Method for predicting the durability of polymer-composite reinforcement in cement concrete

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Abstract. The combination of operational factors increases significantly ageing and failure rate of polymer composite materials under stress-strain conditions. The objective of this study is to develop the method for simulating the behavior of polymer composite reinforcements in cement concrete under stress-strain conditions. The procedure was developed and the setup was upgraded to conduct accelerated testing of polymer composite reinforcements for cement concrete. The significance of the findings for the construction industry lies in the development of methodology for predicting the durability of polymer composite materials under specified operating conditions.

Key words: polymer composite reinforcement, ageing and failure simulation, procedure and setup, accelerated testing.

1 Introduction
It has been over 50 years since polymer composite reinforcements were first introduced in the construction industry, and some experience of its use has been gathered. Its effectiveness for reinforcement of various concrete products and structures has been proven. Among the advantages of the material are low specific gravity, high mechanical parameters, chemical inertness, and low thermal conductivity. Nevertheless, this material has a limited use in the construction industry due to a number of factors. Firstly, polymer composite reinforcements made of glass and basalt fibers have low Young's modulus (usually from 40-50 to 60-70 GPa). Only carbon fibers can provide polymer composite reinforcements with Young's modulus in line with that of steel reinforcements: 200 GPa or higher. Secondly, there are almost no data about durability and service life of polymer composite reinforcements under operating conditions. Most of the experiments focus on determining mechanical characteristics and chemical inertness of polymer composite reinforcements, improving production processes, and testing concrete products [1-6]. There are papers that investigate the influence of elevated temperatures and aggressive media on the properties and durability of polymer composite reinforcements, as well as the combined influence of these factors [7-12].

However, when researchers investigate the durability of reinforcements subjected to aggressive media and elevated temperatures they do not address force factor responsible for building up of stresses in a material. Omission of this factor in durability study makes it impossible to provide a reliable estimate for service life of polymer composite reinforcements under operating conditions.

That’s why, of great current interest is to develop a service life prediction methodology, to conduct studies for assessment of the combined influence of the operational factors on properties and durability of polymer composite reinforcements. The practical relevance of these studies is to expand application of this material and to develop a durability assessment method.
As a rule, initial durability testing of product materials is conducted under laboratory conditions according to special test modes, known as accelerated testing methods that simulate operating conditions. The key condition that makes accelerated testing effective is the similarity of processes: a change in the composition, structure, properties of a test material under full-scale and laboratory conditions within the shortest test time. According to the paper [13], durability predictions for materials and products subjected to accelerated testing can have errors due to different material ageing and failure mechanisms as a result of unreasonably high acceleration factor $k_a$, which is defined as the ratio between full-scale test time $t_{fs}$ and laboratory test time $t_{acc}$.

Significant errors in durability predictions for materials and products subjected to accelerated testing also occur due to incorrect simulation of operating conditions: failure to take account of synergistic effect of influencing factors responsible for material ageing and hence failure.

The major flaw of the current accelerated test standards is a separate cyclical influence of artificial factors. It is out of necessity that operating factors are simulated in this way as no climate chambers are available in the market. It can reproduce several factors simultaneously and simulate their synergistic influence similar to full-scale conditions. Stress-strain behavior is known to increase weathering rate of polymer composite materials several-fold. However, commercially available climate chambers by various manufacturers (ATLAS, Q-Lab, WEISS Umwelttechnik GmbH, etc.) have no force-loading modules. In order to simulate operating conditions for various materials properly, it is usually required to upgrade and provide standard climate chambers with various force-loading mechanisms [14].

This paper describes the possible improvement of the current accelerated testing methods for polymer composite materials, including polymer composite reinforcements. The upgrades have been made in the test benches to simulate ageing and failure of this polymer composite type in cement concretes. The durability prediction procedure has been developed for polymer composite reinforcements under operating conditions.

2 Materials and methods

2.1 Materials

The subject of experimental studies is polymer composite reinforcement. It is a pultruded polymer composite material which is nowadays considered as an alternative to steel reinforcements for some products and structures.

