Cyclic testing of polypropylene fibre reinforced concrete

I G Korneeva

Irkutsk National Research Technical University, Department of Building Production, 83, Lermontov Street, 6640074, Russia
E-mail: inna.k@ex.istu.edu

Annotation. The article studies fatigue limits of polypropylene fibre reinforced concrete under conditions of low-cycle loading of variable intensity. It presents the experimental data based on testing mode under load conditions with constant strain rate. When put to the cyclic test, polypropylene fibre reinforced concrete tends to experience changes in its structural properties. Accordingly, the study has a quantitative assessment of changes in the resistance potential for axial compression of both test concrete samples and prismatic samples subjected to cyclic loads.

Volumetric reinforcement of cement-containing matrices (solutions, concretes) forms [1-5] an internal structure of constructions. The structure is likely to experience external cyclic effects. Similar systems have an increased resistance to fatigue effects due to the ability to redistribute internal stresses between the components of the composite, if distribution is uniform and deformation is compatible.

One of the factors causing fatigue transformations of bearing structural elements in buildings is a cyclic change in their stress-strain state resulted from fluctuating external effects. Structures demonstrate responses to these effects, that are various by nature, and they express this through stress (strain) variation that probably has cumulative consequences. In cement-containing composites, this may result in breaks of internal structure with qualitative and quantitative changes in resistance.

The service life of fibre-containing composites results from targeted design of their structure, including physical and mechanical properties of reinforcing fragments, their size, pore space of matrix, and other factors [1-5].

The previous study has shown that the use of polypropylene fibres with a length of 40 mm allows obtaining optimal structural modification at their volume content of 1.8-2%. The current research is an experimental testing of fatigue endurance of polypropylene fibre reinforced concrete under conditions of low-cycle loading of variable intensity.

Experimental study

For the experimental part of the study, we used prismatic samples (100×100×400 mm) made of fine-grained concrete (cement:fine aggregate:coarse aggregate:water = 1:42:31:0.55), reinforced with polypropylene fibres with an equivalent diameter of 0.8 mm, a length of 40 mm and a volume fraction of 1.5%. Table1 shows the essential parameters of primary components.

Table 1. Initial indicators of polypropylene properties and fibre concrete.

| Material       | Strength, MPa | Modulus, MPa | Maximum deformation | Limits $R_{ey}$ | Density, kg / m³ |
|----------------|---------------|--------------|---------------------|-----------------|-----------------|
| polypropylene  | 145.54        | 2767         | 265 · 10⁵           | 0.32            | 900             |
| fiber concrete | 35.79         | 22607        |                     | 0.74            | 2298            |

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After a three-month hardening period under the standard storage regulations, fatigue tests began, which eliminates the time factor when analyzing the kinetics of changes in the properties of fibre concrete.

We calibrated the major part of samples (Pulsar 1.2) according to the ultrasound speed, which averaged (4175 m/s) with a variation coefficient of 4%. At the same time, the variability of the prism mass was 2.02%. We divided the samples into two groups: a) test samples, b) samples subjected to cyclic compression with a set voltage drop.

The experimentally approved level of maximum stresses is in accordance with the research objectives – the possibility of fatigue degradation of structure based on a limited number of impact cycles. They are the stresses in the range of the upper and lower limits of microcrack formation $R_{cr}$ (according to O. Ya. Berg [1]) and components of 0.6$R_b$. The minimum cyclic loading was 0.2 MPa in the mode of constant deformation rate of 0.04 mm/s, the duration of the load-unload cycle was 1.5 minutes.

In the process of cyclic actions, we collected the following data: diagrams of deformation $\sigma$-$\varepsilon$, modulus of elasticity, energy expended during the cycle, as well as deformations of samples in two directions. Automatically recorded data are with an accuracy of $10^{-5}$. Control measurements of parameters took place after the 1st and every 10 subsequent cycles of effects with a total duration of 200.

Figure 1 shows the trends of changes in the structural properties of fiber concrete under cyclic effects. At the same time, the indicators recorded after ten cycles are taken as initial indicators. In our opinion, this approach reduces the influence of random factors caused by experimental inaccuracies and the inevitable structural adaptability of the material to external influences. This makes it possible to link observed property changes to controlled cyclic loads on a more reasonable basis.

