Changes of the Energy Intensity of Destruction of Autoclaved Aerated Concrete during Compression with Changes in Its Physical Parameters

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Abstract. Conventional in mechanics of material fracture failure criteria GiC and CS based on Griffith's energy concept about development of a fracture. These criteria postulate fact of occurrence the limiting state in the material around the tip of the crack occurs when the rate of elastic energy growth and the rate of its absorption in the bounded zone are equal. For complex composite materials such as concrete, the possibility of applying these criteria remains controversial due to the pronounced heterogeneity of this type of materials, in which the size of the individual rigid elements of the structure is commensurate with the size of the test samples. But the energy nature of destruction is fair and obvious in any materials, so for them there must be an energy criterion of destruction, which not only States the fact of destruction, but also integrally takes into account the expenditure of deformation energy not only on elastic but also on plastic processes, including thermal. The proposed effective specific energy of destruction of the material as a criterion of destruction should take into account all the features of destruction not as a fait accompli, but as a process of accumulation and dissipation of energy in the deformable volume, and not at the tip of a single crack. The article describes a method for obtaining the effective energy density of the destruction and presents results of a study of this magnitude for one of the types of concrete – autoclaved aerated concrete, given that this relatively homogeneous material is the most suitable for pioneering research is relatively new strength parameter for materials with complex structures. To determine the range of possible values of the investigated value, a factorial experiment was performed with variation of such factors as: density, loading speed and water saturation of cellular concrete. The type of dependence of energy consumption of a cubic sample in time from various factors causes the mechanism of destruction of this material – viscous or brittle and describes the process of accumulation of defects in the process of increasing elastic deformation to the moment of destruction.
1. Introduction

At now days concrete is the most common building material in all spheres of human life, which has two hundred years of experience in its use. However, the mechanical properties of this composite material are the least studied of all the structural materials used. This is due to the very complex structure of this artificial stone due to the wide variety of components used to create it, usually of local origin. In this regard, modeling of this material by methods of continuum mechanics is almost impossible task, because continuum mechanics operates with the concept of continuum and currently there are no continuum models reflecting the real behavior of concrete under load.

A new approach to the study of concrete became possible due to the development of fracture mechanics [1 – 4]. Applications of fracture mechanics to the problem of describing the processes of destruction of concrete engaged Yu V Zaitsev [5], S N Leonovich, W Schneider, Y Eberhardsteiner, A A Griffiths, J Irwin were engaged in the development of this area. E M Morozov, G P Cherepanov, V Z Parton, B E Pobedrya, etc.

It was found that the nature of the destruction of concrete is different depending on the shape and number of initial defects (pores, cavities, cracks, adhesion between the matrix and the filler, etc.). Many of the defects are sources of stress concentration, leading to the destruction of bonds at all levels of the concrete structure and to the release of accumulated potential deformation energy on the free surfaces of the defects and concentrated in their characteristic bends. Exceeding the critical level of the intensity of the released elastic energy leads to the beginning of its spontaneous release with a further transition to the specific surface energy of the newly formed microcracks, leading to the destruction of concrete as a result of their coalescence. Thus, the criterion of destruction of concrete, like most materials, can be considered a critical value of the specific potential energy of elastic deformation of its unit volume, provided that this volume can be considered a representative volume for such a complex composite artificial material as concrete.

Since, due to the complexity of the structure of concrete, the load distribution between the atoms of the structure of this material is carried out unevenly and falls only on a part of the interatomic bonds in the cross section, the formation of new fracture surfaces redistribution of stresses will lead to the inclusion of previously unconnected interatomic bonds, which will require additional energy costs for their rupture. The destruction process has a kinetic nature [4], wherein interatomic bonds is carried out by thermal fluctuations, as well as the distribution of heat on the material is uneven, and unevenly distributed, the magnitude of the energy barrier required for the atom to overcome the attraction of neighboring atoms. Therefore, the intensity of the released elastic energy as the failure criterion defined in the end point of the crack, unable to establish the fact of destruction of the material, since the crack development will include previously uninvolved ties or ties that require any long (is the emphasis) the magnitude of the energy barrier to rupture. In this regard, it is advisable to consider the energy expended for the destruction of a representative volume of the material, i.e. its energy intensity, taking into account all the above disadvantages of the criterion proposed by the mechanics of destruction.

The study of the proposed criterion of destruction and the influence of the factor on it in this article is carried out on samples of aerated concrete. This material has a low average density, low sound permeability and thermal conductivity, which allows it to be used as enclosing structures [2, 3, 5, 6,7]. Due to the presence of these properties, as well as sufficient strength, aerated concrete is widely used not only in low-rise construction as structural blocks for self-supporting walls, but also in multi-storey monolithic frame construction as filling blocks enclosing structures and partitions. The properties of this material significantly depend on the density, loading speed and degree of moisture saturation, so they are taken as factors. Therefore, density, loading rate and water saturation are taken as factors.