In polymer composite reinforcements, inorganic (glass or basalt) or carbon fibers are used as reinforcing fibers, and epoxy or vinyl ester compounds – as a polymer binder.

2.2 Development of accelerated testing methods

According to [13], the development of accelerated testing methods include several steps:

- finding energy values of the factors responsible for ageing and failure of materials and developing an operation chart;
- transforming energy values of operational factors to enhanced, but reasonable in terms of influence mechanisms, laboratory test conditions;
- developing requirements for equipment to simulate laboratory conditions of accelerated weather testing.

The primary factors responsible for ageing and failure of polymer composite reinforcements in cement concrete are as follows:

- alkaline medium of pore fluid in cement concrete with a pH of ~13;
- temperature;
- stresses.

For the purpose of accelerated testing methods development, it is required to study the separate and combined influence of the above mentioned factors with different intensities. By increasing the intensity of temperature and stresses to the defined level, with the constant concentration of alkaline...
medium, it is possible to accelerate ageing and failure processes and, as a result, reduce significantly laboratory test time for polymer composite reinforcements. These are well-proven methods of temperature-time and stress-time analogies [15-18] which are also successfully used for predicting durability of building materials [19-22].

2.3 Requirements for the bench to simulate operating conditions of polymer composite reinforcements
When designing and developing the bench to simulate operating conditions of polymer composite reinforcements, it is necessary to consider the following requirements:
- a small bench size to change test conditions by moving the bench between chambers with different artificial factors;
- to be compact as opposed to conventional methods of creep-rupture testing with a system of weights and levers, which makes it impossible to move them during the exposure process. Also, a large size of setups makes it difficult to test several sets of samples simultaneously.
- to adjust stress-strain behavior in samples across the entire range of operating loads all the way to failure;
- to consider specific features of failure mechanics of polymer composite reinforcements.

The majority of standard test methods for polymer composite materials have been developed for plastics with homogeneous structure. They have been copied from those for metals and alloys, which are isotropic materials, and do not consider anisotropy of not directionally reinforced composite materials. Due to a big difference in strength along grain and interfiber shear strength, there are special requirements for not directionally reinforced composite materials in relation to securing of samples in grips and their alignment. If samples are clamped in metal grips of test equipment too tightly they can splinter, and if samples are clamped too loosely they can slip out of grips without any damage to material. Layer separation, destruction at an angle, shear, destruction in a non-working area or grips of a test machine are observed as a result of misalignment due to improper positioning of samples in grips.

In consideration of failure mechanics of polymer composite reinforcements and requirements for a force-loading module in climate chambers, the method of buckling was used to apply long-term static load according to GOST 2492-2015 “Fiber-reinforced polymer bar for concrete reinforcement. Determination of physical-mechanical properties”. This method has a number of advantages both for short-term and long-term tests, there is a detailed description in the studies by A.N. Blaznov et al. [23, 24]:
- load required for failure of polymer composite reinforcements is approximately lower by 60 times than load required for its failure when it is subjected to stretching or compression;
- polymer composite reinforcement behaves like a near-perfect elastic material ensuring that buckled (to the specified deflection level) sample acts as a calibrated spring that “preserves” a specified load level (lateral compression force) for a long period of time;
- in elastic materials subjected to lateral compression, lateral force does not depend substantially on deflection when it increases from the start of its manifestation to failure. That’s why the procedure of sample loading to a specified level can be reduced to its deformation to a specified deformation level;
- as opposed to pure stretching or compression, increase or decrease in stress require moving the ends of a sample within a quite large range. It reduces drastically the errors in setting the stress that can be introduced due to errors which occur during setting and monitoring of a specified deformation level;
- it is possible to take into account and compensate possible changes in stress in the course of testing, which result from a change in stiffness of a sample-spring, by calibrating a sample as a spring during testing. When the stiffness of a sample is changed by a measured value it is sufficient to increase its deflection to the level restoring it to the specified stress;
- decrease in test load and replacement of the load application procedure with deformation procedure make it possible to use compact multi-position test benches for testing;
- sample fails in the central portion, at a considerable distance from the point of load application, therefore, contact stresses, which occur in the area where load is transferred from the loading mechanism to a sample, do not have a significant impact on the sample failure process;
material is subjected to stretching (in the stretched area), compression (in the compressed area), and shearing of layers across the entire section. It makes it possible to conduct integrated assessment of material strength and find the most dangerous loading type;

- polymer composite reinforcement behaves like a near-perfect elastic material, so for test data processing (calculation of stresses and deformation), it is possible to use simple equations known from the monographies about strength of materials with added simple adjusting calculation and empirical equations.

