OPTIMISATION OF NON-DETONATING CHARGES IN POLYMER HOUSINGS FOR CAUTIOUS BLASTING ACTIVITIES IN DIMENSION STONE QUARRIES

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ABSTRACT: In the extraction of large blocks of natural stone for the needs of the construction and decorative-cladding industry, the use of industrial explosives can lead to unwanted losses of expensive raw materials and to the deterioration of the exploitation characteristics of the products. The main reason for the harmful effect of the explosion on the integrity of the rock material in the extracted blocks are the high speed and the intensity of the compressive stresses, caused by the detonation of the explosives. The authors have continued their research on a variety of fast-combusting high-energetic compositions that can fully replace the widely used detonating explosives in the extraction and secondary processing of large stone blocks. Samples from structurally improved plastic containers filled with non-detonating compositions, based on waste gunpowder and metal-containing pyrotechnic mixtures, were subjected to field tests. The experiments were carried out in real conditions on stone blocks with a hardness of f = 16, regarding Protodyakonov. Depending on the lengths of the blast holes, different charge designs were used.

Key words: non-detonating blasting cartridges, propellants, smooth blasting, ornamental stone extraction

ОПТИМИЗИРАНЕ НА НЕДЕТОНИРАЩИ ЗАРЯДИ В ПОЛИМЕРНИ КОРПУСИ ЗА ПРЕЦИЗНИ ВЗРИВНИ РАБОТИ В КАРИЕРИ ЗА СКАЛНООБЛИЦОВЪЧНИ МАТЕРИАЛИ

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РЕЗЮМЕ: При добива на едрогабаритни блокове от естествен камък за нуждите на строително-конструктивната и декоративно-облицовъчна индустрия, употребата на промишлени взривни вещества може да доведе до нежелани загуби на скъпа суровина и до влошаване на експлоатационните характеристики на продуктите. Основната причина за вредното влияние на взрива върху интегритета на скалния материал в добитите блокове са високата скорост и интензитета на напреженията на натиск, породени от детонацията на взривните вещества. Авторите са продължили изследванията си върху разнообразни бързоизгарящи високо-енергетични състави, които могат да заменят пълноценно масово-използваните детониращи експлозиви при добива и вторичната обработка на скални блокове. Проби от конструктивно-подобрени пластмасови контейнери, запълнени с недетониращи състави на базата на отпадъчни барути и металосъдържащи пиротехнически смеси, бяха подложени на полеви тестове. Експериментите бяха проведени в реални условия върху каменни блокове с твърдост по Протодяконов f = 16. В зависимост от дължините на взривните дупки бяха използвани различни конструкции на зарядите.

Ключови думи: недетониращи взривни патрони, метателни взривни вещества, гладко взривяване, добив на декоративен камък

Introduction

In the article “*Non-detonating charges in polymer housings for smooth splitting of rock blocks during primary extraction and secondary cutting*”, published in the “Sustainable extraction and processing of raw materials” journal (Stoycheva and Shishkov, 2020), the authors described the construction of ready-made charges from non-detonating compositions in a hard waterproof package that would reliably protect them from external influences. Field tests in the real conditions of a stone quarry were also described. The results from the experimental blasts showed the need for additional research and field tests to increase the efficiency of the developed charges. In this report, the authors present their research in two ways:

- testing of the initial construction of the products in conditions of decoupled charges with intermediate stemming by dry sand, which aims to seal the space around the cartridges and to prevent the spillage of the composition and the pressure drop;
- constructional changes to increase the strength of the initial ignition pulse and to increase the initial area of combustion in the charge.

Theoretical foundations

To describe the explosive energy, we will consider the ideal setting of a long cylindrical explosive charge, placed in a blast hole drilled in an infinite elastic rock (slab). In case of instantaneous detonation, the energy contained in the explosive is released in three main forms: shock wave energy, stored deformation energy, and energy of rapidly expanding gaseous products. Here it is assumed, that the rock is strong enough compared to the applied explosive load.

