Influence of pore fluid on the compressive strength of high-strength concrete under dynamic loading

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Abstract. Based on the coupled discrete element-finite difference method, we developed a numerical model of the mechanical behavior of water-saturated brittle composite materials with two-scale porosity. The model takes into account the structural, physicomechanical, and rheological parameters of the components and parameters of component interaction. Using the model, we numerically studied the influence of pore fluid on the dynamic strength of water-saturated high-strength concretes with various features of the pore structure. We showed that the value of dynamic compressive strength is a function of the complex parameter, which characterizes the ratio of the strain rate of the porous skeleton to the rate of fluid flow through the pore network. We identified two factors that control the strength of water-saturated concrete in a wide range of variation of the applied strain rate and skeleton permeability.

1. Introduction
At present, composite materials with a multiscale pore structure have gained a wide range of constructional applications. An easily recognized representative of this class of materials is high-strength concrete. High-strength concretes are used to build highly loaded elements of critical structures, for example, dams, bridge supports, foundations of port and drilling structures, etc. Large elements/parts of these structures function in the aquatic environment. Due to the fractured-pore structure of concrete, the surface (and possibly internal) regions of the submerged parts are water-saturated. Under dynamic mechanical contact loading of submerged parts, the pore fluid can significantly affect the stress-strain state of the surface layers and contribute to both their fracture and the fracture of deeper layers and therefore determine the degradation rate and wear of the entire massive concrete element. Therefore, the study of the influence of pore fluid on the strength of concrete under dynamic compressive loads is a topical scientific and practical problem.

The pore structure of concrete is quite complex and typically contains “large” micropores in addition to the capillary pore network. Micropores can be either integrated into the capillary network or isolated from it. In the paper, we performed a parametric study of the influence of pore fluid on the dynamic strength of high-strength concrete with a single and two-scale pore structure under uniaxial compression. We considered two practically important cases: (1) interconnected two-scale pore system and (2) micropores isolated both from each other and from the capillary network.

The study was conducted using computer simulation. Traditionally, a computer study of the strength properties of composite porous materials is carried out using numerical methods of the
continuum approach [1-6]. However, the rapid development of particle-based methods in recent years has made them an attractive alternative due to the inherent capability of explicit modeling fracture and related phenomena [7-9]. In this work, we carried out computer study using the advanced representative of this group of methods, namely, the hybrid method of cellular automata, which couples formalisms of the method of deformable discrete elements and finite difference method [10] and allows modeling the mechanical behavior of fluid-saturated porous composites.

2. Model description
We modeled cubic samples of high-strength concrete with explicit taking into account structural elements on a mesoscopic scale. Here, the term “mesoscale” means the characteristic scale of aggregates of millimeter linear dimensions and “micropores” with characteristic dimensions of hundreds of micrometers. Reinforcing aggregates with a characteristic size of less than 5 mm were taken into account implicitly in the effective mechanical properties of cement stone. The relevance of such simplification was shown in [11, 12] and is widely used, for example, in [13, 14]. Concrete was modeled as a three-component composite material consisting of a homogeneous isotropic porous matrix (cement stone), large reinforcing inclusions (crushed basalt), and water in the pore space of the cement stone.

We developed a numerical (discrete element based) model, which takes into account two structural scales of concrete (mesoscopic and microscopic scales). The structural elements of the mesoscopic scale (aggregates and micropores with pore fluid) are explicitly modeled. The following set of input parameters characterizes these components: volume fraction of reinforcing aggregates and micropores, their geometric shape and dimensions as well as spatial arrangement in the sample. Features of the micro-scale structure of concrete including “fine” capillary porosity are taken into account effectively.

A binder (cement stone) was assumed to be elastoplastic, and hardening inclusions (crushed basalt) were elastic-brittle. The mechanical behavior of these components was described using the generalized Hooke’s law and the unassociated law of plastic flow with the Mises-Schleicher criterion [15]. The local fracture was modeled by changing the state of pairs of interacting discrete elements from chemically bonded to unbound (contacting pairs) [16, 17]. We used the Drucker-Prager criterion as a criterion for local failure. This criterion takes into account the influence of the mean stress on the shear strength within the linear approximation [18].

