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Innovative Compositions of Shotcrete Mixtures for Reinforcement of Underground Mine Excavations

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Abstract

The objective of this article is to develop a polymer-modified shotcrete composition to improve underground mine support. The authors propose a new formulation by integrating an aqueous emulsion of SKS-65 GP grade B latex into cementitious matrices. Methods include X-ray diffraction, particle-size analysis, rheological testing, mechanical strength tests, numerical modeling, in-situ trials at the Zholbarysty mine, and statistical evaluation. Findings show a 45% increase in compressive strength and a 30% reduction in rebound loss compared to standard mixtures. Field core samples confirmed reproducibility, with strength values within 1% of those from laboratory-tested cubes. The improved mix allows a 50% reduction in lining thickness, expanding the tunnel cross-section by 5% and lowering operational costs by 39%. Cost-benefit analysis and cross-sectional evaluation validate the approach's efficiency. The novelty of this work lies in combining microstructural insights with field-scale application, clarifying polymer-film formation mechanisms, and presenting an optimized, scalable shotcrete mix design. This integrated method provides a practical and cost-effective reinforcement solution, advancing current shotcrete technologies for underground operations.

Keywords: Innovative; SKS-65 GP Latex-Enhanced Shotcrete; Underground Mine Workings; Composition of Shotcrete; Support; Supporting Technology.

1. Introduction

1.1. Analysis of Contemporary Domestic and International Research on Underground Mining Support Systems

Over the past decade (2015–2024), underground mining has undergone significant deepening due to the depletion of near-surface ores and rising global demand for minerals. Over 12 billion tons of rock are extracted annually, with more than 45% mined from depths beyond 1,000 meters, where stresses exceed 30 MPa. These conditions increase the risk of collapses, water inflows, and ventilation issues, demanding reliable support systems. However, current technologies, such as shotcrete, still face challenges, including rebound, cracking, and deformation, which often lead to expensive repairs. These issues contribute to annual losses exceeding $7.2 billion and 3.1 million DALYs. Additionally, cement consumption and CO_2 emissions are rising, reaching 1.8 million tons per year [1-3].

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1.2. Geomechanical Aspects and the Stress-Strain State of Rock Masses

Research by Samantha et al. [4] has shown that fiber-reinforced and hybrid shotcrete systems are more effective than traditional metal supports. Streltsov explored shotcrete in coal mines [5], while Shmatovsky & Kolomietc [6] proposed cost-efficient methods. At the Orlovskoye deposit, metal supports were successfully replaced with reinforced shotcrete, supported by developed mixture delivery and plant placement schemes. Despite high capital costs, mechanisation remains limited. Although shotcrete application is 95% mechanized, challenges such as material loss (up to 35%), dust, and poor adhesion persist. However, these issues are gradually being addressed [7].

1.3. Technologies and Mechanization of Underground Mine Support Installation, Including Shotcrete Applications

Recent studies focus on enhancing shotcrete formulations with polymeric and mineral admixtures to improve strength, durability, and sustainability. Thomas et al. [8], Akpanbayeva & Isabek [9], and Lindlar et al. [10] demonstrated how such modifiers improve rheology and application performance. Wang et al. [11] demonstrated that multi-jet nozzles reduce rebound loss, although the effects of temperature and humidity remain unstudied. Elbialy et al. [12] and Alekseev & Bazhenova [13] emphasized the contribution of steel fibers to flexural strength. At the same time, Wang et al. [14] applied fractal dimensionality to analyze pore structure, yet lacked long-term durability assessments. Zhukov et al. [15] explored waterproofing coatings; Panarin et al. [16] examined polymineral binders; Filatiev & Laguta [17] studied nanodiamond additions; Tian et al. [18] evaluated anti-salt admixtures. However, many findings remain limited to laboratory settings, lacking in situ validation. Sustainability-focused work by Konovalova et al. [19], Ahmed Tamer et al. [20], and interface analyses by Hu et al. [21] reflect recent progress. Almenov et al. [22] demonstrated the promising use of polymer-cement fiber shotcrete for metro tunnels. However, gaps persist in evaluating durability under aggressive conditions, cost-effectiveness, and full-scale applications. Emerging innovations include delayed-setting concretes for mining [23] and 3D-printed shotcrete (SC3DP) systems [24], which offer structural benefits but face rheological and precision limitations. Hybrid fibers improve mechanics [25], though economic and durability data remain scarce [26].

1.4. Modern Shotcrete Materials, including Modified Formulations and Polymer Additives

While prior studies significantly advanced knowledge of shotcrete performance, most are confined to laboratory conditions, often using cylindrical specimens that fail to capture the complex relief and dynamic rock pressure changes in real underground environments [27]. Moreover, modified latex applications have been rarely explored in mining contexts, with a focus instead on above-ground or civil engineering applications [11, 28].

1.5. Research Gap and Proposed Contribution

This study presents novel findings from a combination of laboratory and fieldwork on latex-modified shotcrete compositions, comprising cement, sand, crushed stone, latex emulsion, and water. The resultant material exhibits a compressive strength of 46 MPa and exhibits high adhesion to rock surfaces. A comprehensive evaluation of the shotcrete's microstructure, mechanical properties, and its in situ performance enables the tailored development of underground mine support systems, thereby transforming their stability, efficiency, and cost viability.

2. Research Context and Critical Literature Review

2.1. Analysis of Normative and Technical Documentation Regulating Requirements to Composition, Properties, and Technology of Shotcrete Application

Shotcrete (sprayed concrete support) is a multi-component material consisting of a binder, fine and coarse aggregates, and water [13]. Depending on the operational conditions and purpose, various modifying additives can be included, such as accelerating admixtures for setting and hardening, plasticizers, and components that improve the density and water resistance of the hardened material. The optimal type and dosage of additives are selected experimentally, considering the cement characteristics, the composition of the dry cement-sand mixture, environmental temperature and humidity, the presence of aggressive factors, and the economic feasibility of achieving the required properties of shotcrete.

The operational characteristics and cost-effectiveness of sprayed concrete support are determined not only by mining-geological and engineering conditions but also by the physical-mechanical and physical-chemical parameters of the concrete mixture components and the specifics of the application technology. In cases of rapid mining pressure increase, especially when applying shotcrete support immediately after excavation or under water inflow, accelerated setting and hardening of sprayed concrete are necessary. It can be achieved through fast-hardening cements, stiff mixtures with reduced water-cement ratio, efficient compaction, and specialized curing accelerators.

The following requirements are imposed on shotcrete accelerators: they must ensure curing within the specified time, limit the reduction of final strength to no more than 10%, prevent corrosion of reinforcement and equipment, minimize shrinkage, and not complicate the spraying process. Additionally, they should prevent sloughing of thick applied layers, minimize material loss during application, and protect the uncured shotcrete layer from erosion by filtering water. Important requirements also include non-toxicity, availability, and economic feasibility [24, 25, 29].

Studies have shown that many accelerating admixtures, such as calcium chloride, finely ground sodium aluminate, sodium ferrite speck (SES), and sodium aluminate, significantly reduce the water permeability of cured mortar throughout 1 to 6 months. Accelerators also reduce material loss during application, enhance resistance to low temperatures and aggressive chemical exposure, and increase viscosity and adhesion, ensuring strong bonding of shotcrete to smooth and wet rock surfaces [20-23, 30]. However, their use may have drawbacks. Some, including sodium aluminate, finely ground sodium ferrite, and sulfuric acid iron, can reduce the final strength, increase shrinkage, and lower the cement's activity. Therefore, selecting the accelerator type and dosage must be done experimentally, taking into account the properties of the cement, the mixture composition, and the specific working conditions. To meet performance requirements, shotcrete should set within 2-3 minutes, reach a minimum strength of 1.0 MPa after 1 hour, and continue to harden at a normal pace. The choice of accelerators must also reflect the physical and mechanical characteristics of the surrounding rock mass [31, 32].

The components used in this study – including cement, crushed stone, sand, water, and additives – meet the standards of the Republic of Kazakhstan: ST RK 3839-2023 "Portland cement composite and composite cement. Technical conditions" [33], ST RK 1284-2004 "Crushed stone and gravel from dense rocks for construction works" [34], ST RK 1217-2003 "Sand for construction works. Test methods" [35], Interstate Standard GOST 23732-2011 "Water for concrete and mortars. Technical conditions" [36], as well as Interstate Standard GOST 10564-75 "Synthetic latex SKS-65 GP. Technical conditions" [29].

