Model Study for Thermal Deformation and Creep Behavior of Polymers Considering Moisture Diffusion

Tea gen An[a], Youngbin Lim[a], Naksoo Kim[a,*]

[a]Department of Mechanical Engineering, Sogang University, Seoul 121-742, Korea
[*]Corresponding author. Tel. : +82 2 705 8635
E-mail address : nskim@sogang.ac.kr (Naksoo Kim)

ABSTRACT

Polymers Acrylonitrile-Butadiene-Styrene is widely used as a polymeric material for components used in home appliances. However ABS is a viscoelastic material which is subject to creep deformation when exposed to certain ranges of temperature and humidity for long time periods. If the deformation can be predicted, engineer is able to design to minimize the deformation of the product by creep. In this study, the numerical model to predict the creep behavior of polymeric materials was established by experiments and verification procedures. In particular, predicting functions that can predict material constants that express the creep properties of polymeric materials were determined. To verify the numerical model and predicting function, creep tests at temperatures and humidity changing over time were conducted on simple shape specimens. As a result, the numerical model applied the creep constants and diffusivity determined by predicting function could well simulate actual creep behavior resulting from temperatures and humidity.

Keywords: two-layer viscoelastic-plastic model , thermal and humidity creep, ABS (Acrylonitrile-Butadiene-Styrene copolymer), polymer creep behavior.

1 INTRODUCTION

In the this study, to predict the permanent deformation of polymer, the mechanical properties and creep properties of ABS polymer was determined by experiments. Two-layer viscoelastic-plastic models [1-4] were used to define the mechanical properties of ABS polymer having viscoelastic properties and power law creep models with time hardening [4-6].

2 MATERIAL MODEL

2.1 Mechanical property

A two-layer viscoelastic-plastic model [1-4] is a material model that can consider viscoelastic and elastic-plastic properties of materials simultaneously, which is composed of a parallel combination of a viscoelastic layer which is time dependent and an elastic-plastic layer which has nothing to do with time (Fig. 1)

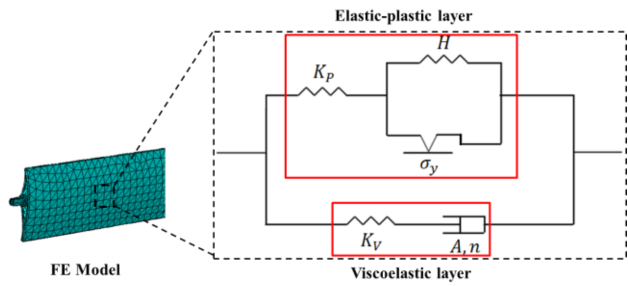


Figure 1: Idealized One-dimensional representation of the two-layer viscoelastic-plastic model to express the deformation of ABS [4].

K_P is the elastic modulus of the elastic-plastic layer, K_V is the elastic modulus of the viscoelastic layer, H is the hardness coefficient of the plastic region, σ_Y is yield stress, and A & n are the material constants of the viscous region.

The total stress σ in two-layer viscoelastic-plastic model is the sum of the stress of viscoelastic layer σ^{EV} and the stress of elastic-plastic layer σ^{EP} (Eq. (1)).

$$\sigma = \sigma^{EV} + \sigma^{EP} \tag{1}$$

$$\sigma^{EV} = \left(\frac{\dot{\varepsilon}_o}{A}\right)^{1/n} \tag{2.a}$$

$$\sigma^{EP} = \sigma_Y + H\varepsilon^{pl} \tag{2.b}$$

$$\sigma = \left(\frac{\dot{\varepsilon}_o}{A}\right)^{1/n} + \sigma_Y + H\varepsilon^{pl} \tag{3}$$

However, it is difficult to express the behavior of polymer according to differences in strain rates by this model. Therefore, to express the differences in strain rates in more details, a modified model was proposed as shown by Eq. (4).

$$\sigma = \left(1 + \left(\frac{\dot{\varepsilon}_o}{A}\right)^{1/n_1}\right) \cdot \left(H\left(\varepsilon_o + \bar{\varepsilon}^{pl}\right)^{n_2}\right) \tag{4}$$

