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# Comparative analysis of the developed and traditional stemmings in terms of resistance to explosion products

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**Abstract**

**Purpose.** The purpose of this study is to evaluate the effectiveness of non-Newtonian water-clay suspensions as blast-hole stemming materials and to compare their performance with that of conventional granular materials.

**Methods.** A mathematical modeling method was applied to develop a mathematical model for calculating the ejection velocity stemming from a borehole during an explosion and rock fragmentation. The model is based on solutions to gas dynamics equations (Riemann) and differential equations of stemming motion under the pressure of detonation products.

**Findings.** An inverse relationship was observed between the density of the stemming material and its ejection velocity: the lower the density, the higher the ejection velocity. The most significant ejection delay (lowest velocity) is provided by stemming made of granite screenings (highest density). The developed stemming based on a high-density suspension (stemming 2, $\rho \approx 1846$ kg/m$^3$) demonstrates better delay results compared to sand, whereas the less dense suspension (stemming 1) is ejected faster. For all investigated explosives, the application of the developed clay-suspension-based stemming ensures a confinement time for detonation products comparable to that of traditional materials.

**Originality.** An original mathematical model has been developed that describes the process of inert stemming ejection, considers gas-dynamic processes in the borehole, and allows evaluating its efficiency using the ejection velocity criterion.

**Practical implications.** The developed non-Newtonian clay suspension fills irregularities in the borehole better than loose materials and solidifies under pressure, ensuring reliable sealing. Moreover, its application enhances environmental safety by suppressing dust and neutralizing harmful gases.

***Keywords:*** *borehole; explosion; explosive; non-Newtonian fluid; rock; stemming; stemming ejection velocity*

## 1. Introduction

Borehole charges play a pivotal role in a wide range of industrial applications, particularly in mining and civil engineering, where drilling and blasting remain the dominant methods for rock fragmentation and excavation. Despite the ongoing development of mechanical excavation technologies, the drilling-and-blasting method remains a leading method in underground and surface mining due to its versatility, relatively low cost, and adaptability to diverse geological conditions. The efficiency of blasting operations directly determines the productivity of downstream processes, including loading, transporting, crushing, and beneficiation of rock materials. Consequently, improving the utilization efficiency of explosive energy remains one of the most important scientific and practical tasks in modern mining [1]-[3].

In conventional blasting with fully coupled charges, the explosive is in direct contact with the borehole wall, resulting in extremely high-pressure peaks in the near-borehole zone. Under such conditions, a significant portion of the released energy is consumed in excessive crushing and pulverization of the rock immediately adjacent to the borehole. At the same time, only a limited part is converted into practical work for macrocrack formation. This leads to inefficient energy utilization, unstable fragmentation quality, and an increased proportion of oversized blocks [4]-[7].

However, regardless of the selected charge structure, the effectiveness of any blasting critically depends on the quality of the borehole stemming. In the absence of proper stemming, up to 50% of the explosive energy may escape directly through the borehole collar during rapid release of detonation products [8]. Such uncontrolled energy losses significantly reduce the contribution of explosive energy to rock breakage, increase air-blast intensity, and raise safety and environmental concerns. Therefore, stemming is a key technological element that effectively confines explosion gases and directs their energy into the surrounding rock mass.

Proper stemming not only prevents the premature release of detonation gases but also significantly influences the

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stress state around the borehole, crack initiation mechanisms, and the overall fragmentation pattern [9]. By providing reliable confinement, stemming prolongs the duration of the pressure action on the borehole wall, thereby enhancing the development of tensile stresses responsible for crack initiation and propagation. As a result, improved fragmentation quality, facilitated by the synergy of proper stemming and deck-charge structure [10], reduced ground vibrations, and a lower proportion of oversize material are achieved. Furthermore, the stemming material can serve secondary functions, such as neutralizing toxic gases and, in the case of liquid stemming, providing dust suppression [11].

For these reasons, the development of efficient advanced stemming materials is considered one of the most urgent scientific and practical challenges in contemporary rock blasting technology.