As noted in the introduction, shotcrete is among the most widely used materials for underground support, applied to rock surfaces using compressed air. Its high adhesion, versatility, and suitability for mechanized application in complex geological conditions make it effective for both temporary and permanent support systems. However, its performance depends heavily on the precise composition of the mix, the selection of components, and the application technology. With growing demands for structural reliability and durability, a comprehensive study of the composition, physical and mechanical properties, and technological parameters of shotcrete is becoming increasingly important. Enhancing strength, reducing cracking, and ensuring resistance to aggressive environments require a scientifically grounded approach to the design and application of shotcrete mixtures. Therefore, optimizing composition, studying key properties, and refining application techniques are urgent and practically significant tasks. Several studies have directly contributed to improving the efficiency, reliability, and safety of underground construction and mine operations [26, 37, 38].

2.2. Identification of Key Factors Affecting Strength, Adhesion, Deformation, and Performance Characteristics of the Material

Based on the analysis of existing technologies and requirements for mine workings support, it is established that they must ensure rock stability, operational safety, and long-term durability under complex geomechanical conditions. Supports must withstand mining pressure, vibrations, cave-ins, and blasting while providing uniform stress distribution and preventing deformation [39, 40]. They should retain bearing capacity under exposure to moisture, acids, salts, and temperature fluctuations, adhere tightly to excavation surfaces to prevent the ingress of water, gas, and loose materials, and remain flexible enough to accommodate ground deformations and redistribute loads. Additionally, ease of installation, cost-effectiveness through reduced material and labor inputs, the use of local materials, and adherence to environmental and occupational safety standards are critical. Therefore, the proper selection and design of support systems are crucial for ensuring safe underground mining operations.

The mechanical and durability performance of shotcrete, commonly used for ground support, is influenced by compositional, technological, and operational factors. These include the type and quality of binder (such as Portland cement or pozzolanic materials), aggregate properties, water-cement ratio, and chemical additives like plasticizers, accelerators, and polymers, which enhance bonding, reduce permeability, and improve frost resistance and longevity [29-32]. Application methods (wet or dry spraying), air pressure, curing conditions, and porosity all affect service life. Additionally, operational conditions such as vibrations, chemical exposure, and freeze-thaw cycles can lead to cracking and loss of adhesion. The interplay of these factors determines the strength and efficiency of shotcrete support, and optimizing composition and application technology is vital for performance [24-26, 29, 37, 38].

3. Research Methodology

The research and development of novel shotcrete formulations, along with the optimization of their application technologies, were conducted using a structured, multi-phase methodology. As schematically shown in Figure 1, this framework comprises successive stages of: (1) comprehensive review of relevant standards and prior research; (2) baseline characterization of conventional shotcrete systems; (3) design and laboratory- scale testing of modified mixtures; (4) pilot- scale field trials in operational mine workings; (5) multivariate statistical and microstructural analyses; and (6) techno- economic and application- procedure optimization:

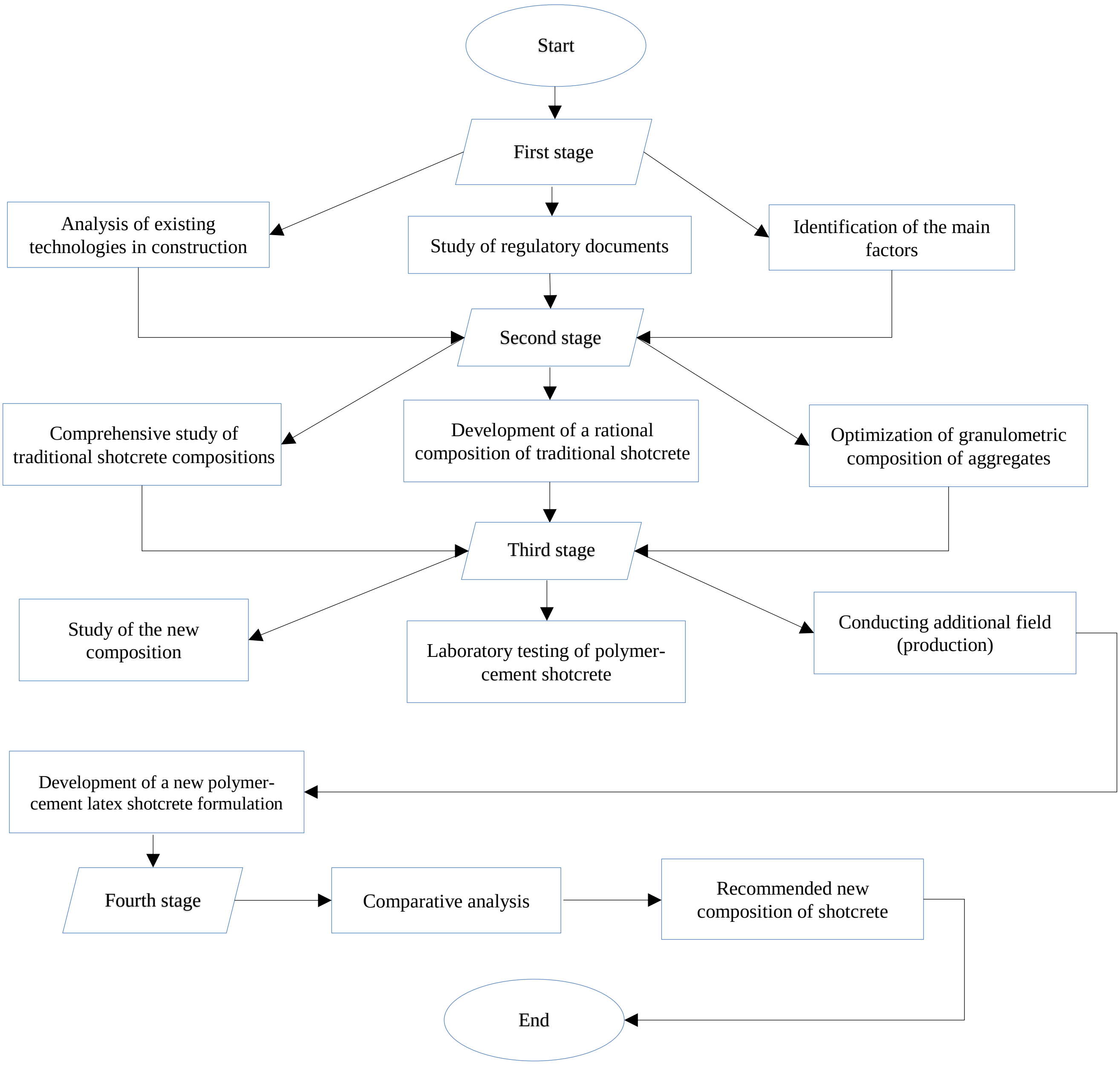

Figure 1. Block diagram of the generalized methodological algorithm for the development of new shotcrete for underground mines working support

The research followed a sequential and integrated approach, starting with a comprehensive review of existing shotcrete technologies, regulatory standards, and domestic and international studies on composition, properties, and application methods. That allowed for the identification of key factors influencing strength, adhesion, deformability, and durability, which informed the experimental design. Laboratory studies were then conducted on conventional shotcrete mixes using Portland cement, pozzolanic binders, and complex binders, with optimized aggregate gradations and water-cement ratios. Mechanical performance was assessed through compressive strength (GOST 10180), tensile splitting (Ø100 × 100 mm, GOST 28570), and adhesion (pull-off tests). All samples were cured for 28 days under standard conditions and tested in triplicate to ensure reproducibility.

Building on the optimized traditional mixes, polymer-modified formulations were developed by incorporating SKS-65 GP grade B latex (2-10% by weight of cement) as an accelerating additive. The modified mixtures were cast into 100 × 100 × 100 mm cubes and tested under the same protocols. The overall methodological framework and experimental setup are summarized in Figure 1, with detailed descriptions and analyses provided in Section 5. This combined approach ensured both laboratory precision and practical relevance, aiming to create a high-performance, reproducible, and cost-effective shotcrete solution for underground mining applications.

