Materials Physics and Mechanics 42 (2019) 691-698 Received: March 3, 2019

ANALYSIS OF THE DYNAMIC BEHAVIOR OF SAND-LIME AND CERAMIC BRICKS

D.A. Lamzin, A.M. Bragov*, A.K. Lomunov, A.Yu. Konstantinov, F. dell'Isola

[1]Research Institute of Mechanics, Lobachevsky National State Nizhny Novgorod Research University, 603950, N. Novgorod, 23 Gagarin Avenue, Russia

*e-mail: bragov@mech.unn.ru

Abstract. The results of dynamic tests on building brick samples were analyzed using the incubation time fracture criterion. The strength and time properties of sand-lime brick and ceramic brick were under study. The tests were carried out using the classical Kolsky method and its modification - dynamic splitting. Strain rates under compression reached $2.5 \cdot 10^3$ MPa/s while stress rates under tension reached $3.5 \cdot 10^2$ GPa/s. It is noted that the strain rate affects the strength and time properties of the materials under study. The parameters of the incubation time fracture criterion were determined on the basis of the experimental deformation diagrams of material in axes stress versus time. Herewith, nonlinear nature of the loading branch of dynamic diagrams was taken into account. Both tested materials qualitatively showed the same change of the mechanical properties.

Keywords: dynamics, brick, split Hopkinson pressure bar, splitting, strain rate, stress rate, incubation time criterion

1. Introduction

The calculation of building structures for a special combination of loads including some time-varying pulse-wave impact of seismic, explosive or shock character is of great interest nowadays. This interest is caused by the increased incidences of natural or man-made hazards, as well as terrorist attacks. Therefore, one of the urgent tasks of modern science is to reduce the consequences of progressive collapse of buildings or structures in emergency situations by means of rational and saving design accounting for the effects of intense short-term impacts on physical and mechanical properties of structural materials.

The solution of this problem is based on fundamental research of properties of structural materials under pulse-wave influences in a wide range of changes in the strain rates. This research should be integrated and include the testing with the analysis of the implementation of specific conditions required by experimental methods. On the basis of experimental data it is necessary to conduct theoretical studies, develop deformation models and fracture criteria which should not be contradicted but confirmed by experimental results. This paper is devoted to the description of the results of experimental and theoretical studies of the processes of dynamic deformation and fracture of brittle building materials. The results of studies of the behavior of concrete, fiber-reinforced concrete, mortar and rocks under dynamic loading are regularly published, for example [1-7] and others. However, the behavior of brick, especially sand-lime brick, has not been thoroughly studied yet, despite the wide application of these materials. Therefore sand-lime brick and ceramic brick were chosen as research object. The experiments were carried out at the facilities that implement the classical Kolsky method for compression tests under uniaxial stress state at high strain rates. In addition, a

http://dx.doi.org/10.18720/MPM.4262019_1

modification of this technique – dynamic splitting (the so-called «Brazilian test») was used to determine the properties of the material at tension. Deformation diagrams were constructed under different dynamic impact regimes, strength and time characteristics were obtained as well as their dependence on stress rate and strain rate as a result of the experiments.

2. Materials and test samples

Samples for the tests were made of ceramic and sand-lime bricks grade 150 in the form of cylinder. Samples for compression tests had a diameter of 20 mm and a length of 10 mm as well as a length of 20 mm for tensile tests (splitting tests). At first, the plates of 10 mm and 20 mm thick were cut off from bricks on a stone-cutting machine with a diamond disc and then cylindrical samples were drilled from these plates for experiments on a drilling machine with a diamond-coated crown

3. Dynamic testing procedures

Among the known methods of dynamic testing of materials the Kolsky method with the Split Hopkinson pressure bar (SHPB) [8] was the most widely used due to its good theoretical validity and simplicity of implementation. Numerous modifications of this technique have been developed [9-12], allowing to determine the various mechanical properties of materials at high strain rates. In this work the classical Kolsky method was used to determine the strength of samples of ceramic and sand-lime bricks under uniaxial compression and its modification the «Brazilian test» (splitting test) [13], which is analogous of the scheme of the tensile testing (Fig. 1).