### 1.1. Literature review

Stemming of blast holes is a critical operation for controlled explosions, preventing gas escape, enhancing rock fragmentation efficiency, and reducing dust and noise, while allowing a 20-25% reduction in explosive consumption [12]-[19]. Improper stemming leads to low fragmentation efficiency, oversized material, misfires, increased drilling and blasting costs, and a higher risk of accidents [12].

The flow behavior of blasthole stemming slurry (BSS), mainly composed of yellow mud (YM), tail mud (TM), or drilling cuttings (DC), was studied, and it was found that its rheological properties follow the Herschel-Bulkley model. The results revealed that increasing TM content reduces fluidity and raises yield stress, whereas increasing DC content enhances fluidity and lowers yield stress; both TM/YM and DC/YM ratios significantly affect shear thickening, differential viscosity, and bleeding rate [20].

In the study [21], nine blasts with cylindrical granite specimens were conducted under different stemming conditions using Pentaerythritol tetranitrate (PETN). At the same time, the blasting process and gas ejection were recorded with a high-speed camera. The results showed that packed sand stemming produced finer rock fragmentation and delayed gas ejection from the collars, whereas partial steel stemming led to earlier gas release and coarser fragmentation.

This study [9] examined blast-induced rock fragmentation under different stemming conditions using numerical modeling and image processing. The results showed that increasing stemming length, reducing air/sand deck length, and using bottom stemming enhance fragmentation efficiency. In contrast, fragment size distribution exhibits the opposite trend, making bottom stemming recommended for practical blasting.

In this study [22], the Trauzl lead block test and a high-speed 3D digital image correlation (3D-DIC) system were used to evaluate the effect of stemming in blast holes with emulsion explosives. The experimental and numerical results showed that shear-thickening fluid (STF)-based stemming produced the highest lead block expansion, displacement, and surface strain compared to sand- and aggregate-based stemming. The application of STF-based stemming is expected to improve rock fragmentation efficiency and reduce blasting vibration by allowing a lower explosive charge per blasthole.

A shear thickening fluid (STF)-based stemming material was developed, and its performance was evaluated through laboratory pressure measurements and full-scale bench blasting tests. The results demonstrate that STF-based stemming exerts lower pressure at the blasthole collar, reduces stemming ejection, and produces finer rock fragmentation than conventional sand stemming [23].

A shock chamber blasting experiment and numerical analysis were conducted to evaluate the pressure confinement effect of stemming materials and plugs in a blast hole. The STF-based stemming material under development was compared with conventional sand stemming, demonstrating superior performance in preventing premature gas release and prolonging the action of detonation gases in the borehole. The STF and plug system provides effective blockage and more efficient utilization of explosive energy [24].

This study [25] investigates the use of Non-Newtonian Fluids (NNF) as stemming materials in underground mining, enhancing energy confinement, reducing environmental impact, and improving blast fragmentation. Field trials at Vale Base Metals demonstrated that NNF stemming reduced median fragment size (D50) by up to 38%, improved energy confinement, and decreased the risk of hole plugging and redrilling. NNF-based stemming offers an alternative to conventional methods, providing safer, more efficient, and sustainable blasting operations.

Shear-thickening fluids (STFs) have emerged as promising stemming materials in blast holes due to their unique rheological behavior under stress. Corn starch suspension (CSS), which exhibits a strong shear-thickening effect, is most effective when used as top stemming, acting as a plug to prevent premature ejection of detonation gases. In contrast, silica dioxide suspension (SDS), with a weaker shear-thickening effect, is better suited for filling the annular space between the explosive charge and the borehole wall, thereby ensuring efficient stress wave transmission and a more uniform pressure distribution. Therefore, the combined use of CSS at the borehole collar and SDS along the borehole length can optimize both gas confinement and energy transfer, improving fragmentation efficiency and operational safety [26].

The experimental results [27] demonstrated that non-Newtonian mixture configurations (NNM-NNM and NNM-sand) provided the highest borehole confinement, as evidenced by the lowest air overpressure and the highest rock mass strain. Due to its ability to retain gas pressure and reflect shock waves, the NNM enhanced energy transmission into the surrounding rock while significantly reducing air-blast intensity and audible noise. These properties enable improved blasting control, potential reductions in drilling and explosive costs, and safer operations, particularly in surface mines near urban areas.

