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THE INFLUENCE OF EXPLOSIVE CHARGE DESIGN ON THE CHARACTER OF SOLID MEDIUM FRAGMENTATION

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Abstract. Underground extraction of mineral resources using blasting methods is accompanied by the release of dust and gases into the mine atmosphere. This factor becomes particularly significant with the intensification of technological processes and in cases of ventilation system malfunction. The purpose of the work is to research the influence of explosive charge design, type and parameters of stemming on the processes of solid medium fragmentation. Stemming, in the context of blasting and drilling, refers to the process of filling a borehole with a stemming material, typically a granular substance like crushed rock or sand, after the explosive charge has been placed. This creates a plug that confines the explosive energy, improving the efficiency and safety of the blast. Experimental studies were conducted to determine the total mass concentration of fine dust particles during the fragmentation of sand-cement models using explosive charges, as well as to observe the dynamics of crack development in organic glass models subjected to blast-induced fragmentation. Stemming of the charge cavities was carried out using materials of varying lengths and compositions. It was established that, during the explosive fragmentation of sand-cement models, there are two distinct ranges of change in the mass concentration of fine dust particles. In the first range, the concentration increases proportionally with the relative length of the stemming. In the second range, an inverse relationship is observed as the relative stemming length increases, the concentration decreases. In particular, the lowest dust concentration was observed when a hardening expansion mixture was used as stemming, whereas the highest concentration occurred with sand stemming. This effect can be attributed to the redistribution of explosive energy along the charge length and the reduction of specific impulse in the near-blast zone, where intense fragmentation of the solid medium occurs. It was also found that, at the initial stage of explosive fragmentation in organic glass models, a network of cracks forms along the entire charge length. In the final stage of fragmentation, an oriented system of cracks develops in the end part of the charge and extends into the depth of the model. The use of a hardening stemming mixture leads to prolonged containment of detonation gases and more efficient utilization of explosive energy. As a result, compared to other types of stemming, cracks of greater length are formed in the end zone of the charge cavity in the organic glass models.

Keywords: explosive fragmentation, dust particles, mass concentration, charge cavity, stemming, network of cracks.

1. Introduction

At the current stage, underground mineral extraction is characterized by increasing mining depths, intensified production processes, and deteriorating ventilation conditions in both production and development areas. The excavation of mine workings in hard rock requires the use of drilling and blasting operations. These processes release dust and harmful gases into the mine atmosphere, resulting in air pollution and a decline in working conditions for miners.

During the detonation of explosives at the "explosive - rock" interface, a zone of plastic deformation or over crushing zone is formed, producing fine dust fractions [1], or alternatively, an "amorphisation" zone [2], followed by the development of a network of radial cracks around the explosive charge.

When driving preparatory mine workings in mines and shafts using explosive energy, dust particles are released into the mine atmosphere. Dust formation is associated with fragmentation, granulation, cracking of mineral grains, increased quartz content, and other factors.

Drilling and blasting operations are the primary sources of dust emissions. The concentration of airborne dust is influenced by several factors, including:

- physical and mechanical properties of the rock [3];

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- properties and mass of the explosive charge;
- method and sequence of blasting operations;
- cross-sectional area of the mine working.

Analysis of modern research and publications. The results of studies on the blasting-induced rock fragmentation [2] indicate that up to 50% of dissipative energy losses at the "explosive - rock" interface are due to the formation of solid particles with diameters of up to 1 μm. It has also been established that the type of stemming used in explosive charges significantly influences the nature of the rock's fragmentation. In particular, the study presented in [4] includes experimental investigations into the explosive fragmentation of cylindrical granite specimens with a diameter of 240 mm and a length of 300 mm. The analysis of the results showed that using sand stemming led to a higher degree of granite fragmentation compared to partial steel stemming. A mechanism for the explosive fragmentation of rock was proposed in [5], suggesting that thermal stresses may be one of the primary causes of material failure. Additionally, the authors considered the transition of the crystal components' microstructure into an unstable state, caused by supersaturation with linear and point defects, as a contributing factor. In [6], the authors presented experimental findings on the influence of geological conditions and blasting parameters in a limestone quarry on the size distribution of rock fragments and the proportion of fine particles. It was shown that the use of explosives with varying detonation characteristics allows for the control of fine particle content in the fragmented rock. In [7], the Riedel-Hiermaier-Thoma model was applied to the fragmentation of rock masses. The study examined how different explosive charge configurations affect the fragmentation behavior. To improve the effectiveness of the explosive process, eccentric charge geometries were employed. The study in [8] involved both physical and numerical modelling to assess the kinetics of fragmentation and the influence of explosive charge design on the rock. The research investigated the fragmentation process of cylindrical samples destroyed by explosion, the evolution of dynamic stresses, and the formation of fine solid particles. Finally, [9] presents a review and analysis of existing models for evaluating zones of crushing and fracturing resulting from blasting. These models are based on analytical, numerical, and experimental approaches.