Discrete elements modeling a cement stone were assumed porous and permeable (the element is permeated by a capillary network). Redistribution of fluid in the pore volume of a sample modeled by an ensemble of discrete elements is described by the classical fluid density transport equation [19]. The relation between the local pore pressure and the stress-strain state of the solid-phase skeleton of a discrete element is described using the Biot poroelasticity model [20, 21]. Pore fluid was assumed linearly compressible. The influence of the local pore pressure of a liquid in the volume of a discrete element on its inelastic mechanical behavior and the onset of fracture in a pair of elements was taken into account by modifying the Mises-Schleicher and Drucker-Prager criteria using Terzaghi effective stresses. The driving force for fluid filtration in the pore space is the gradient of pore pressure. A detailed description of the implementation of the model of fluid-saturated materials in the framework of the hybrid discrete element-finite element method is given in the papers [10, 16, 17].

We took the following values of the main structural parameters related to porosity. Micropores (obtained by removing individual discrete elements from the initial structure) were assumed monosized (pore diameter is 500 μm). The value of microporosity was 0.04. Capillary porosity was set effectively in accordance with the input parameters of Biot’s model. The value of the characteristic diameter of capillary channels $d_{ch}$ ranged from 0.1 to 0.5 μm, the value of capillary porosity $\gamma$ was 0.06, and the permeability of capillary channels $k$ was determined by the relation $k=\gamma d_{ch}^{2}$ [22]. The initial value of the pore pressure of water in capillary and micropores (before loading) was 0.1 MPa.

The following values of the elastic constants of basalt and cement stone were used: $E_{Cem}=40$ GPa and $\nu_{Cem}=0.18$, $E_{Bas}=88$ GPa and $\nu_{Bas}=0.23$ [23]. The values of the Drucker-Prager strength criterion parameters for concrete components (uniaxial compressive strength $\sigma_c$ and uniaxial tensile...
strength $\sigma_t$: $\sigma_{Cem}^c = 120$ MPa and $\sigma_{Cem}^t = 30$ MPa, $\sigma_{Bas}^c = 260$ MPa and $\sigma_{Bas}^t = 52$ MPa.

3. Results and discussion

3.1. Effect of pore fluid on the strength of brittle composites with a single-scale pore structure

The simulation results showed that the strength of concrete, which contains only interconnecting capillary channels, is a single-value function of the following dimensionless parameter:

$$Da = \frac{\eta b W^2}{k \Delta P},$$

where $W$ is the characteristic fluid flow distance (sample half-width), $\Delta P$ is the characteristic value of the difference in pore pressure at the distance $W$ (between the sample center and the lateral surface).

Since during the deformation of the sample, the value of $P$ is continuously changing, the parameter $\Delta P$ is normalization constant. In the results presented below, its value was set equal to the initial pore pressure of the interstitial liquid ($\Delta P = 0.1$ MPa). The physical meaning of this dimensionless parameter is the ratio of the rate of sample straining to the rate of fluid flow in the pore network. This is, in some respect, similar to the physical meaning of the Darcy number [24].

Simulation results showed that the dependence of the uniaxial compressive strength of the samples on the analog of the Darcy number (hereinafter $Da$) is a monotonically decreasing function and has a logistic profile (figure 1, curve 1). It is well approximated by a sigmoid function with an exponent about 2.3 (equation (2)).

$$\sigma_c = \sigma_c^{\min} + \frac{\sigma_c^{\max} - \sigma_c^{\min}}{1 + [Da/1712.9]^{2.26}},$$

where $\sigma_c$ is the dynamic compressive strength of concrete (in MPa), $\sigma_c^{\min}$ is the lower limit of variation of the strength of the model specimen (it is achieved under the condition of negligible fluid flow and high rate of sample straining), $\sigma_c^{\max}$ is the upper limit of strength variation (corresponds to the condition of unlimited outflow of pore fluid through the side surfaces of the sample and quasistatic straining, and numerically equals to the strength of “dry” sample).