The summary of buckling method is as follows (figure 1 a): polymer composite reinforcement is deflected laterally between two supports to ensure the specified tension stress \( \sigma \) in the extreme fibers of the sample midsection. The ends of a polymer composite reinforcement sample should pivot. Maximum stresses that occur in the given sample area are calculated as follows:

\[
\sigma = \pm \frac{P \cdot f}{w},
\]

where \( P \) is the lateral compressive force applied to the ends of a sample; \( f \) is the deflection of a buckled sample; \( w \) is the section modulus of a sample.

![Figure 1. a) Setup for testing samples of polymer composite reinforcement using buckling method; b) Setup of force-loading module for polymer composite reinforcements:](image)

(1) sample of polymer composite reinforcement with semispherical ends,
(2) semispherical hollow on the test bench bed,
(3) semispherical hollow on the base of force-loading component,
(4) force-loading component, bolt,
(5) upper housing of the test bench with welded nuts for force-loading component,
(6) test bench bed, (7) silicone tube, (8) and (9) seals.

\[
f = L \frac{1(8 + 0.2528^2 + 0.0778^2 + 0.0798^2)}{2 \cdot 0.125 - 0.0158 - 0.0068^2} \frac{1}{\pi(1 + 0.5048 + 0.2328^2 + 0.3158^2)}.
\]

where \( \delta \) = \( (L - L_{sup})/L \) is the relative approach of rod ends;

\( L \) is the length of a sample;

\( L_{sup} \) is the distance between the supports of a buckled sample.

Section modulus of a sample \( w \) is calculated as follows:

\[
w = \frac{\pi \cdot d^2}{32},
\]

where \( d \) is the diameter of a sample.

The above equations are suitable for samples with a circular cross section, which are made from materials that exhibit a linear elastic range of stress-strain behavior. The test bench is equipped with
sensors for measuring load and deflection parameters \((P\) and \(f\) in Eq. (1) respectively) to monitor relaxation processes and first signs of failure in a stressed sample. The recommended length of a sample is equal to \(36d.\) Therefore, samples for testing stress-strain behavior with buckling method should be twice or thrice smaller than those for stretching test.

Figure 1 (b) shows the overview of a setup to conduct long-term static tests using buckling method. The sample of polymer composite reinforcement with semispherical ends is positioned in semispherical hollows on the test bench bed made from C-channel. A hollow should have such a radius that ensures no contact between a sample and the test bench bed in the utmost bent state as it causes a change in stress-strain behavior. The force-loading module is a screw with the semispherical hollow in its base. Prior to that, the screw is calibrated and the scale “number of revolutions – movement” is made. It simplifies the sample loading process significantly. It is necessary to provide the specified level of sample deformation in order to set the required level of stress using the buckling method. This level is reached by bringing its ends together, i.e. by moving the force-loading module.

Alkaline medium of concrete is simulated using alkali solution with the composition according to GOST 31938-2012 “Fibre-reinforced polymer bar for concrete reinforcement. General specifications”. Flexible silicone tubes with a diameter of \(5d\) were used to ensure that a container with alkali did not affect the deformation state of samples, and also made it possible to accommodate as many samples as possible in one test bench. The center working portion of the sample was subjected to alkali, the tube length was equal to \(0.5L.\)

Seals for securing the tube on the sample were made from alkali resistant rubber. The seal dimensions corresponded to the inside diameter of the silicone tube, the seal was additionally secured with steel clamps. Prior to long-term testing of polymer composite reinforcements, alkali resistance of seals and silicone tubes was assessed at elevated temperatures: they were held at \(80^\circ C\) for 30 days. No changes in the composition and no influence on pH of the solution under these conditions were observed. Hence these attachments would not introduce errors into test results of polymer composite reinforcements. The advantage of elastic materials for alkali solutions makes it possible to monitor pH of the solution with no sample exposure throughout the entire test time. For this operation, a syringe can be used, but, prior to sampling, it is necessary to ensure air inflow for unhindered fluid intake, for example, by positioning the syringe needle or narrow glass tube into the seal.

