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Ecological and Economic Substantiation of the Modified Borehole Charges Stemming for Gaseous Waste Reduction

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A modified borehole charge stemming, consisting of a suspension of clay material (CM) (> 30% mass) and a surfactant complex (up to 2.5% mass) is proposed. It is justified not only to pursue the goal of increasing blasting efficiency by reducing the borehole charge stemming departure velocity, but also to mitigate the environmental impact of blasting by altering the densitometric and rheological properties of the stemming material. For modifying the composition of the stemming, a densitometric study of CM suspensions in the concentration range of 20–70% mass has been carried out. The deviation of such systems from the additivity law and the behavior of these systems as non-Newtonian fluids due to structure formation processes have been proven; the relative deviations of experimental density values from their additive values have been calculated. Based on densitometric studies of clay suspensions, an approximate polynomial model of the second degree has been developed, that makes it possible to determine the density of suspensions almost up to the critical concentration of structure formation. An important aspect of the proposed technological solution is the availability of the stemming material, its relative cheapness and ease of preparation, and significant adsorption properties. All components of the stemming are eco-friendly; surfactants decompose easily and are permitted in Ukraine and the EU. To substantiate the technological, environmental, economic and legal feasibility of modifying the borehole charge stemming, the authors' methodology, system of criteria, and computer program have been developed based on Thomas L. Saaty's analytic hierarchy process using RStudio; the proposed solution is feasible with a probability of 83.4%. The developed methodology also investigates the compliance with the concepts of a circular green economy and sustainable development, and environmental, social, and governance (ESG) principles.

Keywords: blasting operations and explosion products, borehole charge stemming, borehole charge design, waste management, circular green economy and ESG.

Introduction

The process of explosion, which is actively used in many sectors of the national economy, including the mining industry, is a very fast chemical reaction of oxidation of substances with the release of a huge amount of heat, as a result of which the explosive turns into explosive gases, which in turn create a negative impact on the air environment and adjacent territories. The propagation of the explosive detonation front is caused by three main factors: compression, heating, and various chemical transformations of the explosive components.

During an explosion, the detonation products spread rapidly and expand significantly, causing a pressure surge (disturbance wave) in the environment surrounding the explosive charge, which is called a 'shock wave'. Therefore, to ensure that the maximum amount of explosive energy is directed to the targeted process of rock mass destruction while minimizing the possibility of oversized products and/or too crushed fractions (screenings), as well as excessive amounts of dust, it is necessary to prevent its loss and inefficient use. The problem of improving the safety and environmental friendliness of blasting operations is also important, as the explosion process itself is always accompanied by emissions of huge volumes of toxic substances – a cloud containing nitrogen and carbon oxides and particulate matter suspended in the air.

One of the main factors determining the effectiveness of the explosion is the stemming of borehole charge, which is used to facilitate the complete detonation of the explosive and prevent premature release of detonation products from the hole. Studies show that the material and design of the borehole charge stemming significantly affect not only the effectiveness of the charge, but also the composition of the explosion products, particularly the content of toxic substances, their dispersion over the quarry, other environmental characteristics, etc.

During rock destruction by blasting, the efficiency of the explosion depends on the type of explosive, the design of the borehole charge, including the stemming, the physical and mechanical properties of the rock and the structural and textural features of the massif, the parameters of the hole network, switching schemes, deceleration time, etc.

Quarries typically use cheap bulk inert materials, such as sand, crushed stone, and drill fines, to form the stemming of borehole charges. These materials typically have a high density and a significant coefficient of internal friction, which are important characteristics for ensuring the required explosion conditions. According to scientists (Kumar et al., 2024; Serdaliyev et al., 2025), to achieve high efficiency, the material of the stemming must also have the highest possible adhesive strength, since its locking properties are due to the joint action of the stemming mass inertia and internal friction forces. The material of the stemming can also be plastic, liquid and fast-hardening substances and mixtures. These stemming have a slightly higher cost, but they are also affordable to manufacture, easy and reliable to use, and help to reduce toxic explosive gas emissions. Their locking properties are due to the inertia of the stemming mass, internal friction forces and internal adhesion forces of the stemming.

Many researchers propose using a variety of production wastes as a stemming, such as finely ground metallurgical slag, sludge from the treatment of spent pickling solutions, and hydrolyzed lignin. However, it should be noted that conventionally formed stemming often fail to perform their locking function properly, which results in a decrease in blasting efficiency, an increase in the volume of substandard fractions, excessive consumption of explosives, and an increase in the concentration of toxic components in the dust and gas cloud. Thus, at present, the problems of blasting efficiency in the mining industry still need to be addressed urgently.

According to experts, during the explosion the borehole stemming is significantly compacted to form a so-called 'plug', which then resists the increasing pressure of gaseous explosion products by increasing the friction forces between the particles of the borehole stemming and between the compacted borehole stemming and the borehole walls. It is believed that the higher the rate of application of the load from the charge explosion, the shorter but denser the resulting 'plug' will be (Baluch et al., 2024).

It is known that the locking effect of a stemming during an explosion is determined by its dimensions (length and diameter) and the resistance of its material to dynamic loads. Many papers have been devoted to the study of the effect of the design and composition of the stemming on the efficiency of blasting operations (Himanshu et al., 2023; Ye et al., 2024; Saubi et al., 2025; Serdaliyev et al., 2025). For example, the authors of (Hurin et al., 2019) substantiated a method of stemming a borehole charge, which includes crushing the rock mass to a given particle size distribution, feeding the resulting stemming material into the borehole cavity from the level of the explosive to the level of the ledge surface. This makes it possible to significantly increase the efficiency of locking detonation products and reduce emissions of toxic explosive gases and fine dust during blasting operations in quarries. The authors note that the use of an aqueous surfactant solution will contribute to significant dust suppression.