Research in the field of autoclaved aerated concrete (SOCHI) has been developed by leading industry institutes and laboratories of the USSR (such as Nepielietotas (Tallinn), Nepielietotas (Minsk, Belarus), laboratory of autoclaved materials (Voronezh), etc.). From the position of fracture mechanics, the SOCHI were investigated E M Chernyshev [5].
This article aims to study the intensity of destruction and the influence on it of factors such as: plotnosit, loading rate, water saturation.

Tasks:
1. Sample preparation;
2. Planning experiment;
3. Testing;
4. Building a regression line;
5. Analysis of the result.

2. Method of research
For the experiment we have undertaken, we used the method of physical modeling of the process of destruction of small samples as representative volumes of the material under study. Samples of aerated concrete of cubic shape with dimensions of 100x100x100 mm were destroyed by applying a compressive load on two opposite faces of the cube on a mechanical press such as SHIMADZU AG-X, 250kN-300kN (Figure 2). The load on the sample was applied at a constant speed of movement of the upper plate of the press. The press is equipped with digital sensors of force and movement of the top plate with a strain gauge system of measured values with a signal to the PC via an intelligent interface Converter. The information-measuring system provided fixation of force and displacement values with a measurement discreteness of 0.01 sec. The force sensor has class 1 (1%) and resolution 1/1000, the travel sensor also has class 1(1%).

Simultaneously with the recording of the file array of values of the studied variables was filming the process of destruction of the sample digital camera type AOS/PROMON 500 Streaming High-Speed Camera to analyze the development of the system of cracks, chips, etc.

The obtained values of the investigated values after processing make it possible to plot the dependences of the effective specific energy - the criterion of destruction of aerated concrete for the selected factors: water saturation of the material, its density and loading speed.

3. The parameters of the material
Samples for testing are obtained from two blocks of autoclaved aerated concrete manufactured according to GOST 31360-2007 at the factory OOO "FORCE BET" in Primorsky Krai. According to the passport of the plant, the blocks when shipped from the factory in a "dry" state have 25% moisture, and one has the marking: B3.5 – strength, D600 – density, F75 – frost resistant, the other block, B2, respectively,5, D500 and F75. Further in the work the samples are designated as D500 and D600.

The basis for quantitative assessments of the strength of aerated concrete is its porosity. It is important to know both the overall porosity and pore size distribution, which determines the density of this material and, as a consequence, the strength, since the thickness of the interpore partition of cement stone depends on the relative volume of the sample. Therefore, several sections of aerated concrete samples were studied to obtain data on the porosity of aerated concrete using a microscope Nikon Eclipse MA200 in reflected light in the laboratory of the center for collective use of the FEFU school of Engineering. The resolution of the instrument allows to determine the pores and irregularities with sizes of 0.005 mm. the results of the study the porosity of concrete specimens for testing the energy intensity of destruction are shown below in figures 1, 2 and table 1.
Figure 1. Type of pore structure of aerated concrete: a – grade D500; b – grade D600.

Table 1. The results of the analysis of pores of aerated concrete grades D500 and D600.

|                | D500              | D600 |
|----------------|-------------------|------|
| The number of fields of view | 1                 | 1    |
| The analyzed area, sq. Km      | 18908             | 18908|
| Porosity, %                    | 1.6               | 1.1  |
| The number of pores            | 143               | 126  |
| Minimum size, microns          | 0.3               | 0.3  |
| The maximum size, microns      | 8.4               | 7.9  |
| The average size, microns      | 1.1               | 0.9  |
| Standard deviation, microns    | 1.3               | 1.1  |
| The maximum interparticle distance, microns | 91.3             | 135.5|
| The minimum interparticle distance, microns | 0.6              | 0.7  |
| The average interparticle distance, microns | 12.4             | 13.4 |

Figure 2. Graphs of pore diameter distribution: a) grade D500; b) grade D600.

3.1. Preparation of samples for testing
The samples were obtained by sawing large factory-made blocks and soaking half of them for experiments.

3.2. Sawing unit for cubic samples
Each factory unit dimensions mm 100x400x600 was previously marked to obtain cubic samples with the size of the face 100x100 mm Sawing units was carried out with the help of hand hacksaw. Special
attention during sawing was paid to the evenness of the cut and the parallelism of the new faces. Each sample was measured, weighed and labeled; the data recorded in the log. Faces, the parallelism of which is secured by factory cutting of the original array of parallel cutters (circular saws), was marked on the samples as a work area for loading.