Subsequently, to confirm the laboratory results in real production conditions, samples taken from shotcrete fasteners were tested in the underground mine adit No. 4 of the "Zholbarysty" mine (Republic of Kazakhstan). Field tests were conducted on two separate occasions. The depth of the adit is 230 metres. The host rock types are granodiorites and orgovian sandstones, with average compressive strength (σcs) values ranging from 82 to 128 megapascals. The volumetric density of the rocks has been determined to be 2.7 t/m^3. The cores were extracted using a diamond drilling method that employed a UAD-3 machine. The extraction of cores, measuring 100 mm in diameter and 100 mm in height, was conducted over 28 days following the implementation of shotcrete, with a stepwise progression of 5 meters along the excavation length. The BM-60 concrete mixer was used for feeding the mixture. The coring interval was set at one day, and two samples were collected daily. A total of ten cores were obtained for the study. It is evident that throughout the period during which the works were conducted, the air temperature within the excavation was recorded to be between 16 and 20 °C. Concurrently, the relative humidity levels were documented to be within the range of 60 to 70%. Sampling was conducted in areas where binary shotcrete with latex content ranging from 2% to 10% of cement weight was utilised (five samples), as well as in areas where ternary formulations of shotcrete with a comparable range of latex content were employed (another five samples).

The findings of tests conducted on cores extracted by drilling from the poured-in-place concrete supports installed in underground mine workings were then compared with the results of laboratory-fabricated concrete samples in the form of cubes. The analysis findings indicate that the strength characteristics of shotcrete, as determined by cores and laboratory samples, are nearly equivalent, with a variation in values ranging from 0.4% to 0.9%. A comparison of shotcrete strength in megapascals also revealed no statistically significant differences between the samples that were studied. The objective of this series of studies was to develop rational compositions of shotcrete, aiming to enhance its strength, adhesion, technological, economic, and operational characteristics in the context of underground mine workings. Consequently, the composition of shotcrete was determined to be rational for enhancing its physical, mechanical, and operational properties.

The fourth stage included studies on the economic comparison of shotcrete with traditional composition and mine construction with a modified polymer composition, as well as the optimization of the technology's application and operation.

4. Results and Discussion

4.1. Traditional Method Binary and Ternary Formulations

Within the framework of this study, a comprehensive analysis was conducted of traditional sprayed (shotcrete) concrete compositions commonly used in underground construction practices.

4.1.1. Materials and Mix Design

To achieve the target design strength, we conducted experimental tests on ten mix compositions: five binary mixtures (№1-5, cement:sand) and five ternary formulations (№6-10, cement:sand:crushed stone fraction up to 10 mm). The cement content in the binary mixtures ranged from 280 to 570 kg/m³, while in the ternary formulations, it ranged from 250 to 450 kg/m³. Portland cement of M400 grade, produced by Ust-Kamenogorsk cement plant, was used as a binder. For binary mixtures, the optimum water-cement ratio was 0.35-0.45, and for ternary formulations, it was 0.41-0.52.

Figure 2 shows the preparation of materials for testing, where samples 1-5 represent binary formulations and 6-10 represent ternary formulations, along with the measurement of prepared cubic specimens (100 × 100 × 100 mm) using a caliper.

(a)

(b)

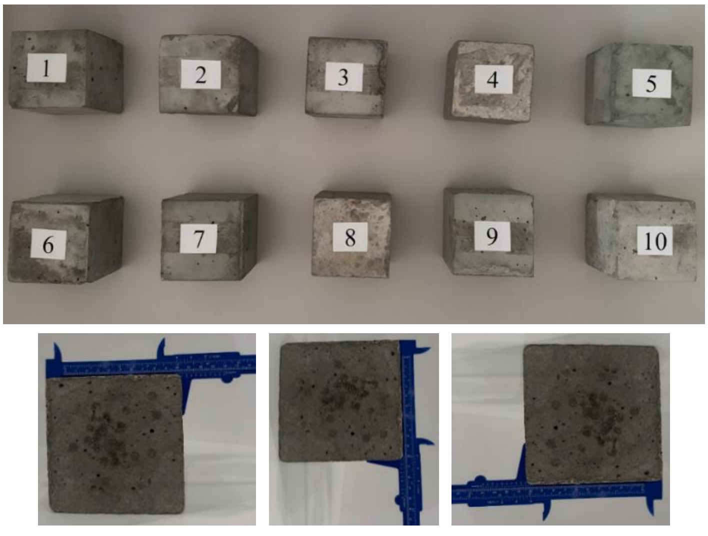

Figure 2. Preparation of materials for testing (a) Top view of mixture 1-5 - binary formulations, 6-10 - ternary formulations; b) Measured mixtures with a caliper (100 × 100 × 100 mm)

Figure 3 shows the particle-size distribution of local raw materials used in this study, with the percentage of each fraction indicated. The materials were sourced from the Ust-Kamenogorsk region. The particle sizes are categorized as follows: 0.16 mm - 5% (fine dust-like particles affecting the workability of the mixture), 0.16-0.63 mm-15% (fine sand improving the filling of voids), 0.63-1.25 mm - 25% (medium sand contributing to density and structure), 1.25-2.5 mm - 30% (coarse sand or fine gravel providing bearing capacity), 2.5-5 mm - 20% (fine crushed stone improving strength and reducing shrinkage), and 5-10 mm - 5% (coarse crushed stone, used sparingly to prevent blockages).

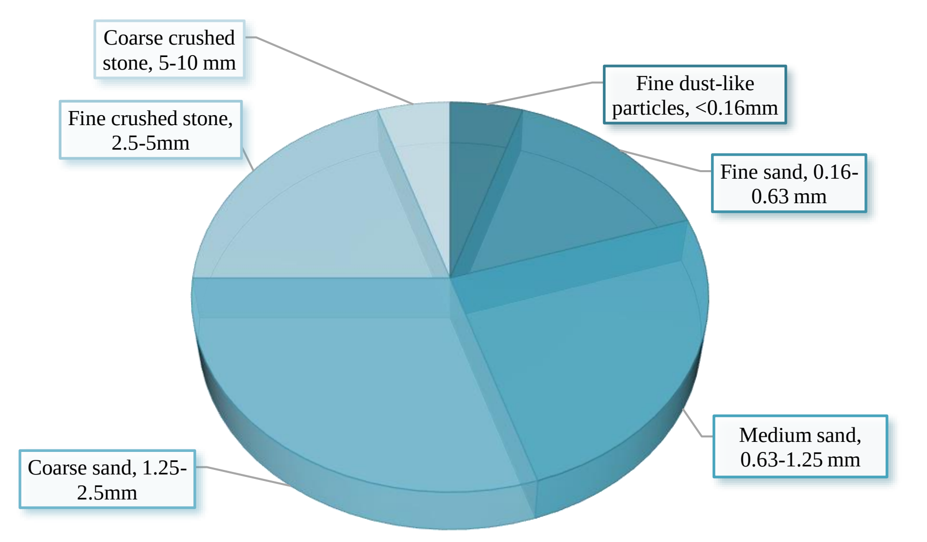

Figure 3. Diagram of the granulometric composition of the materials used

4.2. Laboratory Testing of Mechanical Properties

To determine the strength characteristics, cubic samples measuring 100 mm × 100 mm × 100 mm were prepared. Strength tests of mine construction samples were conducted in the laboratory of KazNRTU named after K.I. Satbayev using a hydraulic press according to the requirements of GOST 10180. Samples were stored under normal conditions, and tests were conducted for periods of 1, 3, 7, and 28 days. Additionally, the strength was determined using a Kashkarov hammer as a reference.

4.2.1. Testing Procedure

The results of laboratory tests investigating the strength characteristics of binary (Mixes 1-5) and ternary (Mixes 6-10) shotcrete mixtures over different curing times are summarised in Table 1.