Choosing a stemming material to adsorb harmful explosive gases, the authors of (Tverda et al., 2021a) paid attention to the chemisorption of explosive gases by quicklime CaO and/or its production waste, as well as to the physicochemical sorption (adsorption) of gases by zeolites. According to the researchers, this design of the stemming will make it possible to almost eliminate nitrogen dioxide NO_2 and carbon dioxide CO_2, which are harmful to human health and the environment, by neutralizing them with calcium oxide; minimize carbon monoxide emissions by introducing zeolites, natural porous aluminosilicates with an extremely developed surface, into the stemming material.

By modifying the composition of the stemming, the authors of (Tverda et al., 2021a) proved the effectiveness of calcium hydroxide – slaked lime $Ca(OH)_2$ as an effective neutralizing component of multifunctional stemming. This design of the borehole charge stemming not only ensures almost complete chemical neutralization of the toxic gases, but also allows to refuse to use zeolites, which significantly reduces the cost of the structure, increases the process manufacturability due to the simplicity of the stemming manufacturing. In addition, the proposed design of the stemming, due to the formation of fine emulsion droplets during the explosion, further contributes to dust suppression.

In (Tverda et al., 2021a; Tverda et al., 2021b; Tverda et al., 2024) several other types of borehole charge stemming formation are described. A method of sequentially inserting a specially prepared gas-adsorbing sealing layer and a layer of available bulk material into the borehole has been proposed. During the formation of such a stemming, considerable attention is paid to the sequence of laying the specified layers of locking materials. First, a sealing gas-adsorbing layer is placed in the borehole – a mixture of slaked lime $Ca(OH)_2$ in the form of a suspension and sodium silicate Na_2SiO_3 thickener, which, when mixed, form a strong mass of sodium hydroxide and water-insoluble calcium silicate because of chemical interaction (1):

$$Ca(OH)_2 + Na_2SiO_3 = CaSiO_3 + 2NaOH \tag{1}$$

Next, a gas-adsorbing layer of a thick suspension of calcium hydroxide $Ca(OH)_2$ is placed directly on top of it, over which the bulk material selected for backfilling is placed.

The authors (Yi et al., 2023) proposed an environmentally friendly and efficient harmful gas inhibitor to reduce the generation of toxic gases during engineering blasting. Their research showed that adding 4% of the inhibitor achieved the best control effect, significantly lowering harmful gas concentrations and improving blasting safety. There are also studies devoted to the use of hydraulic stemming in the form of a shell filled with water. However, this design of the stemming will have a slight locking effect, which limits its use to some extent. In this case, energy losses during detonation of explosives increase, oxidation reactions during the explosion are not ensured to be complete, and the duration of exposure of explosive gases to the borehole walls is reduced. At the same time, rock fragmentation quality deteriorates, production efficiency decreases, the volume of substandard products increases, and the content of toxic gases in blasting emissions rises.

Thus, as literature analysis shows, it is still not possible to simultaneously solve complex technological and environmental problems at the current stage of blasting technology development in mining. The use of bulk materials in the stemming, including waste from various industries, can even lead to increased dust generation, and the presence of polypropylene and/or polyethylene materials in the stemming can lead to a wider range of harmful emissions. Studies devoted to the use of absorbing and/or adsorbing and/or neutralizing agents in the material of the stemming do not substantiate the effectiveness of using such stemming for their main purpose – to lock the detonation products of explosives.

So, the study aims to develop a modified design of the borehole charge stemming, consisting of a highly concentrated clay suspension and a surfactant complex to increase its aggregate stability, and to substantiate the feasibility of the proposed technological solution using the author's methodology based on Thomas L. Saaty's analytic hierarchy process, with assessing its compliance with the principles of circular green economy and sustainable development.

Methods

The study proposes to use highly concentrated suspensions of natural clay materials (CM) (clays, loams, etc.), which mainly consist of highly dispersed aluminosilicates with the general formula $x(Al_2O_3) \cdot y(SiO_2) \cdot z(H_2O)$. Aluminosilicates typically have a layered structure, which is manifested in the sequential alternation of octahedral (alumina) and tetrahedral (silica) lattice layers. In the octahedral layers of clay rocks, in addition to Al^{3+} ions, hydroxyl ions OH^- are also present, which represent crystallization (chemically bound, constitutional) water.

It is known that the main characteristics of CM are determined by their chemical and mineral composition, as well as particle size. The total content of aluminum oxides, silicon oxides and water in clays reaches 75–90%, while the rest is mainly sodium ions Na^+, potassium ions K^+, calcium ions Ca^{2+}, magnesium ions Mg^{2+} and iron ions Fe^{2+}. Loams, in turn, contain up to 30–50% clay fraction and approximately 70–50% solid minerals larger than 0.01 mm. Among clay minerals, the most widespread are kaolinite ($Al_2Si_2O_5(OH)_4$), hydromica, montmorillonite (Al, Mg)[(OH)$_2$][Si$_4$O$_{10}$](Na, Ca)$_x$·4H$_2$O), galoisite ($Al_4(OH)_8[Si_4O_{10}] \cdot nH_2O$, where $n < 4$), palygorskite ($Mg_2Al_2[Si_8O_{20}](OH)_2 \cdot 8H_2O$), etc. At the same time, for example, Fe oxides Fe_2O_3, FeO, Fe_3O_4, titanium dioxide TiO_2 and alkali metal oxides Na_2O and K_2O are usually found in the form of various impurities.

To prepare the concentrated suspensions, the clay material was first dried under natural conditions and then dried at a temperature not exceeding 200°C, since at higher temperatures the clay may lose some of its native properties, particularly its binding ability. The CM was grounded in two stages: coarse and fine crushing by grinding in a porcelain mortar. The prepared material was sieved through a sieve with a mesh diameter of 1 mm until the sample passed through the sieve completely. The prepared material was stored in plastic bags with a corresponding label. The average sample for analysis was taken by the quarting method. To do this, the CM was spread in a thin layer over an area of 1 m^2 and then divided by two diagonals into four equal triangles. A sample was taken from two opposite triangles, then it was mixed again. The described quarting procedure was repeated several times, each time again dividing the CM mass by two diagonals into four triangles until an average sample of the material was obtained in the amount required for the study.