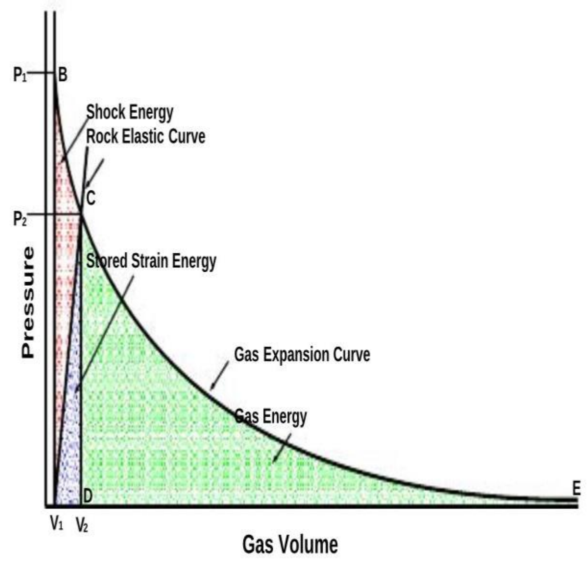

Fig. 1. Different types of energies involved in a blast

Fig. 1 shows the gas expansion and the curves of linear elastic stresses in the rock (in the P-V plane). In this figure, the area ABE below the gas expansion curve represents the total energy available in the explosive. By detonating the explosive, the pressure on the borehole wall increases iinstantly comparable to the atmospheric pressure to P_1. The outward movement of the rock under the applied pressure gives more space to the explosive gases and therefore the pressure drops to P_2, where the balance between the p pressures on the rock wall and the gas is obtained. The area ABCD below the pressure-volume curve shows the total work done by the explosive gases on the scale (Hustrulid, 1999). The DCE area corresponds to the energy remaining in the gas before it is released into the atmosphere, or in the cracks obtained from previous explosions. Due to the elastic deformation of the rock, an amount of energy equal to the area of the ACD is stored as deformation energy in the rock. The difference between the zones ABCD and ACD is the energy of the shock wave, which propagates in the rock and is realised in the form of energy of elastic deformation and kinetic energy. The initial fracture nets in the rock are created by the energy of the shock wave. The gaseous products of the explosion are responsible for the expansion of these cracks to the final fragmentation and movement of the rocks. The time is not explicitly shown in Figure 1, but it should be kept in mind that the pressure and volume of the gases change over time.

Using a charge embedded in a perforation in typical granite and given the above explanation, Hustrulid (1999) shows that only 3% of the total theoretical explosive energy contributes to the impact wave effect in the massif. It should be borne in mind that the assumption of elastic behaviour of the rock around the blast hole is not true, especially in blasting scenarios. Crushing and plastic deformation occur in this area and, therefore, the energy efficiency of the rock crushing explosive is much higher than that of the elastic wave energy (Clark, 1987). For example, for granite rock, the amount of explosive energy transmitted through the area of plasticity has been identified by Fogelson et al. (1959) as 10-18% of the total explosive energy. These results show that high-speed explosives carry more energy to the rock in the form of a shock wave than explosives with low conversion rates. In addition, changing the type of rock can affect the amount of shock wave energy released on it.

As can be seen, the part of the explosive energy consumed by the shock wave is less than 20%. However, the final result of the explosive fragmentation of the rocks depends on this energy and the resulting fracture networks.

Neither the shock wave, nor the gas pressure can be "personally" responsible for the fragmentation of the rocks during blasting; but with their combined action, they play an important role in the process of blasting the massif (Kutter and Fairhurst, 1971; Mohanty, 1982; Persson, 1994; Brinkmann, 1987).

The explosive chemical reaction in the borehole quickly changes the state of the charge from condensed material into a gaseous product with high pressure and high temperature (Bhandari, 1997; Fourney, 1993). This rapid transformation is performed with the velocity of detonation (VOD) and the resulting pressure is called the detonation pressure (Ayala Carcedo et al., 1995). The pressure of gaseous products is related to the detonation pressure and its value is usually considered to be half of the detonation pressure. The shock wave or high-intensity stress that is actually applied to the borehole walls subsequently depends on this pressure, as well as on the coupling ratio of the medium, the ratio of the charge diameter to the borehole diameter, and the rock properties.

