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Study of Dry and Wet Cement Mortar Dynamic Properties

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Исследование динамических свойств сухого и влажного цементного раствора

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С использованием метода разрезного стержня Гопкинсона проведены динамические испытания на сжатие образцов цементного раствора в сухом и увлажненном состоянии. Экспериментально определены разрушающие напряжения и их зависимость от роста скорости приложенной нагрузки. Отмечено, что прочность сухого материала на 10...15% превышает прочность материала в увлажненном состоянии.

Ключевые слова: разрезной стержень Гопкинсона, цементный раствор, прочность, динамические испытания.

Introduction. Brick buildings and protective components of nuclear power plants and of other objects should be designed in view of dynamic loading conditions. Components of these hazardous objects are subjected to the loading modes which are characterized by high amplitudes and short duration. Large complexity and high cost of realization of model and real experiments with account of durability and reliability of nuclear power stations require application of numerical simulations. Modern computers, besides reduction of designing allows also to make a qualitative jump in a level of simulations as regards complexity of calculation circuits when a statement of task, physical usage of nonlinear models of deformation and criteria of destruction, approximation of the accounting of variety of conditions of a loading and properties of materials. In order to verify phenomenological models of structural material behavior, a database of mechanical properties of structural materials (i.e., bricks and mortars) is required, which is at present quite incomplete, inconsistent or unavailable. It is necessary to note that many tasks of design and numerical simulation of dynamically loaded constructions are solved using the mechanical properties of materials obtained from static tests. This fact results in irrational designing of brick constructions subjected to shock or explosive impact loads.

Using the well-known method of Hopkinson split pressure bar [1], the dynamic tests and investigations on the dynamic properties under compression of cement mortar specimens are carried out.

Specimens. For static and dynamic tests, specimens of cement mortar were produced in the special tubular forms as bars and then they were carved in to separate specimens by diamond disk. The end faces of specimens were grinded and polished. The specimens for tests had diameter 18 mm. For investigations on the influence of the scale factor, both effects of inertia and friction, the specimens were made with length 9 mm and 18 mm.

The static properties of cement mortar were investigated under compressive loading until failure. As it was found out, the material has significant scatter of properties. So, the ultimate stress varied from 25 up to 80 MPa, the maximal deformation achieved varied from 1.33 up to 7 %, while the elastic modulus of the initial part of the static diagram varied from 16 to 104 GPa. On the basis of a series of 17 tests, the average values of these parameters are determined: the ultimate stress – 48.6 MPa, the respective deformation – 2.3%, the module of the initial part of the diagram – 49.7 GPa.

During the dynamic testing, specimens of cement mortar were tested in compression using an apparatus based on the Kolsky method. First group of specimens was tested in a condition of delivery (dry), while but the second group of specimens was damped before testing in order to achieve the level of humidity 2–4%. The specimens, as a rule, were loaded uniformly; however, some specimens (those which kept the integrity after one cycle of a loading) were loaded repeatedly with the same or greater amplitude of a loading wave.

Dynamic Test Results. By varying striker velocities (i.e., the loading wave amplitude) loading modes were selected under which specimen either retains its apparent integrity and strength or undergoes destruction. It is very important to determine the minimal stress, at which specimen's destruction begins. Visual inspection of the specimens after testing makes it possible to assess the level of damage. However, such inspection does not give the unequivocal answer to the question: has there begun a destruction in a specimen or has it kept its integrity. The exact answer as regards the beginning of destruction in a specimen is given by the analysis of the strain pulses registered during the tests.

In the absence of damage of the specimen and the presence of a trapezoidal loading incident pulse $\varepsilon^{i}(t)$ of a constant amplitude on the reflected pulse $\varepsilon^{r}(t)$, the amplitude (i.e., the strain rate) first increases and then decreases due to the increase of resistance to deformation of the specimen. At a time determined by the start of decrease of loading in the incident wave $\varepsilon^{i}(t)$, the transmitted pulse $\varepsilon^{t}(t)$ also starts decreasing, while the strain rate determined by the reflected pulse $\varepsilon^{r}(t)$ becoming negative [2]. Thus, before that moment, both stresses and strains increased, that is, active loading of the specimen took place, whereas after that moment the stresses drop almost to zero, and the deformation resulted decreases by some value, determined by the unloading ability of the material and calculated while using the negative part of the reflected pulse.

For the case of failure of the specimen, the situation is different. At the initial loading stage, the pressure [pulse $\varepsilon^t(t)$] and the strain rate [pulse $\varepsilon^r(t)$] in the specimen also grow simultaneously. However, upon reaching the point of the maximum stress, an avalanche-like failure starts developing in the specimen. And, though the amplitude of the loading pulse remains practically constant, the compression wave cannot completely pass through the failing specimen and its resistance to deformation steadily decreases; the stresses drop and the strain rate increases.