A clay suspension is a colloidal polydisperse system containing water as a dispersion medium and a hydrophilic dispersed phase – clay particles with a diameter of approximately 0.0001–0.1 mm. The study analyzed highly concentrated suspensions with CM content above 30 % by mass. To increase the aggregation stability of the studied highly dispersed colloidal systems, a specially prepared surfactant complex containing two main components was used – the surfactant Twin-80, a natural polysorbate with monooleate as its active ingredient, and triatomic alcohol – glycerol $C_3H_8O_3$. Twin-80 belongs to the class of nonionic surfactants, whose molecules are not capable of dissociation in aqueous medium. The selected component of the surfactant complex, polysorbate, is easily biodegradable and is authorized for use in Ukraine and the EU.

The surfactant complex was introduced into the system in an amount of up to 2.5% mass. Such a low concentration of the surfactant complex is due to the special structural and mechanical properties of the formed adsorption layers and ensures the aggregation stability of the studied highly dispersed colloidal systems. The mechanism of action of diphilic surfactant molecules is manifested in the fact that its molecules can be adsorbed on the phase separation surfaces in the form of thin monomolecular layers, according to Langmuir's theory, forming strong protective shells. This, in turn, significantly reduces the interfacial surface tension and protects the fine clay particles from coagulation and loss of aggregate stability by the suspension. As a result, the introduction of the proposed surfactant complex into the studied clay suspensions prevents clumping (coagulation) and subsequent sedimentation of CM particles, which is especially important when preparing suspensions of extremely high concentrations above 55–60% mass. Thus, even at the critical concentration of structure formation, the suspension remains stable, ensuring a uniform distribution of CM particles in the volume of the colloidal system.

As noted, clay suspensions were prepared from pre-ground and sieved through a 1 mm mesh sieve CM powder. To do this, the surfactant complex was prepared beforehand and rubbed with the CM prepared according to the described method. Then, the demineralized water in the quantity of half of the calculated mass of dry CM was added. Thoroughly mixing the resulting mixture with a magnetic stirrer, the second part of the calculated mass of water was gradually added to obtain concentrated suspensions (20–70% by mass). Next, the system was stirred for 1–2 hours using a magnetic stirrer. Since a double electric layer is formed on the surface of the clay particles of the suspension, demineralized water with a pH of ≈ 7 was used to avoid rapid coagulation of the CM under the influence of coagulating electrolyte ions.

The density of the studied suspensions was measured by the pycnometric method at a temperature of 20°C with a density check by an areometer. The pycnometer was previously calibrated with distilled water at the same temperature. Experimental determinations were performed in five replicates to obtain results with a significance level $\alpha = 5\%$. The results of the experiments were processed with statistical methods of analysis using MS Office Excel; experimental error is ±1.0 kg/m^3. The reliability of the obtained approximation model was assessed by the coefficient of determination R^2, considering that the closer its value tends to 1, the better the approximation function reflects the relationship between the studied variables. So, the resulting model with $R^2 \geq 0.998$ was considered as good, adequately describing the phenomena under study. The regression coefficients were also calculated, and the significance of the determination coefficients was checked with Student's t-test.

Substantiation of the feasibility of the proposed technological solution was performed using the author's methodology based on Thomas L. Saaty's analytic hierarchy process approach (AHP). AHP is a tool for making complex decisions by breaking them into a clear, step-by-step structure – hierarchical system (Saaty and Vargas, 2013; Gu et al., 2018), that helps compare different criteria and make well-informed choices. The hierarchical system includes the overall goal, evaluation criteria, and alternatives. AHP applies pairwise comparisons to quantify the relative importance or preference of each element using a consistent ratio scale obtained on the basis of the expert judgment. In this study, the comparisons were made using Thomas L. Saaty's nine-point fundamental scale, where 1 corresponds to equal importance, and 9 highlights the most significant preference of one criterion over another.

For the study, we developed a unique computer program in YAML format to process the results of the expert evaluation, run calculations, and produce visual results. This program uses the 'ahp' package, created by C. Glur (CRAN, 2016), and is working through RStudio (Posit, 2025) with R version 4.0.3 (CRAN, 2025). Our paper (Kofanov et al., 2024a) provides a detailed explanation of all the peculiarities of Thomas L. Saaty's AHP approach usage, which are also important for the current study. The paper showcases the methodology for evaluating the compliance of the innovative projects with circular green economy and sustainable development principles.

A key part of using the AHP approach correctly is checking the inconsistency indicator (also known as the consistency ratio), which is explained in detail in (Saaty and Vargas, 2013; Kofanov et al., 2024a). This indicator in the study is calculated with the 'ahp' package and must be below 10% to consider the results trustworthy. Our earlier studies (Kofanov et al., 2024a; Kofanov et al., 2024b) have shown that mathematical and data-based methods, including AHP, are effective in the fields of environmental safety, circular green economy, and sustainable development.

Results and Discussion

For non-Newtonian fluids, the dynamic viscosity mostly depends not only on temperature and pressure, but also on the shear stress applied to the system. That is, the viscosity of such systems changes with the shear rate. This is because such systems usually have a spatial structure that can be destroyed and gradually restored under external influence. Thus, liquids of this group demonstrate a nonlinear nature of the yield curve (or even this curve may not start from the origin), and the nature of changes in their mechanical and rheological properties under stress depends on the composition and structure of the system, the nature of interaction of its particles, molecules, etc.