The experiment [28] demonstrated that using a non-Newtonian mixture as borehole stemming significantly improves confinement by retaining gas pressure and reducing air overpressure, due to its solid-like behavior under shear stress. This allows more efficient transmission of explosive energy into the rock mass, enhances strain and vibration propagation, and promotes the formation of new fractures. Comparisons with sand and air stemming confirmed that non-Newtonian mixtures provide superior blast energy control and can reduce blast noise intensity.

The study [29] demonstrated that the stemming material plays a crucial role in controlling explosive energy transmission and rock fragmentation. Clay stemming produces the highest fragment mass, the largest crater area, and the most significant energy utilization by focusing the explosive effect on the crater-forming surface. Mixed materials, such as water-clay, produce finer fragments (< 2 mm), while sand-clay produces medium-sized fragments (2-10 mm), allowing control over fragment size distribution. Additionally, the stemming material affects peak strains and strain rates, determining whether the explosive energy is directed primarily toward the crater or the upper surface of the specimen.

The study [30] demonstrated that using a shear-thickening fluid (STF) stemmed material improved tunnel blasting performance compared to sand, yielding higher tunnel advance rates and better rock fragmentation. Combining STF with a plug slightly increased the advance rate but did not significantly enhance fragmentation. STF stemming alone provided the best control over fragment size, reducing the average rock fragment size by approximately 61% compared to sand stemming.

Overall, existing studies convincingly demonstrate the high potential of non-Newtonian, shear-thickening materials to improve blast-hole confinement and fragmentation efficiency. However, most of these investigations focus on experimental validation or empirical performance indicators. At the same time, the fundamental gas-dynamic mechanisms governing the interaction between detonation products and suspension-based stemming remain insufficiently quantified.

### 1.2. Shortcomings of existing studies and scientific gap

Despite the extensive research into granular stemming materials, several significant shortcomings remain in the existing body of knowledge. Most current studies focus on the macroscopic results of blasting – such as fragmentation size or vibration levels – without providing a detailed gas-dynamic analysis of the interaction between detonation products and non-Newtonian materials. There is a lack of rigorous mathematical models that specifically address the transition of water-clay suspensions from a fluid to a near-solid state under the extreme impact of an explosion.

Furthermore, while traditional materials like sand and granite screenings are well documented, their comparison with high-density suspensions in terms of ejection velocity is poorly documented in the literature. Most models treat stemming as a rigid piston, ignoring the internal deformation and the ability of suspension-based materials to seal borehole irregularities. This creates a scientific gap in understanding how the rheological properties of clay suspensions influence the duration of pressure action compared to conventional dry materials.

Additionally, the dual role of stemming as both an energy-confinement tool and an environmental safety agent is rarely analyzed through a single mathematical framework. There is a need for a comprehensive study evaluating the efficiency of non-Newtonian stemming based on the ejection velocity criterion, while also considering its practical advantages in dust suppression and gas neutralization.

Therefore, the scientific novelty of this study lies in the development of a gas-dynamic mathematical framework for evaluating the effectiveness of suspension-based stemming materials using the ejection velocity criterion, which enables a direct, physically justified comparison between non-Newtonian water-clay suspensions and traditional granular materials.

### 1.3. Definition of the research objective

The primary objective of this study is a comparative assessment of the effectiveness of non-Newtonian water-clay suspensions as stemming materials in comparison with traditional granular materials. It is important to note that although the specific rheological features of such suspensions, particularly their ability to structure and vary in viscosity, represent their fundamental advantage, these properties were not the direct subject of mathematical modeling at this stage of the research. The focus is centered on testing the hypothesis that, even when considering only inertial parameters (density) and gas-dynamic resistance, the developed formulations can provide competitive confinement of detonation products.

To achieve this goal, a mathematical model was developed based on solutions to the Riemann equations and the equations of motion, with the ejection velocity as the key evaluation criterion. The study aims to establish the relationship between material density and its confinement time within the borehole. The obtained modeling results demonstrate that, based on their inertial characteristics, the developed suspensions provide gas confinement indicators that are not inferior to, and in some cases exceed, those of traditional materials. This allows for the assertion of high potential efficiency for the proposed materials, even without accounting for their additional physicochemical properties.

