Prediction of Creep for a Reinforced Concrete Beam Strengthened with an External Reinforcement System Using the Stepped Isothermal Method

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Abstract. The principle of analogies is known to be true for most polymers. This principle makes it possible to shorten the duration of an experiment for durability prediction by changing the intensity of various factors without affecting rheological properties of a polymer. Specifically, temperature (temperature-time superposition) or humidity (humidity-time superposition) are changed. There is an impressive amount of studies about successful application of the principle of analogies for prediction of polymer durability. However, the absence of legal framework makes it legally impossible to use this method for prediction of durability of external reinforcement systems. In the accelerated weather test laboratory of Kazan State University of Architecture and Engineering, a number of tests was performed, which were based on the principle of analogies, to predict the durability of structures strengthened with an external reinforcement system. This method was studied in regard to its suitability for reinforced concrete beams strengthened with an external reinforcement system. The method was developed to predict the durability of these structures for the entirety of their operating period by performing short-term laboratory tests.

Keywords: CFRP · Epoxy · Concrete · Creep test · Time-temperature superposition principle · Stepped isotherm method

1 Introduction

One of the important factors that affect durability of reinforced concrete structures strengthened with external reinforcement systems with epoxy binders is creep [1–3]. The existing studies discuss development of creep under constant loading and register its stabilization within 120 days. However, the development of creep may be of a different nature under conditions of varying temperature factors. Thus, this raises the question about prediction of creep for structures strengthened with an external reinforcement system under specific temperature conditions [4, 5].

The principle of time-temperature superposition is known to be true for most polymers. According to this principle, varying temperature does not affect rheological properties of a polymer. However, it makes it possible to shorten a time interval, which

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is useful when applying this principle for investigation and prediction of stress-strain behaviour of polymer materials [6–8].

The principle of time–temperature superposition is a well-established method for such materials as polyurethane [9–11], asphalt [12–15] and bitumen [16–18], rubber [19], geopolymers [20]. Also, there are studies that prove the adequacy of the time–temperature superposition for epoxy binders [21, 22].

However, it is more convenient to predict creep of large structures using the stepped isothermal method (SIM) [23] based on the principle of time–temperature superposition. The papers [24, 25] provide the results of SIM application for prediction of creep of geoplolymers. The advantage of this method is that it makes it possible to predict creep of a polymer material for up to 100 years within a short time (24 h).

This paper investigates the possibility of using the stepped isothermal method to predict creep of reinforced concrete beams strengthened with an external reinforcement system.

2 Materials and Methods

2.1 Making Samples

The test beam samples were made from B15 concrete, section of 120x140 (h) mm, total length of L = 1000 mm. In the lower area, the beams were strengthened with two bars Ø8 A400 with a length of 1000 mm.

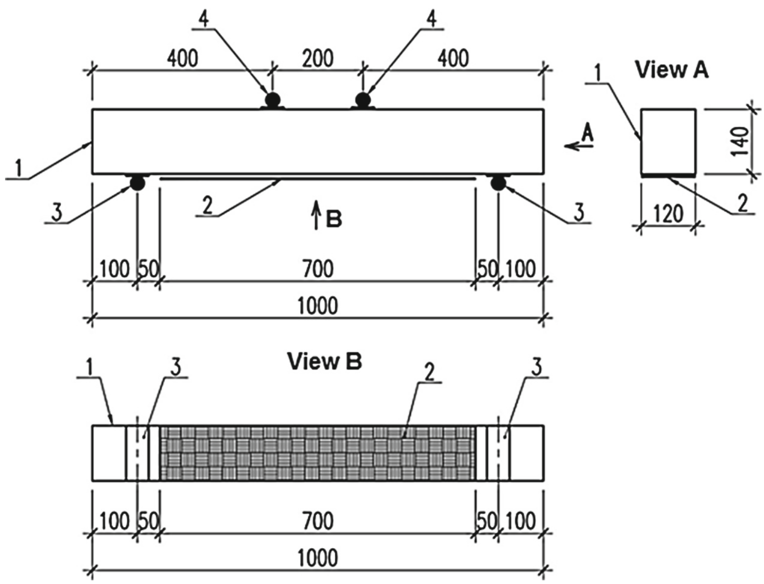

Fig. 1. Layout of beam reinforcement with carbon fiber cloths: (1) reinforced concrete beam; (2) polymer composite; (3) holding supports; (4) loading supports.