2.2 Creep property

In general, creep is the tendency of a solid material deforming permanently under the influence of mechanical stresses over time. In the present study, the power law creep model with time hardening was used as a creep model to express the creep properties of ABS polymer. The power law creep model with time hardening expresses creep strain rates ($\dot{\bar{\varepsilon}}^{cr}$) as shown by Eq. (5) considering time, stress, and temperatures [4-6].

$$\dot{\bar{\varepsilon}}^{cr} = C \cdot \tilde{q}^{n_c} \cdot t^m \tag{5}$$

$\tilde{q}^{n_c}$ is equivalent deviatoric stress, t is total time, and C, m and n_c are creep constants that can be expressed as functions of temperatures. However, the present study is intended to define creep behavior including temperature and humidity. Since the creep behavior of materials may vary depending on the ratio of elastic modulus K_P and K_V of the viscoelastic and elastic-plastic layers, factor f that represents the ratio of elastic modulus was defined as shown by Eq. (6) [4].

$$f = \frac{K_V}{(K_P + K_V)} \tag{6}$$

3 EXPERIMENTAL AND RESULT

3.1 Determine the material properties by experiments

To minimize the differences between test results and finite element analysis (FEA) results, the objective functions were used as shown by Eq. (7.a) and (7.b) respectively. In these equations, N represents sampling point, superscript C represents FEA values, superscript m represents test values, F represents loads, and D represents deflection.

$$\phi_o(A,n_1,H,\varepsilon_o,n_2) = \sum_{i=1}^{N}\left(\frac{F_i^C - F_i^m}{F_i^m}\right) \tag{7.a}$$

$$\phi_o(C,m,n_c,f) = \sum_{i=1}^{N}\left(\frac{D_i^C - D_i^m}{D_i^m}\right) \tag{7.b}$$

3.1.1. Mechanical property

To determine the material parameters, tensile test was conducted according to temperature and strain rate. The gauge length of specimen for tensile test is 40 mm, the width is 7 mm, and the thickness is 3 mm respectively (Fig. 2) [7]. Experimental condition is as in the following: Temperature (20, 30, 60, 90℃), Tensile speed (10 mm/min (0.004167 s^{-1}), 300 mm/min (0.125 s^{-1})). Load-stroke response is measured in each condition (8 cases).

The material constants derived through the modified model showed differences smaller than the original model. (Table 1).

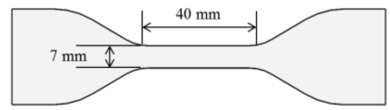


Figure 2: Shape of ABS specimen used in the tensile test.

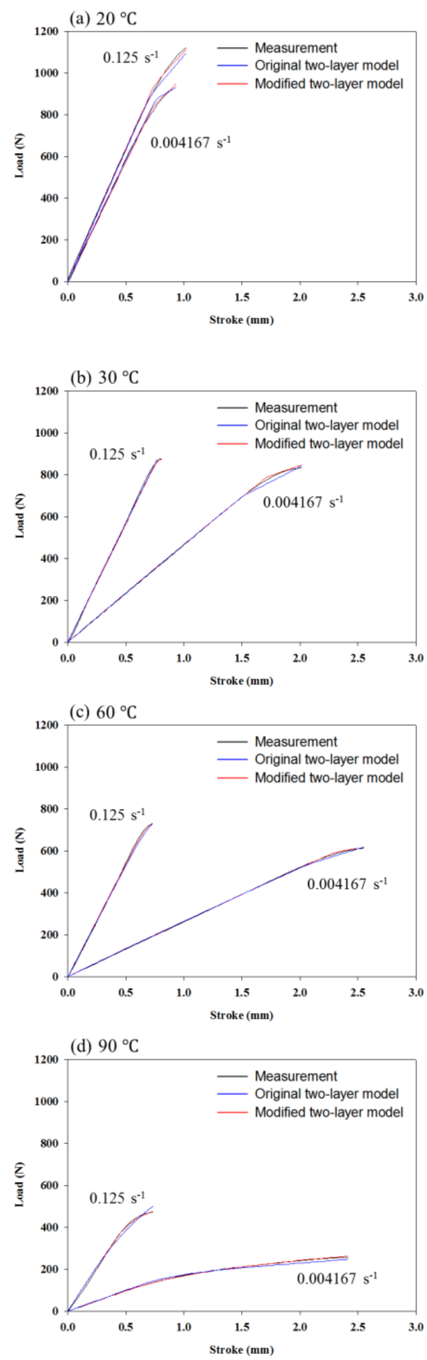


Figure 3: Comparison between test results and the calculation results obtained through the original model/those obtained through the modified model: (a) 20℃, (b) 30℃, (c) 60℃, (d) 90℃.