While the present study focuses on inertial and gas-dynamic aspects, the results obtained provide a robust scientific basis for subsequent investigations into the rheological response of suspensions under explosive loading and their environmental benefits.

## 2. Methods

To quantitatively assess the efficiency of borehole charge stemming, it is necessary to formulate a physical and mathematical model of the interaction between detonation products and the stemming material.

We consider the process occurring immediately after the detonation of an explosive charge placed in a borehole. Following detonation, high-pressure gaseous products form and begin to expand, exerting pressure on the stemming material above the charge. Under the action of this pressure, the stemming begins to move toward the borehole collar and may be ejected if the impulse transmitted by the detonation products is sufficient.

The objective of the model is to determine the velocity of stemming ejection, which serves as an integral indicator of the energy transferred from the detonation products to the stemming material and, consequently, characterizes the effectiveness of gas confinement within the borehole.

To simplify the analysis while preserving the essential physics of the process, the following assumptions are adopted. The process is formulated in one dimension along the borehole axis. The detonation products are treated as a compressible gas obeying the equations of gas dynamics. The expansion of detonation products is assumed to be isentropic. Friction between the stemming and the borehole walls is neglected, which corresponds to the assumption that the impulse action of the detonation products dominates over resistive forces at the initial stage of motion. The interface between detonation products and the stemming is treated as a moving boundary. Under these assumptions, the interaction between detonation products and the stemming can be described by one-dimensional gas-dynamic equations with

Riemann solutions for rarefaction waves. The stemming ejection velocity is chosen as the main evaluation criterion because it directly reflects the momentum transferred to the stemming. A lower ejection velocity corresponds to more effective confinement of detonation gases. After formulating the physical and mathematical model and defining the governing assumptions, we introduce the geometric and mass parameters of the system.

Let $H$ be the length of the charge, $H_s$ be the length of the stemming, $m$ be the mass of the charge, and $M$ be the mass of the stemming (Fig. 1).

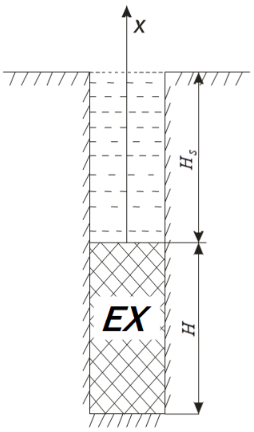


***Figure 1. Design of a borehole charge***

Immediately after the start of the movement of the boundary between the detonation products and the stemming, a rarefaction wave will pass through the detonation products, the movement of which is described by Riemann solutions of gas dynamics equations, which, under the isentropic law of expansion of detonation products $pV^3 = const$, have the form:

$$\begin{cases} x = (v-c)t + F(v) \\ v + c = const \end{cases}, \tag{1}$$

where:

$p$ – pressure;

$x$ – coordinate;

$V$ – volume;

$t$ – time;

$v$ – the velocity of the detonation products;

$c_n$ – velocity of sound in the detonation products.

Taking into consideration the initial conditions $x = 0$, $v = 0$, $c = c_n$ at $t = 0$, we can define the function $F(v)$ and $const$: $F(v) = 0$, $const = c_n$. A differential equation describes the movement of the stemming:

$$M\frac{dv}{dt} = pS\ , \tag{2}$$

where:

$S$ – the cross-sectional area of the borehole.

We can obtain the following equation:

$$M\frac{dv}{dt} = Sp_n\left(\frac{c}{c_n}\right)^3 = Sp_n\left(\frac{c_n - v}{c_n}\right)^3 = Sp_n\left(1-\frac{v}{c_n}\right)^3. \tag{3}$$

Considering that:

$$p_n = \frac{1}{8}\rho_{ex}D^2,\ c_n = \sqrt{\frac{3}{8}}D\ , \tag{4}$$

then:

$$M\frac{dv}{dt} = \frac{S\rho_{ex}c_n^2}{3}\left(1-\frac{v}{c_n}\right)^3 = \frac{mc_n^2}{3H}\left(1-\frac{v}{c_n}\right)^3, \tag{5}$$

where:

$\rho_{ex}$ – density of the explosive substance;

$D$ – detonation velocity of the explosive substance.