Longitudinally, the beams were strengthened with one layer of FibARM Tape-230 carbon fiber tape with a width of 120 mm, with the longitudinal cloths being 50 mm from the supports. Epoxy compound FibArm Resin 230 + was used for reinforcement. The layout of reinforcement and supports is shown in Fig. 1.

Load carrying capacity of the reinforced beams was determined by means of calculations according to the instructions specified in SP 164.1325800.2014 [26]. Breaking load of the beam is $P_{break} = 40$ kN.

2.2 Equipment and Instruments

Load frame 1 was made to apply load to beams (Fig. 2). The beams rested on cylindrical supports 3, 4 (Fig. 1) via the metal plates. Loading was performed with hydraulic jack 3 (Fig. 2) via the traverse beam with two-point distribution of forces in the beam. Figure 2 shows the loading layout for the beam in the test bench.

The load P on the traverse beam was measured with radial pressure gauge 9 (Fig. 2) on pump 6 (Fig. 2).

The deflections in the middle of the beam were measured with dial gauges ICh10–0.01 5 (Fig. 2).

Temperature exposure was simulated in thermal vacuum chamber STBV-1000-IV (ILKA, GDR) 2 (Fig. 2), directional infrared heater 4 (Fig. 2) was used to provide uniform heating of the composite. The temperature of the composite was monitored using thermocouples 7 (Fig. 2) which were installed between the surface of concrete and composite.

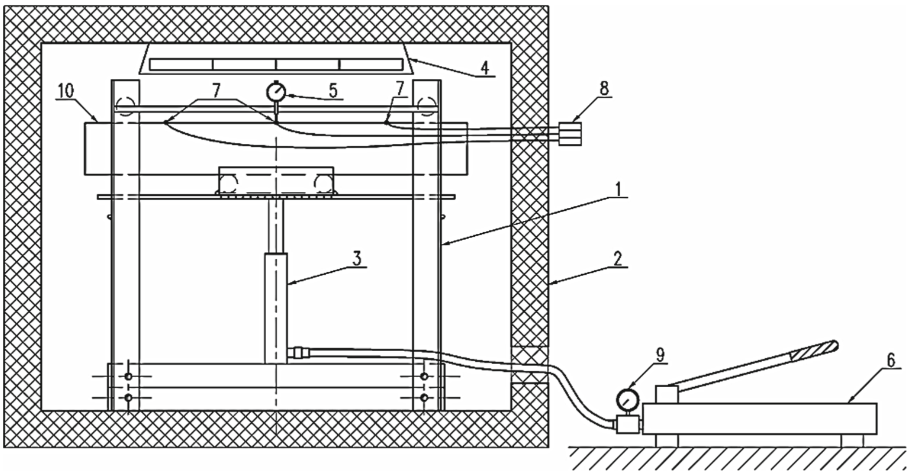

Fig. 2. Layout of the loading system: (1) load frame; (2) climate chamber; (3) hydraulic jack; (4) infrared heater; (5) dial gauge; (6) hydraulic pump; (7) thermocouple installation points; (8) bank of thermocouple indicators; (9) pressure gauge; (10) test sample.

2.3 Test Procedure

The time-temperature relationship for creep of the reinforced concrete beam strengthened with the external reinforcement system was studied under conditions of constant load at gradually changing temperature. The test load was 70% of the breaking load. The duration of one temperature cycle was 2 h. The initial temperature was 25 °C, the final temperature was 55 °C, the temperature interval was 5 °C. The total experiment duration was 14 h.

The experiment algorithm is as follows:

1. The test bench is put in the thermal vacuum chamber (Fig. 3), and the initial temperature of the experiment is set.
2. After the temperature reaches the constant level and the beam is heated the initial deflection values are recorded.
3. The sample is loaded until the test load is achieved, and the beam deflection is recorded.
4. Then every change in deflection during the temperature cycle is recorded.
5. After the time of the temperature cycle runs out the temperature is increased by 5 °C.
6. The sample is heated until the current cycle temperature is reached.
7. Up to the end of the experiment, the steps 4–6 are repeated.

The data of thermal creep at gradually changing temperature are used to plot a master curve to predict deflections of the structure for the required operating temperature over the long term.

Fig. 3. Test bench.

Master curve plotting order (Fig. 4):

1. Creep curves for different temperatures are plotted in one plot (Fig. 4a). Time (t, s) is measured on the horizontal axis, deflection (f, mm) is measured on the vertical axis at different temperatures.
2. Then the creep curve is divided into separate segments, where each of them corresponds to a certain temperature step, and is replotted on coordinates creep modulus E, kN/m – log time l_{nt}, s (Fig. 4b).