Table 1. Strength characteristics and economic indicators of 1 m³ binary and ternary shotcrete mixtures depending on curing time

Mix ID (n)	Formulation shotcrete	Cements kg/m³	Sand, kg/m³	Crushed stone, g/m³	W/C ratio	Crushed stone fraction, % by mass	Compressive strength MPa at the age of (day)				Cost, USD/m³
							1 day	3 day	7 day	28 day	
Binary formulation (C:S:W)											
1	1:3.8	280	1064	-	0.4	-	0.7 ± 0.1	3.8 ± 0.2	11.2 ± 0.5	15.7 ± 0.7	41.55
2	1:2.9	360	1044	-	0.39	-	1.2 ± 0.1	4.1 ± 0.2	11.8 ± 0.5	17.4 ± 0.8	47.60
3	1:2.4	400	960	-	0.37	-	1.9 ± 0.2	4.0 ± 0.3	13.9 ± 0.6	22.2 ± 0.8	49.28
4	1:1.9	470	893	-	0.36	-	2.1 ± 0.2	4.9 ± 0.3	15.3 ± 0.6	23.1 ± 0.9	53.67
5	1:1.4	570	798	-	0.35	-	2.5 ± 0.2	5.3 ± 0.3	17.0 ± 0.7	23.7 ± 1.0	59.97
Ternary formulation (C:S:CS:W)											
6	**1:2.8:2.7**	**250**	**700**	**675**	**0.47**	**41**	**2.2 ± 0.2**	**4.2 ± 0.3**	**12.1 ± 0.5**	**18.3 ± 0.8**	45.2
7	**1:1.9:2.5**	**300**	**570**	**750**	**0.45**	**46**	**2.0 ± 0.2**	**4.8 ± 0.3**	**13.4 ± 0.6**	**19.4 ± 0.9**	48.51
8	**1:1.8:1.6**	**350**	**630**	**560**	**0.44**	**36**	**3.0 ± 0.3**	**6.4 ± 0.3**	**18.2 ± 0.7**	**27.4 ± 1.1**	49.98
9	**1:1.4:1.5**	**400**	**560**	**600**	**0.43**	**38**	**4.1 ± 0.3**	**7.6 ± 0.4**	**20.3 ± 0.8**	**30.7 ± 1.2**	53.48
10	**1:1.4:1.0**	**450**	**630**	**450**	**0.42**	**30**	**3.4 ± 0.3**	**6.7 ± 0.3**	**19.7 ± 0.8**	**29.3 ± 1.2**	55.89

Note: Material prices - Cement M400: 35000 KZT/ton (equivalent to 70 USD/ton); Sand: 5000 KZT/ton (equivalent to 10 USD/ton); Crushed stone Sand: 6000 KZT/ton (equivalent to 12 USD/ton), the density of crushed stone is 1400 kg/m³, Water - 45 tg/m³ (0,10 USD/м³); water density - 1000 kg/m³. Material prices are based on the rates as of February 10, 2025. The conversion from tenge to USD was performed using the exchange rate of 1 USD = 500 KZT, effective on the specified date.

Table 1 provides detailed information on mix ID, cement, sand, crushed stone content, water-cement ratio (W/C), crushed stone fraction by mass, and compressive strength at 1, 3, 7, and 28 days. The formulations are reported both as absolute mass (kg m^{-3}) and as cement:sand:crushed stone ratios.

Optimal W/C ratios (0.35-0.45) were determined through preliminary trials to balance workability (evaluated by flow table tests) and compressive strength. For each mix and curing age, at least three specimens (n = 3) were tested, and results are reported as mean ± standard deviation (±σ). The observed variability remained below ±5%, confirming high statistical reliability. A series of studies have been conducted on binary and ternary compositions of traditional shotcrete, the results of which indicate that the mixtures used in the third and ninth tests are rational in terms of both strength characteristics and economic feasibility. As shown in Table 1, ternary mixes consistently outperformed binary mixes in compressive strength across all curing ages. Binary mixes developed strength from 0.7 ± 0.1 MPa at 1 day to 23.7 ± 1.0 MPa at 28 days, while ternary mixes ranged from 2.0 ± 0.2 MPa to 30.7 ± 1.2 MPa over the same period. Notably, mix 9 achieved approximately 30% higher 28-day strength compared to the best-performing binary mix (Mix 3), despite using less cement, which highlights the beneficial effect of optimized aggregate composition and modifying additives. The experimental procedure followed GOST 10180-2012 standards for compressive and flexural strength testing. Specimens were 100 × 100 × 100 mm cubes, cured under controlled conditions (23.9°C, relative humidity ≥95%). Loading was applied at a constant rate of 0.5 MPa/s, and all equipment was calibrated annually to ensure accuracy and precision.

Field tests were conducted at Adit No. 4 of the Zholbarys mine to assess rebound losses during dry-mix shotcrete application with BM-68 equipment. The nozzle-to-surface distance ranged from 0.8 to 2.0 meters. A 1000 cm^2 polyethylene sheet was placed under the sprayed surface to collect rebound material. Measurements were repeated three times, and averages were calculated. Incorporating a latex-modifying additive (SBR latex, 3% by cement mass) reduced rebound losses from 34.3% to 30%, representing a ~10.3% decrease in material waste. Correlation coefficients ranged from 0.89 to 0.95 with a confidence level of 95-98%, confirming the high reproducibility of results.

The strength tests revealed that plain mixes (without additives) exhibited brittle failure, characterized by vertical cracks extending from the point of load application, often accompanied by large fragment detachment. Modified mixes (with SBR latex and silica fume, featuring a 10% cement replacement) exhibited an increased number of fine diagonal and network-like cracks. Fractures developed more uniformly, with delamination occurring at the matrix-aggregate interfaces, indicating improved crack resistance and a more uniform stress distribution. At optimal additive content, crack development slowed, and thin microcracks formed in the upper and lateral areas without sharp fracture. This behavior indicates enhanced plasticity, suggesting that modifying additives improves both the mechanical strength and fracture behavior of shotcrete, resulting in more predictable and durable performance. Typical crack patterns and fracture modes are presented in Figure 4 which shows the testing conditions of the mixes: (a) condition of the specimens before testing, (b) condition of the specimens after testing, (c) testing conditions and numerical results, (d) conditions of first crack formation, (e) conditions of second crack formation, (f) conditions of specimen failure.

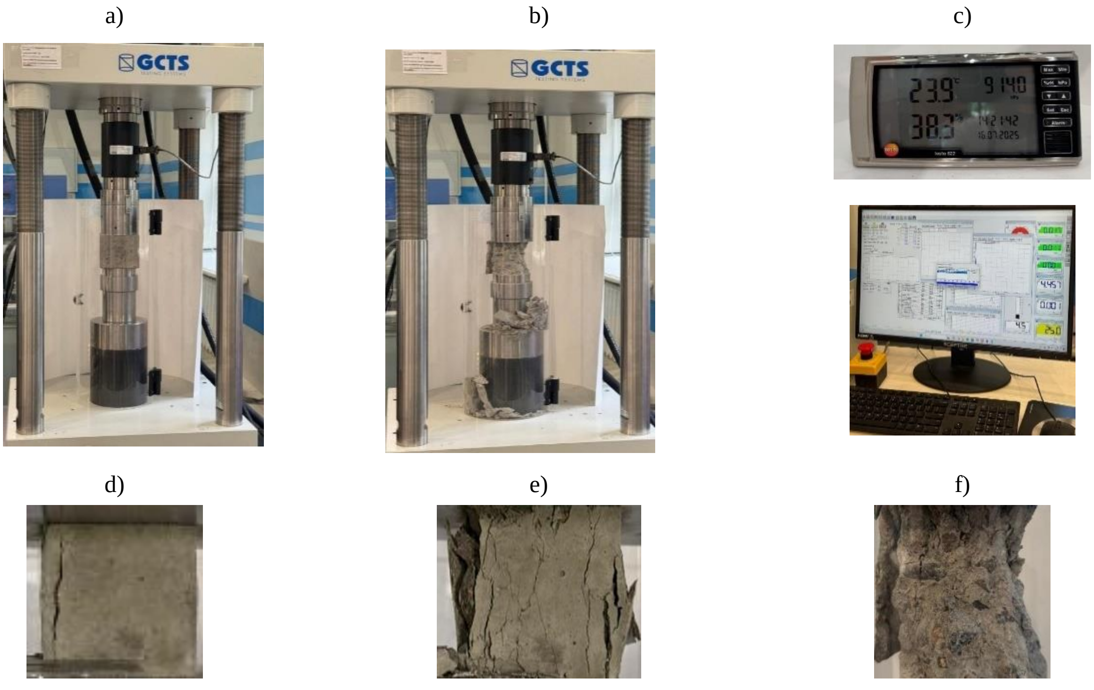

Figure 4. Compression testing of specimens 1 in GCTS hydraulic press: a) before; b) after; c) test status and numerical results; d) first crack creation; e) second crack creation; f) fractured specimens

Visual observations of crack development were performed without the use of magnification devices, employing macroscopic inspection. The documentation of characteristic failure patterns was carried out using a digital camera (12 MP resolution) under controlled lighting conditions to ensure sufficient surface contrast. The analysis concentrated on evaluating the orientation, nature, and distribution of cracks, as well as identifying the predominant failure mechanisms (brittle or plastic) based on the shape and direction of crack propagation. Quantitative evaluation of crack parameters (e.g., total crack length or the number of cracks per unit area) was not conducted in this study; the analysis was qualitative. Compressive strength tests were performed exclusively using a hydraulic press with a controlled loading rate (0.5 MPa/s), and results were recorded via integrated software. It should be noted that no measurements were conducted using a reference hammer (e.g., Kashkarov hammer) or similar devices. Consequently, no correlation coefficients (e.g., R^2) were determined between the methods. Figure 5 illustrates the temporal dynamics of the increase in shotcrete strength, based on experimental findings from tests conducted on samples numbered 1 through 5. These samples consisted of binary mixtures with varying cement contents, ranging from 280 to 570 kg/m³.