We have a separable differential equation. Separating the variables, we obtain:

$$\frac{d\left(1-\frac{v}{c_n}\right)}{\left(1-\frac{v}{c_n}\right)^3} = -\frac{m \cdot c_n}{3M \cdot H}dt\ . \tag{6}$$

Integrating (6) and taking into consideration that when $t = 0$, $v = 0$, we determine the stemming ejection velocity as:

$$v_s = c_n\left(1-\left(\frac{2mc_n t}{3M \cdot H}+1\right)^{-\frac{1}{2}}\right). \tag{7}$$

Formula (7) defines the law of change in the speed of stemming over time. Considering that:

$$m = \rho_{ex}SH\ ,\ M = \rho_s SH_s\ , \tag{8}$$

it can be written as:

$$v_s = c_n\left(1-\left(\frac{2\rho_{ex}c_n t}{3\rho_s H_s}+1\right)^{-\frac{1}{2}}\right), \tag{9}$$

where:

$\rho_s$ – the density of the stemming.

Thus, for the construction of the mathematical model, the following simplifications are adopted: the process is considered in a one-dimensional formulation along the borehole axis; the detonation products are treated as a compressible gas, which can be approximated as ideal; the expansion of the gas is isentropic; friction between the stemming and the borehole walls is neglected, corresponding to the assumption that the impulse action of the detonation products dominates over resistive forces at the initial stage of motion; the stemming itself is treated as a rigid body, meaning that material deformation during motion is neglected, which distinguishes this model from the classical "piston" approach.

These assumptions allow focusing on the main physical essence of the process, the momentum transfer from the detonation products to the stemming, and simplify the mathematical description for the subsequent analysis of stemming ejection velocity.

The developed mathematical model can be applied to both traditional and innovative materials, in particular to water-clay suspensions with non-Newtonian rheological properties.

## 3. Results and discussion

An explosion of a borehole charge with a length of $H = 10$ m is considered, and the length of the stemming is $H_s = 3$ m. The following are used as explosives: Hramonit 79/21, Amonit 6-ZHV, Ukrayinit-PP-1 and Anemix (power gel), the characteristics of which are given in Table 1.

***Table 1. Main characteristics of explosives***

| Explosive | Density, kg/m$^3$ | Detonation velocity, m/s | Isentropic index | Velocity of sound in detonation products, m/s | Propagation velocity of detonation products, m/s |
|---|---|---|---|---|---|
| Hramonit 79/21 | 950 | 3300 | 1.248 | 1832 | 1281 |
| Amonit 6-ZHV | 1000 | 4520 | 1.84 | 2928 | 1375 |
| Ukra-yinit-PP-1 | 1500 | 4500 | 1.25 | 2756 | 1428 |
| Anemix (power gel) | 1300 | 5000 | 1.24 | 3052 | 1634 |

A comparative analysis of the impact of stemming material on its velocity was conducted, considering such traditional tamping materials as sand ($\rho_s$ = 1600 kg/m$^3$), granite screenings ($\rho_s$ = 2650 kg/m$^3$) and proposed stemming material, which is a suspension of clay material, water, and stabilizer. A series of experiments were carried out, the results of which showed that the suspension acquires non-Newtonian properties at a concentration of 35% ($\rho_s$ = 1251.6 kg/m$^3$) (stemming 1) and above, however, it is not advisable to use a suspension with a concentration higher than 75% ($\rho_s$ = 1846.1 kg/m$^3$) (stemming 2).

Using the developed mathematical model, the ejection velocity of different types of stemming as a function of time was calculated with Amonit 6-ZHV (Fig. 2).