One of the shortcomings of studies aimed at establishing the patterns of rock fragmentation by explosive charges lies in the ambiguity surrounding the description of the interaction mechanisms between detonation waves and the walls of explosive cavities, as well as their propagation through solid media. In particular, the influence of rock structure on the nature of its failure under the action of short-term dynamic loads remains insufficiently understood. Preference is often given to numerical modelling, the results of which do not always correspond to real-world observations.

The previously unsolved part of the problem. The mechanism of rock fragmentation by blasting remains an insufficiently studied subject. In particular, this applies to the influence of explosive charge designs on the processes of rock comminution within the brittle fragmentation zone and the mechanisms of crack formation. A deeper understanding of these processes enables improved efficiency of blasting operations and contributes to the reduction of harmful dust and gas concentrations in the working area during underground excavation.

The purpose of the work is to research the influence of explosive charge design, type and parameters of stemming on the processes of solid medium fragmentation.

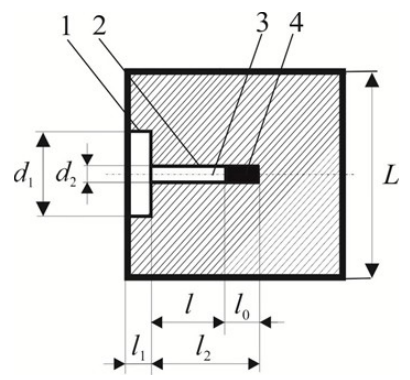
2. Methods

The research results presented in this study were obtained using methods of physical modelling of explosive rock fragmentation.

Research Objectives. The research includes the determination of the mass concentration of fine dust particles generated during the explosive fragmentation of solid media, and the analysis of crack formation processes associated with different stemming types and parameters.

3. Experimental Part

Experimental studies of the dust release process during explosive fragmentation of solid media were carried out on models at the Institute of Geotechnical Mechanics named by M.S. Poliakov of National Academy of Sciences of Ukraine (IGTM NAS of Ukraine). Due to the complexity of conducting experiments to justify the designs and parameters of borehole explosive charges under industrial conditions, a method of physical modelling of solid medium fragmentation processes using scaled models was chosen (Fig. 1)



1 – cavity simulating part of the mine working; 2 – charging cavity simulating a borehole; 3 – stemming; 4 – explosive charge; d_1, d_2 – cavity diameters, m; l_1, l_2 – cavity lengths, м; l_0 – length of the explosive charge, m; l – stemming length, m

Figure 1 – Schematic of the experimental model

Cubic-shaped models were cast in pre-prepared forms using a sand–cement mixture. Once the models had reached 30% of their ultimate compressive strength, they were removed from the forms and subsequently cured in open air until full strength was achieved [10]. The physical properties of the sand–cement models were as follows: compressive strength – 13.5 MPa; density – 1910 kg/m³; longitudinal wave velocity – 3080 m/s.

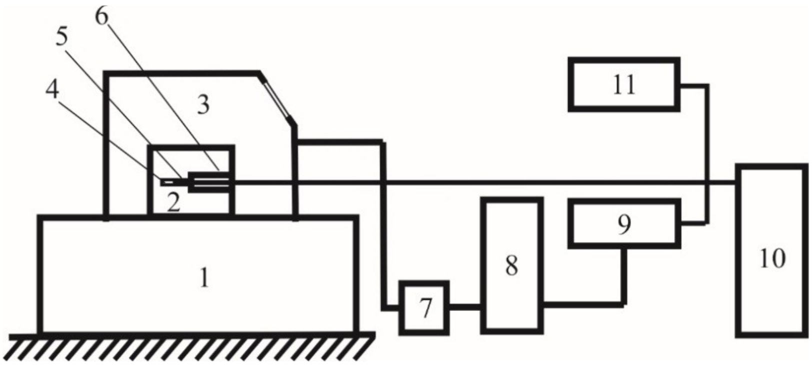
After the creation of the cubic model, cylindrical cavities were successively formed at the center of one of its faces (Fig. 1). The first cavity simulated a section of a rock excavation, while the second represented a blast borehole. In preparing the sand–cement models, it was ensured that the borehole diameter was not less than the critical detonation diameter of the explosive – the minimum diameter of a cylindrical explosive charge required for sustained detonation along its length.

