Prediction of Creep of Polymer Concrete

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ABSTRACT: Polymer concrete possesses viscoelastic properties conditioned by relaxation processes in the polymer binder. Their acceleration with an increase of temperature (principle of time–temperature equivalence) is used in predicting the long-term creep of polymer concrete. Physical aging of the polymer binder influences the creep of polymer concrete. To predict the long-term creep accounting for the aging process, an attempt to improve the time–temperature equivalence principle was undertaken. As a result of the experimental study of polyester resin-based concrete and its structural components (a resin unfilled and filled with diabase flour), it has been established that the changes in the creep compliance of the material follow according to the principle of the time–aging time equivalence with the reduction function depending on aging temperature. To predict the long-term creep of polymer concrete, a function of the time–temperature–aging time reduction was applied. © 1999 John Wiley & Sons, Inc. J Appl Polym Sci 71: 1949–1952, 1999

Key words: polymer concrete; polyester resin; creep; physical aging; time–aging time equivalence principle

INTRODUCTION

Polymer concretes are increasingly considered as structural components for use in civil building, on account of their enhance strength-to-weight ratios. One of the most important aspects of durability and dimensional stability of these materials is their long-term viscoelastic behavior, which is conditioned by the relaxation processes in the polymer binder. Acceleration of the processes with an increase of temperature (principle of time–temperature equivalence) is widely used in predicting the long-term creep of polymers and polymer-based composites. Appropriation of the time–temperature equivalence principle in predicting the creep of polymer concrete is confirmed experimentally.[1,2]

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Over a broad range of service temperatures the binder in the polymer concrete is either in a glassy or glass transition state, with no thermodynamical equilibrium. Therefore, one would expect that the process of physical aging in the polymer binder would proceed and affect the creep of the polymer binder and concrete. So, to make a more refined prediction of the creep of the polymer concrete, the aging processes must be taken into account.

Theory

The physical aging of polymers results in retardation of the relaxation processes. Its effect on creep is expressed as follows: obtained under the same test conditions, the creep compliance curves of the material at different ages are combined into one master curve by shifting along a logarithmic time axis.[3] The value of the shift factor, $-\ln a_{ag}$, is dependent on the aging time t_{ag}, and for aging

temperatures T_{ag} close to the glass transition temperature T_g is expressed as follows

$$\ln a_{ag} = -\mu \cdot \ln t_{ag}, \quad (1)$$

where $\mu \sim 1$ for all the polymers.[4]

The results of experimental investigation of creep of epoxy binders[5] showed that prolonged exposure at temperatures higher than T_g causes effects whose outward manifestations are similar to physical aging. For each of the binders studied, the analytical dependence $a_{ag}(t_{ag},T_{ag})$ in the form

$$\ln a_{ag} = -\alpha \cdot (1 - e^{-k \cdot t_{ag}}), \quad (2)$$

where

$$k = k_0 \cdot e^{-\beta/T_{ag}} \quad (3)$$

can be described by means of the same values of coefficients, k_0, α, β over a wide range of aging temperatures (both below and above T_g).

Physical aging in the temperature region far below T_g, particularly in the region of operation temperatures (0–20°C), has not been adequately studied. The amount of experimental data is lacking to check the appropriation of eqs. (2), (3), or (1).

In most cases, physical aging takes place during the long-term creep. Taking into account the above mentioned, the principle of time–aging time equivalence may be applied to describe the creep compliance curve. In accordance with the principle of equivalence on a reduced time

$$t' = \int_0^t a_{ag}(s, T(s)) \cdot ds, \quad (4)$$

where $a_{ag}(t_{ag},T_{ag})$ is a reduction function or the time–aging time scale factor, $a_{ag}(t_{ag},T_{ag}) \leqslant 1$, the viscoelastic compliance is expressed as follows $I(t) = I(t')$. Such a method of attack was not considered in the literature.

As for physical aging of polymer composites, some authors[6] studied the frequency dependence of real and imaginary components of the complex shear modulus, as well as the stress relaxation under shear, for carbon fiber-reinforced plastic and the corresponding binder in a block. It was found that prolonged exposure at elevated temperatures causes the same changes of the properties of the composite and the binder: their reduction functions $a_{ag}(t_{ag},T_{ag})$ coincide in each of the tests carried out. For these materials, the reduction functions determined by the two above-named methods were found to coincide. The coincidence of the reduction functions of the glass fiber-reinforced plastic and the corresponding binder was obtained by an experimental study of creep by some authors,[7] where several series of tests of a unidirectionally reinforced composite by submerging it at an angle of φ =15, 45, 90° in the direction of the reinforcement were conducted. The reduction function $a_{ag}(t_{ag},T_{ag})$ was found to be the same.

No previous systematic investigation has been made on the physical aging of thermoset polymers with mineral filler, particularly, polymer concrete and its structural component—the polymer binder.