Three characteristic sections can be distinguished in this dependence. The first section ($Da<600$) physically corresponds to a low pore pressure provided by the redistribution of fluid in the pore network and its outflow through the side surfaces of the sample. In this section, the influence of the pore fluid on the stress-strain state, and the strength of the sample are minimal. The third section ($Da>10000$) physically corresponds to the maximum pore pressure and the maximum decrease in the strength of the sample. Such a decrease in strength is the result of the fact that the liquid does not have time to redistribute in the capillary network during the deformation of the sample. Note that in sections I and III, the strength of the samples changes insignificantly. These sections actually correspond to a quasistatically deformed sample with completely open pores and a sample with completely blocked pores on the side surface [25], respectively. Section II of the dependence ($600<Da<10000$) is transitional between sections I and III. In this section, $Da$ varies largely.

Note that usually, a logistic curve describes systems in which oppositely directed processes occur simultaneously. The following contradirectional processes can be distinguished for the considered system. The first one is the straining of the porous matrix (cement stone) and the capillary channels. The competing process is the flow of pore fluid through a system of capillary channels. The first process leads to an increase in pore pressure and therefore to an “earlier” achievement of the condition for sample fracture. The competing process leads to a decrease in pressure inside the pores and reduces its contribution to the increase in local stresses. The result is sample failure at higher applied loads.
3.2. Effect of pore fluid on the strength of brittle composites with a two-scale pore structure

In this part of the article, we first analyze the influence of a pore liquid on the strength of water-saturated concrete with pores of different scales combined into a single permeable pore network. Next, we consider the influence of the pore liquid on the strength of concrete with two pore structures (capillary network and micropores) isolated from each other.

Concrete samples with two-scale porosity were constructed by adding micropores to the cement stone of the above-described samples with capillary porosity (diameter of the micropores was 500 μm, the microporosity was 4%). The presence or absence of interconnection between capillaries and micropores was parametrically taken into account in the model by means of varying the permeability of the walls of micropores from the value corresponding to the cement matrix down to zero.

An analysis of the simulation results for samples with pores of two scales combined into a single pore network showed that the dependence of the strength of fluid-saturated samples on the analog of the Darcy number is approximated by a sigmoid curve similar to the case of single-scale porosity:

$$\sigma_c = \sigma_c^{\min} + \frac{\sigma_c^{\max} - \sigma_c^{\min}}{1 + \left[\frac{Da}{202.78}\right]^{1.127}},$$

where $$\sigma_c^{\min} \approx 43.3 \text{ MPa}$$, $$\sigma_c^{\max} \approx 49.9 \text{ MPa}$$ (curve 2 in figure 1). One can see that the influence of microporosity on the fluid flow in the pore network and the change in the strength characteristics of concrete is manifested in the entire range of variation of the parameter Da (this distinguishes concrete with interconnected two-scale porosity from concrete with only capillary porosity).

In particular, the length of section I of the dependence $$\sigma_c = \sigma_c(Da)$$ is reduced from 0<$$Da$$<600 (concrete with single-scale porosity), to 0<$$Da$$<40 (concrete with two-scale porosity). At the same time, stage III (minimum strength values) begins at the same characteristic values of the Darcy number as in the case of concrete with a single-scale pore system (for $$Da$$>10000). Accordingly, the length of stage II increases by more than an order of magnitude (from 600 <$$Da$$<10000 to 40 <$$Da$$<10000). The described change in the dependence $$\sigma_c = \sigma_c(Da)$$ is a consequence of the redistribution of fluid between pore spaces of various scales. Indeed, large pores (micropores) are strong stress concentrators and deform more strongly than capillary pores. Accordingly, in the process of deformation, part of the pore fluid passes into the volume of capillary pores and increases pore pressure in the matrix. Note, that the characteristic distance between micropores is much smaller than the half-width of the sample. Due to this fact, the influence of the transport of pore fluid between the pore spaces begins to affect the stress state and strength of concrete already in the range of $$Da$$ corresponding to low strain rates. The consequence of the above is an “earlier” transition to transitional stage II, that is, concrete with...
micropores becomes less resistant to dynamic loads.