The analysis of experiment results proved high sensitivity of all parameters to the considered effects. However, they differ in their direction and dynamics. The modulus of elasticity and the magnitude of longitudinal deformations at maximum stresses appear relatively stable with a moderate initial increase (up to 30-40%). There was inaccuracy of kinetic change in the values of transverse deformations. The behavior of particular samples reveals a tendency to stabilize the transverse deformation after 40-50 loading cycles, which indirectly indicates the completion of fatigue transformation with a predominant positive effect.

The changes in longitudinal and transverse deformations affect the kinetics of the Poisson's ratio estimated by their correlation (figure 1D). With a significant variation of experimental data (more than 40%), there is a tendency for its decrease with stabilization by 0.12÷0.14, which is significantly lower than generally accepted values [1-5]. It should be noted that the value of transverse deformations coefficient (figure 1E), estimated by the ratio of increments at individual stages, significantly exceeds the value of 0.5. That is, in accordance with generally accepted ideas [6-9], cyclic loading leads to the accumulation of internal micro-destructions. The fact that the proportion of plastic deformations in total longitudinal deformations at the maximum cyclic loading is constantly increasing confirms this assumption. Although growth dynamics is ambiguous (figure F), there is a clear trend of its increase.

The above experimental data indicate fatigue transformation of polymer fibre concrete under the influence of cyclic effects of the accepted range. The results of ultrasound examination of samples prove this. At the end of the cycle loads, the ultrasound speed was reduced by 11.8%. To quantify changes in the resistance potential, we performed comparative experiments for axial compression of test samples and cyclically loaded prismatic samples. We performed mechanical tests by means of Instron 5989 used in automatic mode with a constant deformation rate of 0.004 mm/s. A sensor of this automatic complex performed force control with an accuracy of 1 kN, and extensometers controlled deformation. Table 2 shows the average values of the monitored parameter. Cyclical effects of the accepted level and their duration did not have any impact on the strength of fine-grained fibre concrete, including the statistical parameters of its distribution. Their variability is less than 4%, which is significantly lower than normalized value.
The elasticity modulus increases significantly (19.7%) at a high distribution density (about 9%). With comparative strength stability, this indicates an increased sensitivity of deformation properties to fatigue processes. As mentioned earlier, the equipment provided testing with no prior centering accompanied by automatic recording of deformations up to the moment of physical destruction. In this case, differential analysis of the deformation structure on the ascending and descending branches becomes possible. There are initial ($\varepsilon_0$) deformations of "tooth" type [1, 4] with a concavity towards the stress ordinate. Their physical nature is problematic [1, 5] caused mostly by structural defects. It is obvious that they experience residual deformations under cyclic effects, which leads to a nearly two-fold reduction in axial compression tests. Compression of internal structural imperfections helps to reduce the limit of proportionality and longitudinal deformations corresponding to the maximum load. The identity of their changes indirectly indicates the common nature of fatigue processes that cause them.

As for the descending branch of the chart, taking into account the regulatory restrictions on the use of this resistance potential [10-17], the comparative analysis refers to a section corresponding to a 20% stress reduction ($\sigma = 0.8 \sigma_{\text{max}}$). The experimental samples have a longer section length compared to the test samples, which indicates their increased ability to redistribute internal forces.

The transverse deformations of samples subjected to cyclic effects changed significantly. If we take into account that these deformations are associated with the processes of micro-destructions, then their reduction after cycles is due to greater structural adaptability to force influences.

1. Polypropylene fibre reinforced concrete (PFRC) has a high fatigue resistance to a few cycles of moderate intensity forces.

2. Multiple directions and non-monotonicity of changes in significant indicators of PFRC design properties determine the need for a differentiated approach to the analysis and evaluation of fatigue effects from cyclical external influences.

3. Fatigue transformation of PFRC accompanies a decrease in the potential of its ability to internally redistribute efforts.

