Abstract

An integrated approach to the control of cracking processes and destruction of concrete, including the kinetics of crack growths depending on the duration and the magnitude of the external load is proposed. Based on the accumulated theoretical and experimental data it is determined that elastic and plastic deformations developed in the action under the action of the applied load due to the forming or development of different defects in concrete structures. The results of the experimental research to establish the strength and crack resistance parameters of fine-grained basalt fibrous concretes are presented. The values of strength changes with different indices of loading rate and kinetic characteristics of micro cracking, the activation energy and the effective activation volume were obtained. Development of different defects along with the destruction of concrete was investigated by indirect methods. The integral assessment of cracking processes and destruction of concrete allows defining the integral characteristics of materials under the impact of mechanical loads. For testing the experimental facilities with a wide range of concrete samples loading rates were used.

Keywords: strength; crack resistance; rate of stress; defects in concrete structures; kinetic of destruction

1. Introduction

As it known, the basis of fracture mechanics of materials is the theory of Griffiths [1]. Lately it has been developed at the analysis of processes of destruction of solid bodies [2-12]. In these works it was considered stress state of material with the existing crack. This crack received the development from stresses emerging inside the...
material. Destruction occurs if the crack loses the equilibrium. In this case the crack crosses the material at the speed of sound and the material is divided into parts. In the process of manufacturing and operation of heterogeneous materials micro- and macro-cracks arise. Under the influence of stress they are begin to grow. Characteristics of crack resistance of the material are the energy criterion GC - effective energy of destruction, as well as the power criterion KIC - critical stress intensity factor under normal detachment [2]. Such detachment is most dangerous for crack growths.

2. Relevance

In GOST 29167 crack sizing methodology is recommended when equilibrium tests of concrete using capillary and optical methods. This method has its drawbacks. In particular, the process of the crack length registration is carried out in a phased load of samples with conditioning of a duration of 60 .. 120 s. Concrete structure has a large number of inclusions. They are potential stress concentrators [2-4, 13 etc.]. At the time of conditioning the growth of cracks can occur continuously. Therefore, during testing of concrete samples it is necessary to measure lengths of the developing crack continuously.

Getting of the full charts of deformation and determination of crack resistance characteristics through direct tests of concrete is highly labour-intensive and technical complexity. Therefore, the application of methods to identify dependencies between viscosity of destruction and the speed of load of samples is actual and prospective. In earlier studies of C. Mindessa, etc. [14-16], B. Nikolaou [17], I.M. Grushko [18], R.O. Bakirov [19], Y.M. Bazhenov [20], N.I. Popov [21], A.P. Vashchenko [22], V.V. Stolnikov [23] and others the rate of stress was changed within the range of 10-3 to 103 MPa/s. The effect of shock loads was tested at speeds of 104 – 105 MPa/s [16].

The measuring of dimensions and crack growth rate using load cells can be the most perspective. They stick to the path of crack, which is initiated by a notch. Definition of energy and strength characteristics of concrete at the same time with the measuring of the length and rate of the crack is possible because of using standard highly sensitive equipment.

3. Statement of the problem

To get the most information about the mechanical properties of concrete it is advisable to use an integrated approach. It allows to get energy and strength parameters of fracture mechanics in conditions of a stable nature destruction. Under the same test the length and speed of growth cracks can be determined. The definition of such characteristics on different test machines with finding parameters of fracture mechanics and crack growth rate separately does not give reliable results. This is due to the different hardness of testing equipment and high coefficients of variation (more than 20%) of the values of the measured parameters.

The elaboration of model of cracking and destruction process of concrete combines technological advances, new theoretical and experimental data. It will allow comprehensively to evaluate the physical-mechanical properties and to predict the durability in time before the destruction. This is necessary during elaboration and optimization of compositions and concrete structures, taking into account various factors [4, 24].

4. Theoretical part

It is known that the model of destruction is based on phenomenological approach. It takes into account the formation of cracks at the macro level and microscopic mechanism of origin and evolution of micro pores and micro-cracks. Currently existing theories include deformation, strength and energy criterions. There is also kinetic theory of strength and durability. With respect to concretes they have lacks. Therefore, the quantitative estimation of the probability of destruction of composite materials in these approaches is based on a large number of simplifications [4].