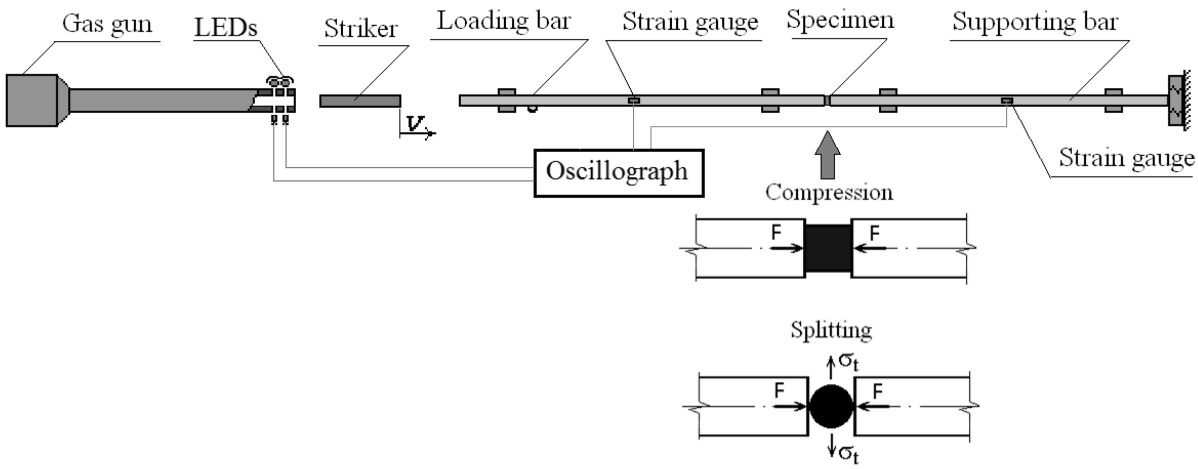


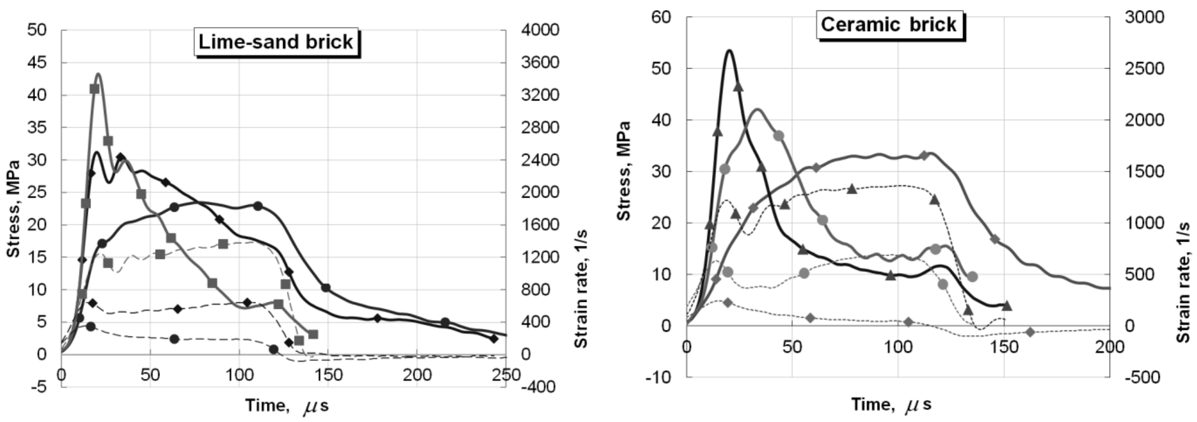
Fig. 1. Methods used in dynamic testing of ceramic and lime-sand bricks

The setup for dynamic tests consisted of a pneumatic loading device - a gas gun with a control system a complex of measuring and recording equipment and a replacement set of measuring bars with a diameter of 20 mm. Registration of initial experimental data was carried out using strain gauges glued on the lateral surface of measuring bars signals from which were transferred to a digital storage oscilloscope, using schemes of dynamic tensometry. Then the oscillograms were saved digitally and processed using the original software.

4. Behavior of materials under uniaxial compression

This section presents our results of dynamic compression tests of cylindrical samples, whose dimensions are indicated in section 2. Cylindrical bars with a diameter of 20 mm and a length of 300 mm were used as strikers. The amplitude of the loading wave was changed by varying the velocity of the striker. Herewith, the achieved loading regimes made the sample either retain apparent integrity with small cracks on the surface or fall completely to pieces and even «into dust».

