Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

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Version of record first published: 02 Apr 2012.

To cite this article: K. K. Biswas , M. Ikueda & S. Somiya (2001): Study on creep behavior of glass fiber reinforced polycarbonate , Advanced Composite Materials, 10:2-3, 265-273

To link to this article: http://dx.doi.org/10.1163/156855101753396744

Adv. Composite Mater., Vol. 10, No. 2,3, pp. 265–273 (2001)

Study on creep behavior of glass fiber reinforced polycarbonate

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Abstract—In this study, tests on creep behavior of glass fiber reinforced polycarbonate were carried out at elevated temperatures. The result showed that creep behavior of GFRPC composites represented good agreement with Arrhenius reciprocation law of time–temperature. The effect of fiber volume fraction on creep behavior was also been studied. Here two shift factors — a modulus shift factor and a time shift factor — were introduced to draw the grand master curve of the creep compliance curves of various fiber contents. It became possible to estimate the creep behavior of GFRPC composites with any fiber contents using the grand master curve of creep compliance master curves and time and modulus shift factors. So it became possible to design materials for creep by reinforcing quantity of fibers to obtain the required objectives.

Keywords: GFRPC; creep compliance; Arrhenius equation; grand master curve.

1. INTRODUCTION

Plastics, especially fiber reinforced plastics (FRPs), are light in weight but yet are sufficiently strong to withstand high loads. As a result, in aerospace vehicles, like aircrafts, FRPs are used as substitutes for metal alloys. An important aspect of their composite structural performance is the visco-elastic behavior of the FRP which, as a polymeric solid, is elastic in that it recovers its shape but is viscous enough that it creeps. Due to the fact that FRPs are not simple elastic solids, it is always necessary to take into account not only the stress, but also the time of applied stress. Much research has been done by Struik [1] on time–temperature dependence, especially on the physical aging of amorphous polymers and their composites. Kunio [2] has also investigated the mechanical properties, specifically with regard to the time–temperature dependence of some visco-elastic bodies. To

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evaluate the visco-elastic properties of polymers, temperatures must be specified clearly and taken into consideration. Gates and Feedman [3] are also performing research on the time dependence of different kinds of thermoplastics. Visco-elastic materials [4] are characterized by a fundamental concept on the linearly visco-elastic mechanical behavior under uniaxial stress–strain state and its mathematical representation in both the differential equation based on the spring-dashpot model and the integral form arising from the superposition principle.

The visco-elastic behavior [5, 6] of polymer composites is also dependent upon stress and temperature. Because FRPs are used in the primary structural materials of aircraft, spacecraft, etc. as well as in their secondary structural materials, high durability and high reliability over long periods regarding their deformation become important issues. They show changes in visco-elastic behavior at their operational temperatures. The structure of some casings has to withstand high temperature environments. Some pre-stress is introduced into the structures during molding as well as manufacturing. Also, in practical uses, the structures have to carry some dead loads. Therefore, at higher temperature, creep occurs in these materials. It becomes essential then to study the creep behavior of these structural materials. On the other hand, as the properties these composites are time dependent, composites of polycarbonate are widely used in parts of automobiles, vehicles, window glasses, roof rail, etc. In the previous studies [7–9], creep behavior of stainless fiber-PPE and other composites were carried out. Thus, it also becomes important to investigate the creep behavior of glass fiber reinforced polycarbonate.

2. EXPERIMENTAL

2.1. Materials

In this study, glass-fiber reinforced polycarbonate (GFRPC) with various fiber volume fractions was used as test material. The matrix used, polycarbonate (PC), was a thermoplastic resin. The glass transition temperature of PC was about 150°C. Here, fiber weight fractions of the test specimens were 0% (resin matrix itself), 10%, 20% and 30% and the specimens were denoted hereafter as G0, G10, G20 and G30 respectively. The test specimens were molded by injection molding process to a dimension of 152.1 × 12.8 × 6.5 mm.