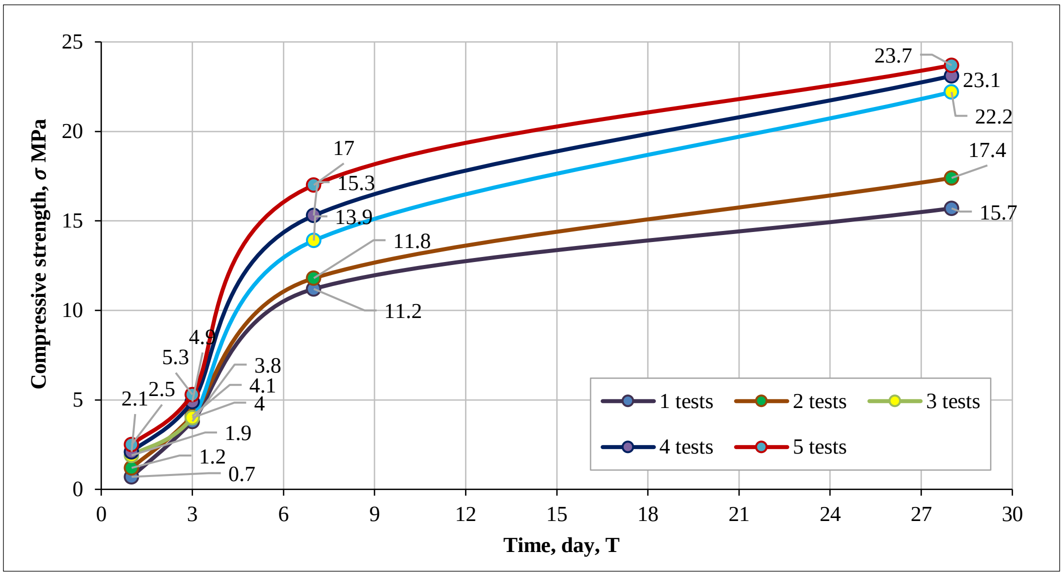

Figure 5. Dynamics of strength gain of shotcrete in time (in days) when testing specimens №1-5 made of different binary mixtures with varying cement content in the range of 280-570 kg/m³ (1. C:S=1:3,8, C=280 кg/m³; 2. C:S =1:2,9, C=360 кg/m³; 3. C:S =1:2,4, C=400 кg/m³; 4. C:S =1:1,9, C=470 кg/m³; 5. C:S =1:1,4, C=570 кg/m³).

Figure 6 dynamics of strength gain of shotcrete in time (in days) when testing specimens №1-5 made of different binary mixtures with varying cement content in the range of 280-570 kg/m³ (1. C:S=1:3,8, C=280 кg/m³; 2. C:S =1:2,9, C=360 кg/m³; 3. C:S =1:2,4, C=400 кg/m³; 4. C:S =1:1,9, C=470 кg/m³; 5. C:S =1:1,4, C=570 кg/m³) (Produced by the authors)

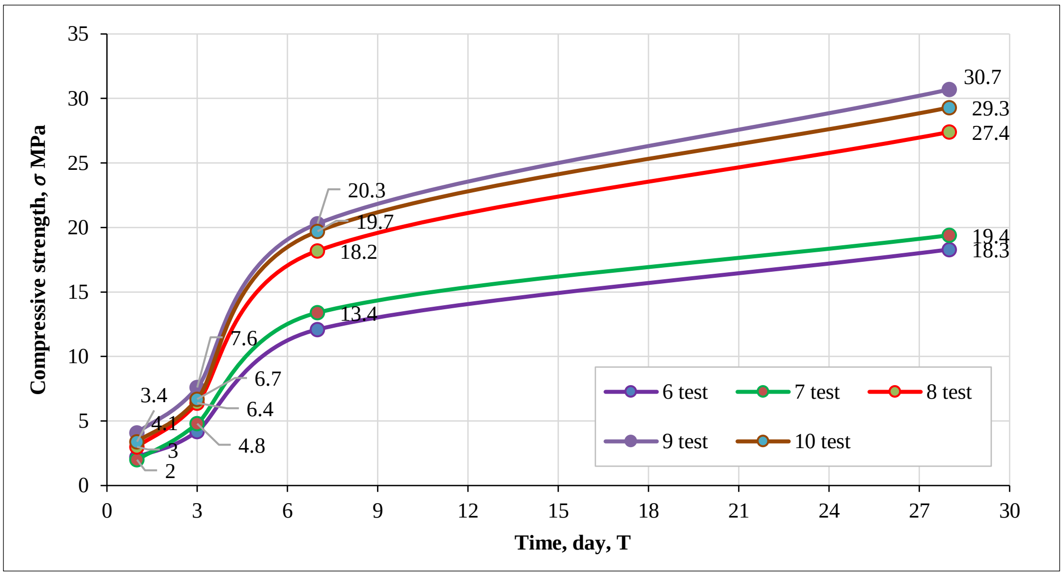

Figure 6. Dynamics of shotcrete strength growth as a function of time (per day) when adding different amounts of cement (in the range of 250-450 kg/m³) to a ternary formulations of shotcrete mixture with different composition (6 - C:S:CS=1:2,8:2,7; C=250 кg/m³; 7 - C:S:CS =1:1,9:2,5; C=300 кg/m³; 8 - C:S:CS =1:1,8:1,6; C=350 кg/m³; 9 -C:S:CS = 1:1,4:1,5; C=400 кg/m³; 10 - C:S:CS =1:1,4:1,0; C=450 кg/m³).

The results of experimental studies and a comparative analysis of the strength and economic characteristics of traditional compositions, including binary and ternary formulations, for shotcrete (sprayed concrete), are presented separately for each type of composition.

4.3. Analysis of Strength Characteristics of Binary Shotcrete Mixtures

The results of a series of tests on samples with serial numbers 1-5 (Table 1, Figure 2), conducted using binary mixtures (cement + sand), revealed the regularities in the formation of strength characteristics depending on the mass ratio of components, as well as cement consumption.

It was found that the strength of shotcrete pavements directly depends on the amount of cement used in the mixture. With an increase in its content, accelerated hardening and growth in strength are observed (Figures 4 and 5). Thus, already 7 days after application, the strength of the samples increases from 9 MPa (at a cement content of 280 kg/m^3, test 1) to 15 MPa (at 570 kg/m^3, test 5). After 28 days, the strengths were 16 MPa and 24 MPa, respectively, corresponding to a 50% increase, with a 104% increase in cement consumption. This result highlights the significant impact of cement content on the material's strength properties, particularly during the initial stages of curing (see Figure 6).

However, further analysis of the strength of samples with numbers 3, 4 and 5 revealed an important feature: with a relative increase in cement consumption from 400 to 570 kg/m^3 the strength characteristics increase insignificantly - from 22.2 to 23.7 MPa (by 6.33%), while the cement consumption increases by 42.5% (Table 1, Figure 7). It indicates the existence of a limiting efficiency in increasing the cement component. When the concentration reaches approximately 400 kg/m^3, further increasing its content in the mixture is not accompanied by a proportional increase in strength, but rather leads to a significant increase in the cost of the composition.