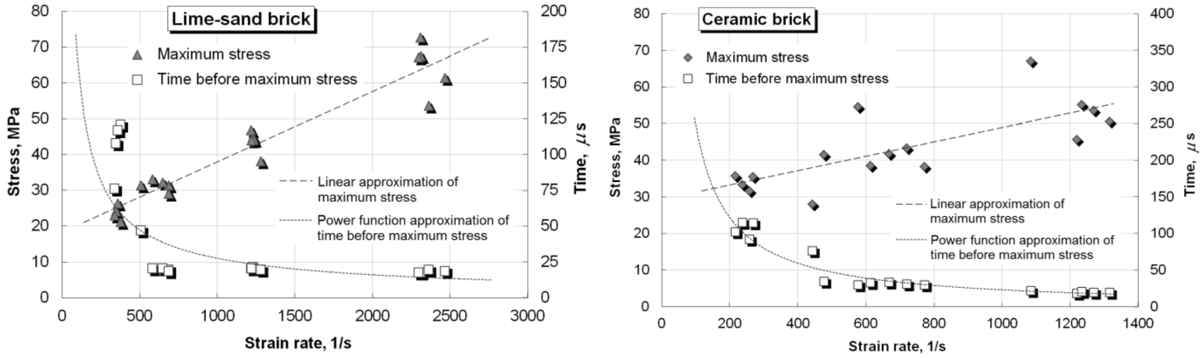
In general dynamic tests are performed when the sample is loaded with an intense pulse short-term loading which can cause a non-homogeneous stress state of the sample due to the propagation of stress waves in it and considerable inertial forces can also affect the sample. Therefore, to fulfill the main prerequisite of the Kolsky method, namely, the realization of a uniaxial stress state with a uniform distribution of stresses and strains along its length, the results of research and some recommendations for brittle material described in [14–16] were taken into account. Thus, the ratio of the length to the diameter of the samples was within the recommended limits of 0.3-1.0. A thin layer of grease was applied to the ends of the measuring bars before testing in order to reduce the influence of frictional forces during the radial expansion of the sample. An analysis of the change of the synchronized pulses of strain of measuring bars in time has shown that the forces at the ends of the sample are practically equal and the state of its equilibrium deformation takes place. Therefore, our dynamic compression tests were carried out under conditions of a one-dimensional and uniform stress state of samples.



a b

Fig. 2. Deformation diagrams of samples of lime-sand (a) and ceramic (b) brick at compression

Figure 2 shows the average deformation diagrams with strain rate history obtained for some regimes of dynamic loading of samples made of sand-lime and ceramic bricks. The solid lines show the dependences $\sigma \sim t$ (the left vertical axis is stress) and the dotted curves show the dependence $\dot{\varepsilon} \sim t$ (the right vertical axis is the strain rate). At the same time the same markers on the curves (solid lines and dashed lines) correspond to a certain loading regime. According to the deformation diagrams the values of the mechanical characteristics of the materials were determined: and the time before maximum stress at different strain rates. The dependencies of these mechanical characteristics versus the strain rate for sand-lime (Fig. 3a) and ceramic (Fig. 3b) bricks were constructed. The colour markers in the figures correspond to the maximum stresses (the left vertical axis is stress) and the colourless markers correspond to the times before maximum stresses (the right vertical axis is time). The same figures show approximations of experimental values of mechanical properties by different mathematical functions. The plotted dependencies indicated that with increasing strain rate the maximum stresses increase and the time before maximum stress decreases for both tested materials. This trend was noted in the testing of other brittle materials, for example [3,5,6].