The density of the stemming material, as well as its viscosity, is of great importance for ensuring the locking of explosive gases and ensuring the quality of rock crushing during blasting operations, as it determines the amount of hydrostatic pressure on the borehole walls. Increasing the density of the stemming material will prevent the premature release of harmful detonation products (gaseous waste) and will also increase the sorption of toxic substances included in them. In the mechanics of non-Newtonian fluids, the density is not a constant value but depends on several technological factors (Li and Chen, 2023). Thus, in the study, using densitometric measurements, it was confirmed (*Fig. 1*) that the studied colloidal systems (concentrated aqueous suspensions of CM) really behave as non-Newtonian liquids, starting from a CM concentration above 7–10 % by mass, which can be traced by the relative deviations of the density values of these systems from the value calculated according to the law of additivity (2) (*Table 1*):

$$d_s = (d_c \cdot m_c + d_w \cdot m_w) / (m_c + m_w) \quad (2)$$

where d_c – density of the dispersed phase (particles of CM); d_w – density of the dispersion medium (water); m_c and m_w – the masses of the dispersed phase (CM particles) and the dispersion medium (water), respectively.

So, as it can be seen from the *Table 1* the largest relative deviations in the results calculated by the model approximation *equation (3)* are observed in the range of CM concentrations of 30–60% by mass.

$$d_s = 0.0991\ x^2 + 3.9623\ x + 991.46\ (R^2 = 0.998) \quad (3)$$

where x – concentration of CM particles, % mass; R^2 – determination coefficient.

Thus, the proposed technological solution for modifying the borehole charge stemming is because clays and clayey rocks can form aggregate-resistant suspensions with water that do not coagulate quickly. At the same time, the use of such a stemming material has significant advantages over the described traditional methods. The use of highly concentrated clay suspensions as a stemming material makes it possible to significantly improve the environmental performance of blasting processes due to the active adsorption of harmful gases by clay particles during the bubbling of these gases through a viscous colloidal system. The good adsorption properties of clay minerals have been known for a long time, not only for harmful gaseous substances, but even for radionuclides. Such adsorption activity of CM can be explained by two main mechanisms, which involve, firstly, physicochemical adsorption of toxicants on the surface of clay particles and on the inner surface of cavities; and, secondly, in the presence of charged explosion products – ion exchange for ions that are impurities to aluminosilicates (Tokarský, 2018; Arris-Roucan et al., 2023; Arris-Roucan et al., 2025; Lamrani et al., 2025). At the same time, the proposed borehole charge stemming allows to increase the efficiency of the explosion by reducing the speed of the stemming, which is associated with the nature of the behavior of non-Newtonian systems that experience an increase in viscosity under the influence of high forces, providing better retention of explosion products (gaseous waste) in the borehole and an increase in the degree of charge energy utilization.

Fig. 1. *Change in density of suspension with CM concentration at 20°C*

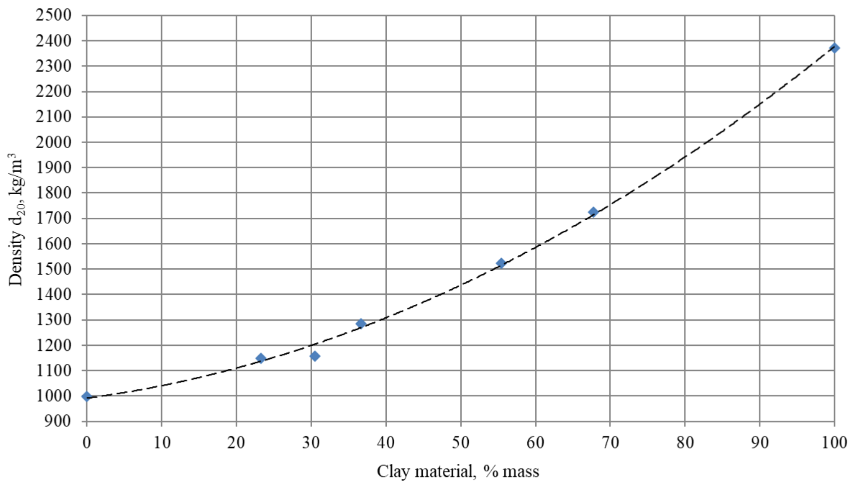


Table 1. *Relative deviations of the suspension density values calculated by the approximation model (3) from their additive values by (2)*

N	CM concentration, % mass	Calculated suspension density values, d_{20}, kg/m^3	Relative deviation of suspension density values from additive, δd_{20}, %
1	0.00	991.46	–
2	23.27	1137.32	15.90
3	30.50	1204.50	17.69
4	36.65	1269.79	18.29
5	55.38	1514.83	16.16
6	67.70	1713.91	12.55
7	100.00	2378.69	–

The chemical properties of the stemming material (a highly concentrated clay or loamy suspension) can be further modified by adding chemically active calcium hydroxide, calcium oxide and/or fine calcium carbonate with a particle size of up to 40 microns. The expediency of using slaked and quicklime as a neutralizing agent is substantiated in detail in the papers (Prosandieiev and Kozlova, 2011; Tverda et al., 2021a; Tverda et al., 2021b). Thus, the NO_x formed because of the explosion (Oluwoye et al., 2017), particularly NO_2, can interact with water (dispersion medium of the clay suspension), forming simultaneously strong nitrate and weak nitrite acids, which are further converted into calcium nitrates and nitrites as it is shown in chemical reaction *equations (4)–(6)*:

$$2NO_2 + H_2O = HNO_3 + HNO_2 \quad (4)$$

$$2HNO_3 + Ca(OH)_2 = Ca(NO_3)_2 + 2H_2O \quad (5)$$

$$2HNO_2 + Ca(OH)_2 = Ca(NO_2)_2 + 2H_2O \quad (6)$$

When fine calcium carbonate (chalk) is used as an additive to the stemming material and free oxygen is present in the explosion environment, the process of neutralizing harmful gases will occur in accordance with chemical reaction *equations (7)* and *(8)*:

$$CaCO_3 + 2NO_2 + 0.5O_2 \longleftrightarrow Ca(NO_3)_2 + CO_2 \quad (7)$$

$$CaCO_3 + CO_2 + H_2O = Ca(HCO_3)_2 \quad (8)$$

As noted by scientists (Phillips, 2013; Tverda et al., 2021b; Sanyal, 2024), these substances usually remain atomized in the air, and therefore, not reaching the maximum height of the dust and gas cloud, they settle near the explosion site, preventing contamination of the areas adjacent to the quarry. Carbon monoxide CO does not react with water, but when it enters the air, it can be oxidized to carbon dioxide, which will subsequently react with the corresponding calcium compounds – oxide (reaction *equation (9)*), hydroxide (reaction *equation (10)*) or carbonate (reaction *equation (8)*):

$$CaO + CO_2 \overset{t^\circ}{=} CaCO_3 \quad (9)$$

$$Ca(OH)_2 + CO_2 = CaCO_3 + H_2O \quad (10)$$

In addition, due to the formation of an acidic salt, calcium bicarbonate, additional adsorption of carbon dioxide generated during the explosion is possible (chemical reaction *equation (8)*). Although CO_2 is not considered a toxic gas, its excessive release into the environment significantly increases the carbon footprint, affecting climate change on the planet. The small size of chalk particles (up to 40 μm) (Phillips, 2013; Tverda et al., 2021b) significantly increases the area of its absorbing surface, contributing to a more complete and rapid interaction with nitrogen oxides. Thus, the use of fine chalk as a component of the stemming also proves to be quite effective, given that many quarries have calcium carbonate as overburden. However, when preparing a clay suspension as a stemming material, it is important to remember that in this case, the pH of the medium must be controlled, avoiding the use of acidified water (with a pH < 5.0). This is since alkaline additives to the stemming material, such as slaked and quicklime, and fine calcium carbonate, can react with it in an acid-base interaction. The use of the surfactant complex in the preparation of clay suspensions, in addition to improving their aggregate stability, will additionally help reduce dust formation and, as a result, improve the environmental situation near the quarries.

To ensure that the environmental and economic advantages of the proposed modification of borehole charge stemming are not only theoretically justified but also practically viable, a structured decision-making framework is required. Therefore, the next stage of our study focused on assessing and substantiating with the help of Thomas L. Saaty's AHP approach the feasibility of using the proposed technological solution – the modified borehole charges stemming. Based on this approach, we developed the author's methodology and computer program that can be used on mining enterprises for the evaluation of the feasibility of other stemming constructions, too. The core component of the AHP approach is the criteria hierarchical structure, which defines what exactly will be evaluated during the decision-making process, as well as all the interrelationships between the elements of this hierarchy. The developed hierarchical structure is presented in *Fig. 2* and is designed taking into account the results of our previous studies on the analytic hierarchy process, environmental management and sustainability, circular green economy, and waste management (Tverda et al., 2021b; Kofanov et al., 2024a; Kofanov et al., 2024b).

As can be seen from *Fig. 2*, the authors' criteria system consists of four levels. Level 1 is the goal – substantiate the feasibility of using the proposed technological solution – the modified borehole charges stemming. Level 2 is dedicated to the four high-level criteria – technological feasibility of the proposed solution (T), environmental safety, sustainability, and circularity (E), economic feasibility and resource effectiveness (Ec), and regulatory requirements for safe blasting operations (L). Mid-level criteria (or subcriteria) are at level 3 of the hierarchy, and each group of these criteria corresponds to the particular high-level criterion. So, the following mid-level criteria correspond to the high-level criterion, technological feasibility of the proposed solution.

The first one is the efficiency of using explosive energy for rock blasting (T1) – this subcriterion estimates how effectively the energy released during an explosion is used to fragment the rock mass so it is not lost through such channels as outgoing gases (gaseous waste) or uncontrolled shock waves. Such an efficiency directly influences both the quality of rock fragmentation and the amount of crushed material output, with the right size to satisfy the consumer's needs.

The second T-subcriterion, stemming components accessibility (T2), evaluates the practical accessibility of materials for the modified stemming near the mining enterprise. This includes geographic proximity of raw material sources (such as clay soils or industrial by-products), logistical considerations, and ease of extraction or collection.