Rocks are a porous and heterogeneous material. The existence of microcracks, discontinuities, and voids are inherent to them. Their mechanical behaviour depends on the speed of the impact and on the pressure. Concrete and rock show similar behaviour during static and dynamic loading. Also, they are strong in compression and weak under tension (Rossamanith and Uenishi, 2006). Previous studies have shown that under static uniaxial loading of concrete, the internal microcracks propagate mainly in the axial direction. These micro-defects formed as a result of tension (Bischoff and Perry, 1991) and some of them eventually merged to form the plane of damage. In the case of a load with a high level of deformation and a sharp increase in compressive stress, there is not enough time for the development or propagation of microcracks. However, many more microcracks can be activated compared to the low deformation load scenario. It has been suggested that this behavior may be the result of a transition from a state of uniaxial stress to a state of uniaxial strain without lateral dilation. Therefore, the sample cannot be unloaded radially and effective confining stress would be applied to the central core of the sample (Bischoff and Perry, 1991). This leads to a significant increase in the dynamic strength of brittle materials. Similarly, near the charge (and at least at the initial moment), the rock is almost under uniaxial strain condition (Ruest et al., 2006) with much higher values for its dynamic strength.

At this initial stage, the instantly applied shock wave on the borehole walls is in the form of compression in all three cylindrical coordinates (radial, tangential and axial). If the dynamic compressive strength of the rock is reached in this area, the so-called "shear bands" begin to form at different points along the perimeter of the borehole wall, extending to places where the compressive load falls below the rock strength. At extremely high pressures, these shear bands interconnect and pulverise the rock around the borehole (the crushed zone). The size of this zone increases with the increasing detonation pressure and depends on the tighter contact between the explosive charge and the wall of the blast hole. At the same time, the applied shock wave expands the borehole and the pressure of the gas products decreases accordingly.

As the shock wave moves away from the borehole, its magnitude falls below the size of the local dynamic compressive strength and under this condition, no shear damage occurs. When the compressive stress wave passes through the drillhole area, a tangential (hoop) tension develops behind it, which can prolong the existing disturbances in the solid medium or create new radial cracks. When there is a close free surface, the incident pressure wave turns into a tensile wave and is reflected back into the rock due to the difference between the acoustic impedances of the rock and the air. If the dynamic tensile strength of the rock is exceeded, peeling cracks appear near the free surface.

Flaws and fissures of different sizes and orientations are areas of weakness in the rocks. Under tensile loading, these available problem areas lead to crack activation and growth (Grady and Kipp, 1980; Atkinson, 1989). The growth and coalescence of these cracks during the time of load application lead to damage of the material. Slowly applied loads activate only larger defects and the stress level is not high enough to activate the smaller ones, thus contributing to the fragmentation process. Due to the smaller number of contributing defects, larger fragments can be obtained and the expected threshold for material damage is low. Conversely, by applying a load faster, higher stress levels can be achieved before the defect zones merge. In this case, the smaller size of the fragments and the higher visible threshold for damage to the solid medium are a consequence of the contribution of a larger number of defects in the fragmentation process.

During all these processes, the explosive gases invade intensively into the newly-formed cracks caused by the shock wave, looking for a way to the open face. The interaction between the explosive gases and the shear strips helps to further expand and propagate cracks in the array. In addition, the energy of the hot gaseous products transmits enough momentum to the crushed rock mass to push it away, forming a so-called "muck pile". The release of gaseous products into free space finally reduces their pressure to the level of the atmospheric pressure.