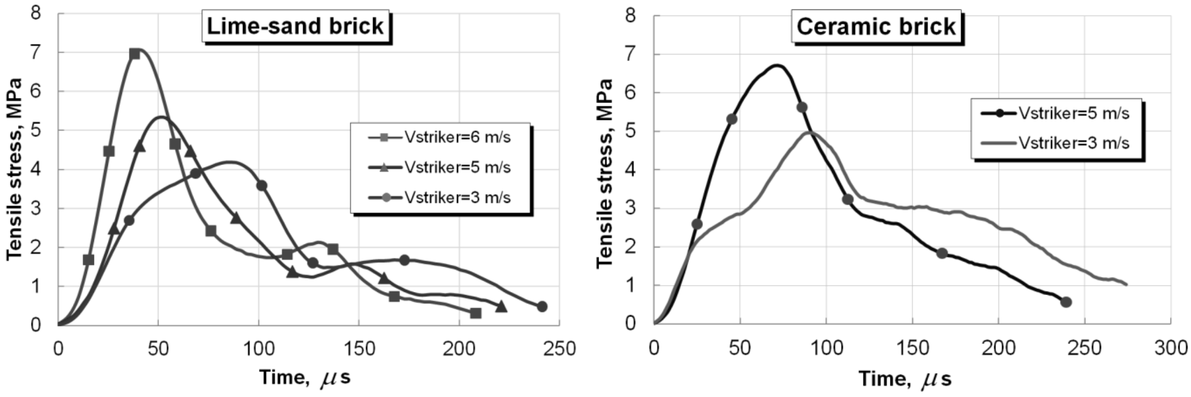
a b

Fig. 3. Dependencies of mechanical properties versus the strain rate for lime-sand (a) and ceramic (b) bricks at compression

Maximum stress values can be taken from deformation diagrams at different strain rates as the ultimate strength characteristics of a brick under compression. The strength of the material can be characterized by the values of the maximum stresses achieved in experiments with samples that retained their integrity after testing. However, higher values of fracture stress of brick were obtained in the process of dynamic loading. Such behavior of materials is due to the dynamic nature of the load and is determined by two competing processes occurring in the sample: the process of formation, growth and coalescence of microcracks and micropores into macropores and cracks, on the one hand, and the wave nature of the load increase in the material, on the other. If the stress rate exceeds the intensity of the process of fracture, the sample with already formed and developing sources of destruction can be overloaded, i.e. can withstand for some time more and more increasing loads.

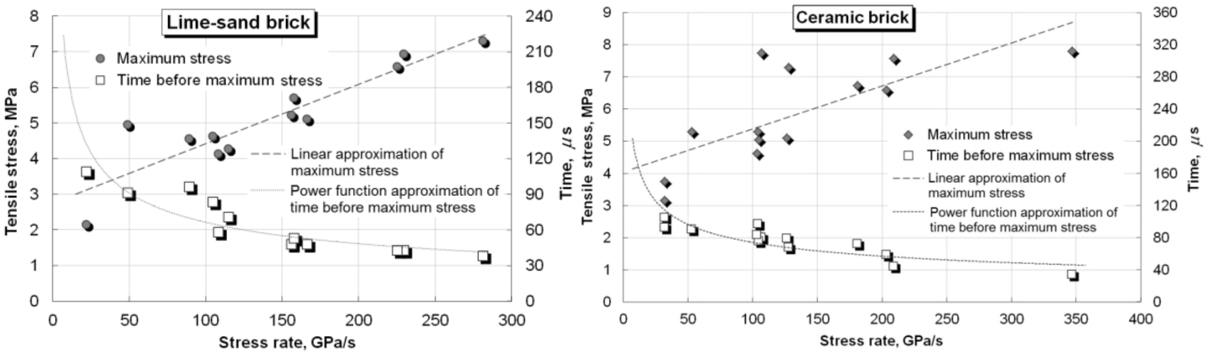
5. Behavior of materials under splitting

This section presents our results of dynamic tensile (splitting) tests of cylindrical samples, whose dimensions are indicated in section 2. The amplitude of the loading wave was changed during experiments by varying the velocity of a cylindrical striker of 20 mm in diameter and 300 mm in length. The analysis of this technique was carried out in [13] where it is noted that the «Brazilian test» can be used to determine the tensile strength of brittle materials when the elastic behavior of the material and the state of equilibrium deformation of the sample are observed and its fracture occurs along the diametrical plane. To assess the implementation of these conditions the graphs of the change of the synchronized impulses of strain of the measuring bars in time were examined which showed the practical equality of forces acting on the lateral surfaces of the sample which causes the state of equilibrium deformation. The ends of the measuring bars were covered with a thin layer of grease before the test to reduce the effect of frictional forces on the process of deformation of the sample. In addition, the crack formation or complete destruction of the samples into two halves occurred along a diametrical plane.



a b

Fig. 4. Deformation diagrams of samples of sand-lime (a) and ceramic (b) brick at splitting



a b

Fig. 5. Dependencies of mechanical properties versus the stress rate lime-sand (a) and ceramic (b) bricks at splitting

The average time history of tensile stress obtained for different loading regimes of the samples made of ceramic and sand-lime bricks under the velocity of the striker are shown in Fig. 4. These curves were analyzed in the same way as in compression. The values of the mechanical properties of the materials: the maximum stress and the time before maximum stress were determined in each test. As a characteristic of the loading regime at splitting, the stress rate was adopted, but not the strain rate, as at compression. Stress rate was determined as the slope of the ascending branch of time history of tensile stress. The plotted dependences of the mechanical characteristics on the values of the stress rate (Fig. 5) showed that with the stress rate growing, the strength of materials increases and the time before maximum stress decreases which was also characteristic of compression tests.