3.3. Study of the process and volume of water absorption of aerated concrete

Full soaking the cubes in water, we undertook to, first, to accurately determine the speed and degree of their saturation, and secondly to determine the change in their compressive strength using the intensity of the destruction of the wet concrete compared to dry. In the process of soaking, two prototypes were weighed in fixed time intervals: 30 minutes; 1, 2, 3, 4 hours and 12 hours; their mass in the water-saturated state was fixed. The results are presented as a graph in Figure 3.

The graph shows saturation curves degenerate into a horizontal line, i.e. samples of the brand D500-class 2.5 MPa and brands D600 class 3.5 MPa has absorbed the maximum amount of moisture for 2.5 h. Graphs show the relative value of the mass of pore water of saturated sample in comparison with its mass in the initial "dry" state.

The results suggest that at the time when the water saturation curve degenerated into a horizontal line, i.e. the rate of water absorption became zero, the samples absorbed the maximum amount of moisture. Based on this, the samples - cubes of aerated concrete were kept in water for at least three hours, in the future water-saturated samples were tested on the press. Tested samples in factory production in the" dry " state have 25% humidity. The results obtained by us during the soaking of the samples are presented in Figure 3, talk about a very high rate of water absorption of this material, so the results of the planned study should give an understanding of the influence of this parameter on the strength parameters of aerated concrete.
3.4. Planning experiment

**Table 2.** Matrix of experiment planning.

| Factors            | Z1   | Z2   | Z3   |
|--------------------|------|------|------|
| Density, kg/m³     | 550  | 50   | 500  |
| Strain rate, mm/s  | 3    | 2    | 0.5  |
| Humidity           | 0,5  | 0.5  |

| Experience Number  | Factor Variation Levels |
|--------------------|-------------------------|
| 1                  | +                       |
| 2                  | -                       |
| 3                  | -                       |
| 4                  | +                       |
| 5                  | +                       |
| 6                  | -                       |
| 7                  | +                       |
| 8                  | -                       |

As a model adopted "black box". Input parameters (factors) are by definition uncorrelated, compatible and vary, as shown in table 2. As for the variation of the humidity level of aerated concrete, the minimum level is 0, "dry". For the maximum level, which is indicated by the symbol 1, adopted "water-saturated".

A characteristic of the complexity of the object of study is the number of different States of the sample as a result of its loading on the compression fracture test press, taken by it at different, non-repeating levels of variation of factors, which is equal to $N = 2^3 = 8$. Thus, in the matrix of experiment planning it is necessary to have 8 lines-experiments (table 2).

4. Testing

A cubic sample of aerated concrete with known density and humidity, selected according to the planning matrix, was placed between the press plates in parallel.

The upper press plate having hinged to its upper movable frame is set to a constant in the experience of speed, according to the matrix of experiment planning. During the experiment, the behavior of the sample is recorded by video. To exclude accidental loss of any experience from the analysis, it was customary to test 3 samples in each of them. Tests of water-saturated samples were carried out not less than 6 hours after their immersion in water, the sample was tested as soon as it was taken out of the water.

The force of influence on the sample and the movement of the loading plate are the main parameters of the loading process of the sample, read with a discreteness of 0.1 s and recorded in digital format on a laptop for further processing of the results. The sample is loaded to the complete loss of its load-bearing capacity as a structure, i.e. to the destruction of one of the splitting options, as the corresponding entry in the log is made.
5. Experimental result

Typical patterns of destruction of dry and wet samples are shown in the photos (figure 4 and 5).

Figure 4. A characteristic type of destruction of the sample of dry aerated concrete D600.

Figure 5. A characteristic type of destruction of the sample of water-saturated aerated concrete D600.

As a result of experiments were obtained values of specific energy of fracture of concrete $\varepsilon_{cr}$, which was calculated as the quotient of spent on the destruction of the sample energy $U_e$ of the testing machine to the volume of the tested sample $W$. The output value $y_i$ (specific crushing energy $\varepsilon_{cr}$) for the three samples in each experiment and the statistical characteristics of the obtained values of the studied quantities are summarized in table 3. The maximum dispersion of the energy intensity of destruction is observed in experiment 1, and the minimum in experiment 5. The values of deviations are due to the different internal structure of the samples, as well as the errors of the test machine. In the water-saturated state (experiments 5-8) the specific energy intensity decreased significantly due to the influence of moisture on the cement stone in the samples of aerated concrete.