2.2. Methods

To eliminate the effects of thermal history, the specimens were heated to 160°C ($T_g + 10°C$) and held for 10 min and then quenched to test temperatures in air. Creep tests were carried out by the 3-point bending test method using a creep test machine in a Yamato Fine Oven DH42. Tests were made at several temperatures between 90°C to 140°C, which were below the glass-transition-temperature (150°C) of the composites. Plane-wise creep tests were done with a span of 120 mm and

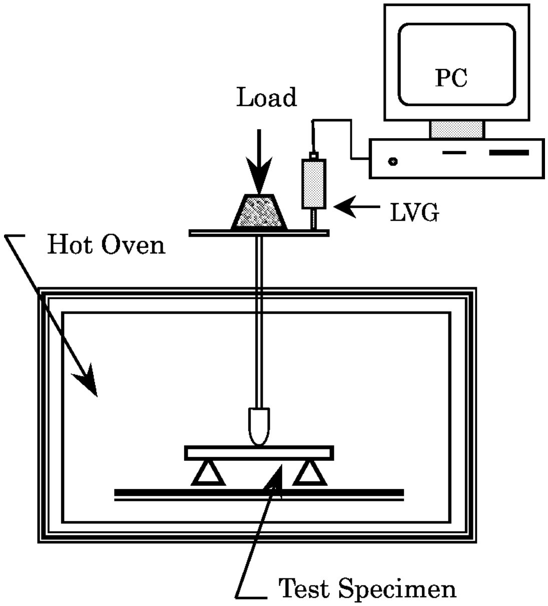


Figure 1. Schematic presentation of creep test machine for three-point bending creep test.

the applied loads were 1/10th of their bending strengths. Each test specimen was inserted in the test chamber at room temperature and then the temperature was raised to that of the test. Creep deflections at the middle of the specimen were measured with a transducer (linear deflection gauge) and data at corresponding times were recorded in an on-line computer. Figure 1 shows the schematic presentation of experimental setup.

3. RESULTS AND DISCUSSION

3.1. Creep behavior of GFRPC

Before executing the creep test, a three-point bending test was carried out to calculate the flexural strength and flexural modulus. The machine used was an Instron type bending test machine (TCM-5000 MNB Inc.). The span was taken as 16 times that of the specimen's thickness and the cross-head speed was 1 mm/min. The flexural strength and flexural modulus increased slightly with the increase in fiber volume fraction. Table 1 shows the mechanical properties of these composites.

To evaluate the creep behavior of GFRPC, the creep compliance was calculated from the creep data. Figure 2a shows the creep compliance curves of G10 composite. At lower temperatures, from about 90°C to 110°C, the creep compliance was almost invariant with time but an insignificant increasing tendency was observed. At 120°C the rate of increase was considerably higher. In contrast, at higher temperatures, specifically above 130°C, the creep compliance rapidly increased with

Table 1.
Static mechanical properties of GFRPC composites at room temperature

Materials	G0	G10	G20	G30
Weight fraction (%)	0	10	20	30
Volume fraction (%)	0.0	5.0	10.6	16.8
Bending modulus (GPa)	2.1	3.5	5.6	7.7
Bending strength (MPa)	85.3	114.7	141.9	163.3

time. The creep compliance curves exhibited the typical creep behavior, i.e. at any constant temperature the creep compliance increased with the increase in time and at a specific time the creep compliance increased with the increase in temperature.

To verify time–temperature dependence of these polymer composites, creep compliance master curves were drawn at 120°C as reference temperature by shifting the creep compliance curves. The Arrhenius time–temperature shift factor could be calculated from the following equation:

$$\log a_{T_0}(T) = \frac{\Delta H}{2.303R}\left(\frac{1}{T} - \frac{1}{T_0}\right), \tag{1}$$

where a_{T_0} is the time–temperature shift factor, R is the gas constant (8.31 J/mol·K), ΔH is the energy of activation, T_0 is the reference temperature and T is the arbitrary temperature.

The time–temperature superposition was established by drawing the master curve shifting the short-term creep data according to the following steps.