A charge composed of a mixture of pentaerythritol tetranitrate (PETN) (80%) and solid rocket fuel (20%) was placed into the borehole. The total mass of the explosive charge was 200 mg.

Geometric parameters of the model: L = 150 mm; $d_1 = 0.5 \cdot L$; d_2 = 7 mm; $l_1 = 0.25 \cdot d_1$; $l_2 = (2/3) \cdot L$; l_0 = 20 mm. The relative stemming length varied from $l/l_0 = 2.6$ to $l/l_0 = 5.6$.

The mouth of the borehole was sealed using the following types of stemming: sand stemming with a grain size of 0.25 mm; clay stemming; sand-clay stemming; and an expanding compound that solidifies upon curing.

The total mass concentration of fine dust particles produced by the explosive fragmentation of the sand–cement models was measured using a dedicated experimental rig (Fig. 2)



1 – site for samples and equipment; 2 – model; 3 – explosion chamber; 4 – explosive charge; 5 – stemming; 6 – cavity for simulation of mine workings; 7 – mini vacuum pump; 8 – dust accumulation tank; 9 – dust meter; 10 – explosive network initiator; 11 – notebook

Figure 2 – Block diagram of the stand for experimental studies of dust emission processes during explosive fragmentation of models

A sand-cement model was placed inside a blast chamber (Fig. 2), where the detonation of an explosive charge was carried out using an electronic device. Subsequently, suspended dust particles were collected following the partial or complete fragmentation of the model using a miniature vacuum pump. The resulting gas–dust flow was directed into a container for dust accumulation. The mass concentration of solid particles (up to 100 μm) was measured using a dust meter. The obtained values of mass concentration, along with video surveillance data, were transmitted to a laptop for further processing.

Experimental studies on the crack formation process during explosive fragmentation of models made of optically active materials were carried out at the IGTM NAS of Ukraine. The experiments were conducted under laboratory conditions using three-dimensional models made of organic glass.

The models were rectangular prisms with dimensions of 200 × 200 × 150 mm. The model size was chosen to eliminate the influence of free surfaces on the development of the cracking zone caused by reflected stress waves.

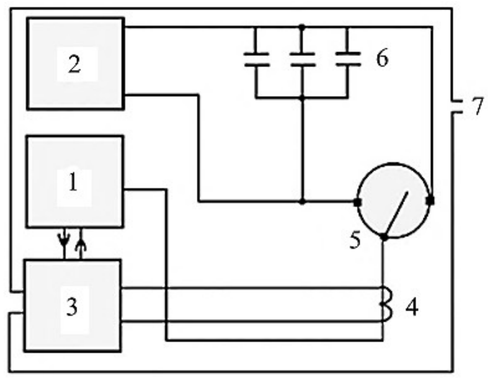
The time required for the formation of the crack zone should not exceed or fall short of twice the time needed for the compression wave to travel to the model boundaries. Therefore, the linear dimensions of the model must be at least twice the extent of the cracking zone.

In the prepared models, a charge cavity (simulating a blast hole) was drilled at the center of one face, measuring 105 mm in length and 6 mm in diameter.

The mouth of the blast hole was sealed using the following types of stemming: a sand-clay mixture; sand with a grain size of 0.25 mm; and a swelling compound that expands upon hardening. The length of the stemming varied from 20 mm to 22 mm. The mass and composition of the explosive mixture, as well as the length of the charge cavity, were identical to those used in the dust concentration experiments (Fig. 2).

During the experiments, a test setup was employed consisting of the following equipment: a high-speed video recording system; a strobe lamp; a lens system for focusing the light flux; a control panel; a blast chamber; storage capacitors; and an electronic device for synchronizing the detonation with the strobe flash.