In both cases, non-linearity of the initial part of the loading branch and a considerable difference between the loading and unloading branches can be noted. In the case of a failed specimen, pressure starts decreasing after reaching its maximum, with the constantly growing strain. As the time of the deformation process is short, disintegrated parts of the specimen remain between the ends of the pressure bars during the test and suffer partial compaction. This process is similar to high-rate deformation of non-cohesive soils. After the effect of the loading pulse has stopped, the compacted particles retain some low unloading ability appearing in the form of partial recovery of the specimen form following its unloading [the negative part of relation $\dot{\varepsilon}_s(\varepsilon_s)$].

For the analysis of the test results it is convenient to subdivide all the dynamic tests performed into 4 main groups:

1. tests of dry specimens with small energy of the loading wave, when specimens remain undamaged;
2. similar tests of wet specimens;
3. tests of dry specimens with large energy of the loading wave, when specimens completely collapse;
4. similar tests of wet specimens.

For the estimation of scatter in the material properties of cement mortar, 3–4 specimens of both geometries were tested within each group. After computerized processing of the initial pulses (i.e., calibration, synchronization, smoothing using the integrated spline functions) the true dynamic diagrams were obtained. Diagrams of the modules of loading branches, values of the experimental stresses, the average values of a strain rate and stress rate were determined.

For groups 3 and 4, the maximal stress in the specimen produced during testing is the ultimate strength of the material σ_u. For groups 1 and 2, the maximal values of stress registered in tests are not the ultimate strength of material, insofar as the specimens did not break during tests. In Table 1, the average values of the specified are given parameters for each group of tests.

Table 1

Dynamic Compression Test Data

Group No.	t_f, μs	σ_u, MPa	ε_f, %	E, GPa	$\varepsilon_{\max}$, %	$\dot{\varepsilon}_{\max}$, s^{-1}	$\dot{\varepsilon}_{av} = \varepsilon_{\max}/t$, s^{-1}	$\dot{\sigma}_{\max}$, MPa/μs
1	73	109.25	1.3	18	1.5	406	149	7.0
2	64	96.00	2.0	11	3.6	567	297	5.5
3	36	136.00	1.8	17	10.0	1174	746	13.0
4	45	114.00	3.3	9	9.0	1522	974	10.0

Further, in Figs. 1–4, the deformation diagrams of specimens of cement mortar of two various geometries are given. In each figure, the diagrams of one group are presented. For comparison, the average static diagram is shown in Fig. 1.

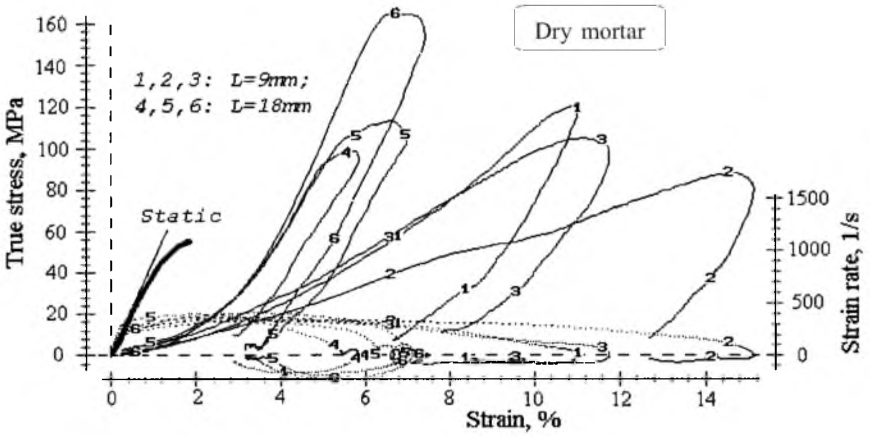

Fig. 1. Dynamic diagrams of specimens of various geometries (group No. 1) as compared to the static diagram.

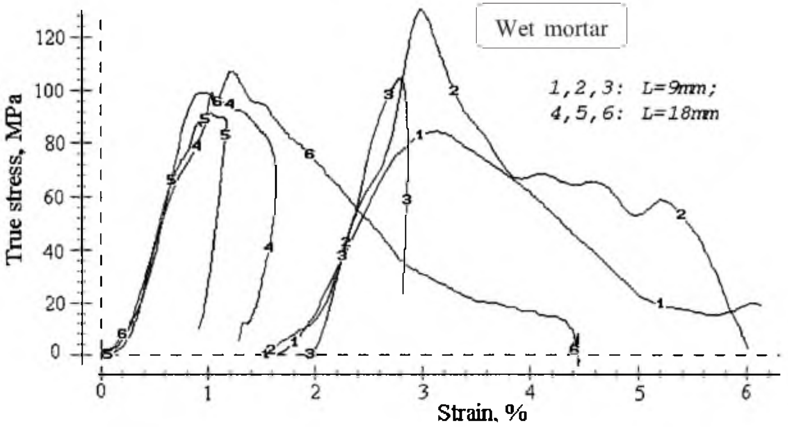

Fig. 2. Dynamic diagrams of specimens of various geometries (group No. 2).