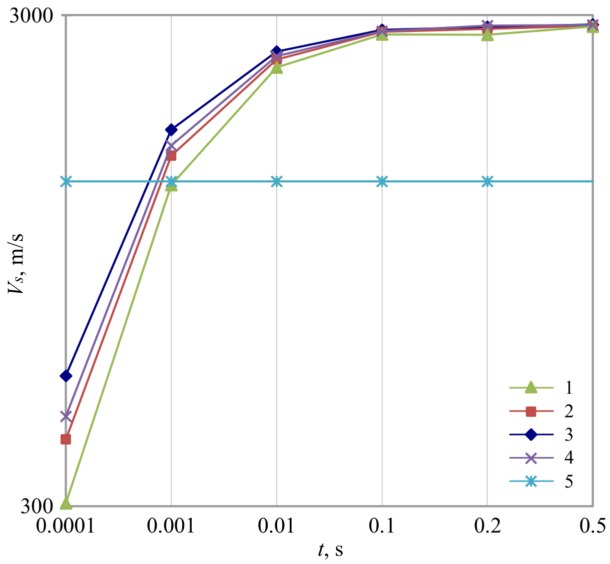


***Figure 2. Dependence of the ejection velocity of different types of stemming on time during the explosion of Amonit 6-ZHV: 1 – stemming 1; 2 – stemming 2; 3 – sand; 4 – granite screenings; 5 – ejection velocity of detonation products***

An analysis of Figure 2 shows that, during the explosion of Amonit 6-ZHV, the ejection velocity of the stemming is inversely proportional to its density: lower-density stemming exhibits higher ejection velocities from the borehole. Therefore, the highest ejection velocity is achieved for stemming 1, then for sand stemming, followed by stemming 2 and granite screenings. The difference in velocities is quite significant at the initial stage of the explosion, but over time it decreases, and at $t$ = 0.1 s they practically coincide.

The ejection velocity of granite screening stemming, which exhibits the lowest value at $t = 10^{-4}$ s amounts to 75.33% of that for stemming 1; 50.33% of that for sand stemming; and 34.86% of that for stemming 2.

At $t = 2.45 \cdot 10^{-3}$ s (corresponding to the detonation products exiting the borehole in the absence of stemming), the respective values are 17.32%, 12.15%, and 8.9%.

For the Amonit 6-ZHV charge, the delay in stemming ejection relative to the unstemmed detonation product exit amounts to 1.00 ms for gravel; 0.90 ms for sand; and 0.80 ms and 0.95 ms for stemming 1 and stemming 2, respectively.

Figures 3 and 4 show the results of calculating the ejection velocity of different types of stemming over time during the explosion of modern explosives: Anemix and Ukrayinit-PP-1.

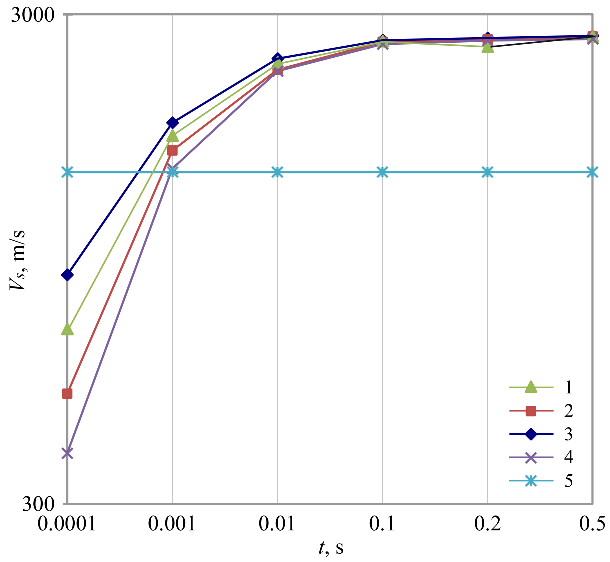


***Figure 3. Dependence of the ejection velocity of different types of stemming on time during the explosion of the Anemix: 1 – stemming 1; 2 – stemming 2; 3 – sand; 4 – granite screenings; 5 – ejection velocity of detonation products***