2.4 Bench for accelerated testing of polymer composite reinforcements

A series of test benches was manufactured according to the above mentioned algorithm. Each test bench can accommodate up to 10 samples. The configuration of the test bench makes it possible to apply load to each sample individually so that in one test bench, different samples can be tested, various deformation levels can be set, various compositions of aggressive media can be used, etc. Due to its compactness (figure 2 a) and portability, the modular test bench can be put inside climate chambers with various artificial factors (figure 2 b), it can be moved without affecting stress-strain behavior of samples during cyclic tests (figure 2 c-d) and for microscopic tests, etc.
2.5 Experimental program

For the purpose of this paper, the tests were conducted at various levels of long-term static loading and without it. Load was applied using the buckling method. Temperature was also used as a factor that normally accelerated ageing of a material. Two types of tests were conducted.

Type 1: the samples were held in the alkali solution (composition according to GOST 31938-2012) at various temperatures 20°C, 40°C, 50°C, 60°C, no stress-strain conditions.

Type 2: the samples were held in the alkali solution (composition according to GOST 31938-2012) at a temperature of 50°C. The tests were performed under stress-strain conditions with three deformation levels equivalent to 0.2, 0.4, 0.6 of the buckling strength of polymer composite reinforcements (hereinafter referred as to R).

3 Results and discussion

3.1 Patterns of change in strength of polymer composite reinforcements

The strength relationships for different exposure stages of the non-stressed (figure 3) and stressed (figure 4) samples were obtained.

Figure 2. Modular test benches for different types of tests:
(a) compact arrangement of test benches,
(b) portability of test benches: placing active test benches in the thermal vacuum chamber,
(c), (d) cyclic testing in the alkali solutions at the normal temperature.

Figure 3. Experiment results for type 1 (conditions: different temperature levels and alkali solution) with linear approximation.
Figure 4. Experiment results for type 2 (conditions: different load levels, temperature of 50°C, and alkali solution) with linear approximation.

Figure 5. (a) definition of $K_T$ function; (b) definition of $K_{I_{mg}}$ function (the points indicate the coefficient values obtained by approximation of strength experiment data).
As seen, for all the tests, the pattern of change in strength with high correlation level is described by linear functions. Therefore, in the period equal to accelerated test time, residual strength can be defined by the following type of function:

$$\sigma_{res} = R - K_{lng} K_T \tau,$$

(4)

where $R$ is the initial strength of a material, MPa; $K_{lng} = f(m_{lng})$ is some function of long-term load level $m_{lng}$, which defines the influence of specified stress-strain behavior on a change in initial strength of a material; $m_{lng}$ is the long-term load level in fractions of initial strength; $K_T = g(T)$ is some function of exposure temperature $T$, which defines the influence of temperature on a change in initial strength of a material; $T$ is the sample exposure temperature, °C; $\tau$ is the sample exposure time.

Therefore, the problem of defining the pattern of change in residual strength reduces to the definition of $K_{lng}$ and $K_T$ functions. Let us accept that with a long-term load level of $m_{lng}=0$, the function is $K_{lng}=1$.

Then, in order to define $K_T$ function, let us consider its values obtained by type 1 test:

$$K_T(T=20^\circ C) = 1.4802; \quad K_T(T=50^\circ C) = 15.132;$$
$$K_T(T=40^\circ C) = 6.5234; \quad K_T(T=60^\circ C) = 22.226.$$

By approximating the experiment values of $K_T$, let us define general function for the test material (figure 5 a) in the range of test temperatures. The range of definition can be extended without additional studies provided that there are suitable justifications.