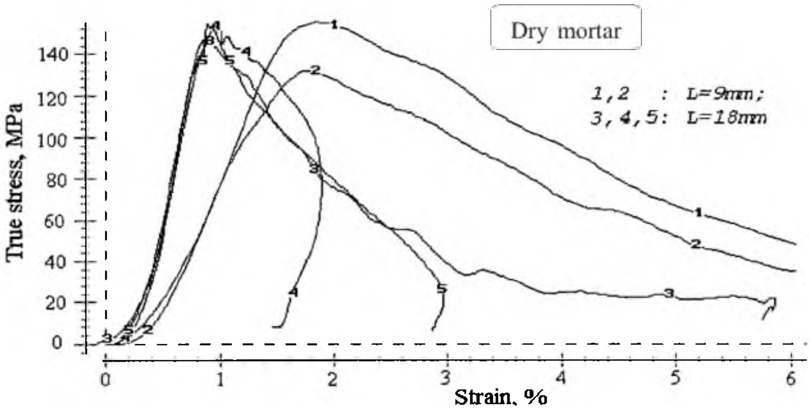

Fig. 3. Dynamic diagrams of specimens of various geometries (group No. 3).

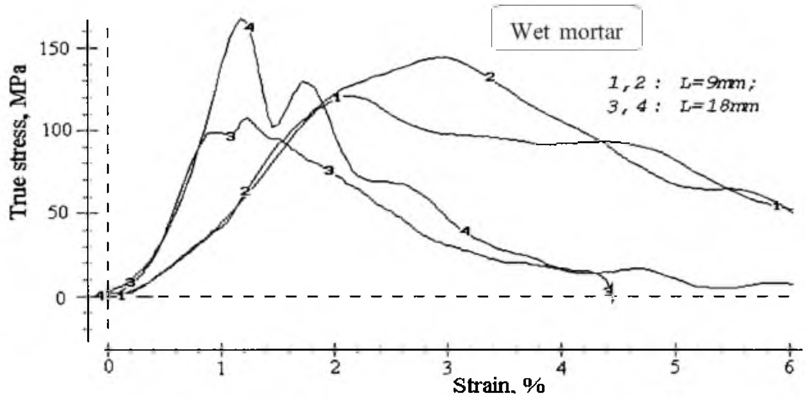

Fig. 4. Dynamic diagrams of specimens of various geometries (group No. 4).

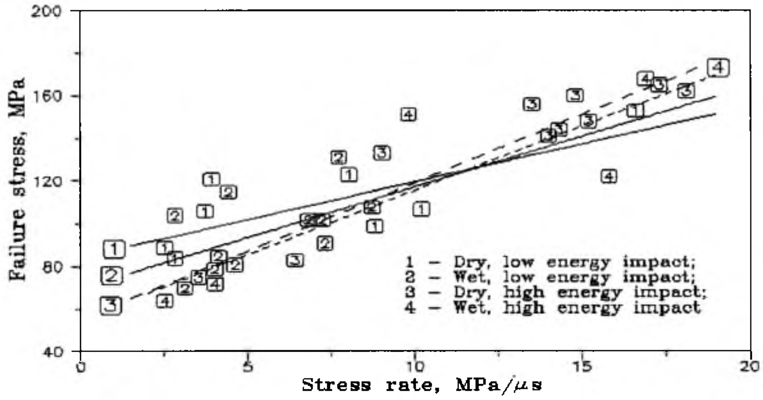

Fig. 5. The ultimate stress dependence on the stress rate.

It is easy to see quite a strong influence of length of examined specimens on the diagrams: longer specimens have more abrupt loading branches. In comparison with the static loading conditions, the specimens under a high-speed loading remain undamaged at considerable loading levels.

When processing the experimental data, in addition to average strain rates $\dot{\varepsilon}_s$, maximum values of stress rates $\dot{\sigma}_s$ in the specimen were determined for each test. Figure 5 depicts the stress-rate dependence of the ultimate stresses for each groups of the cement mortar. It is evident that the breaking stresses grow with the stress rate for all types of tests. It is noteworthy that the presented results can be approximated by linear relations $Y = AX + B$ with the parameters given in Table 2.

Table 2

Constants for the Stress-Rate Dependence Determination of the Ultimate Stress

Group No.	A	B, MPa
1	3.51	84.5
2	4.71	70.1
3	6.36	55.5
4	5.92	55.9

Discussion. The maximum stress and the corresponding strain values obtained from the deformation diagrams of the tests where the specimens retained their integrity were taken as the ultimate compressive characteristics of the concrete material. However, the diagrams of 3 and 4 groups testify that even higher strength values were obtained in the dynamic loading tests. Such behavior of the materials is explained by a dynamic character of loading and is determined by two competing processes taking place in the specimens: 1) a process of nucleation, growth and coalescence of microcracks and micropores into macropores and cracks, and 2) wave-like increase in the loading level. If the increase in stress is higher than the intensity of the failure process, then a specimen with already developed failure zones can be overloaded, that is, can withstand increasing loads during some time.

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Резюме

За допомогою методу розрізного стрижня Гопкінсона проведено динамічні випробування на стиск зразків цементного розчину в сухому і зволоженому стані. Експериментально визначено руйнівні напруження й їхню залежність від росту швидкості навантаження, що прикладається. Відмічено, що міцність сухого матеріалу на 10...15% перевищує міцність матеріалу у зволоженому стані.

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