MATERIALS AND EXPERIMENTS

Polymer concrete made on the basis of polyester resin Vinalkid 550P filled with marble flour, filler volume content c_1 = 28.3 ± 0.8%; and with crushed marble aggregate, volume content c_2 = 63.2 ± 0.8% (binder volume content is about 26%) was studied. The specimens of concrete in the conditionally initial state (as received) and after preliminary exposure at temperatures T_{ag} = 40, 60, and 90°C both below and above the resin glass transition temperature, $T_g \sim$ 70°C, during time t_{ag}: 97, 182, 225, and 315 days were tested.

The polymer binder made on the basis of the same polyester resin Vinalkid 550P filled with diabase flour, filler volume content, c_1 = 27.7 ± 0.8% was also studied. The specimens of binder as received and after preliminary exposure at temperature T_{ag} = 60°C during t_{ag}: 180, 250, and 317 days were tested.

Polyester resin Vinalkid 550P filled with diabase flour, as well as unfilled resin Vinalkid 550P, were also tested in conditionally initial state (as received) and after aging in a laboratory condition (T_{ag} = 20°C) for 12 and 13 years, respectively.

All the specimens of polymer concrete, binder, and resin initially were heated to a temperature above T_{ag} (80°C in the case of T_{ag} =20, 40, and 60°C, and 100°C in the case of T_{ag} = 90°C) and then quenched from this temperature to T_{ag}. Creep tests under compression were conducted at a laboratory temperature (20°C) using the known methods.[1] Stress levels did not exceed 20% of the strength, while the limit of linear viscoelasticity of the materials was 30–35% of the strength.[1] So,

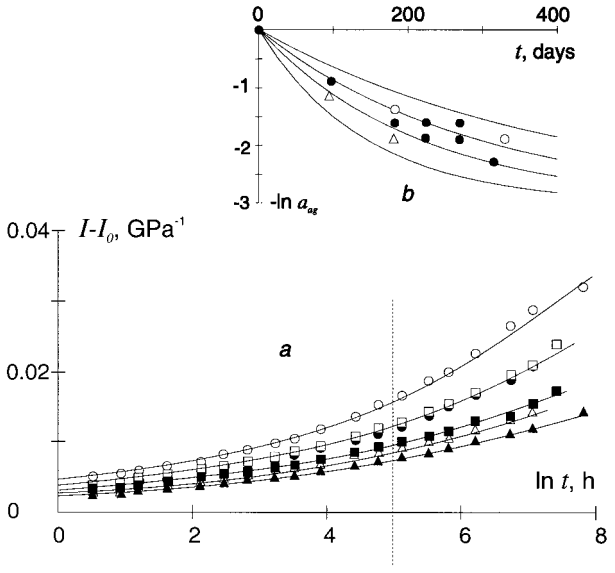

Figure 1 (a) Creep compliance curves of polymer concrete at different aging temperatures T_{ag} and times t_{ag}: T_{ag}=60°C; t_{ag}: 0 (○), 182 (□), 270 (■) days; T_{ag} = 90°C; t_{ag}: 91 (●), 182 (△), 222 (▲) days. (b) Time–aging time scale factor for different aging temperatures T_{ag}: 40 (○), 60 (●), and 90 (△)°C; points—experimental data, lines—approximation by eqs. (2) and (3).

the creep tests were conducted in a linear region of viscoelastisity.

RESULTS AND DISCUSSION

As an example, creep compliance curves of polymer concrete of different ages, corresponding to temperatures T_{ag} = 60 and 90°C, are shown in Figure 1(a). One may conclude that a change of the viscoelastic compliance of the polymer concrete after aging at elevated temperatures follows the analogy principle with its reduction function a_{ag}, depending on aging time and temperature. Evaluation of a_{ag} from long-term (t = 69 days = 1656 h) creep experiments [Fig. 1(a)] shows its variation on time t. The effect may be caused by the aging of as-received polymer concrete during the creep experiment. Therefore, to determine the time–aging time scale factor a_{ag}, the initial parts ($t < 100$ h) of the creep compliance curves were used. A time–aging time scale factor a_{ag} as a function of aging time and temperature was described by means of expressions (2) and (3). The parameters α = 3.0, k_0 = 0.0243 h^{-1}, and β = 1610 K^{-1} were determined by approximation of the experimental data [see lines in Fig. 1(b)].