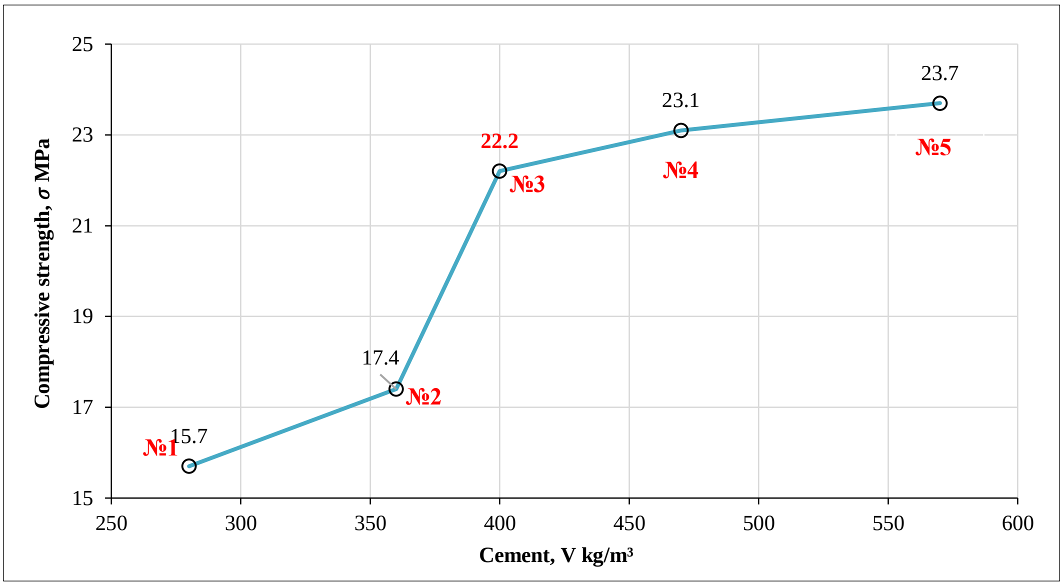

Figure 7. Dependence of the strength of binary shotcrete (samples 1-5) on cement content

Hence, the optimal mass ratio of cement to sand (1:2.4) was identified as providing the best compromise between mechanical performance and cost effectiveness. At a cement consumption of 400 kg per 1 m^3 of mixture (No. 3 test), this composition provides the necessary level of strength and reliability of fasteners at a rational material cost.

4.3.1. Comparative Economic Analysis of Binary Shotcrete Formulations

As already mentioned, in addition to strength characteristics, the most important indicator of the effectiveness of shotcrete support in the construction of underground structures is its economic feasibility.

Mine construction, along with high load-bearing and strength characteristics, must also meet the requirements of economic efficiency, which implies a rational relationship between the performance and costs of its construction. In particular, the structures should meet the condition of minimizing total costs:

$$\sum S \rightarrow \min \tag{1}$$

where $\sum S$ - total costs, including the cost of materials (cement, aggregates, additives), labor costs, work time, as well as costs associated with the maintenance and repair of the support during its service.

Considering the calculation of the cost of 1 m^3 of shotcrete taking into account this condition, the following formula is proposed, which allows for determining the full cost of one cubic meter of material, taking into account material, energy, operating, and depreciation costs (in tenge):

$$S = S_m + S_e + S_o + S_a = \frac{\gamma}{k(1-x)}\left(\frac{P_c+P_s+P+P_w CS}{2+K+CK} + q + \frac{f_1 C_p P_e + f_2 a P_a}{\rho} + \frac{\sum \beta_i Q_i}{N\alpha}\right) \quad (2)$$

where; S - total cost of 1 m^3 of shotcrete; S_m, S_e, S_o, S_a - components: material, energy, operating and amortization costs; γ coefficient that takes into account losses due to material rebound; k - compaction factor; x - material loss rate; P_c- cement price (consumption); P_s- sand price; P - plasticizer cost; P_w- price of water; CS - crushed stone price; K - coefficient taking into account transportation and overhead costs; CK - conditional coefficients that take into account regional adjustments; q - unit cost of other additives; f_1 and f_2 - energy and compressed air cost conversion factors; C_p- power consumption; P_e - electricity price; a - volume of compressed air; P_a- compressed air cost; ρ - mixture density; β_i, Q_i - coefficients and volumes of operating resources; N - number of shifts; α - productivity factor.

Based on the proposed formula, a comparative analysis of the economic efficiency of shotcrete mixtures obtained by the composition of samples №1-5 and № 6-10.

The results of the comparative economic analysis, which aimed to determine the most rational compositions of binary shotcrete, are presented in Table 1 and Figures 8 and 9.

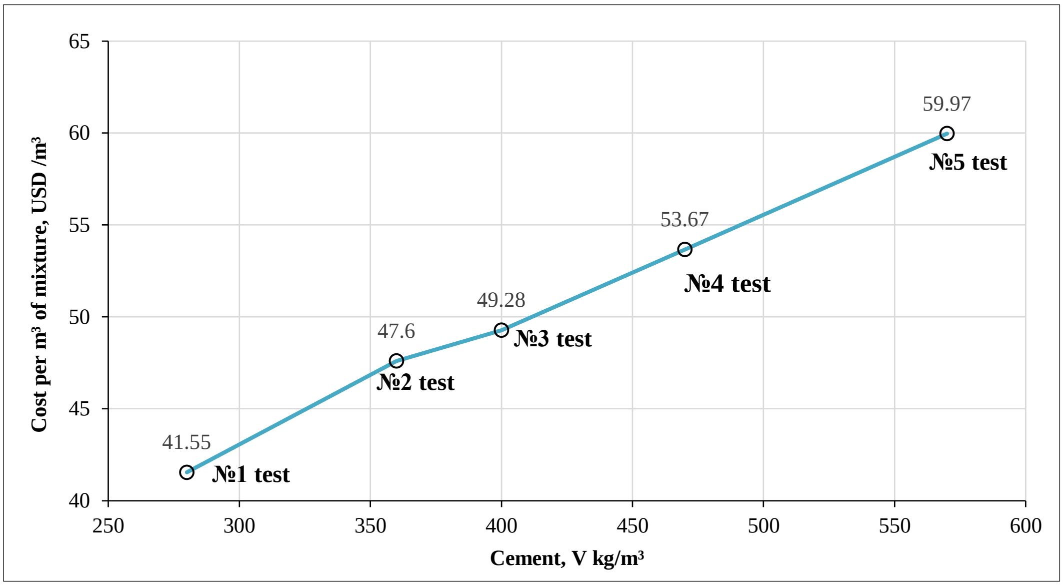

Figure 8. Dependence of the cost of 1 m^3 of shotcrete on the mixture composition (Samples 1-5; 1 - sample, composition C:S=1:3,8; 2- sample, composition C:S =1:2,9; 3 - sample, composition C:S =1:2,4; 4 - sample, composition C:S =1:1,9; 5- sample, composition C:S =1:1,4).

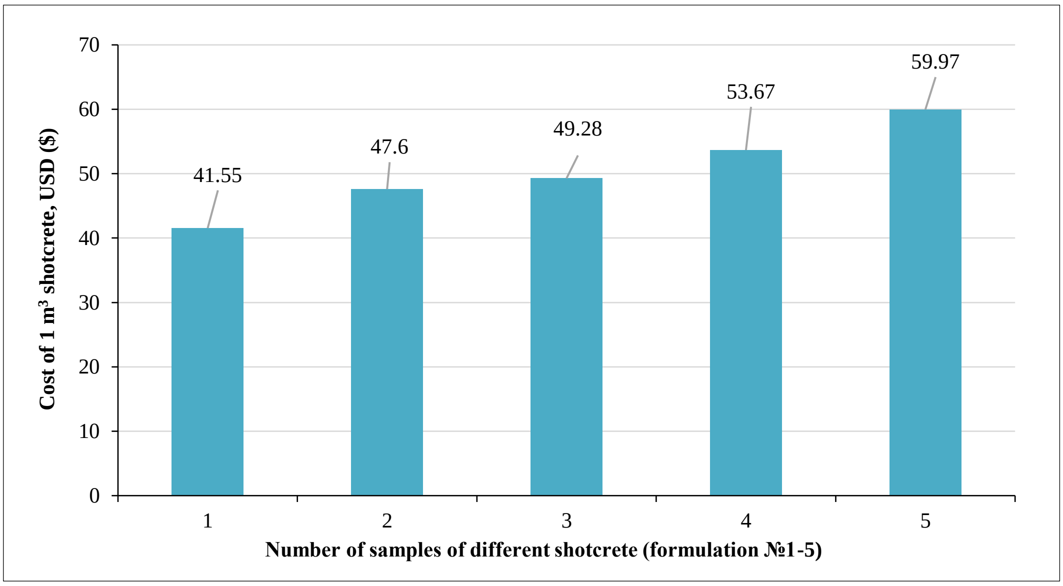

Figure 9. Histogram of comparison of binary shotcrete compositions (№1-5) by the indicator of economic feasibility

From the economic point of view, it was found that the lowest cost of shotcrete mixture is observed in the first and second tests (Figures 8 and 9). However, the cost reduction in these variants is accompanied by a significant decrease in the material's strength characteristics, which does not allow for ensuring the reliability of the fastenings in mine workings and, accordingly, excludes the possibility of their practical application in underground conditions. At the same time, the compositions used in the third, fourth, and fifth tests provided strength characteristics that meet regulatory requirements, allowing us to recommend them for use in underground mining operations.