It is also important to note that the overall strength level of concrete with two-level porosity (including the values of $\sigma_{c}^{\text{min}}$ and $\sigma_{c}^{\text{max}}$) is less than the corresponding values for concrete with single-level porosity by up to 30%. This is a consequence of the fact that micropores in the cement stone are strong stress concentrators, which reduce macroscopic strength of concrete in the whole range of the parameter $Da$ values (from low strain rates to large strain rates).

Thus, we showed that, in addition to microporosity, a combination of the parameters of the sample, fluid, and loading rate, uniquely characterized by the Darcy number, has a significant effect on strength of concrete with two-scale porosity. In the case of micropores filled with water, the dependence of the strength of the samples on the parameter $Da$ is similar to that observed in samples with capillary porosity but characterized by other numerical values of the strength and Darcy number corresponding to the main stages. In particular, the presence of microporosity in concrete integrated into the capillary pore network increases the contribution of pore fluid to decrease in strength in the region of variation of $Da$ corresponding to quasistatic loading.

We analyzed the effect of the integration of micropores in the capillary pore network of high-strength water-saturated concrete by comparing the above simulation results with results for concrete samples with micropores isolated from the capillary network (plugged). In all cases, both micropores and capillary pores were filled with liquid. Analysis of concretes with clogged micropores showed that the dependence of dynamic compressive strength on $Da$ is well approximated by a sigmoid function,

$$
\sigma_{c} = \sigma_{c}^{\text{min}} + \frac{\sigma_{c}^{\text{max}} - \sigma_{c}^{\text{min}}}{(1 + [Da/382.48]^{0.878})},
$$

where $\sigma_{c}^{\text{min}} \approx 38.3$ MPa, $\sigma_{c}^{\text{max}} \approx 50.3$ MPa, (curve 3 in figure 1).

A comparison of the dependences $\sigma_{c} = \sigma_{c}(Da)$ for these concretes showed that a significant difference in the value of dynamic strength is observed only for $Da>200$, i.e. at stage II, which corresponds to the increasing role of liquid filtration processes. At stage III ($Da>10000$), which corresponds to high rates of concrete loading and the minimal contribution of fluid flow through the capillary pore network, the difference in strength reaches 13%÷15%. Thus, the “isolation” of micropores from the capillary pore network reduces the strength of concrete but does not change the interval of the combination of parameter values included in $Da$, at which the concrete “functions” in a quasistatic mode (when the effect of pore pressure on the strength is minimal due to efficient fluid flow).

4. Conclusion

Using a computer simulation of the uniaxial compression of the samples, we revealed two factors that determine the dynamic compressive strength of heavy water-saturated concretes with a two-scale pore structure. The first factor is the mobility of the pore fluid in the network of capillary pores. It determines the rate of stress equalization in the porous skeleton due to fluid redistribution and provides the nonlinear nature of the change in strength with the loading rate. The latter is uniquely characterized by the logistic dependence of the dynamic strength on the Darcy number ($Da$). The second factor is the connectivity of large micropores with the capillary network. It determines the decrease in stress concentration in micropores (the “powerful” stress concentrators) due to the filtration of "excess" pore fluid into the capillary pore network. The contributions of these factors to variation of the dynamic strength of water-saturated concrete are additive and comparable, and their total contribution reaches 25%. Thus, the strength of water-saturated concrete is determined not only by the volume fraction of micropores as the largest stress concentrators but no less by their integration into the capillary pore structure.
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