Table 3. Specific energy to failure ($N \cdot mm/cm^2$), statistical characteristics.

| №  | $y_1$ | $y_2$ | $y_3$ | The average $\bar{y}$ | Selective dispersion |
|----|-------|-------|-------|-----------------------|----------------------|
| 1  | 29,56 | 31,01 | 33,93 | 31,50                 | 4,95                 |
| 2  | 29,17 | 25,25 | 27,79 | 27,40                 | 3,95                 |
| 3  | 18,83 | 19,43 | 20,86 | 19,71                 | 1,09                 |
| 4  | 10,52 | 13,55 | 13,09 | 12,38                 | 2,67                 |
| 5  | 25,21 | 24,99 | 26,08 | 25,43                 | 0,33                 |
| 6  | 16,73 | 15,30 | 15,93 | 15,99                 | 0,51                 |
| 7  | 6,86  | 10,82 | 9,58  | 9,08                  | 4,11                 |
| 8  | 6,39  | 6,56  | 7,81  | 6,92                  | 0,60                 |

The average value of the variance: 2,28
The standard deviation of the coefficients: 0,31
It is accepted for the given problem that the mathematical model connecting specific energy of destruction with values of the factors lying in an interval between their upper and lower levels has the form of a linear dependence of a kind:

\[ y = f(x_1, x_2, x_3), \]

where \( x_1, x_2, x_3 \) are factors in the interval between the lower and upper levels.

Equation (2) for the case of the study of the influence of three factors on the output parameter \( y \) (specific energy of destruction) is written as a linear regression equation:

\[ y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3, \]

where \( b_0, b_1, b_2, b_3, b_{12}, b_{13}, b_{23}, b_{123} \) – coefficients of the regression equation for the selected factors and their combinations.

To calculate the coefficients of the regression equation (3), a system of equations is composed:

\[
\begin{align*}
  b_0 + b_1 + b_2 - b_3 + b_{12} - b_{13} - b_{23} - b_{123} &= 31,50, \\
  b_0 + b_1 - b_2 - b_3 - b_{12} + b_{13} - b_{23} + b_{123} &= 27,40, \\
  b_0 - b_1 - b_2 + b_3 - b_{12} + b_{13} + b_{23} - b_{123} &= 19,71, \\
  b_0 - b_1 - b_2 - b_3 + b_{12} + b_{13} + b_{23} - b_{123} &= 12,38, \\
  b_0 + b_1 + b_2 + b_3 + b_{12} + b_{13} + b_{23} + b_{123} &= 25,43, \\
  b_0 - b_1 + b_2 - b_3 - b_{12} + b_{13} + b_{23} - b_{123} &= 15,99, \\
  b_0 - b_1 + b_2 - b_3 - b_{12} + b_{13} - b_{23} - b_{123} &= 9,08, \\
  b_0 - b_1 - b_2 + b_3 + b_{12} - b_{13} + b_{23} - b_{123} &= 6,92. \\
\end{align*}
\]

The values of the regression coefficients calculated by the least squares method based on the results of the experiments are presented in (Table 4).

**Table 4. Calculated regression coefficients of the system of equations (4).**

| \( b_0 \)    | \( b_1 \)   | \( b_2 \)   | \( b_3 \)   | \( b_{12} \) | \( b_{13} \) | \( b_{23} \) | \( b_{123} \) |
|--------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 18.55        | 6.53        | 2.88        | 4.20        | 0.51        | 0.18        | 0.02        | 1.31        |

The coefficients obtained by the calculation were checked for significance using the student’s criterion according to the formula (5):

\[
\begin{align*}
  \text{if } |b| > \bar{b} = t_{kp} \cdot S_{coef} &\quad \text{the coefficient is significant}, \\
  \text{if } |b| < \bar{b} = t_{kp} \cdot S_{coef} &\quad \text{the coefficient insignificant},
\end{align*}
\]

where \( t_{kp} \) – student test; \( S_{coef} \) – the standard deviation of the coefficients from their mean.

\[ t_{kp} = f(\alpha; k) = f[0.05; 16] = 2.12, \]

where \( \alpha \) – the level of significance in relative units \( \alpha = 0.05 \); \( k = n(m-1) \) – degrees of freedom; \( n \) – the number of experiments with variants of factors; \( m \) – the number of experiments in each experiment. In this case, \( k = 12 \), and the index of the significance level of factors \( \bar{b} = 0.65 \).