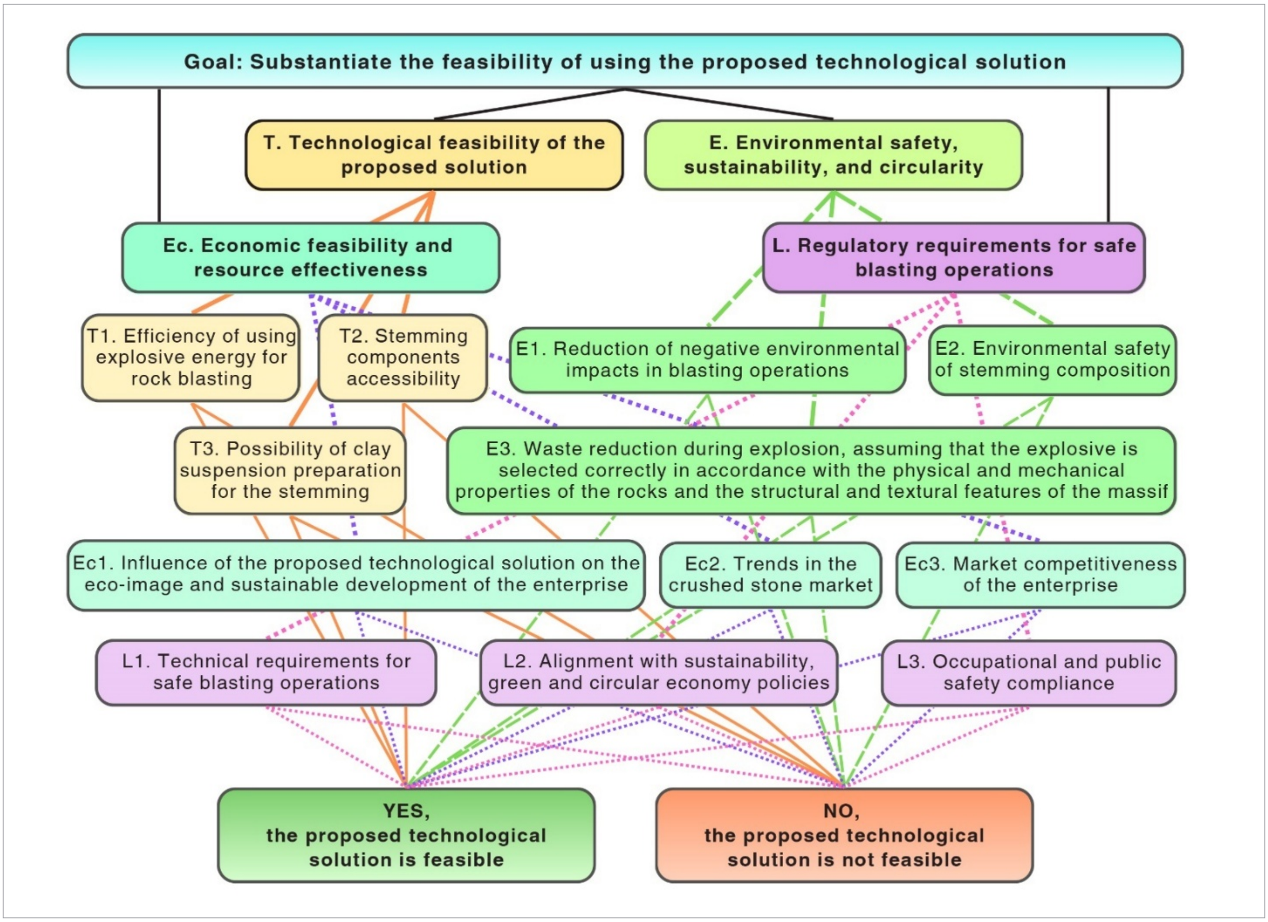
At the same time, the third T-subcriterion, possibility of clay suspension preparation for the stemming (T3), assesses how practically feasible it is to prepare and apply a clay suspension to seal the borehole after placing explosive charges. For this T-subcriterion, it is essential to consider how easily the clay suspension components can be mixed in the correct proportions and how conveniently the suspension can be prepared in the field conditions of the mining enterprise. Another important aspect is how smoothly the suspension can be filled into the borehole and create an effective stemming layer.

Of particular interest for this study are the subcriteria corresponding to the high-level criterion, environmental safety, sustainability, and circularity (E). The first one, reduction of negative environmental impacts in blasting operations (E1), assesses how effectively the stemming material, particularly clay suspension, minimizes the emission of harmful substances during blasting. This includes reducing the emission of dust, toxic gases, and other pollutants released during the explosion. A key factor is how well the stemming provides a locking effect that traps these gases inside the borehole, preventing them from entering the atmosphere. Additionally, the adsorption properties of clay particles play an important role, as their surface can capture and retain gases molecules, further reducing the environmental impact of the blasting process.

The second E-subcriterion, environmental safety of stemming composition (E2), evaluates the chemical and physical properties of the stemming that influence overall environmental safety. Insufficiently degradable components can accumulate in the surrounding soil and water systems near the mining enterprise. Such accumulation can lead to long-term ecological impacts. The last E-subcriterion, waste reduction during explosion, assuming that the explosive is selected correctly by the physical and mechanical properties of the rocks and the structural and textural features of the massif (E3), focuses on minimizing the generation of waste material during the rock blasting process. When the explosive is correctly matched to the geological characteristics of the rock massif and the stemming performs effectively, the resulting fragmentation is more controlled leading to improved efficiency of subsequent crushing operations.

The high-level criterion, economic feasibility and resource effectiveness (Ec), is also represented by three mid-level subcriteria. The first one is the influence of the proposed technological solution on the eco-image and sustainable development of the enterprise (Ec1). With the help of this subcriterion, it can be estimated how adopting the proposed technological solution enhances

Fig. 2. *Authors' hierarchy criteria system to substantiate the feasibility of using the proposed technological solution – the modified borehole charges stemming*



the environmental reputation and ensures the sustainable development of the mining enterprise. A positive eco-image can strengthen stakeholder trust, improve relations with local communities, and open access to green financing or grant programs. Demonstrating a commitment to sustainable practices and aligning with the European Green Deal principles can provide a significant advantage in the crushed stone market. This will help the enterprise to meet the consumer demand for responsible production.

The second Ec-subcriterion, trends in the crushed stone market (Ec2), considers the trends and perspectives in the crushed stone market in Ukraine and the countries to which products are exported or potentially can be exported, including the consumption of crushed stone in civil engineering, road, and military-industrial construction, etc. At the same time, the third Ec-subcriterion, market competitiveness of the enterprise (Ec3), assesses how the usage of the modified stemming influences the quality of the crushed stone production and how this affects the competitive advantages of the mining enterprise. This also includes the potential for the recycling of production waste.

The fourth and last high-level criterion is regulatory requirements for safe blasting operations (L). The first L-subcriterion, technical requirements for safe blasting operations (L1), evaluates whether the proposed technological solution meets the technical requirements for safely conducting blasting operations in mining enterprises. It focuses on the engineering aspects of blasting, including selecting and applying stemming material. This L-subcriterion also considers whether the stemming provides reliable locking under particular geological conditions and supports the stable functioning of the entire blasting system.

The next L-subcriterion is alignment with sustainability, green and circular economy policies (L2), which assesses whether the modification supports international, national, or industry-level policies, including closed-loop material cycles, green innovation incentives, ESG (environmental, social, governance) guidelines, etc. The last L-subcriterion is occupational and public safety compliance (L3), and it evaluates the compliance of the technological solution with safety standards aimed at protecting both workers involved in blasting operations and communities living in locations near the enterprise. A practical solution should minimize immediate operational hazards and contribute to a safe working environment and public safety over the entire lifecycle of its usage.