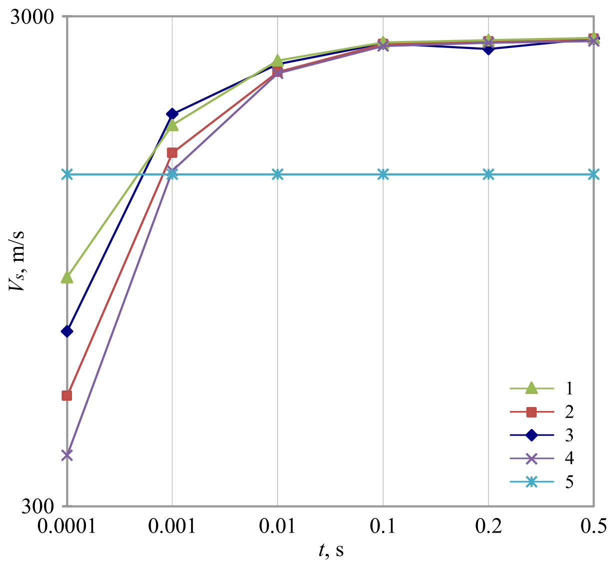


***Figure 4. Dependence of the ejection velocity of different types of stemming on time during the explosion of the Ukrayinit-PP-1: 1 – stemming 1; 2 – stemming 2; 3 – sand; 4– granite screenings; 5 – ejection velocity of detonation products***

From the analysis of these figures, it can be concluded that when both explosives explode, the same regularity is observed as for the reference explosive: the ejection velocity of the stemming is inversely proportional to its density.

Thus, during the explosion of Anemix, the ejection velocity of granite screening stemming constitutes. At $t = 10^{-4}$ s: 75.0% of that for stemming 1; 47.3% of that for sand stemming; and 32.5% of that for stemming 2.

At $t = 1.89 \cdot 10^{-3}$ s (corresponding to the detonation products exiting the borehole in the absence of stemming): 59.42, 38.66, and 27.1% of the respective values.

For using Ukrayinit-PP-1 the ejection velocity of the stemming made of granite screenings at $t = 10^{-4}$ s is 74.02% the ejection velocity of the stemming 1; 46.6% of the sand stemming; 32.28% of the stemming 2. At $t = 2.45 \cdot 10^{-3}$ s (time of detonation products exit from the borehole in the absence of stemming), these values are 14.05, 9.88, and 7.25%, respectively.

For Ukrayinit-PP-1, the ejection velocity of granite screening stemming amounts to:

– at $t = 10^{-4}$ s: 74.02% of that for stemming 1; 46.6% of that for sand stemming; and 32.28% of that for stemming 2;

– at $t = 2.45 \cdot 10^{-3}$ s (corresponding to the detonation products exiting the borehole in the absence of stemming): 14.05%, 9.88%, and 7.25% of the respective values.

For the Anemix charge, the delay in detonation product exit relative to the unstemmed case amounts to 1.20 ms for gravel; 0.81 ms for sand; and 0.82 ms and 0.96 ms for stemming 1 and stemming 2, respectively. For Ukrayinit-PP-1, the corresponding delay times are 0.99 ms (gravel), 0.80 ms (sand), 0.80 ms (stemming 1), and 0.95 ms (stemming 2).

In existing studies, mathematical models describing the interaction between detonation products and stemming using gas-dynamic equations, rarefaction waves, and analytical evaluation of stemming ejection velocity are largely absent. Most works focus on experimental comparisons of materials or numerical models, without providing a systematic quantitative prediction of stemming behavior under actual detonation conditions. In contrast, the present study develops a mathematical model of gas dynamics and stemming motion, allowing the assessment of the influence of material properties, charge geometry, and other parameters on the ejection velocity. This approach opens new methodological opportunities, complements numerical and experimental data, and provides a basis for systematic comparison of the performance of various materials, including both conventional and innovative systems.

The scientific novelty of this work lies in combining a gas-dynamic mathematical model with Riemann solutions to describe the motion of detonation products and stemming, a combination not found in existing studies, which mostly rely on experiments or numerical models without analytical treatment. The proposed model enables quantitative evaluation of the ejection velocity as a function of the physical parameters of the charge and stemming, as well as a formalized assessment of the effectiveness of non-Newtonian systems, such as clay-based or STF materials, with the potential to incorporate their rheological properties in the future. Thus, while individual effects, such as the influence of material, length, and structure of stemming, have been previously investigated experimentally and numerically, the present approach to mathematical description and quantitative prediction of stemming behavior during detonation is novel and significantly expands the possibilities for controlling and optimizing rock fragmentation processes in blasting operations.