During comparative analysis of strength characteristics and cost indicators of binary compositions of shotcrete (samples №1-5), it was found that the highest value of compressive strength was demonstrated by composition №5, reaching 23.7 MPa. However, the cost of this composition was the highest among the studied variants - 59.97 c.u. per 1 m^3 (Table 1). At the same time, the compositions used in tests 1 and 2 showed the lowest values of strength - 15.7 MPa and 17.4 MPa, respectively (Table 1), which makes them unsuitable for use as supports for mine workings, especially in conditions where high reliability and durability of the structure are required.

The composition used in the third test provided a strength of 22.2 MPa, at a cost of only 49.28 c.u. per 1 m^3 (Table 1, Figure 9). Even though the strength of this composition is inferior to that of composition №5 by only 6.33%, its cost is lower by 21.69%, which makes it much more effective from the economic point of view. Thus, as a result of a comprehensive analysis of physical-mechanical and economic characteristics of binary compositions of shotcrete, it was found that the most rational for practical use is the composition used in the third test, with a ratio of components cement:sand:water=1:2.4:0.43. Previous studies have shown that this composition provides the optimal ratio of strength and cost, which makes it the preferred option among all the studied binary mixtures.

The peculiarity of the specified composition is the consumption of cement in the amount of 400 kg per 1 m^3 of the mixture at the ratio of cement and sand C:S=1:2.4. Such a selection of components allows to achieve the required strength characteristics while reducing material intensity and production costs, which is especially important in the conditions of underground construction, which imposes increased requirements to the economic feasibility of applied technologies and materials. The obtained results confirm the expediency of using this composition in underground construction practice, focusing on achieving an optimal balance between the operational properties and economic performance of construction materials. Generalized data from the comparative analysis are presented in Table 1 and graphically illustrated in Figures 7 and 8.

4.4. Analysis of Strength Characteristics of Ternary Formulations Shotcrete Mixtures

Within the framework of experimental studies on ternary formulations of shotcrete (cement, sand, crushed stone), a series of tests was conducted on samples with serial numbers 6-10 (Table 1, Figure 6). The purpose of the experiments was to determine the influence of component composition and consumption on the strength characteristics of sprayed concrete. It was found that the use of coarse aggregate, specifically a crushed stone fraction up to 10 mm, contributes to the increase in the strength of sprayed concrete. In the case of using cement-sand-chippings mixtures with the ratio of components C:S:CS=1:2,8:2,7 and cement consumption of 250 kg/m^3 (test 6), as well as C:S:CS=1:1,9:2,5 with cement consumption of 300 kg/m^3 (test 7), the ultimate strength ofshotcrete after 28 days was 18.3 and 19.4 MPa, respectively. The specified strength level is estimated to be insufficient for the reliable fastening of mine workings in complex geomechanical conditions.

The highest strength values were obtained for specimens of series 8, 9, and 10, in which the strength after 28 days amounted to 27.4 MPa (test 8), 30.7 MPa (test 9), and 29.3 MPa (test 10), respectively. Especially high results were demonstrated by the compositions of series 8 and 9 (Figure 10), which allows us to consider them as optimal in terms of strength characteristics.

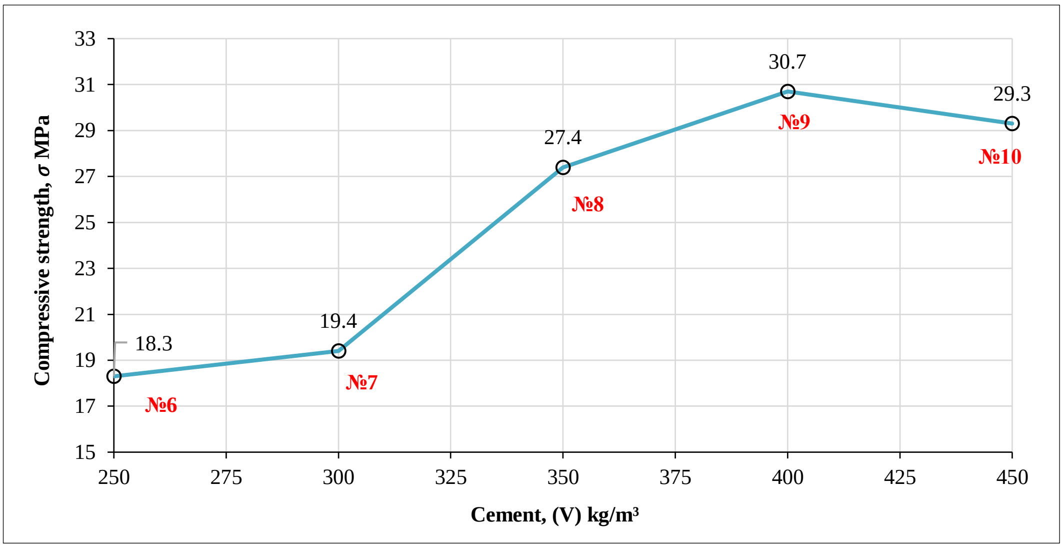

Figure 10. Dependence of the strength of shotcrete ternary formulations (samples №6-10) on cement content

The highest strength values were obtained for specimens of series 8, 9, and 10, in which the strength after 28 days amounted to 27.4 MPa (test 8), 30.7 MPa (test 9), and 29.3 MPa (test 10), respectively. Especially high results were demonstrated by the compositions of series 8 and 9 (Figure 10), which allows us to consider them as optimal in terms of strength characteristics.

The addition of crushed stone fraction up to 10 mm to the mixture has a positive effect on its strength characteristics. However, when the content of coarse aggregate exceeds 50%, material losses due to rebound increase, which requires limiting its share to 20-50%.

Based on the conducted tests, rational compositions of ternary formulation mixtures for shotcrete are established:

- Cement:sand:crushed stone=1.0:1.8:1.6:0 (test 8);
- Cement:sand:crushed stone=1.0:1.4:1.5 (test 9).

Thus, from engineering, geological, and economic perspectives, the optimal cement consumption is in the range of 350-400 kg/m³, provided the specified component ratios are observed. The complex of conducted studies enabled the revelation of the main regularities determining the strength and quality of sprayed concrete, as well as the justification of a rational mixture composition, ensuring the reliability of support for mine workings in challenging mining and geological conditions.

The results of the present study are consistent with the conclusions presented in the works of researchers from CIS countries and foreign countries, who have devoted themselves to the technology of supporting mine workings with shotcrete concreting [1, 3].

4.4.1. Comparative Economic Analysis of Ternary Shotcrete Formulations

Shotcrete of ternary formulations composition (cement:sand:crushed stone) has become widespread in the construction industry, especially in the construction and strengthening of underground structures, as well as in other engineering structures, where there are increased requirements for strength characteristics, reliability, technological adaptability, and, most importantly, economic efficiency of the material used.

As mentioned above, scientific research aimed at determining the rational composition of ternary formulations, providing an optimal ratio of physical and mechanical characteristics, as well as economic indicators, is particularly relevant. The results of such studies enable the reasonable selection of mine construction composition based on specific operating conditions, which contributes to improving the overall efficiency of construction solutions, providing the required level of structural reliability, and reducing total costs.

The results of comparative economic analysis, conducted to determine the most rational compositions of ternary formulations for sprayed concrete, are shown in Table 1, as well as in Figures 11 and 12.