3.1.2. Creep Property

To define the creep behavior of ABS polymer, the tests were conducted in a chamber where temperatures and humidity levels could be controlled to be maintained or changed over time. The creep tests were conducted by placing load on test specimens made for creep tests (Fig. 4). The test specimens were in the form of 350 mm long, 100 mm wide, and 3 mm thick plates. The tests were conducted for approximately 100 hours and the vertical displacement (deflection) of the weight was measured while the tests were in progress to derive displacement responses over time. The displacement of the weight was measured once every 5-minute using a Pontos 3D (Real-time deflection meter) so that non-linear displacement responses could be also measured smoothly.

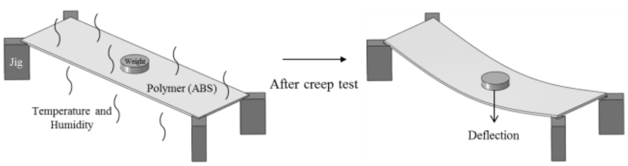


Figure 4: Schematic diagram of creep tests of ABS polymer.

The resultant material constants derived as those that minimize differences from test results are as shown in Table 2 and the results of comparison between FEA results and test results are as shown in Fig. 5.

Case	TP (℃)	RH (%)	C	m	n_c	*f*
1		0	1.0 x 10^{-7}	-0.46	0.89	0.71
2	30	45	2.1 x 10^{-7}	-0.46	0.84	0.73
3		90	4.7 x 10^{-7}	-0.46	0.84	0.73
4		0	1.5 x 10^{-6}	-0.10	2.71	0.72
5	60	45	3.2 x 10^{-6}	-0.15	1.9	0.79
6		90	6.1 x 10^{-6}	-0.3	1.69	0.90

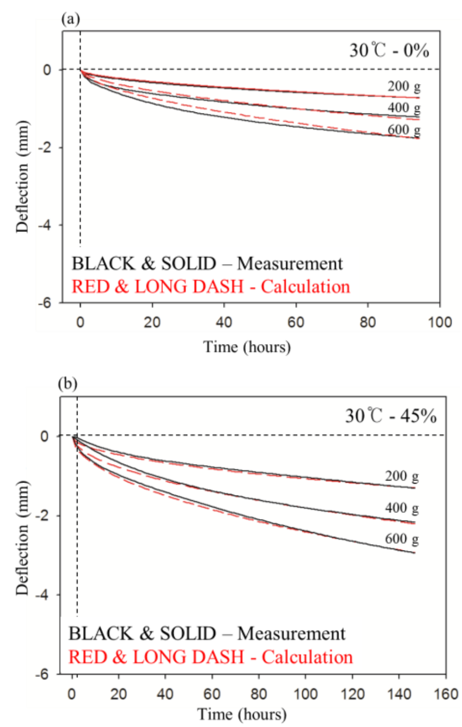
Table 2: The parameters of creep property about temperature (TP) and relative humidity (RH).

Using the creep constants defined for the six temperature/humidity conditions, interpolation functions that can predict creep constants for certain temperatures and humidity levels were derived on reviewing the results shown in Table 3. In addition, a equation for predicting a creep constant for conducting interpolation as Eq. (8) of creep constants for humidity first and for temperature thereafter was derived as shown by Eq. (5).

$$C,m,n,f=(a\times RH(\%)+b)\cdot e^{(c\times RH(\%)+d)\cdot TP(℃)} \quad (8)$$

Parameter	a	b	c	d
C	4.0 x 10^{-10}	2.0 x 10^{-9}	-6.0 x 10^{-5}	0.0923
m	-0.0377	3.7384	0.0007	-0.0703
n_c	0.0016	0.2786	-0.0002	0.0383
f	-0.0013	0.7076	8.0 x 10^{-5}	0.0003

Table 3 : Regression coefficient of creep parameters.



