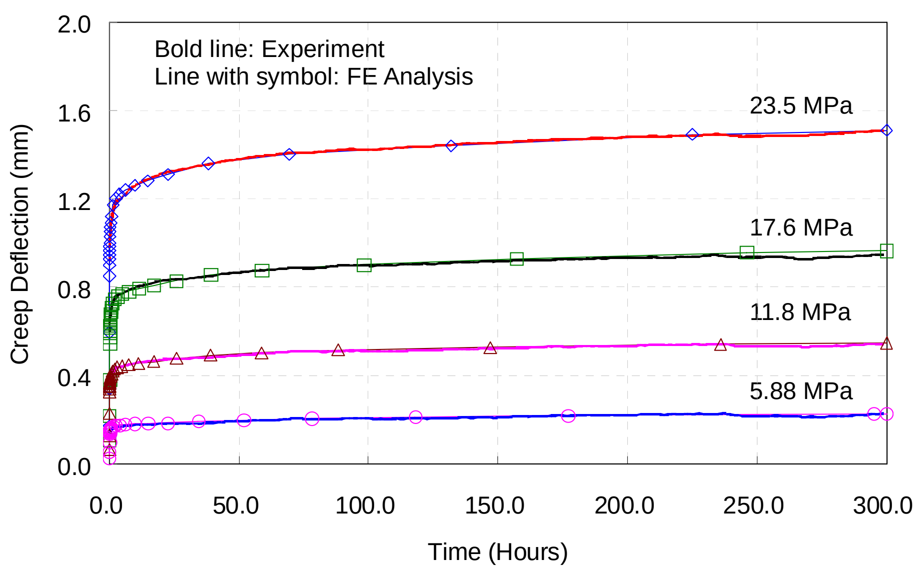


Figure 7. Comparison between LFT creep tests and FEA results at 80°C

To check the effect of the new two methods in predicting the creep behavior of plastics, two different creep models, one power-law creep with one constant creep modulus and time regional power-law models with time-stress modulus, are investigated on the base of the short-term LFT creep test at 80°C. One power-law creep parameters are calculated over 0.2 ~ 300 hours and the 25-hour creep modulus is used as one constant creep modulus in Table 3. The one power-law creep with constant creep modulus did not track the primary and secondary creep phase as shown in Figure 8.

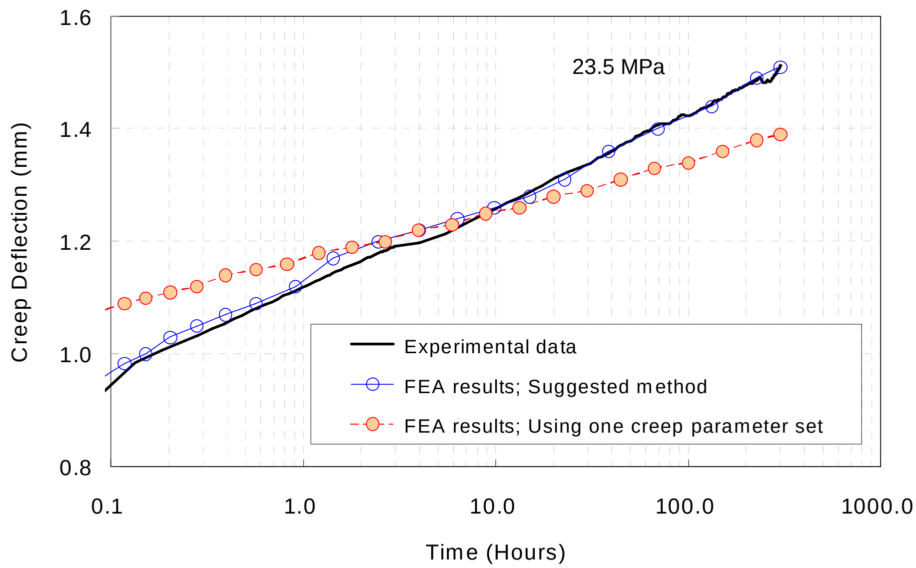


Figure 8. Evaluation of the effect of the different creep models for LFT at 80°C

In case of one power-law creep with time-stress modulus the deflection was less than the one of creep test, so that the plastics could be overestimated.

5.2 Prediction of long-term creep behavior

By using surface spline method, Equation 7, the basic time-stress modulus obtained from short-term creep test has been expanded in order to predict the long-term creep behavior of the materials used. The time-stress modului of LFT at 80°C is listed Table 4.

Table 4. Expanded time-stress modulus of LFT at 80 °C

Time(hour) / Stress(MPa)	500	1000	5000	10000
5.88	4368.69	4235.52	3926.31	3793.14
11.76	3939.59	3889.05	3794.93	3754.39
17.64	3249.14	3162.28	2960.62	2873.76
23.52	2687.00	2623.00	2473.39	2408.83

The 1000-hour long-term creep test is performed for only LFT in this work and has been compared with FEA results. They have a good coincidence between test and FE prediction as shown in Figure 9.