From what has been described so far, it is clear that in order to avoid the formation of unwanted cracks in the detached rock blocks and in the main massif, it is necessary to avoid detonation that creates supersonic pressure waves causing destructive stresses in the material. We should work with energetic materials which, in their explosive chemical decomposition, will not cause the spread of a shock wave in the rock environment. Low-speed explosives affect solids with the energy of gaseous products from the explosion. The non-detonating cartridges, presented by Stoycheva and Shishkov (2020), contain precisely such explosive compositions. The analyses of the field tests led the authors to the conclusion that, to improve the efficiency, some changes in the design of the products and in the way of the charge construction in the explosive holes will be needed.

Experimental part

The main aim of the present study is to continue the experiments with ready charges of non-detonating compositions in polymer housings described by Stoycheva and Shishkov (2020). The formulations published by (Shishkov and Stoycheva, 2019) have been used.

- **Mixture #1**: “flash-powder composition” 65% $KClO_4$ + 35% Al (dark) with Oxigen Balance = -1,12%;
- **Mixture #2**: 80% gridded Double base powder + 20% NH_4NO_3 prills with Oxigen Balance = -7,92%;
- **Mixture #3**: 70% gridded Single base powder + 25% NH_4NO_3 + 5% Al (dark) with Oxigen Balance = -5,19%;

The observations on the behaviour of the explosive mixtures (Mixture # 2 and Mixture # 3) were carried out in the real conditions of a quarry for the extraction of blocks from magmatic rocks with a hardness coefficient of, according to Protodyakonov, f = 16. To compare the results from the blasting of different charges, they were tested under approximately the same conditions. Rock formations with three open surfaces and a crack on the fourth side or with four open surfaces were selected. Two parallel vertical blast holes with a length of 1.80 m and a diameter of $\varphi = 38 \div 42$ mm were drilled in each of the four rocks. The distance between the two blast holes was not more than 0.60 m., so that the value of the compressive stresses in the shared zone between the two charges was sufficient to form perpendicular tensile stresses that would create a connecting crack between the holes. Under the influence of expanding gaseous products, this crack should continue to propagate evenly to the free surfaces perpendicular to its plane.

Field tests with non-modified construction of the charges in blast holes with stemmed empty spaces

In (Stoycheva and Shishkov, 2020), the authors noted, that the use of chained charges without an intermediate stemming allows for an even distribution of explosive gas pressure along the entire length of the blast hole. Thus, the compressive stresses on the walls of the hole are the same and the chance of forming a crack in an undesirable direction becomes smaller. However, the results of the tests of Mixture #2 and Mixture #3 showed a weakened explosive effect caused by the spillage of the granules in the gaps between the explosive charges. This led to the conclusion that new experiments had to be conducted, with filling the spaces between the containers with inert stemming to reduce the free volumes and to create better conditions for increasing the pressure. Ten items were filled with each of the two mixtures. The amount in one full container of Mixture #2 was 30 g and of Mixture #3 was 35 g. The ignition of the composition in the hull was again with a regular electric igniter for pyrotechnic purposes with smooth burning of the head, which was placed in the middle of the bulk charge. The prepared samples were used to build multi-deck decoupled charges in drill-holes with a larger diameter.

Chained charges of five explosive containers with the same content and air gaps of 100-120 mm between them were placed in each blast hole (Fig. 2). Thus, the total length of each “garland” charge was 1.30 m.

After the explosive chains hung in the blast holes, the gaps and free space between the containers and the walls of the hole were filled with fine sand. Thick paper plugs were placed on top of the last container and a reliable inert stemming, 0.60 m long, was built. The wires of the electric blast circuits from the two adjacent holes with equal charges were connected in parallel to the main cable. Two experimental blasts were carried out - each with the same type of charges from the respective explosive mixture.

