Changes properties of concrete with cyclic low-temperature impacts

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Abstract. The analysis of concrete fracture in the process of exhaustion of its frost resistance. Statistical regularities and kinetics of ultimate strength upper limit of microdestruction and deformative values are established. A steady decline in the fracture toughness was found during cyclical freezing and thawing (FTC). Fatigue transformation of concrete long-term operation in severe climatic conditions is characterized with an increase in the danger of brittle fracture.

1. Introduction
Long-term operation of reinforced concrete structures is objectively associated with a certain probability of stress-strain state fluctuations due to changes in the magnitude and conditions of application of loads, background manifestation of seismic activity, alternating temperature differences and other factors [1-5].

The most important factors in the interaction of construction with the environment [1-5] is the change in damping properties of concrete caused by cyclic degradation and hysteretic energy dissipation. Fatigue fractures occur at fluctuating impact levels significantly lower than the calculated values.

In a comparative cyclical manifestation, such impacts can be classified as few-repeated and the structural-mechanical changes by them as low-cycle fatigue. Their distinctive feature is the ambiguous, cumulative nature of the consequences, as well as the interdependence of the impact magnitude (number of cycles) and the functional response of object.

2. Research methodology
The fracture toughness was estimated by the ratio of energy absorbed during compression of concrete samples at the stages of conditionally elastic ($W_e$) and plastic ($W_p$) deformation. In this case, the level of stresses corresponding to the upper boundary $R_{UFC}$ and plastic, taken until stress $\sigma_b = 0.8\sigma_{ult}$ on the descending branch of the $\sigma-\varepsilon$ diagram, crack formation is assumed to be the limit of conditionally elastic resistance. The equipment used in the study (Instron 5989) allowed for automatic loading with a constant deformation rate (0.05 mm/s) and simultaneous recording of $\sigma-\varepsilon$ and energy of absorption up to the moment of complete destruction of test samples. The influence of severe climatic conditions was simulated by daily cycles of freezing ($-40 \pm 2 ^\circ C$) and thawing in water at a temperature of $20 \pm 2 ^\circ C$. The frequency of mechanical tests was taken in accordance with the previously established [10, 11] kinetics at FTC of significant structural properties of concrete. Its specificity is governed by the ambiguity of consequences of frosty transformation of concrete and is due to the simultaneous development of opposite phenomena determining the extreme nature of changes in strength and deformability. This determines the feasibility of intermediate (in the range of normalized frost resistance
F) valuations at the stages of ascending and descending vectors reflecting the dynamics of changes in the controlled parameters.

Experimental studies were carried out on prismatic samples (100×100×400) made of concrete composition (Cement:Sand:Gravel:Water=1:1.75:2.9:0.45) under normal conditions of monthly hardening and long-term (more than 2 months) storage until temperature and humidity tests. Standard tests of cubic samples established frost resistance of concrete, which is 35 cycles of the adopted level of cooling. Selection of samples is performed using calibration rejection by their density, estimated by the speed of ultrasound. The total number of samples tested in the main mode was 84 prisms. The minimum number of samples at the stage of T-W impact was 12, thereby allowing to perform their statistically acceptable generalization. The agreement of the theoretical and experimental distribution of the indicators of the controlled parameters was evaluated according to the Pearson criterion [12] as ensuring the minimum error in accepting the hypothesis and evaluating the required quantile of concrete properties.

3. Results and their discussion
Basic statistical distributions of significant parameters of strength and deformability at various levels of exhaustion of the standard resource of frost resistance (n = N/F) are shown in Table 1.

Presented values correspond to:

- $R_{vrc}$ - stress level of a sharp (more than 2-fold) increase in lateral deformations at the ascending stage of loading;
- $\varepsilon_{p,ult}$ - deformation (‰) at the peak of loading;
- $\varepsilon_{p,max}$ - deformation (‰) at the time of 15% load reduction at the stage of pseudoplastic deformation;

Significant differences in the dynamics of changes in all controlled parameters are evident in both comparison of the average values and the distribution density of their random realizations. Kinetics of strength and the upper boundary of crack formation with increasing negative distribution asymmetry is characterized by comparative statistical homogeneity. The latter indicates increased variability of fatigue strength and, as a consequence, a more significant decrease of the normalized 5% quantile.

Monotonous acceleration with a tendency toward stabilization is observed in the indicators of ultimate compressibility. The asymmetry of distribution and spread of realization are characterized by moderate growth at stages of T-W impacts corresponding to the frost resistance of concrete.

The most significant and statistically significant are the changes in deformation of concrete at the descending stages of loading. A moderate (up to 18%) increase $\varepsilon_{p,max}$ occurs until the exhaustion (50-60%) of normalized frost resistance resource. Subsequently, a significant decrease in the potential of pseudoplastic deformation is observed with a change in the asymmetry of the distribution and shift of the corresponding quantiles.

Fatigue changes in concrete resistance are clearly supported by diagrams $\sigma - \varepsilon$ reconstructed based on average values of experimental data at different stages of T-W impacts (Figure 1). There is a steady tendency in increasing the slope of the curves to the axis of deformations, which is an indirect confirmation of the decrease in the modulus of elasticity. Apparent is the increase in deformations on the descending branches with a simultaneous more intense drop in the load.