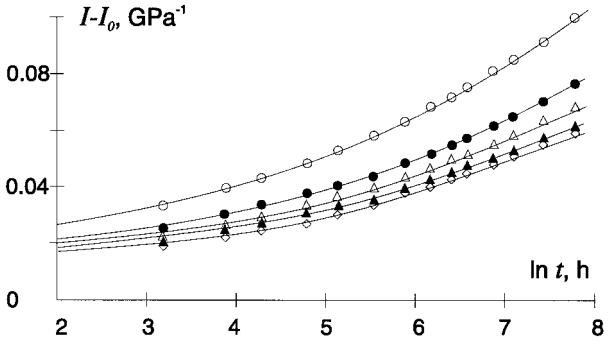

Figure 2 Creep compliance curves of polyester resin filled with diabase flour at aging temperatures T_{ag} and times t_{ag}: T_{ag}= 60°C, t_{ag} = 0 (○), 180 (●), 250 (△), 317 (▲) days; T_{ag} = 20°C, t_{ag} = 13 (◇) years.

These parameters may be used in the evaluation of the changes of compliance of the polymer concrete after aging at temperatures T_{ag} in the range from 40 to 90°C, i.e., including the glass transition region of the polymer resin ($T_g \sim 70$°C). Their applicability at lower temperatures, for example, laboratory temperature T_{ag} = 20°C, should be checked experimentally.

Creep compliance curves of the polymer binder—polyester resin filled with diabase flour—of different ages at T_{ag} = 60°C, are shown in Figure 2. The values of time– aging time scale factor a_{ag} at different aging times t_{ag} are the same as for the polymer concrete [see Fig. 1(b)]. It must be emphasized that the two above-mentioned composites—polymer concrete and polymer binder—are different both in filler types (diabase and marble) and its volume content (27.7 and 63.2%), but both

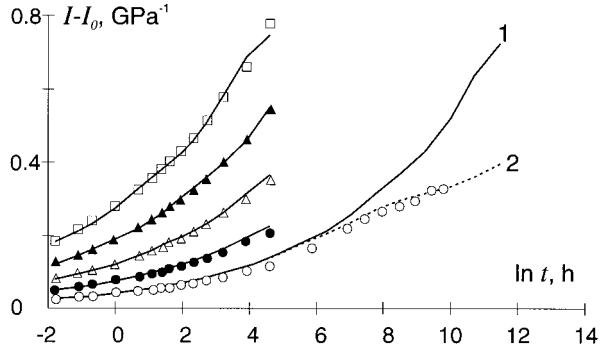

Figure 3 Short- and long-term creep compliance curves of polyester resin at temperatures T = 20 (○), 30 (●), 40 (△), 50 (▲), and 60 (□)°C; experiment (points), approximation by eq. (5) and prediction (lines 1 and 2) on the basis of time–temperature equivalence principle accounted for (2) and did not account for (1) the aging.

Table I The Retardation Spectrum of Unfilled Polyester Resin

i	Retardation Times τ_i (h)	Amplitudes b_i (GPa^{-1})
1	0.109×10^{-1}	0.281×10^{-1}
2	0.142×10^{1}	0.216×10^{-1}
3	0.174×10^{2}	0.383×10^{-1}
4	0.208×10^{3}	0.777×10^{-1}
5	0.316×10^{4}	0.163
6	0.750×10^{5}	0.430

of them are made on the basis of the same polyester resin. Thus, we may assume that the aging-related changes of compliance of the binders based on the above-mentioned resin and unfilled resin in the block are described by the reduction function $a_{ag}(t_{ag},T_{ag})$ with the same parameters, k_0 and β. For the aging under laboratory conditions (T_{ag} = 20°C) over 12–13 years, the absolute value of ln a_{ag} goes no higher than 3. This is borne out by the experimental data (see Fig. 2).

To predict long-term creep of polyester resin on the basis of short-term creep experimental curves at different temperatures T (20, 30, 40, 50, and 60°C) (Fig. 3), a time–temperature equivalence principle was used. A series of the curves at different temperatures T was approximated by the formula

$$I(t) = I_0 + \sum_{i=1}^{n} b_i \cdot (1 - \exp(-ta_T/\tau_i), \qquad (5)$$

where $I_0 = 1/E$ is the instantaneous elastic compliance, τ_i, b_i ($i = 1, \ldots n$) is the retardation spectrum, and a_T is the function of time–temperature reduction.

$$\ln a_T = 0.1 \cdot \Delta T. \qquad (6)$$

The parameters of approximation (see Table I) were used to construct the long-term creep compliance curve with eq. (5). The calculated creep compliance curve deviates from the experimental one at $t \geq 400$ h. Accounting for the effect of physical aging on the creep of polyester resin by the reduced time t' (4), the prediction was made. It coincides with experimental data.

CONCLUSIONS

Changes of viscoelastic compliance of the polymer concrete during aging are in line with the analogy principle with its reduction function being dependent on aging time and temperature.

Changes of viscoelastic compliance of the polymer concrete and its polymer binder are the same; their time–aging time scale factors coincide.

Accounting for the effect of aging by introduction of the reduced time scale, the prediction of long-term creep of the polymer binder became more precise.

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