Figure 3 presents a block diagram of the recording system for the process of explosive fragmentation of organic glass models.

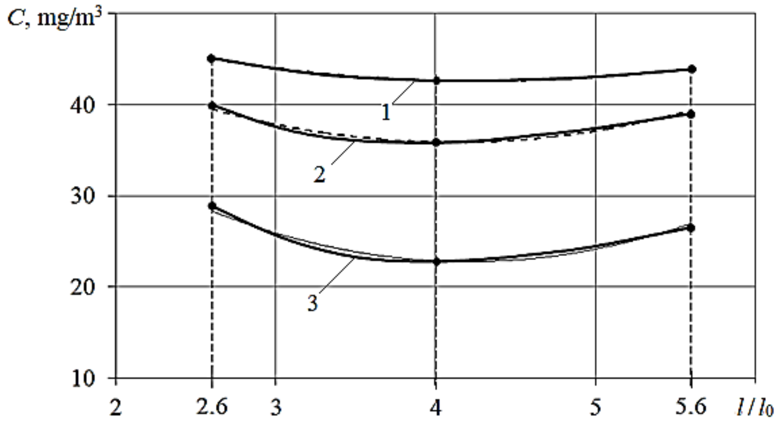


1 – control panel of the video surveillance installation; 2 – high voltage source;
3 – device of synchronization and delay of detonation of electric detonators;
4 – start coil of the synchronization device; 5 – pulse lamp; 6 – shop of capacitors;
7 – electric detonator.

Figure 3 – Block scheme of the system for recording explosive fragmentation of models

4. Results and Discussion

Figure 4 shows the experimental relationship between the total mass concentration of fine dust particles released during explosive fragmentation of sand–cement models and the relative stemming length and its type.



- - - - – regression curves; 1 – sand stemming; 2 – clay stemming; 3 – cemented stemming

Figure 4 – Dependence of the total mass concentration of fine dust particles during explosive fragmentation of sand-cement models on the relative length and type of stemming

The analysis of the obtained results (Fig. 4) shows that at a relative stemming length of l/l_0 = 2.6, the maximum mass concentration of fine dust released during explosive fragmentation of the models is observed. For sand stemming, clay stemming, and cemented stemming, the peak values of dust concentration are 45 mg/m³, 40 mg/m³, and 29 mg/m³, respectively. When the relative stemming length increases to l/l_0 =4.0, the dust concentration decreases by 7.0%, 11.25%, and 22.4%, respectively. However, when l/l_0 > 4.0, a reverse trend is observed.

Thus, the highest dust emission is characteristic of sand stemming, while the use of cemented stemming results in the lowest dust concentration. This pattern can be explained by the redistribution of the explosive energy along the charge length and the reduction of the specific impulse in the near-field zone of the explosion, where intense fragmentation occurs. The radius of this zone varies from 2*R* to 10*R*, where *R* is the charge radius, m.

Based on experimental data, regression equations were derived (Fig. 4):

- for sand stemming

$$C=0.8381\cdot(l\cdot l_0^{-1})^2-7.2197\cdot l\cdot l_0^{-1}+58.131,\ R^2=0.9878;$$