The coefficient is $K_T=15.132$ for the test of type 1, which has been conducted at a temperature of $T=50^\circ C$. Then, using the values ($K_{lng} K_T$) obtained by approximation of type 2 test data, we find for various levels:

$$K_{lng}(m_{lng}=0) = 1; \quad K_{lng}(m_{lng}=0.4) = 10.02.$$

Empiric values of the coefficient of $K_{lng}(m_{lng})$ are approximated using the same approach as that applied for definition of the function for coefficient of $K_T$ (Fig. 5, b).

Therefore, Eq. (4) can be used to predict residual strength of samples of polymer composite reinforcements, which are tested in alkaline medium at temperatures of from 20°C to 60°C with loads of from 0 to 0.6R, where:

$$K_T = 0.0008 \cdot T^{2.4831}; \quad K_{lng} = 0.9517 \cdot \text{e}^{3.835 \cdot m_{lng}}.$$

It should be noted that for a relatively small range, coefficients of $K_T$ and $K_{lng}$ can be considered as one-variable functions: temperature or long-term load level respectively. However, it should be determined individually if the given approach can be used for the time range where the pattern of change in residual strength for different types or test conditions follows different rules and differs from the linear one.

3.2 Assessment of error of long-term strength values

The pattern of change in residual strength for all conditions in two test sequences, which is predicted using the specified algorithm, in the range equal to the test time, provides the results with an error of not more than 10%. It is comparable with experimental scatter. Figures 6-7 show the comparison between the curves of prediction and experiment for tests of type 1 and 2 respectively.
3.3 Possibilities of application of the proposed durability assessment method

If a sample fails during the exposure, the existing stress in the sample is equal to its residual strength. Hence, the sample that is exposed to $m_{\text{Ing}}$ of $R$ at the time of failure will have $\sigma_{\text{res}} = m_{\text{Ing}} R$. In view of this, let us define the durability of a sample under specified conditions from Eq. (4):

$$\tau^* = \frac{R \cdot (1 - m_{\text{Ing}})}{K_{\text{Ing}} \cdot K_T}.$$  (5)

Using this relationship, it is possible to find time to failure for different long-term stress levels and temperatures, which are not included in the experimental program (figure 8).
These data are easy to use to plan experiments for laboratory testing of polymer composite reinforcements, i.e. to predefine the expected durability. Therefore, it makes it possible for a researcher to plan the duration of experiment and period required for monitoring the kinetics of change in ageing values.

The data, which are obtained using Eq. (5) and are in the time range equal to the time of type 1 and 2 tests, can also be used to predict by the methods of temperature-time and stress-time analogies.

4 Conclusion
1. The paper shows the significant flaws of the current accelerated test standards for various materials and products. They are caused by separate cyclic influence of artificial factors due to the commercial unavailability of climate chambers that reproduce climatic factors and stresses.
2. The requirements for accelerated test methods and equipment were specified on the basis of the operating conditions of polymer composite reinforcements in cement concrete.
3. The buckling method was used to simulate stress-strain behavior of polymer composite reinforcement samples. It simplifies the force-loading module, as well as increases the accuracy in reproduction of this operational factor for laboratory test modes.
4. The procedure and modular test bench were developed to simulate ageing and failure of polymer composite reinforcements in cement concrete. The test bench makes it possible to change test conditions by increasing a number of functional blocks and moving to climate chambers with various artificial factors. The test bench can be used to test polymer composite reinforcements subjected to stresses, liquid aggressive media, and a wide range of temperatures. Tests can be conducted under a separate or combined influence of the factors.
5. The specified accelerated test approach and experimental data processing method can be used to assess the influence of stress-strain behavior on the strength properties of polymer composite reinforcements when exposed to liquid aggressive media. The advantage of this approach is that it reduces the quantity of test types, which results in a smaller quantity of samples, shorter duration and less equipment to obtain necessary data about a material. The following data processing makes it possible to plan new tests and make predictions using the analog method, i.e. it can define the level of allowable long-term load for the specified service life of a structure.
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