Creep modulus is calculated using the following formula:

$$E = P/f(t) \tag{1}$$

where P is the test load;
$f(t)$ is the deflection at a given time.

3. The creep modulus curves for different temperatures are shifted along the time axis to align them with each other with partial overlap (Fig. 4c).
4. The creep modulus-log time curve is replotted on coordinates «deflection-log time» (Fig. 4d).

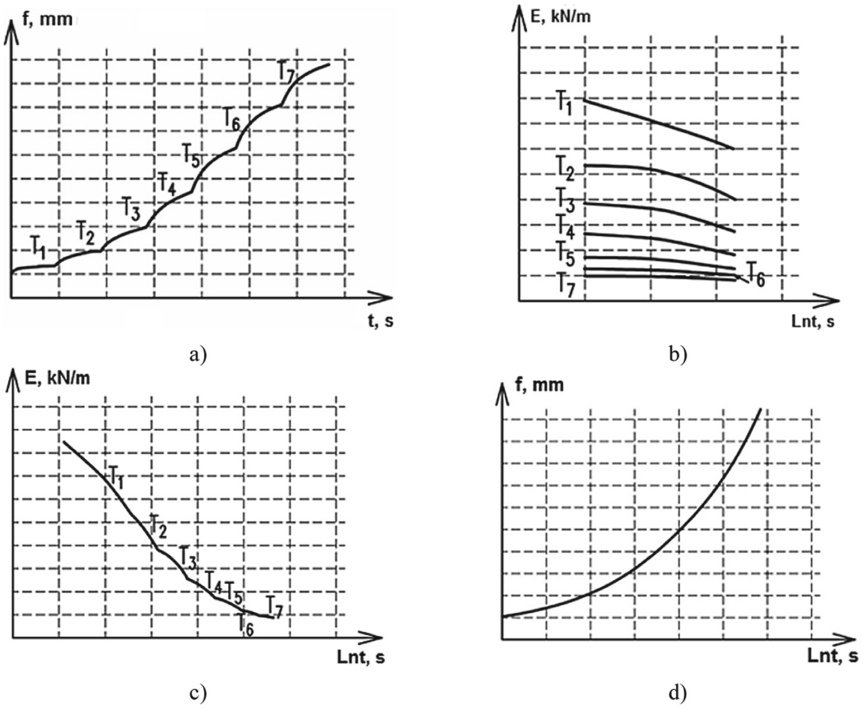

Fig. 4. Plotting of a master curve for the stepped isothermal method.

The resulting master curve is a predicted long-term creep curve for normal temperature.

3 Results and Discussions

Figure 5 shows the results of the experimental investigation of creep of the reinforced concrete beam strengthened with the external reinforcement system using the stepped isothermal method.

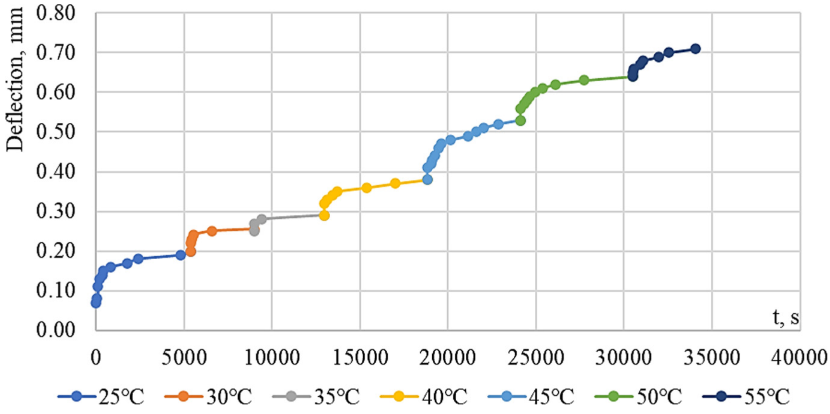

Fig. 5. Temperature dependence of deflections in time.