Table 2. Comparative evaluation of changes in strength and deformation properties.

| Controlled parameter                                    | Index            | Dimension | Experimental | Test    | Change   |
|----------------------------------------------------------|------------------|-----------|--------------|---------|----------|
| Prismatic strength                                       | $R_b$            | MPa       | 34.57        | 35.79   | 0.966    |
| Elasticity modulus                                       | $E_b$            | MPa       | 27072        | 22607   | 1.197    |
| Longitudinal deformation at maximum load                  | $\varepsilon_b,\text{max} \cdot 10^5$ | %         | 215          | 265     | 0.811    |
| Longitudinal deformation at fracture ($0.8 \sigma_{\text{max}}$) | $\varepsilon_b,\text{ult} \cdot 10^5$ | %         | 281          | 318     | 0.884    |
| Proportionality limit on the ascending branch             | $\varepsilon_b,\varepsilon \cdot 10^5$ | %         | 129          | 159     | 0.811    |
| Initial deformations (compressions)                       | $\varepsilon_0 \cdot 10^5$ | %         | 23           | 42      | 0.548    |
| Length of the downward branch of deformations             | $(\varepsilon_b,\text{ult} - \varepsilon_b,\text{max}) \cdot 10^5$ | %         | 66           | 53      | 1.245    |
| Transverse deformation at maximum load                    | $\varepsilon_b,\text{max} \cdot 10^5$ | %         | 88           | 153     | 0.575    |
| Transverse deformations at failure                        | $\varepsilon_b,\text{ult} \cdot 10^5$ | %         | 376          | 474     | 0.793    |
Figure 1. Kinetics of structural properties under cyclic loads.
References

[1] Berg O Ya Physical bases of strength of concrete and reinforced concrete M 1962 p 96
[2] Bazhenov Yu M Concrete under dynamic loading M. stroizdat 1970 p 273
[3] Rabinovich F N Composites based on dispersed reinforced concrete. Questions of theory and design, technology, construction M. DIA 2004 p 563
[4] Karpenko N I General models of reinforced concrete mechanics M stroizdat 1996 p 416
[5] Gvozdev A A (Ed.) 1978 New in the design of concrete and reinforced concrete structures (Moscow) p 202
[6] Morris A D and Garrett G G A comparative study of the static and fatigue behaviour of plain and steel fibre reinforced mortar in compression and direct tension. Int J Cem Compos Lightweight Conc 1981 3(2) pp 73–91
[7] Wang H L and Song Y P Fatigue capacity of plain concrete under fatigue loading with constant confined stress Mater Struct 2011 44 pp 253–62
[8] Cachim P B, Figueiras J A and Pereira P A A Fatigue behavior of fiber-reinforced concrete in compression Cem Conc Comp 2002 24(9) pp 211–7
[9] Castillo E, Fernandez-Cantelli A and Ruiz-Ripoll M L A general model for fatigue damage due to any stress history. Int J Fatigue 2008 30 pp 150–64
[10] Paskova T and Meyer C Low-cycle fatigue of plain and fiberreinforced concrete. ACI Mater J 1997 94(4) pp 273–85
[11] Grzybowski M and Meyer C Damage accumulation in concrete with and without fiber reinforcement. ACI Mater J 1993 90(6) pp 594–604
[12] Zhang J, Stang H and Li V C Experimental study on crack bridging in FRC under uniaxial fatigue tension. J Mater Civil Eng 2000 12 pp 66–73
[13] Yin W and Hsu T C C Fatigue behavior of steel fiber reinforced concrete in uniaxial and biaxial compression. ACI Mater J 1995 92(1) pp 71–81
[14] Gao L and Hsu T C C Fatigue of concrete under uniaxial compression cyclic loading ACI Mater J 1998 95(5) pp 575–81
[15] Lee M K and Barr B I G An overview of the fatigue behaviour of plain and fibre reinforced concrete Cem Concr Comp 2004 26 pp 299–305
[16] Ghosni N, Samali B and Vessalas K Evaluation of structural behaviour of polypropylene fibre reinforced concrete beam under cyclic loading 23rd Australasian Conf. on the Mechanics of Structures and Materials (ACMSM23) 9-12 December 2014 (Byron Bay:Australia) ed. S T Smith
[17] Kormeeva I G 2019 Extensibility of fibre reinforced concrete IOP Conf. series: materials science and engineering (2019) 667 012044