- for clay stemming

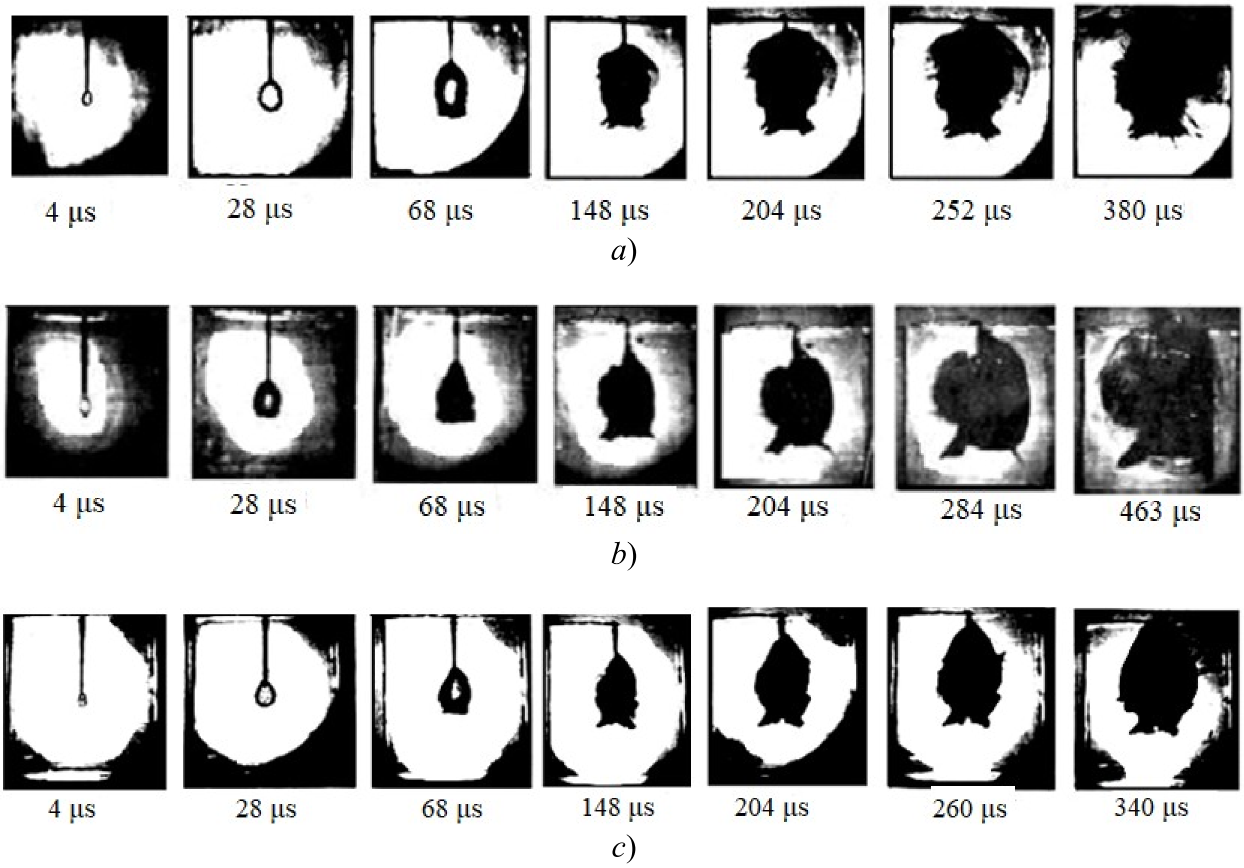
$$C=1.592\cdot(l\cdot l_0^{-1})^2-13.098\cdot l\cdot l_0^{-1}+62.805,\ R^2=0.9418;$$

- for cemented stemming

$$C=2.1606\cdot(l\cdot l_0^{-1})^2-18.174\cdot l\cdot l_0^{-1}+60.981,\ R^2=0.9556,$$

where R represents the approximation error.

Figure 5 presents photographic results of the explosive fragmentation process in organic glass models for different stemming types at a relative stemming length of l/l_0= 5.4



(*a*) sand-clay stemming; (*b*) sand stemming; (*c*) cemented stemming

Figure 5 – Photographic recording of explosive fragmentation of organic glass models at different time intervals

The analysis of Figure 5 shows that 10 μs after charge detonation, the shock wave front generates a stress wave that propagates along the charge axis toward the model's free surfaces. As a result, by 68 μs, a network of cracks is formed along the entire length of the charge. Subsequently, the explosion cavity expands, and the crack network continues to develop deeper into the model from the charge face.

It was established that the onset time of ejection for sand-clay (Fig. 5, *a*) and sand stemming (Fig. 5, *b*) ranges between 340 μs and 380 μs, while for cemented stemming (Fig. 5, *c*) it ranges between 450 μs and 480 μs.

The analysis of Fig. 5, *a* reveals that, when using sand-clay stemming, the fragmentation front assumes an elliptical shape in the time interval from 4 μs to 68 μs. In the bottom part of the blast cavity, cracks form and extend into the model to depths of three to five charge diameters.

In the case of sand stemming (Fig. 5, *b*), the crack lengths are reduced. In the direction of the charge cavity collar, the fragmentation crater volume increases, accompanied by the formation of a developed crack network.