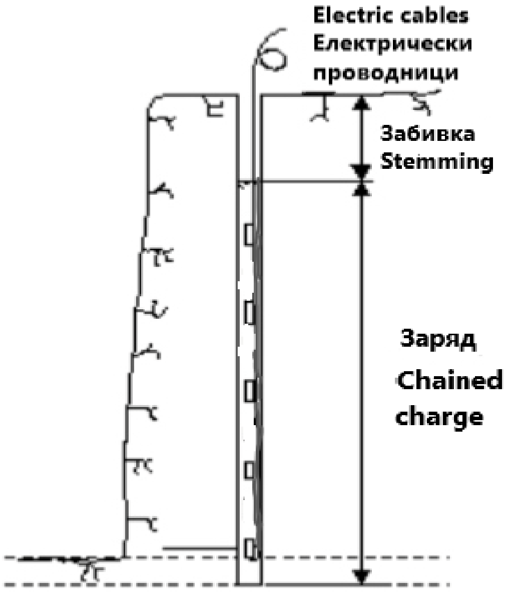

Fig. 2: Configuration of the explosive charge inside the blast-hole

Field tests of charges with a forcing pyro-element to increase the strength of the initial impulse in blast holes with stemmed empty spaces

In this experiment, to amplify the initial ignition pulse and to increase the initial combustion area, an additional structural element was added to the charge. It was a double-plugged, thin-walled polymer tube with a diameter of 4 mm and a length of 100 mm, filled with 8 g of fast-burning sound-light pyrotechnic composition Mixture # 1. The electric igniter was installed in this "boosting element". When assembling the explosive device, the forcing element was held centrally in the empty container while the main charge (Mixture #2 or Mixture #3) was poured evenly and sealed around it. 10 items with Mixture #2 and 10 items with Mixture #3 were made using this technology. The loading of the blast holes in the other two stones was performed in the same way as described in point 3.1.

Results and discussion

During the experimental blasting of the charges with Mixture #2 without a forcing pyro-element in blast holes with stemmed gaps, a good splitting of the rock body in the intended direction and a satisfactory displacement of the treated block were observed. No residual combustion was observed after the explosion in the rock.

After the experimental blasting of the charges with Mixture #3 without a forcing pyro-element in blast holes stemmed gaps, a very good splitting of the stone in the desired direction and good displacement of the treated rock body could be noticed. There was no residual burning in the crevice after the blast.

The blasting of the experimental containers with Mixture #2, activated by additional boosting elements in explosive holes with stemmed free spaces, caused an excellent splitting of the rock body in the direction between the blast holes. The displacement of the stone block was impressive. The lack of residual combustion after the explosion in the rock is evidence of a complete explosive conversion of the mixture.

The effect of the experimental blasting of the samples with Mixture #3 ignited with the additional forcing charge in explosive holes with stemmed gaps was slightly better than that described with Mixture #2. Despite the addition of aluminum, which increases the temperature and the rate of explosive conversion, in this case there was no formation of unwanted micro-cracks either. There was a smooth crack and a strong enough expansion of the cleavage. No residual flames were observed.

Regardless of the narrow space and the significantly increased rate of explosive chemical reaction, the charges in all four cases showed no signs of transition from deflagration to detonation.

Conclusions

The results of the field tests for improvement of the ignition pulse for coarse-grained non-detonating mixtures based on waste smokeless gunpowder show that the optimisation of the technique for applying sound-light pyrotechnic compositions in the form of boosting charges in elongated hulls is the right solution of the problem with adulterate deflagration, described in (Stoycheva and Shishkov, 2020). In combination with the approach for stuffing the free spaces between the individual non-detonating cartridges and the walls of the blast hole, an advanced technique for the extraction and secondary splitting of large stone blocks was obtained. On the other hand, cheap raw materials (waste smokeless gunpowder and ammonium nitrate) give a potential for high economic and environmental efficiency of the developed explosive devices.

The results received by the new experimental blastings show that, at this phase, the achieved parameters are satisfactory and no additional research and field tests are needed to increase the efficiency of these ready-made charges. After successful marketing of the described products and in case of adequate market interest, the technology for their manufacturing can be easily introduced into production.

Regarding the specific features of the supply of waste smokeless gunpowder, the authors plan to focus their future research in the development of new non-detonating high-energy compositions with other inexpensive components.

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