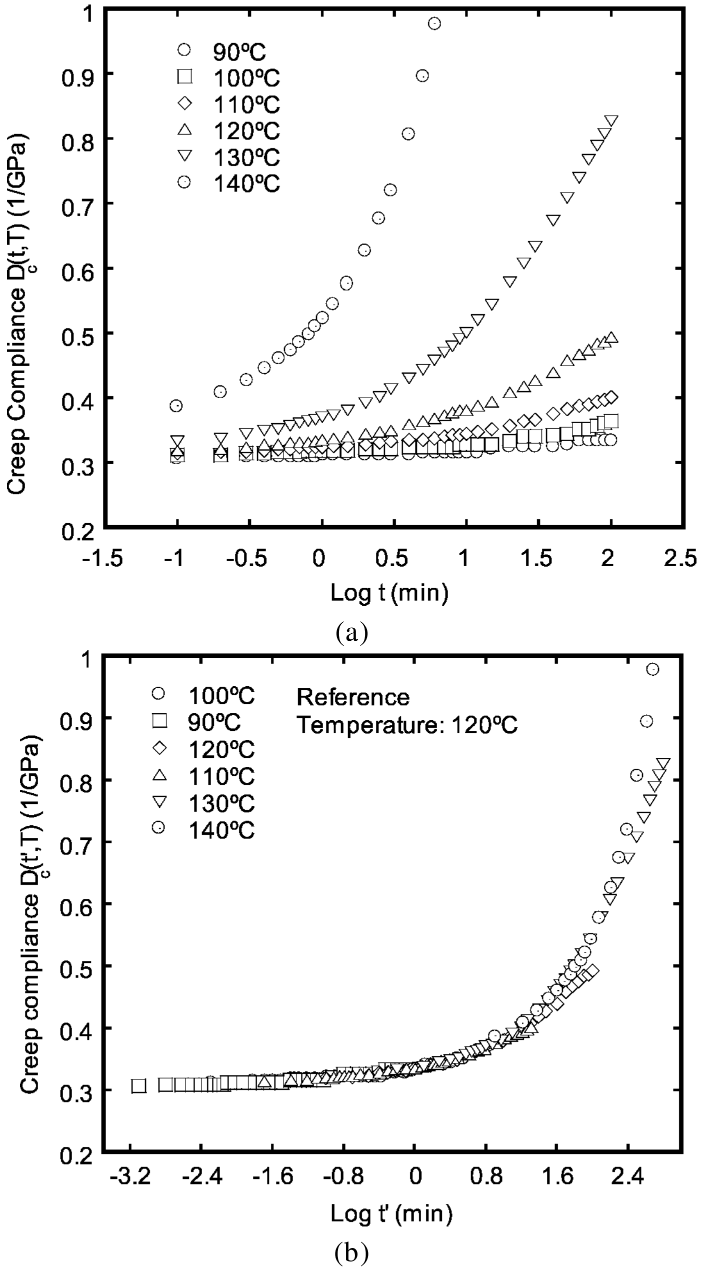
1. Taking a suitable temperature as the reference temperature and fixing the coordinates of the data curve of this reference temperature.
2. Taking the reference temperature as the base and shifting horizontally the other data curves of all other temperatures along the time axis to make one overlapped smooth curve.
3. Obtaining the master curve by replacing the time t of each shifted curve by the physical time t' at the reference temperature T_0.
4. By investigating the relation between temperature and the shift quantity a_{T_0} of each data curve while drawing the master curve, the time–temperature shift factor of that material is calculated.

To draw the creep compliance master curve, the time–temperature shift factor during the shifting operation can be defined as follows:

$$a_{T_0}(T) = \frac{t}{t'}, \tag{2}$$

where t is the creep time and t' is the physical time.

By applying the above shifting operation, the creep compliance master curve and shift factor curve were drawn. To draw the creep compliance master curves,



(a)

(b)

Figure 2. (a) Creep compliance curves of glass fiber reinforced polycarbonate (G10). (b) Master curve of creep compliance of glass fiber reinforced polycarbonate (G10).

the short time side (short-term-creep side) of compliance curves was adjusted to overlap.

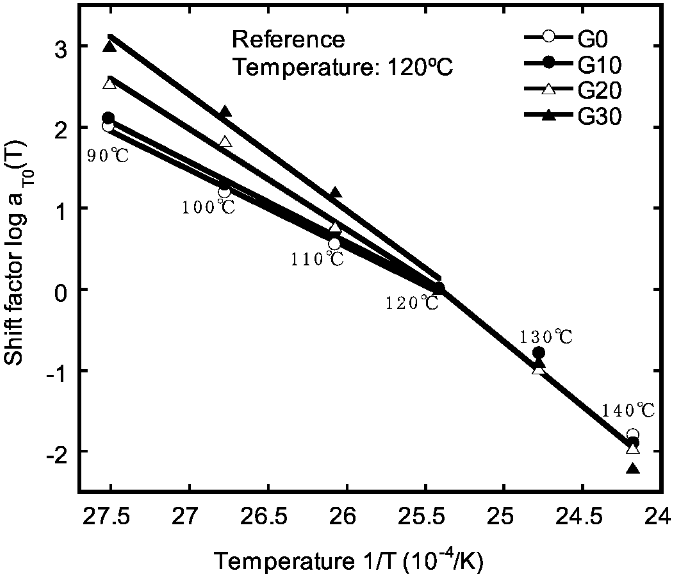


Figure 3. Time–temperature shift factors of GFRPC and polycarbonate resin.