Further research in this area is essential for advancing both the theoretical understanding and practical application of blasting processes. First, extending the mathematical model to account for the rheological behavior of non-Newtonian materials, such as clay suspensions, will enable quantitative prediction of the effectiveness of different stemming types and the optimization of their composition and properties for specific geological and technological conditions in mining practice. This, in turn, can improve the safety and environmental performance of blasting operations by reducing uncontrolled ejection of detonation products and dust emissions, minimizing energy losses, and enhancing the overall stability and efficiency of rock fragmentation under real mining conditions.

Second, future experimental and numerical studies aimed at validating and calibrating the proposed model will enhance its reliability under real operating conditions. Such efforts will enable the development of practical guidelines for selecting stemming materials and charge geometry, optimizing explosive consumption, and improving rock fragmentation efficiency. In the long term, this line of research will contribute to a more systematic approach to blast design, combining analytical modeling with experimental data, and ultimately supporting safer, more efficient, and more environmentally responsible blasting practices.

## 4. Conclusions

Analysis of the stemming ejection velocity calculations shows that using the proposed stemming material (clay suspension) during the detonation of various explosives is advisable, as the delay time for the release of detonation products falls within the typical range for traditional stemming materials. Meanwhile, the longest delay time for stemming ejection during rock destruction with all types of explosives is observed with gravel stemming, which is explained by its higher density, while the shortest delay time is observed with stemming 1.

The use of stemming 2 results in a significant increase in the delay time of its ejection, which is significantly greater compared to the use of sand. Thus, it can be concluded that the proposed stemming is an effective means of controlling the parameters of blasting operations during mineral extraction, as its use, along with traditional stemming, significantly slows the ejection of detonation products. This increases the duration of the explosion products' impact on the rock mass, thereby improving the quality of rock crushing.

## Author contributions

Conceptualization: NR, OH; Formal analysis: NR, OT, KT, OH, OK; Investigation: NR, OT, KT, OH, OK; Methodology: NR, OH; Project administration: OT, KT; Resources: OK, SK, ML; Supervision: OT, KT; Validation: OH, OK, SK; Visualization: NR, ML; Writing – original draft: NR, OT, OH, OK; Writing – review & editing: KT, SK, ML. All authors have read and agreed to the published version of the manuscript.

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## Conflicts of interest

The authors declare no conflict of interest.

## Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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## Порівняльний аналіз розробленої та традиційних забійок за критерієм опору продуктам вибуху

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**Мета.** Метою цього дослідження є оцінка ефективності неньютонівських водно-глинистих суспензій як матеріалів для забійки свердловин та порівняння їх ефективності з традиційними сипучими матеріалами.

**Методика.** Застосовано математичне моделювання для розроблення математичної моделі розрахунку швидкості вильоту забійки зі свердловини під час вибуху та руйнування гірської породи. Модель базується на розв'язках рівнянь газодинаміки (Рімана) та диференціальних рівняннях руху забійки під дією тиску продуктів детонації.

**Результати.** Встановлено обернену залежність між щільністю матеріалу забійки та швидкістю її вильоту: чим менша щільність, тим вища швидкість вильоту. Найбільшу затримку вильоту (найменшу швидкість) забезпечує забійка з відсіву граніту (найвища щільність). Розроблена забійка на основі суспензії високої щільності (забійка 2, $\rho \approx 1846$ кг/м$^3$) показує кращі результати затримки порівняно з піском, тоді як менш щільна суспензія (забійка 1) вилітає швидше. Для всіх досліджуваних вибухових речовин застосування розробленої забійки на основі глинистої суспензії забезпечує час утримання продуктів детонації, який є співмірним із традиційними матеріалами.

**Наукова новизна.** Розроблено математичну модель, яка описує процес вильоту інертної забійки, враховуючи газодинамічні процеси у свердловині, та дозволяє оцінити її ефективність за критерієм швидкості вильоту.

**Практична значимість.** Розроблена неньютонівська глиниста суспензія краще за сипучі матеріали заповнює нерівності свердловини, а під дією тиску затвердіває, забезпечуючи надійну герметизацію. Крім того, її використання підвищує екологічну безпеку шляхом зменшення пилоутворення та нейтралізації шкідливих газів.

***Ключові слова:*** *свердловина; вибух; вибухова речовина; неньютонівська рідина; гірська порода; забійка; швидкість вильоту забійки*

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