6. Theoretical interpretation of test results

The obtained experimental data were used for identification of the Morozov-Petrov strength criterion [17, 18], which is based on the concept of incubation time. According to the criterion, material fracture occurs at time t^* when:

$$\frac{1}{\tau}\int_{t^*-\tau}^{t^*}\sigma(\mathrm{t})dt \geq \sigma_c, \quad (1)$$

where $\sigma(t)$ is stress time history in material point, τ and σ_c are material constants. Integration is performed over a time interval of duration τ.

Physically this means that the fracture at some point of the material will occur at the time t^*, if the stress integral over a certain time interval τ previous to t divided by τ will exceed a certain threshold value σ_c. The parameters τ and σ_c do not depend on the loading rate.

The common way of parameter identification is in linear approximation of loading branch of stress history (Fig. 6). In this case $\sigma(t) = \frac{\sigma^*}{t^*} t$ and equation (1) becomes:

$$\frac{1}{\tau}\int_{t^*-\tau}^{t^*} \frac{\sigma^*}{t^*} t dt = \frac{1}{2}\frac{\sigma^*}{t^*}(2t^* - \tau). \tag{2}$$

If the strain rate (or stress rate) dependence of failure stress is known, then using equation:

$$t^* = \frac{\sigma^*}{E\dot{\varepsilon}} = \frac{\sigma^*}{\dot{\sigma}}, \tag{3}$$

where E is material elastic modulus, σ^* is material strength, $\dot{\varepsilon}$ is strain rate, $\dot{\sigma}$ – stress rate, t^* is time of fracture.

One can determine the model parameters values using the linear regression:

$$\sigma^* = \sigma_c + \frac{\tau E}{2} \cdot \dot{\varepsilon} = \sigma_c + \frac{\tau}{2} \cdot \dot{\sigma}. \tag{4}$$

However, in real experiments the time variation of the stress in the sample is not linear, and the strain rate is not constant. In this case the nonlinear approach to the model identification is considered to be more correct. The scheme of model identification based on a series of experiments is shown in Fig. 7.

Time variations of stress in some experiment (for example, on compression) are considered. The moment of failure corresponds to the maximum value of the stress. Then the value of the interval τ is chosen and the integrals, expressing the squares S_1, S_2, …S_N.

$$S_i = \int_{t^*-\tau}^{t^*} \sigma_i(t')dt'. \tag{5}$$

The values of the model parameters that describe the failure in the set of experiments in the best way are determined when solving the optimization problem:

$$\sum_{i=1}^{N}\left(\frac{1}{\tau}\int_{t^*-\tau}^{t^*} \sigma_i(t')dt' - \sigma_c\right)^2 \underset{\tau,\sigma_c}{\longrightarrow} min. \tag{6}$$