Figure 2b shows the creep compliance master curves of G10 composite. In this figure, the horizontal axis shows the physical time. The creep compliance curves at lower than the reference temperature (120°C) were shifted towards the shorter time (left) side on the time axis and those at the higher temperatures were shifted towards the longer time (right) side on the time axis. The shift factor curves for each of the composites were plotted on an Arrhenius-type graph as in Fig. 3. Each shift factor curve shows two straight lines indicating that the creep phenomena represent good agreement with the Arrhenius reciprocal law of time–temperature.

3.2. Effect of fiber contents on creep behavior

The left side of Fig. 4 shows four creep compliance master curves of G0, G10, G20 and G30 composites at 120°C. From this figure it is clear that with the increase in fiber volume fraction, considerable changes of visco-elasticity occurred and the composite could withstand higher temperature for a longer time. It was observed that the creep compliance was lower for a composite of higher fiber volume fraction. The result indicates that the GFRPC composites of higher fiber volume fraction can withstand longer time than that of the lower fiber volume fraction. The increase in fiber volume fraction caused an increase in the static elasticity part of the visco-elastic polymer composite. This indicated that increase in fiber contents decreased the creep compliance and thus suppressed visco-elastic deformation. Thus the fiber content played a prominent role in creep behavior of GFRPC composites.

To make only one master curve for all fiber volume fraction materials, the master curves on each fiber volume fraction's FRP were shifted to the horizontal and vertical direction. This master curve of the master curves was called the grand

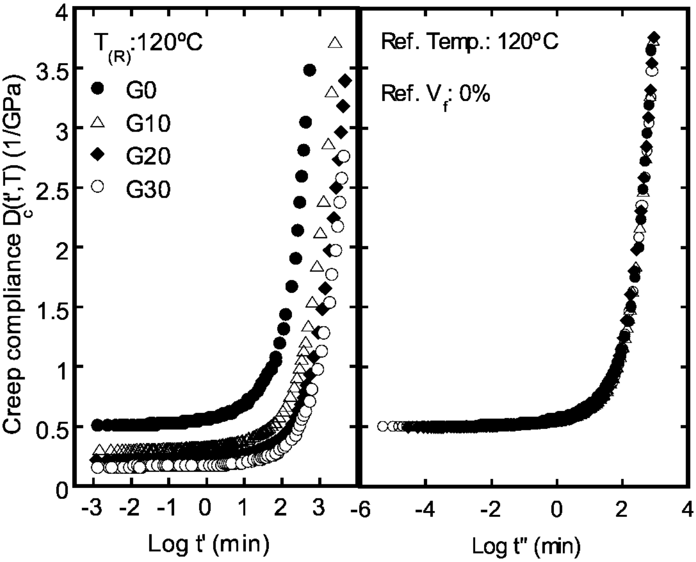


Figure 4. Master curves of creep compliance and grand master curve of GFRPC.

master curve. Here two shift factors, a modulus shift factor (vertical shifting) and a time shift factor (horizontal shifting) were introduced to draw the grand master curve. The bending modulus of these materials depended on the law of mixtures, as shown in equation (3):

$$E_C = (\alpha E_f V_f + E_m(1 - V_f)), \tag{3}$$

where α is a material constant, E_f and E_m were the modulus of fiber and resin and V_f and V_m were volume fraction of both materials, respectively. From this equation, the compliance value was calculated as follows:

$$D_C = A/E_C = A/(\alpha E_f V_f + E_m(1 - V_f)), \tag{4}$$

where A is an experimental constant for each material. The value of compliance of the modulus is expressed as $1/E$, but under real experimental conditions it does not show the reciprocal value of the modulus usually.