Level 4 of the authors' hierarchy criteria system represents the alternatives section with two options: Yes, the proposed technological solution is feasible; No, the proposed technological solution is not feasible. After all calculations, the alternative that receives 75% or more is considered the one to be chosen. If no alternative achieves a score of at least 75% in the evaluation, the procedure must be repeated, and appropriate adjustments should be made to the technological solution – the design of the modified borehole charge stemming.

According to the developed methodology, a group of three qualified experts was involved in the AHP-based evaluation. Each of them received clear instructions on how to complete the pairwise comparisons based on the hierarchy structure (*Fig. 2*). All further data input and calculations were done by the research team using dedicated software, described in the methods section. So, the experts were not required to work with the software directly. However, experts' qualification must correspond to both the general requirements peculiar to all AHP-based studies, which are characterized in detail in (Kofanov, Kofanova, Tkachuk, et al., 2024), and the unique requirements specific to this study.

Three key specific requirements considered during the expert selection process in this study are the following. The first requirement is objectivity and reliance on evidence. Experts must give unbiased, well-justified assessments based on real characteristics of the proposed technological solution, not on assumptions or personal preferences. To do this, they need to use not only their own experience in the field but also trustworthy sources such as technical reports, regulatory documents, enterprise data, environmental assessments, and relevant academic or industry publications.

The second requirement is that experts have the relevant expertise and practical experience. Taking into account that there are four different directions of the criteria in the hierarchy, the experts need solid knowledge in several fields. These include blasting technologies, environmental safety, sustainable resource management, circular green economy. It is also important that experts understand relevant legislation and policy frameworks, such as the UN sustainability goals, circular economy principles, European Green Deal polices, etc. The third requirement is dedicated to consistency in evaluation. Experts should use the same logic and standards when comparing all criteria and subcriteria to ensure the reliability of the results.

So, according to the developed methodology using the authors' AHP hierarchical structure (*Fig. 2*) and computer program, we substantiated that the modified stemming composition will significantly increase the environmental friendliness of the crushed stone production process. The quantitative results of the methodology implementation in the RStudio software are shown in *Fig. 3* and demonstrate a clear preference for the proposed stemming based on the evaluation criteria (*Fig. 2*). At the top hierarchy level, we can see that the weight of 'Yes, the proposed technological solution is feasible' is 83.4%; the weight of 'No, the proposed technological solution is not feasible' is 16.6%. Inconsistency indicator at this level is 7.0% and is within the acceptable limit, which is up to 10%.

To analyze this outcome in more detail, next we will consider the specific weight values and inconsistency indicators derived from the AHP analysis (*Fig. 3*). Technological feasibility has a total weight of 41.9%, with 'Yes' holding 36.2%, 'No' 5.7%, and inconsistency 8.2%. The inconsistency here is slightly higher than for the overall highest decision level, but still below 10%. Technological feasibility is the strongest criterion, meaning it contributes most to the decision model. Within technological feasibility, the highest T-subcriterion is the efficiency of using explosive energy for rock blasting at 27.5% total weight. Then comes stemming components accessibility with 10.2%, followed by the possibility of clay suspension preparation for stemming with 4.3%. The gap between 27.5% and 4.3% shows that the T1 subriterion is determined as the most important in this context.

Environmental safety, sustainability, and circularity have a total weight of 32.6%, with 25.2% for 'Yes,' 7.4% for

'No,' and inconsistency 7.0%. This time inconsistency is again within the acceptable limit of 10%. Within the E-subcriterion group, reduction of negative environmental impacts in blasting operations weighs 19.6%, environmental safety of stemming composition 9.5%, and waste reduction during explosion 3.6%. Thus, it is visible that the main focus here is on reducing negative environmental impacts; however, the other two E-subcriteria also contribute to the 'Yes' alternative, substantiating the overall feasibility of the proposed technological solution.

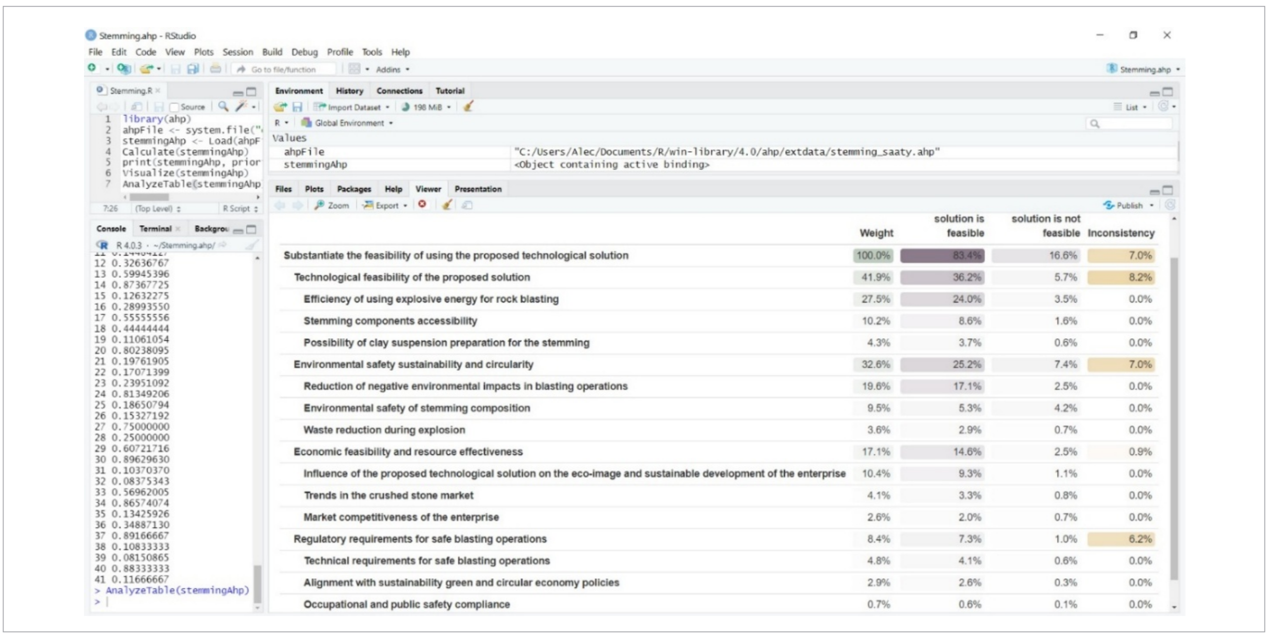
Economic feasibility and resource effectiveness criterion has a total weight of 17.1% with 'Yes' being 14.6%, 'No' being 2.5%, and inconsistency being 0.9%. This is the lowest inconsistency ratio across all criteria, showing a very consistent judgment set for it. Inside this Ec-subcriteria group, influence on eco-image and sustainable development of the enterprise holds 10.4%, trends in the crushed stone market 4.1%, and market competitiveness of the enterprise 2.6%.