Synthesis of accumulated theoretical and experimental data enabled to determine that under the action of the applied loads in the sample elastic and plastic deformations are developed. Their proportion depends on the size and number of defects in the structure of the material. Interaction of different defects (pores, cracks, vacancies, embedded atoms, dislocations) leads to micro- and makro-destruction from shearing, bending and tearing off.
According to the authors of [25], under the influence of small loads in structure of cement gel point defects are formed with the activation volume. It calls the amount of about one atom of the material in which the deformation occurs when one thermal activation. The resulting deformations are described by equations of the kinetic theory of strength. Nonhomogeneous deformations cause the change of the gradient of chemical potential of defect structure. At small stress a redistribution of concentration of defects is carried out over long periods of time. This leads to stress relaxation at the micro level. The increase of the mobility of the smallest particles (atoms) with the growth of the applied load changes their interaction with higher-level defects: for example, dislocations. They have sizes 100 ... 1000-10 m. In the structure of the concrete, as well as in any crystalline material, there are also similar defects.

Growth of cracks at the destruction of concrete considered from the positions of the kinetic theory of strength and durability connects with the change of the activation energy \( U_0 \) and effective activation volume \( \gamma \) (\( \gamma = v \times n \), where \( v \) - the activation volume, \( n \) – the overstress coefficient). According to works [26, 27] the growth of cracks and the transition from one stage to another stage is accompanied with an increase in activation energy. It means about changing of micro-mechanisms and crack growth rate. The phase transformations are the cause of the regime change according to researchers [28]. They can be connected with spot defects (vacancies, dislocations).

Depending on the duration and magnitude of the load it is possible to create vacancies and their phase transition at different rates into the pores and micro-cracks. At low rates of the application load the effective activation volume \( \gamma \) equals to several hundred of atomic volumes. This corresponds to the size of dislocations. As we know, the motion of dislocations results to the appearance of micro-, macro cracks and reduction of the strength of the concrete.

Researches of concrete were carried out according to the methodology [29]. It was determined that increasing the rate of loading the values of effective activation volume decrease. Therefore, the role of point defects increases, but dislocations – falls, strength of concrete under dynamic loading increases. The obtained data of experiments proved the influence of the rate of loading on change of concrete strength. According to these data it is possible to determine the kinetic parameters of cracking (\( U_0 \) and \( \gamma \)) and define the share of various defects in the micro-mechanism of the process of destruction.

Determination of activation energy \( U_0 \) and effective volume \( \gamma \) in samples at different rates of stress was carried out according to the formula [29]:

\[
\sigma_p = \frac{KT}{\gamma} \ln \left[ 1 + \frac{\tau_0}{KT} \exp \left( \frac{U_0 \omega \gamma}{KT} \right) \right]
\]

where: \( \sigma_p \) – applied stress, MPa;
\( K \) – Boltzmann constant;
\( T \) – absolute temperature;
\( \tau_0 \) – pre-exponential multiplier, 10-12 s;
\( U_0 \) – activation energy, J;
\( \gamma \) – effective activation volume, m3;
\( \omega \) – rate of stress, MPa/s.

For receiving the dependency of strength from the rate of stress it is necessary to use the widest range of speeds loading of testing machine. The maximum value of the strength of a cement stone, mortar and concrete, mostly, was fixed at rate of stress \( 102 – 103 \) MPa/s [4, 16 – 18, 30]. The further increase of the rate of stress showed the scatter of the strength [16, 30] or even its decline [17]. This was due to the approaching of the rate of stress to the rate of concrete relaxation.

5. The results of the experimental researches

It was specially designed the assembly for experimental appraisal of concrete by the offered method [4, 26, 27]. It allows simultaneously to determine the kinetic parameters of micro-cracking [29] and to load samples at rates from 10-7 to 10 m/s. Researches were carried out for quantitative assessment of the strength and crack resistance parameters taking into account the influence of the composition of the concrete, type of the filler and the amount of superplasticizer.
Researchers were carried out for study of the effect of different dosages of superplasticizer «Sika ViscoCrete 5-800». Samples of size 40×40×160 mm were made on the basis of cement-sand mixture (C:S = 1:2). For manufacture of samples Portland cement CEM I 42,5 N, sand with fineness modulus 1.91, basalt fibrous in quantity 1.4 kg/m3 were used.