For this reason, the creep compliance curve might be decreased according to the increase in the fiber volume contents. When the master curve on the resin matrix was chosen as a reference material, the amount of shift in the curve along the compliance axis was as follows:

$$\beta_C = A/(\alpha E_f V_f + E_m(1 - V_f)) - A/E_m, \tag{5}$$

where β_C is a shift factor for the vertical direction. This value depended on the change of modulus as shown in equation (5). So this value is called the Modulus shift factor.

It was found from the results of master curves that the master curve moved to the right side, i.e. the creep compliance curve shifted towards the long time side with increase in the fiber volume fraction. This means reinforcement of fibers has an arresting effect on viscoelastic deformation. It is supposed that this phenomenon is the same as the change of viscosity caused by rigid material such as powder and fiber mixed in liquid. The viscosity of liquid does not change by the composite materials but the macroscopic coefficient of viscosity of a composite depends on the amount of it. For a viscoelastic solid, the resin matrix is considered as a viscous liquid. If the coefficient of viscosity increases, the creep deformation is usually arrested. From this affect, creep compliance curves obtained under some temperature conditions must be shifted to the long time direction but also master curves shift to right side with increasing fiber content. This shift factor is called the Time shift factor. Thus, the Time shift factor can be defined as

$$a_{Tt'} = \frac{t'}{t''}, \tag{6}$$

where t' is physical time and t'' the modified time.

The right side of Fig. 4 shows the grand master curve of four creep compliance master curves of G0, G10, G20 and G30 composites at 120°C. The grand master curve was drawn by shifting the creep compliance master curves horizontally and vertically to overlap each other. In this case, G0 was used as the reference.

In Fig. 5, the horizontal and vertical shift factors are denoted as time and modulus shift factor respectively. Here, modulus shift factor has been denoted as a_{TDc}. The grand master curve represents a smooth curve. The time and modulus shift factor curve also showed a consistent relation with fiber contents. Thus it became possible to estimate the creep behavior of composites with any fiber contents and at any

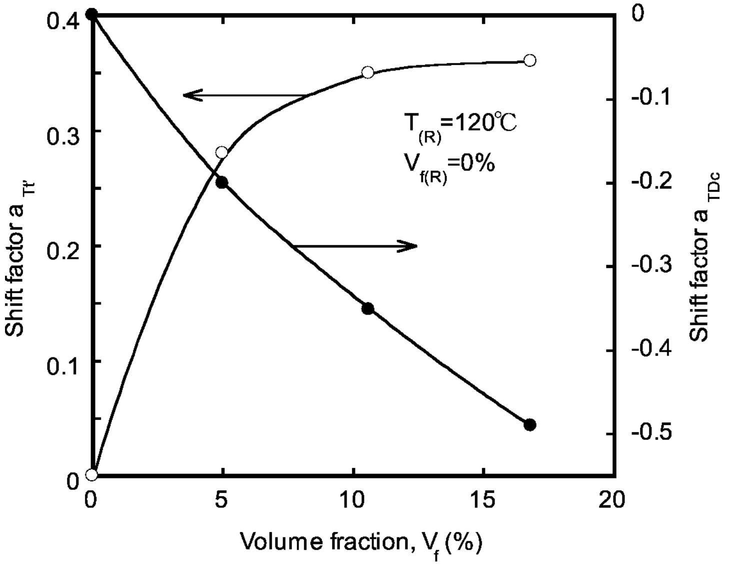


Figure 5. Time and modulus shift factors of GFRPC.

temperature using the grand master curve of creep compliance master curves and time and modulus shift factors.

4. CONCLUSIONS

Experiments on the creep behavior of GFRPC composites were performed in this study. Major conclusions obtained from this study are as follows. At any constant temperature the creep compliance increased with increase in time. Again, at a specific time, the creep compliance increased with increase in temperature. Creep phenomena of GFRPC composites comply with the Arrhenius reciprocal law of time–temperature. There were significant effects of fiber volume fraction in creep behavior. With the increase in fiber volume fraction, considerable changes of visco-elasticity occurred and the composite could withstand higher temperature and for a longer time. Thus it became possible to estimate the creep of composites with any fiber contents using the grand master curve of creep compliance master curves and horizontal and vertical shift factors. So it become possible to design materials for creep by reinforcing contents of fibers to obtain the required objectives.

Acknowledgement

This research has been supported by Grant in Aid for Scientific Research under grant no. 10650679.

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