Regulatory requirements for safe blasting operations criterion has a total weight of 8.4% with 7.3% for 'Yes,' and only 1.0% for 'No;' inconsistency – 6.2%. Inside this L-subcriteria group, technical requirements for safe blasting operations weigh 4.8%, alignment with sustainability, green and circular economy policies 2.9%, and occupational and public safety compliance 0.7%.

The total weight is highly concentrated on two clusters: technological feasibility (41.9%) and environmental safety (32.6%), together accounting for 74.5% (joint contribution to the 'Yes' alternative is 61.4%). Economic feasibility and regulatory requirements together account for 25.5%. This shows clear prioritization towards technological and environmental considerations over economic and legal ones.

However, despite their lower calculated priority in the overall weight, economic and legal criteria with their respective subcriteria play an important role in the decision-making process. Their joint contribution of 21.9% to the 'Yes' alternative, compared to only 3.5% to the 'No' alternative, confirms their alignment with the feasibility of the proposed stemming material modification. These criteria, like the technological and environmental ones, consistently support the implementation of the solution. If, on the contrary, economic and legal criteria had contributed more substantially to the 'No' alternative, this would have raised concerns regarding the overall feasibility of the proposal. Moreover, surpassing the 75% threshold stated in this study as a benchmark for reliable decision-making would have been quite difficult to obtain in such a case. Then it would be necessary to revise the technological solution and repeat the AHP evaluation. Nevertheless,

Fig. 3. *The application of the authors' program in RStudio and resulting calculations for substantiation of the feasibility of using the proposed technological solution – the modified borehole charges stemming*



for the modified stemming material proposed in our study, all the criteria and sub-criteria showed the advantage of the 'Yes' alternative over the 'No' alternative with an 83.4% probability that the proposed technological solution is feasible.

Conclusion

The paper proves that the use of non-Newtonian fluid-based systems as stemming material for borehole charges – concentrated clay suspensions enhanced with a complex surfactant additive – demonstrates a range of significant advantages. This approach not only increases the technological efficiency of rock blasting due to the unique rheological properties of non-Newtonian systems, but also contributes to reducing the stemming ejection velocity, thereby improving the overall utilization of explosive energy. Particularly noteworthy is the fact that, when using slaked or unslaked lime in combination with the proposed stemming material, there is near-complete neutralization of harmful gases – gaseous waste – generated during the explosion. Additionally, this type of stemming is economically affordable, easy to implement, and safe to use.

A modified borehole charge stemming consists of a suspension of clay material in the concentration range of 20–70 % mass and a surfactant complex (up to 2.5% mass). A densitometric study of investigated CM suspensions has been carried out; the deviation of such systems from the additivity law and the behavior of these systems as non-Newtonian fluids due to structure formation processes have been proven, the relative deviations of experimental density values from their additive values have been calculated. Based on densitometric studies of investigated clay suspensions, an approximate polynomial model of the second degree has been developed, that makes it possible to determine the density of suspensions almost up to the critical concentration of structure formation. An important aspect of the proposed technological solution is significant adsorption properties of CM suspensions.

The results of the Analytic Hierarchy Process analysis confirm that the modified stemming material for borehole charges is feasible with a high probability – 83.4%, exceeding the 75.0% decision threshold. At the same time, the inconsistency indicator for all criteria and subcriteria is within the acceptable limit – less than 10.0% confirming that the obtained results are reliable. The proposed solution is substantiated primarily by technological feasibility (contribution to the 'Yes' alternative is 36.2%) and environmental safety, sustainability, and circularity (with a contribution of 25.2%). This indicates that the proposed stemming clay suspension is not only attractive from a technological point of view, but at the same time, it has a safe composition, it effectively adsorbs harmful gases emitted during an explosion, and it corresponds to the circular green economy and ESG principles.

Although the economic (with a contribution to the 'Yes' alternative of 14.6%) and regulatory (7.3% accordingly) criteria groups were less influential in the overall weight, their joint contribution supports the market relevance and legal acceptability of the solution. In particular, the subcriterion dedicated to the eco-image and sustainable development of the enterprise (with a contribution of 9.3%) demonstrates that this solution strengthens the enterprise's sustainability image, which can improve access to green financing and increase competitiveness under ESG-driven market conditions. The regulatory evaluation confirmed that the stemming complies with current safety and policy requirements.

In addition to proving the feasibility of the proposed stemming design, the developed AHP-based methodology and authors' software tool, created using RStudio and the R programming language, offer a practical decision-making instrument for mining enterprises. The approach is reproducible and applicable to similar assessments of other eco-innovations in mining enterprises, not only in Ukraine, but in the European Union and other locations around the world. The methodology allows to provide a transparent quantitative evaluation of mining innovations against multiple sustainability and performance criteria, ensuring consistency in judgments.

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