Based on the 5% level of sensitivity of the investigated value to the change of a single factor, the mathematical model describing the specific energy consumption for mechanical destruction of the sample of aerated concrete compressive load, takes the form:

\[ y = 18.55 + 6.53x_1 + 2.88x_2 - 4.20x_3 + 1.31x_1x_2x_3. \]

Checking the adequacy of equation (7) with significant coefficients, performed using Fisher's criterion, showed \( F_{calc} = 0.76 < F_{tab} = 3.2 \), that the obtained equation adequately reflects the results of the experiment, i.e. the chosen mathematical model corresponds to the statistics of the data obtained from the experiment.

Typical graphs of energy intensity of destruction of concrete on the speed of deformation of samples of brands D600 and D500 are depicted in figures 6, 7. Additional velocity values \( (v_1 = 0.05 \text{ mm/s and } v_2 = 1.00 \text{ mm/s}) \) were chosen to estimate the effect of traverse velocity outside the considered
range of variation on the energy intensity of aerated concrete destruction. The results are shown in (Figure 7). The General graph of change of energy intensity of destruction of concrete samples of grades D500 and D600 depending on the factors influencing it is shown on (Figure 8).

6. Discussion of experimental results
According to table 5, it can be seen that the energy intensity of the material has a small dispersion and all values are concentrated near its mathematical expectation.

Based on the obtained linear regression equation (6), it follows that we can state: all the studied factors influence: density and humidity of aerated concrete, as well as the rate of its loading, affect the energy intensity of destruction. The influence of paired interactions of these factors on the investigated parameter was significant only in the case of interaction of three factors at once.

Graphs (figures 6-8) illustrate that the specific energy of destruction of samples of aerated concrete in the dry state increases with increasing speed. This is due to the fact that in the areas of stress concentrators, such as microcracks, pores, cavities, there is loosening of the cement stone structure as a result of the movement of dislocations of its crystal lattice, so the promotion of the breakaway crack requires more energy to achieve the maximum stresses in the zones of their concentration to break the bonds of the cement stone structure and the formation of new surfaces.

Since at higher energy the speed of its absorption of the structure remains constant, characteristic for this material in the dry state, plastic deformations in cement stone does not have time to develop in proportion to the increase of elastic deformation, thus absorbing a portion of incoming energy. Therefore, the destruction of the samples of AAC is a brittle type. In the case of brittle destruction of aerated concrete, destruction with the presence of sound was also observed, which is due to the inability of the surface of the formed crack to perceive all the elastic potential energy of deformation, which leads to its release in the form of a sound wave that propagates energy in the air.

![Figure 6. Schedule changes in the energy intensity of destruction of aerated concrete brand D500 depending on the course of the traverse: a-dry; b-wet.](image-url)
In the speed range of 0.1–1.0 mm/s, a linear change in the energy intensity of the samples is observed (Figure 9), however, in the range of 0.05–0.1 mm/s, the dependence is nonlinear as a result of the active development of plastic deformations.

In the water-saturated state, the energy intensity of destruction of aerated concrete is reduced, which corresponds to a decrease in its mechanical characteristics.

However, the nature of the change in the specific potential strain energy of samples in the water-saturated state (Figure 9) at a speed range of 0.05–0.5 mm/s radically different from the nature of the same curve for dry samples.

7. Summary
To achieve the goal of our study, tests were conducted that allowed us to obtain the following results:
1. With increasing density the energy intensity of destruction increases;
2. In the "dry" state, at a deformation rate of 0.1-0.5 mm/s (0.1-1 mm/s) for D600 (D500) samples, there is an increasing linear relationship between the energy intensity of destruction and the speed;
3. In the "dry" state, at a strain rate of 0.01-0.1 mm/s, there is an increasing nonlinear relationship between the specific fracture energy and the velocity for the D500 grade;
4. In the "dry" state of samples, the destruction is fragile.
5. Complete water saturation of samples significantly reduces the specific energy of destruction;
6. For water-saturated samples of D600 grade at a speed of 0.1-0.5 mm/sec (0.1-1 mm/s), there is an increasing linear relationship between the specific energy of destruction and the velocity;
7. For water-saturated samples of the D500 brand at the rate of deformation in the range of 0.01-0.1 mm/s, a decreasing nonlinear relationship between the specific fracture energy and the velocity is observed;
8. In the water-saturated state of the fracture samples is viscous.
In the results observed anomaly of increase of specific energy of destruction of the brand D500 saturated aerated at a rate of deformation in the range of 0.01-0.1 mm/s. Based on these results it becomes obvious the need for further research in two directions.
First, it is necessary to expand the range of application rates of the load, especially in the left part of the scale and to Supplement the proof of the existence of a critical loading rate, for which the emerging anomaly of increasing the energy intensity of destruction for moistened aerated concrete is possible.
Second, to complement the study of the energy intensity of destruction of aerated concrete normal humidity for different values of porosity and pore size ratios.

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