The quantity of superplasticizer «Sika ViscoCrete 5-800» was 0,5 % and 1 % from the mass of cement. Mixtures had the same consistence. Samples maturated in normal conditions at a temperature (20+2) °C and relative humidity (95+5) %. Strengths at bend and compression were determined at the age of 28 days. Maximum strength limits Rbtfc during tests of samples from fine-grained basalt fiber were received at rates of stress 102 MPa/s. Further increase of the rate of stress to 104 MPa/s did not lead to growth of strength limit of the samples. This corresponds to the experimental results of work [4, 16, 17, 29, 30] and the proposed model. According to experimental data the strength increases with the growth of the rate of stress. However, at a speed of about 1 MPa/s the strength curve has a flushing in the direction of the sharp increase of strength. The analysis of anomalous dependence can build on the basis of the kinetic theory of strength. It takes into account the thermal fluctuations of the atoms in the crystal lattice of solid. At the time of application of the mechanical load the activation volume increases. The break of the nuclear connection may happen in it. At the reduction of the effective activation volume the concentration of stresses occurs in a small area. It corresponds to the volume of point defects. Their share in the massive cracking is small, so concrete strength increases.

The properties of strength and crack resistance of samples from fine-grained concrete with basalt fiber were determined in Table 1.

Table 1. Strength and crack resistance properties of fine-grained basalt fiber concrete.

<table>
<thead>
<tr>
<th>№</th>
<th>Number of additives «Sika»% from mass of cement</th>
<th>R_{bfc}, MPa</th>
<th>R_{bsc}, MPa</th>
<th>R_{b}, MPa</th>
<th>γ·10^{-28}, m⁴</th>
<th>U₀·10^{-19}, J</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>6,3</td>
<td>3,5</td>
<td>42,86</td>
<td>2,74/1,57</td>
<td>2,39/1,78</td>
</tr>
<tr>
<td>2</td>
<td>0,5</td>
<td>8,12</td>
<td>5,93</td>
<td>63,45</td>
<td>2,34/1,56</td>
<td>2,98/2,31</td>
</tr>
<tr>
<td>3</td>
<td>1,0</td>
<td>7,89</td>
<td>5,60</td>
<td>58,14</td>
<td>2,54/1,78</td>
<td>2,47/1,87</td>
</tr>
</tbody>
</table>

where: R_{bfc} – modulus of rupture of concrete, received at standard rate of stress;
R_{bsc} – concrete compression strength, received at standard rate of stress;
R_{b} – critical value of modulus of rupture of concrete received at testing samples under conditions of absence of crack growth (it is determined at high rate of stresses);
γ – effective activation volume, under line – the value of γ before flushing, below the line – after flushing;
U₀ – activation energy, under line – the value of U₀ before flushing, below the line – after flushing.

When receiving the strength values for all samples the decrease of effective activation volume γ with a slight decrease of activation energy U₀ after "flushing" was found. The flushing corresponds to the rate of stress ≈ 1 MIIa/s [4]. As a result, the strength of samples increases (table 1). The lowering of the activation energy and the increase of the effective activation volume show the decrease of strength and crack resistance in the transition from fibrous concrete with a dosage of additions 0,5 % and 1 % to samples without superplasticizer.

Analysis of the data showed that the addition to the raw mix the addition «Sika ViscoCrete 5-800» promoted reducing its water cement ratio, increasing the average density and strength of fibrous concrete. The optimal dosage of superplasticizer «Sika ViscoCrete 5-800» in the amount of 0,5 % from the cement mass was determined.

6. Conclusions

Increase of strength with growth of rate of loading indirectly illustrates the process of formation and development of point defects with their further transfer to micro-pores, micro-and makro-cracks. Tests of samples with different rate of loading allow to refuse the direct determination of length and rate of crack. This considerably simplifies the method of researches, but does not reduce the reliability of the obtained values of parameters of crack resistance and
the time before the destruction of the concrete. This method is based on the methods of mechanics of destruction with the development of main cracks, and on the kinetic theory of strength with the formation and development of defects at the micro level (point defects, dislocations, micro-pores, cracks).

References