The observed differences in directivity, kinetics, and distribution of concrete properties indicators confirm the ambiguity of the fatigue effects of cyclic low-temperature and humidity impacts. From that follows the need for a differentiated approach to the selection of criteria of durability for specific design situations. At the same time, the feasibility of a generalized (integral) assessment of structural modification is confirmed. Fracture toughness, as such an indicator, is considered below. It is characterized by the ratio of the energy aspects of concrete resistance to compression at stages of FTC.

Full energy consumption ($W$), absorbed during testing of samples were determined in an automatic mode as the square of diagrams $\sigma - \varepsilon$. Fractional components of energy at the stages of conditionally elastic ($W_v$) and plastic ($W_{pl}$) deformation are determined from the corresponding sections of the reconstructed diagrams (Figure 1). Where in, functioning of $W_v$ corresponded to the area of the diagram limited by the level $R_{v,crc}$ and $\varepsilon_{p,ult}^v$; and $W_{pl} = W - W_v$. The assessment of fracture toughness ($W_{fr}/W$)
obtained in this approach seems to the most optimistic, as objective inaccuracies in the model analysis lead to an overestimation of the plastic resistance potential.

Figure 1. Compression diagram model reconstructed from experimental data (numbers on the curves are numbers FTC).

Figure 2 shows the curves characterizing the change in energy parameters during T-W impacts. A steady tendency towards an increase in the energy dissipated during compression is observed at the initial stages of FTC. Moreover, it is mainly due to the predominant increase (up to 66%) of the elastic resistance potential. Functioning of plastic deformation increases more moderately and does not exceed 14-18%. The maximum energy increase is timed to the moment of exhaustion of 50-60% of the standardized resource (grade) of concrete frost resistance. After the cycles corresponding to “F”, functioning of elastic resistance exceeds the initial value, while plastic deformation is less than the initial by more than 10-12%. Based on the tests (N/F=1.29), the components of the energy of fracture are almost identical (Figure 3).

Figure 2. Change in energy of fracture during T-W impacts.

Such kinetics of energy parameters is a reflection (consequence) of the structural modification of concrete at FTC, leading to a change in the physical laws of its resistance to force impact. Moreover, objective data suggest an increase in the likelihood of a brittle nature of fracture as the frost resistance resource is exhausted. This is confirmed by a steady decrease in fracture toughness at FTC, numerically equal to the ratio $W_{pl}(N)/W(N)$, (Figure 3). If normative methods of calculation using nonlinear
deformation models are considered and redistribution of forces in the sections of statically indeterminate systems, the decrease in the fracture toughness in reinforced concrete elements of the “northern” execution should be regulated. The correction provided for in clause 6.1.27 [14] is clearly insufficient. This is confirmed (Figure 3) by a significant difference in the kinetics strength and fracture toughness.

![Graph](image)

**Figure 3.** Dynamics at FTC of strength, energy and fracture toughness.

4. Conclusions
1. Fatigue transformation of the structure of concrete subjected to cyclic temperature and humidity impacts is characterized by a steady decrease in fracture toughness, evaluated by the ratio of energy consumption of plastic and total deformation.
2. Long-term operation of reinforced concrete elements in severe climatic conditions is associated with an increase in the danger (risk) of brittle fracture.
3. When designing the fracture toughness, it is advisable to perform calculations in a probabilistic formulation by using differentiated coefficients of reliability depending on a particular design situation.
| Magnitude of frost impact | Prismatic strength, $R_b$ Average, MPa | Dispersion, MPa$^2$ | Coeff. of asymmetry | Ultimate deformations, $\varepsilon_{b,ult}$ Average, % | Dispersion | Coeff. of asymmetry | Max deformations, $\varepsilon_{b,max}$ Average, % | Dispersion | Coeff. of asymmetry | Upper boundary of microdestruction, $R_{b,erc}$ Average, MPa | Dispersion, MPa$^2$ | Coeff. of asymmetry |
|--------------------------|----------------------------------------|----------------------|---------------------|-----------------------|-----------|---------------------|-----------------------|-----------|---------------------|-----------------------|----------------------|---------------------|
| 0                        | 24.0                                    | 9.12                | -0.38               | 1.64                  | 0.10      | -0.58               | 2.55                  | 0.24      | -0.57               | 18.0                  | 9.1                  | -0.50               |
| 0.29                     | 24.5                                    | 12.1                | -0.43               | 2.34                  | 0.18      | -0.54               | 2.67                  | 0.21      | -0.51               | 19.4                  | 13.2                 | -0.56               |
| 0.57                     | 22.8                                    | 13.8                | -0.49               | 2.88                  | 0.32      | -0.59               | 3.02                  | 0.25      | 0.50                | 17.5                  | 16.1                 | -0.59               |
| 0.89                     | 20.2                                    | 29.7                | -0.81               | 3.15                  | 0.78      | -0.84               | 2.78                  | 0.45      | 0.72                | 15.0                  | 14.0                 | -0.75               |
| 1.29                     | 18.5                                    | 26.1                | -0.84               | 3.18                  | 1.04      | -0.96               | 1.91                  | 0.23      | 0.75                | 12.0                  | 13.2                 | -0.90               |
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