Temperature(℃)	*A*	n_1	*H*	ε_o	n_2	Young's modulus (MPa) 10 mm/min (K_P)	Young's modulus (MPa) 300 mm/min
20	0.75	0.80	84.978	0.000027	0.071	2280	2480
30	0.65	0.965	74.602	0.00012	0.102	1382	2195
60	0.31	1.212	52.976	0.0021	0.11	780	2055
90	0.01	2.224	10.345	0.0013	0.132	621	1558

Table 1: Determined constants of modified two-layer viscoelastic-plastic model for ABS material.

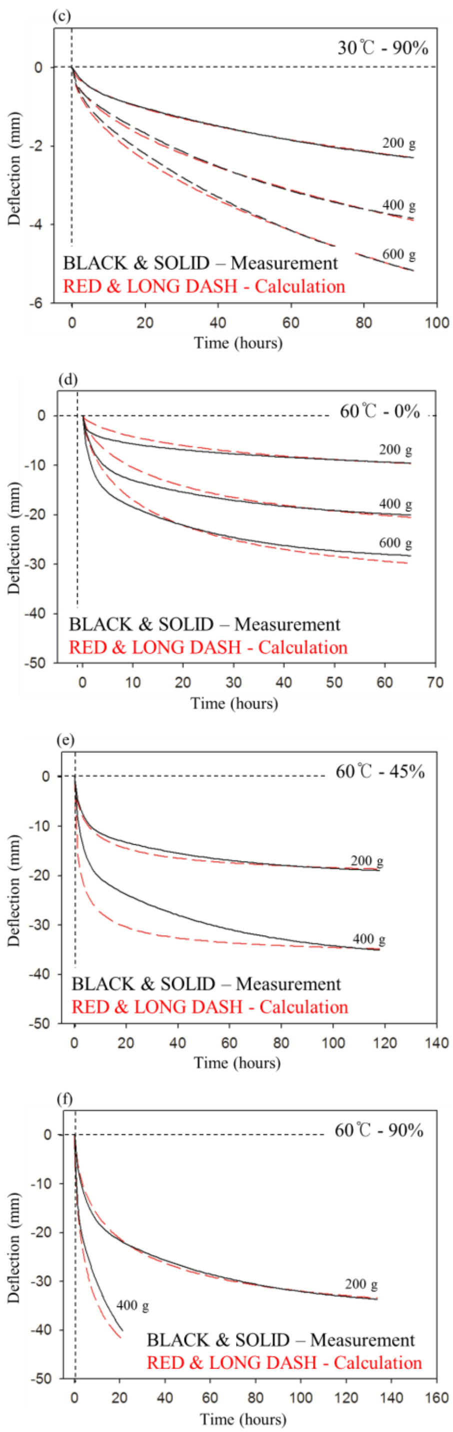


Fig. 5. Comparison of the results of creep tests of ABS polymer and FEA results: (a) case 1 (30℃, 0%), (b) case 2 (30℃, 45%), (c) case 3 (30℃, 90%), (d) case 4 (60℃, 0%), (e) case 5 (60℃, 45%), (f) case 6 (60℃, 90%).

4 SUMMARY AND CONCLUSION

the two-layer viscoelastic-plastic model was selected as a material model that can define the mechanical properties of ABS polymer having viscoelastic properties and then a modified two-layer viscoelastic-plastic model that can better express the effects of strain rates than the existing model was proposed. Material constants that made around 1% differences between the calculation results using the modified material model and tensile test results at different temperatures and strain rates were derived to define the mechanical properties of ABS polymer. The creep model constants were interpolated and defined as functions of temperature and humidity so that creep behaviors under certain temperature/humidity conditions can be shown.

5 FUTURE STUDY

To express the behavior of diffusing humidity, the test will be done which is measuring the deflection of polymeric plate with aluminum tape that is attached to one side of plate to prevent moisture diffusion. In addition, To verify the numerical model and interpolation functions, creep tests of a simple shaped specimen will be conducted under temperature/humidity conditions changing over time and the results will be compared to the calculation results of the numerical model.

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