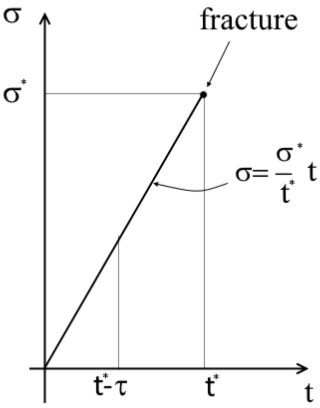


Fig. 6. Linear approach to criterion identification

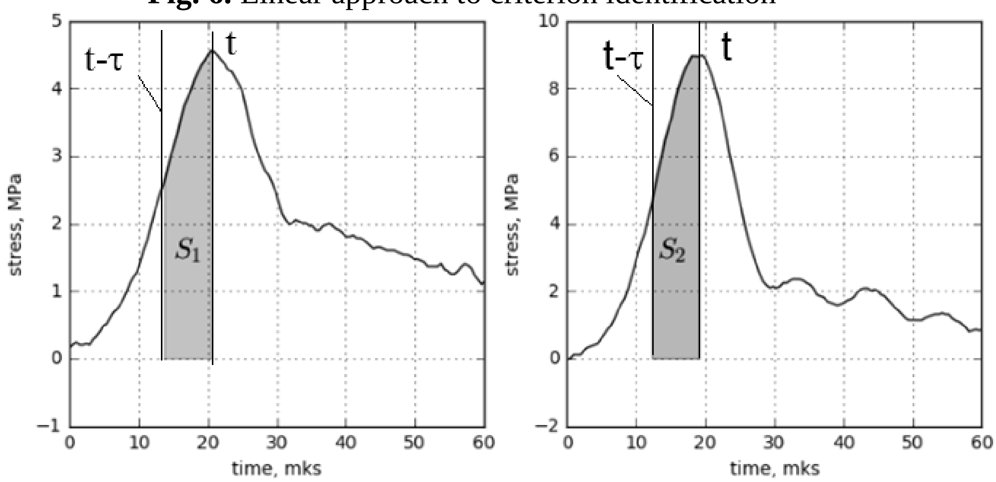


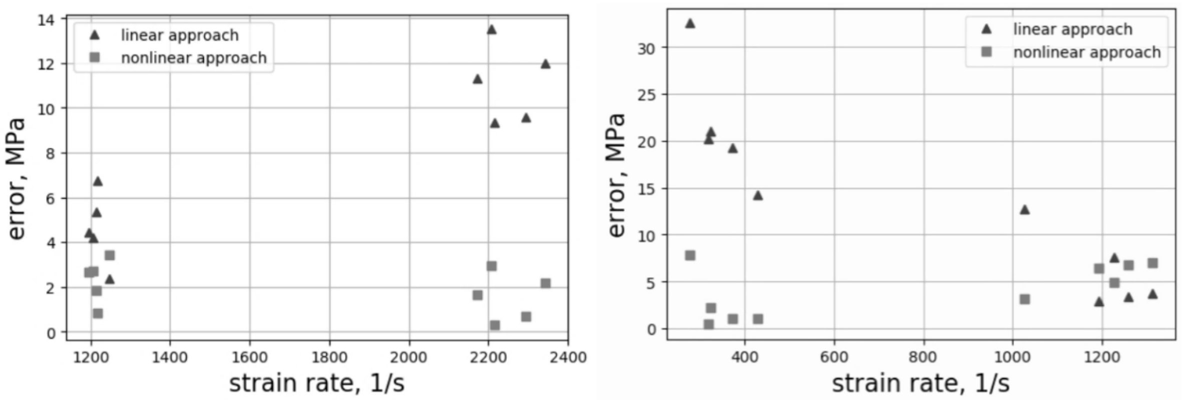
Fig. 7. Nonlinear approach to criterion identification

Figure 8 shows the differences of the left and the right parts of equation (1), calculated for the stress histories obtained in real experiments by formula:

$$error = \left|\frac{1}{\tau}\int_{t^*-\tau}^{t^*}\sigma(\mathrm{t})d\mathrm{t} - \sigma_c\right|, \qquad (7)$$

where incubation time τ was obtained in the ways described above.

Triangles correspond to the parameters determined using the linear approximation method, squares correspond to the parameters, calculated taking into account the nonlinear nature of the stress change in the sample over strain. It is clear that the use of nonlinear approach allows to predict more accurately the fracture conditions.



a b

Fig. 8. Model identification approaches comparison: a – lime-sand brick (σ_c =13.1 MPa, τ=28 μs - nonlinear approach, τ=11,3 μs - linear approach), b – ceramic brick (σ_c =13.7 MPa, τ=49 μs- nonlinear approach, τ=17,9 μs - linear approach)

7. Conclusions

Uniaxial compression and tensile (splitting) tests with the use of the Kolsky method and its modification were carried out for samples made of ceramic and sand-lime bricks. The obtained experimental results are characterized by a temperate scatter and show the influence of the stress rate and strain rate on the strength and time properties of the tested materials. The maximum stresses increased and the time before maximum stress decreased with increasing stress rate and strain rate for both studied materials. On the basis of the experimental data, the parameters of the incubation fracture time criterion were determined for both materials using linear and nonlinear approaches. It is noted that the use of nonlinear approach allows to predict more accurately the fracture conditions. Comparing the mechanical behavior under dynamic loading, we can say that both tested materials qualitatively showed the same change of the properties both under compression and under tension.