Figure 5, *c* shows that with cemented stemming, the formation of a stress wave front initiates progressive fracturing into the model, alongside an enlargement of the fragmentation crater towards the collar of the charge cavity.

At the final stage, the fragmentation front exhibits a complex configuration consisting of an oriented crack network at the charge face, extending into the model primarily at angles ranging from 45° to 50° (Fig. 5). Furthermore, when cemented stemming is used, the crack lengths are 1.5 to 2 times greater compared to the other stemming types.

5. Conclusions.

The research allows us to draw the following conclusions.

1. During the explosive fragmentation of sand-cement models with different stemming types, a reduction in the mass concentration of fine dust particles is observed as the relative stemming length increases from 2.6 to 4.0. The lowest dust concentration is recorded when using a hardening (cementitious) stemming mixture, whereas the highest concentration occurs with sand stemming.

2. At 68 μs after the detonation of the explosive charge, a network of cracks forms along the entire length of the charge cavity in the organic glass model. In the final stage of the fragmentation process, an oriented fragmentation network develops in the end zone of the cavity, with cracks propagating into the model at angles predominantly between 45° and 50°. Notably, the crack lengths when using hardening stemming are 1.5 to 2 times greater than those observed with sand or sand–clay stemming.

3. The use of a hardening stemming mixture increases the duration of confinement for the detonation gases, thereby reducing the consumption of explosive material and decreasing the generation of fine dust particles.

Conflict of interest

Author states no conflict of interest.

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ВПЛИВ КОНСТРУКЦІЇ ЗАРЯДІВ ВИБУХОВОЇ РЕЧОВИНИ НА ХАРАКТЕР РУЙНУВАННЯ ТВЕРДОГО СЕРЕДОВИЩА

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Анотація. Підземна розробка корисних копалин вибуховим способом супроводжується викидами в рудникову атмосферу пилу та газів. Цей фактор найбільш виражений у разі інтенсифікації технологічних процесів і порушенні роботи систем вентиляції. Метою роботи є дослідження впливу конструкцій зарядів вибухової речовини, типу та параметрів набивок на процеси вибухового руйнування твердого середовища. У контексті вибухових і бурових робіт набивка означає процес заповнення свердловини забійним матеріалом, зазвичай сипучою речовиною, такою як подрібнена порода або пісок, після розміщення вибухового заряду. Це створює своєрідну «пробку», яка стримує вибухову енергію, підвищуючи ефективність і безпечність вибуху. Було проведено експериментальні дослідження по визначенню загальної масової концентрації дрібнодисперсних частинок пилу при руйнуванні піщано-цементних моделей зарядами вибухової речовини та динаміки розвитку тріщин при вибуховому руйнуванні моделей з органічного скла. При герметизації зарядних порожнин використовувалися набивки змінної довжини із різних матеріалів. Встановлено, що при вибуховому руйнуванні піщано-цементних моделей існує два діапазони зміни масової концентрації дрібнодисперсних частинок пилу. У першому діапазоні величина масової концентрації збільшується прямо пропорційна відносній довжині набивки. У другому діапазоні при збільшенні відносної довжини набивки спостерігається зворотна залежність. Зокрема мінімальна масова концентрація спостерігається при використанні набивки із суміші, що розширюється при твердінні. Максимальна масова концентрація характерна при використанні піщаної набивки. Цю особливість можна пояснити перерозподілом енергії вибухової речовини по довжині заряду, а також зниженням питомого імпульсу в ближній зоні вибуху. В цієї зоні спостерігається процес інтенсивного дроблення твердого середовища. Встановлено, що на початку процесу вибухового руйнування моделей з органічного скла відбувається формування мережі тріщин по всій довжині заряду. На завершальному етапі процесу руйнування утворюється орієнтована система тріщин, які розташовані в торцевій частині заряду і спрямовані вглиб моделі. Встановлено, що використання набивки із суміші, що твердіє, призводить до збільшення тривалості замикання газоподібних продуктів детонації та більш ефективного використання енергії вибуху. Це пояснює, що у порівнянні з іншими типами набивок, в торцевій частині зарядної порожнини в моделі із органічного скла утворюються тріщини більшої довжини.

Ключові слова: вибухове руйнування, частинки пилу, масова концентрація, зарядна порожнина, набивка, мережа тріщин.