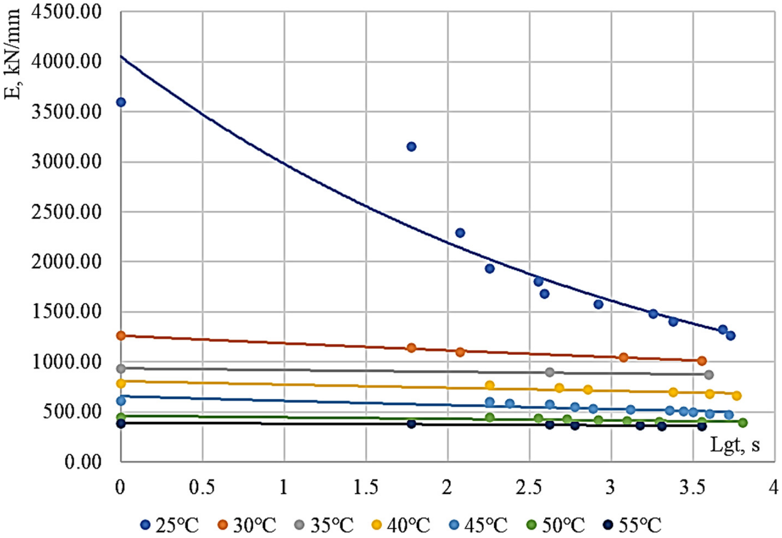

Fig. 6. Relationship between creep modulus and time.

Let us replot the resulting creep curves for each temperature cycle on coordinates «creep modulus-log time» (Fig. 6). It can be seen from the graph in Fig. 6 that the resulting curves are similar. It indicates that the test sample behaves as a thermorheologically simple system within the specified temperature ranges. Thus, the plots show that rheology of the materials is not affected within the studied temperature range.

To construct a prediction master curve for the creep modulus, we shift the curves of the creep modulus until they coincide one after another (Fig. 7). Next, we rearrange the creep modulus curves into the creep versus time curve, the resulting data were used to plot the master creep curve (Fig. 8).

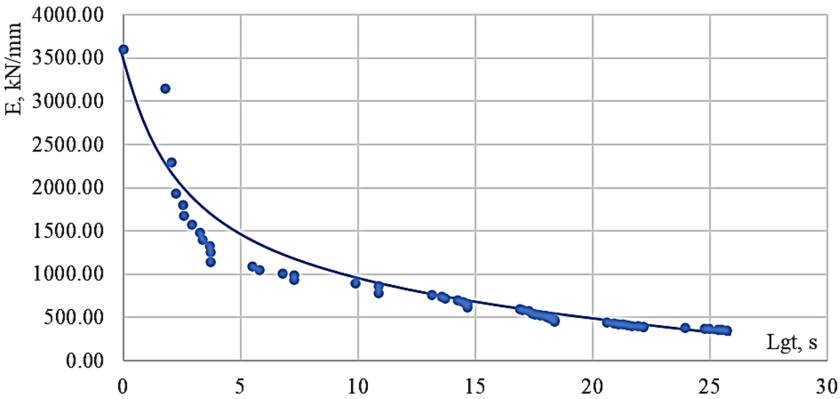

Fig. 7. Master creep modulus curve.

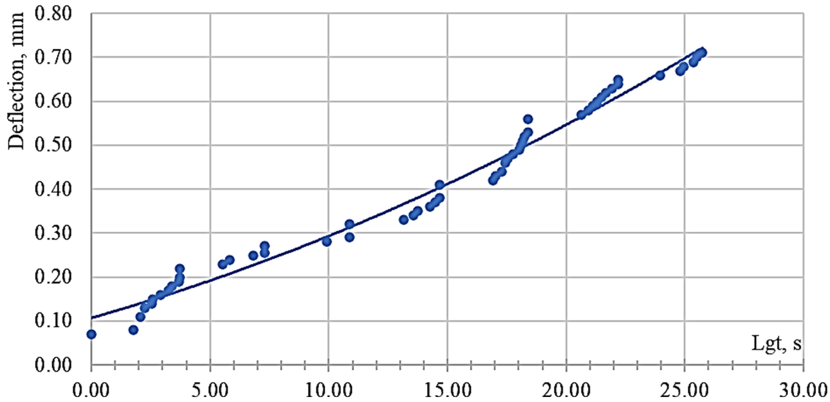

Fig. 8. Master creep curve.

4 Conclusions

The experimental analysis showed that the stepped isothermal method could be used to evaluate creep of a reinforced concrete beam strengthened with an external reinforcement system. In future, the designed method can be used for development of adhesives for external reinforcement systems. Importantly, this method takes into consideration the combined action of a system which consists of adhesive, concrete, and carbon fiber.

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