Acknowledgements. *The experimental research was carried out at the expense of the grant of the Russian Science Foundation (project № 17-79-20161). Theoretical interpretation of test results is financially supported by the Federal Targeted Program for Research and Development in Priority Areas of Development of the Russian Scientific and Technological Complex for 2014-2020 under the contract No. 14.578.21.0246 (unique identifier RFMEFI57817X0246).*

References

[1] Bischoff PH, Perry SH. Compressive behaviour of concrete at high strain rates. *Materials and Structures.* 1991;24(6): 425-450.

[2] Hao H, Tarasov BG. Experimental study of dynamic material properties of clay brick and mortar at different strain rates. *Australian Journal of Structural Engineering* 2008;8(2): 117-132.

[3] Bragov AM, Karihaloo BL, Petrov YV, Konstantinov AY, Lamzin DA, Lomunov AK, Smirnov IV. High-rate deformation and fracture of fiber reinforced concrete. *Journal of Applied Mechanics and Technical Physics.* 2012;53(6): 926-933.

[4] Xu H, Wen HM. Semi-empirical equations for the dynamic strength enhancement ofconcrete-like materials. *International Journal of Impact Engineering.* 2013;60: 76-81.

[5] Bragov AM, Petrov YV, Karihaloo BL, Konstantinov AY, Lamzin DA, Lomunov AK, Smirnov IV. Dynamic strengths and toughness of an ultra high performance fibre reinforced concrete. *Engineering Fracture Mechanics.* 2013;110: 477-488.

[6] Smirnov I, Petrov Y, Volkov G, Abramian A, Verichev S, Bragov A, Konstantinov A, Lamzin D. Dynamic strength of limestone in terms of the incubation fracture time criterion. *Procedia Materials Science.* 2014;3: 778-783.

[7] Petrov YV, Karihaloo BL, Bratov VV, Bragov AM. Multi-scale dynamic fracture model for quasi-brittle materials. *International Journal of Engineering Science.* 2012;61: 3-9.

[8] Kolsky H. An investigation of the mechanical properties of materials at very high rates of loading. *Proceedings Physical Society of London*. *Section B.* 1949;62(11): 676-704.

[9] Bragov AM, Lomunov AK. Methodological aspects of studying dynamic material properties using the Kolsky method. *International Journal of Impact Engineering.* 1995;16(2): 321-330.

[10] Bragov AM, Grushevsky GM, Lomunov AK. Use of the Kolsky method for studying shear resistance of soils. *DYMAT Journal.* 1994;1(3): 253-259.

[11] Bragov AM, Lomunov AK, Sergeichev IV. Modification of the Kolsky method for studying properties of low-density materials under high-velocity cyclic strain. *Journal of Applied Mechanics and Technical Physics.* 2001;42(6): 1090-1094.

[12] Bragov AM, Lomunov AK, Konstantinov AY, Lamzin DA. A modified Kolsky method for determining the shear strength of brittle materials. *Technical Physics Letters.* 2017;43(1): 130-132.

[13] Rodriguez T, Navarro C, Sanchez-Galvez V. Splitting tests: an alternative to determine the dynamic tensile strength of ceramic materials. *Journal de Physique IV.* 1994;4(C8): 101-106.

[14] Li QM, Meng H. About the dynamic strength enhancement of concrete-like materials in a split Hopkinson pressure bar test. *International Journal of Solids and Structures.* 2003;40(2): 343-360.

[15] Zhang M, Wu HJ, Li QM, Huang FL. Further investigation on the dynamic compressive strength enhancement of concrete-like materials based on split Hopkinson pressure bar tests. Part I: Experiments. *International Journal of Impact Engineering.* 2009;36(12): 1327-1334.

[16] Li QM, Lu YB, Meng H. Further investigation on the dynamic compressive strength enhancement of concrete-like materials based on split Hopkinson pressure bar tests. Part II: Numerical simulations. *International Journal of Impact Engineering.* 2009;36(12): 1335-1345.

[17] Morozov N, Petrov Y. *Dynamics of Fracture*. Berlin: Springer; 2000.

[18] Petrov YV, Utkin AA. On the dependence of dynamic strength on loading rate. *Material Science.* 1989;25(2): 153-156.