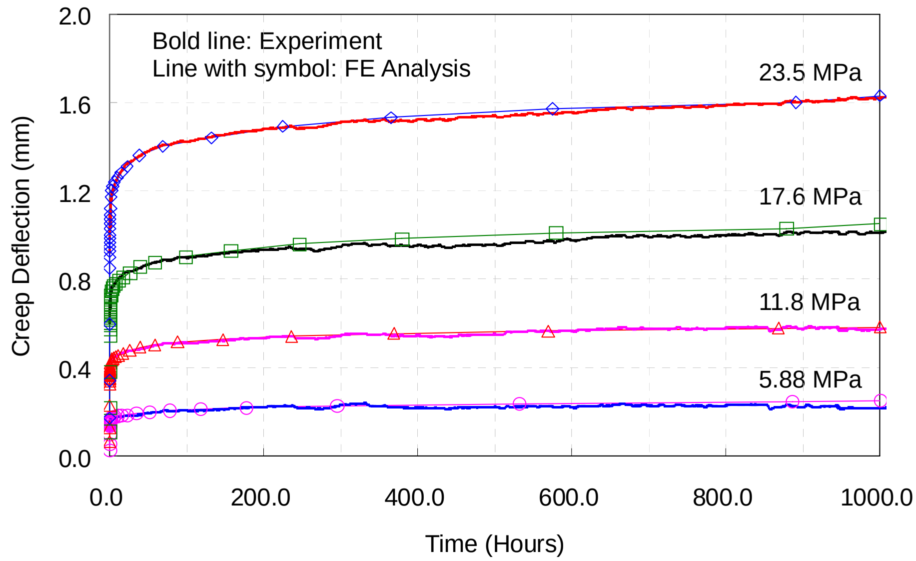


Figure 9. Comparison of long-term (1000 hours) creep results for LFT at 80°C

For the evaluation of the difference between the creep model with time-stress modulus and the creep model without time-stress modulus, LFT creep analysis is carried out over 10,000 hours. In case of no expansion of time-stress modulus it has less deflection than the others. As creep test is continued, the deflection gap is increased more and more as shown in Figure 10.

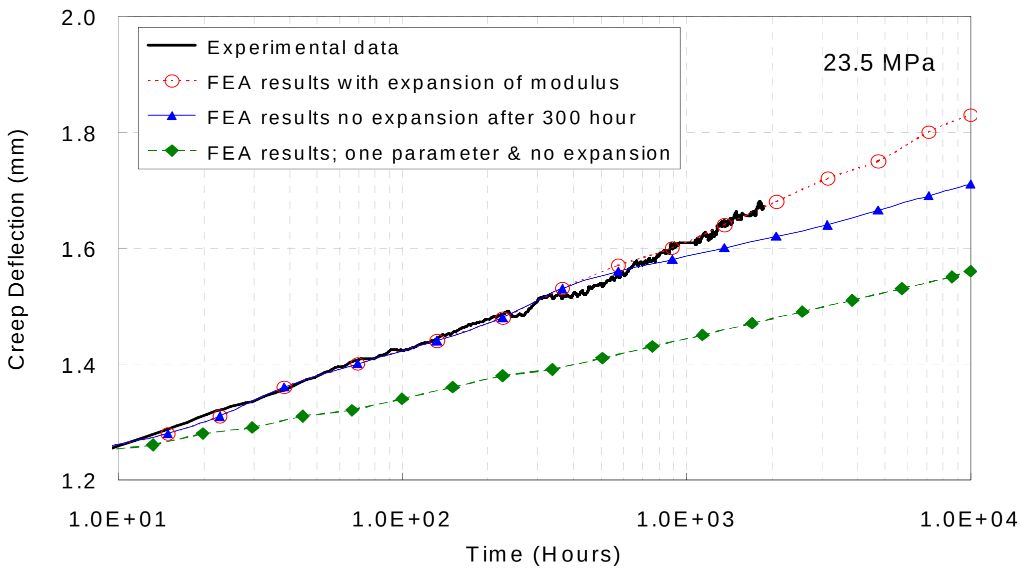


Figure 10. Evaluation of the effect of the time-stress modulus in predicting long-term (10,000 hours) creep behavior of LFT at 80°C

Hence for the reliable prediction of long-term creep behavior of plastics time-stress modulus has to be considered.

6. Conclusion

Short-term creep tests of general ABS, PC/ABS and LFT under constant loads at variable temperatures are reported. The results gathered are fitted with power-law time hardening creep model. The high quality method for quickly providing long-term creep behavior of plastics is developed. To analyze the reliability and validity of the proposed method, the creep analyses based on the proposed method have been compared with the creep tests of three different plastics. The comparison between the FEA results and the creep tests has shown that, when both time regional power-law creep parameters and time-stress modulus are considered, this method can track both primary and secondary creep behavior over a long time. Therefore this new method would be universally acceptable and useful for predicting creep behavior in plastics design.

7. References

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