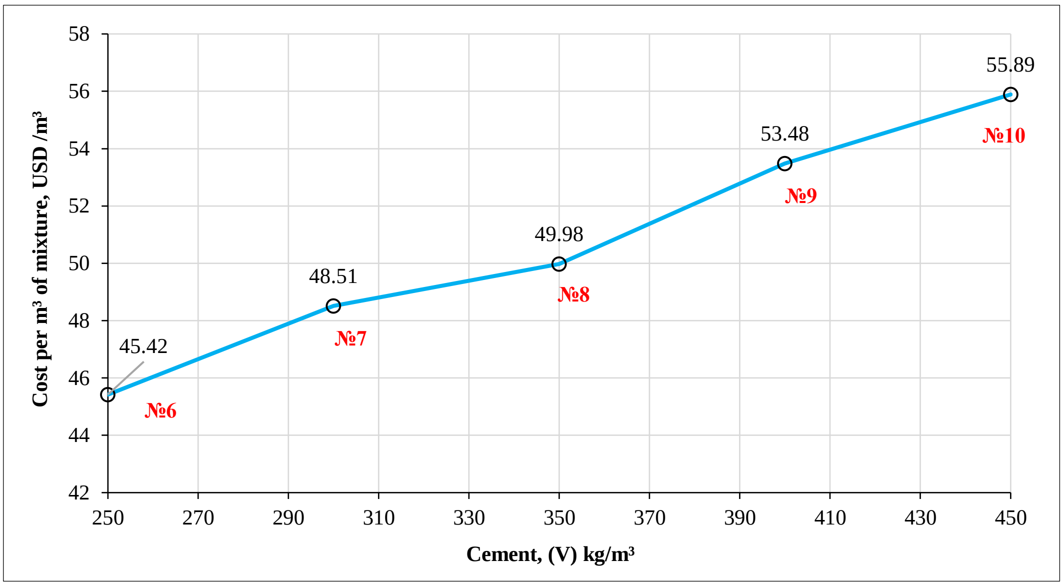

Figure 11. Graph of dependence of the cost of 1 m³ of ternary formulations shotcrete (samples 6-10) on the amount of cement in the composition of the mixture

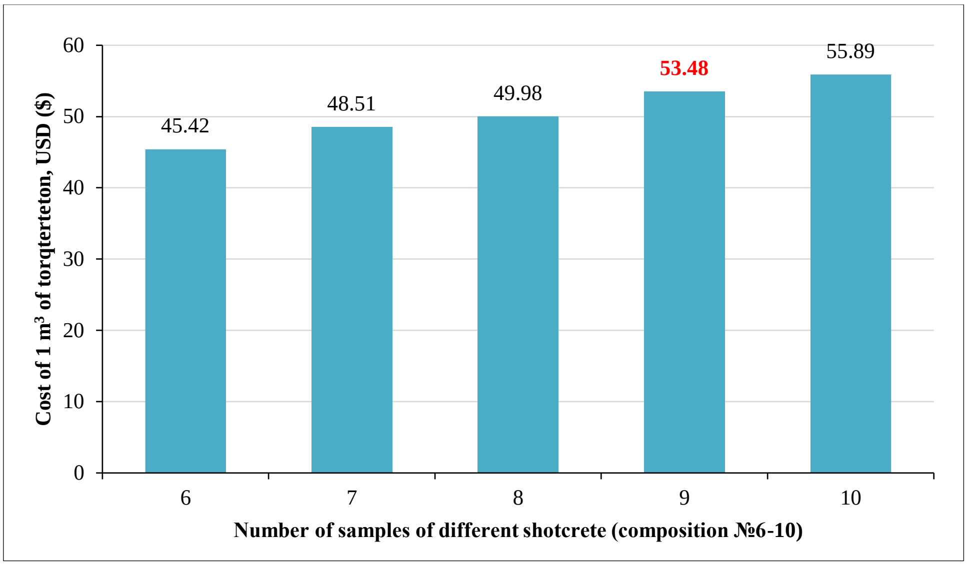

Figure 12. Histogram of comparison of ternary formulations compositions of shotcrete (№6-10) on the indicator of economic feasibility

To identify the most rational composition of ternary shotcrete formulations (Cement:sand:crushed stone), a comparative analysis of five experimental mixtures (#6-10) differing in cement consumption in the range from 250 to 450 kg/m³ was conducted. The compressive strength (in MPa) and the cost of 1 m³ of concrete mixture (in USD, at the exchange rate of 1 USD = 500 KZT as of February 10, 2025) were used as efficiency criteria. Five compositions (№6-10) of ternary shotcrete formulations with varying proportions of cement, sand, and crushed stone were considered in the analysis. The main evaluation criteria were compressive strength and the cost of 1m³ of concrete mixture.

Considering both economic and technical indicators, the best option among the studied ternary formulation compositions of underside support is composition №9. It demonstrates a maximum compressive strength of 30.7 MPa at a relatively moderate cost of 1 m³ of concrete mixture (see Table 1, Figures 10 and 11), making it the most rational option. Such a composition can be recommended for wide practical application, especially in those structures where high strength is required in combination with optimal economic costs.

The following composition is the most reasonable among the ternary formulations under consideration from the position of the optimal ratio "strength/cost": cement consumption - 400 kg/m³, sand to crushed stone ratio - 1.4:1.5. Rational ternary formulations composition when using the traditional methodology №9 determined the ratio of components: cement:sand:crushed stone:water=1:1,4:1,5:0,48. This compound offers a balanced combination of high strength and an acceptable cost, confirming its effectiveness for engineering solutions in conditions of limited budgets and high-performance requirements.

General conclusions on the strength and economic study of binary and ternary formulations of traditional shotcrete. In the presented data, when cement consumption in binary mixtures increases from 400 to 570 kg/m³, the increase in compressive strength is only 6.75% (from 22.2 to 23.7 MPa), despite a 42.5% increase in cement consumption. A similar trend is observed in ternary formulations (Table 1): composition No. 9 (400 kg/m^3 cement) provides a maximum strength of 30.7 MPa. In comparison, a further increase in cement to 450 kg/m^3 (composition № 10) leads to a decrease in strength to 29.3 MPa. The mechanism of this phenomenon is attributable to two key factors:

Changes in the water-cement ratio (W/C) are of particular significance in this field. When the cement flow rate is increased without a proportional increase in water, the W/C is known to decrease, thereby limiting the development of hydration processes. In circumstances where the water-to-cement ratio (W/C) is low, a proportion of the cement may remain dehydrated due to an insufficient water supply. This phenomenon results in an incomplete utilization of the material's inherent strength potential. This effect is particularly pronounced when the density is transitioned from 400 to 570 kg/m^3 in binary mixtures, where strength growth is minimized with a significant increase in cement input.

The rheological properties of the mixture are as follows: An increase in the amount of cement results in an increase in the mixture's viscosity and a decrease in its mobility, which complicates the application and compaction of the material. This process has been shown to lead to the formation of voids and microdefects within the structure, which in turn can compromise the adhesion of components and, consequently, the overall structure's strength characteristics. Consequently, in ternary formulations (see Table 1), composition № 10, which contains the highest cement content, demonstrates a 4.6% reduction in strength in comparison with composition № 9.

It can thus be concluded that the deceleration of strength gain at cement consumption levels over 400 kg/m³ is attributable to the combined effect of two factors. Firstly, there is a reduction in the water-cement ratio, and secondly, there is a deterioration in the rheological characteristics of the mixture. The consequence of these factors is that they limit the effectiveness of excessive cement doses. The following analysis will examine the sensitivity of economic parameters to changes in the cost of cement. In addition to the calculations performed (Table 1), a simple sensitivity analysis of the cost of 1 m³ of shotcrete to a ±10% change in the price of cement was performed. The results of the calculations are presented in Table 2.

Table 2. Sensitivity of the cost of 1 m³ of shotcrete to a ±10% change in the cost of cement

№ composition	Base cost, USD	At +10 % to the cement price, USD	At -10 % to the cement price, USD
Test 3 (binary composition)	49.28	51.73	46.83
Test 9 (binary composition)	53.48	55.84	51.12

Note: The changes in cement prices from 70 to 77 USD/t and then to 63 USD/t were used in the calculation.

The following conclusions were drawn from the sensitivity analysis: For compound #3 (binary), a ±10% change in cement price results in a ±2.45 USD change in the cost of 1 m³ of mix, representing approximately 4.97% of the base cost. For composition No. 9 (three-component), a similar change in cement price results in a cost change of ±2.36 USD (4.42% of the base cost). It can thus be concluded that the cost of the material demonstrates moderate sensitivity to changes in cement price, validating the selection of these rational compositions, as they exhibit not only high physical and mechanical potential, but also stable economic indicators in the event of market fluctuations in cement prices.

According to the results of the conducted research, the following conclusions are formulated:

- The optimum cement consumption for binary and ternary formulations of shotcrete is 400 kg/m³. A slowdown in strength growth accompanies further increases in dosage, and in some cases, its reduction.
- Traditional compositions № 3 (binary) and № 9 (three-component), which provide an optimal balance of physical and mechanical characteristics and economic efficiency, are recognized as the most rational by the criterion “strength-cost”.

The results obtained fully align with the research objectives, which aim to enhance the strength, adhesion, and durability of shotcrete while also reducing its cost and carbon footprint. Laboratory and pilot-scale tests confirmed that the use of latex additive SKS-65 GP grade 'B' allows increasing compressive strength to 46 MPa (+45%) and reduce rebound loss to 10% (-30%), which is consistent with the data of Wang et al. [11] on the reduction of plastic resistance and increased applicability when modified with latexes. In addition, improvements in crack resistance, water resistance, and adhesion confirm the conclusions of Zhang et al. [17] on the ability of styrene-butadiene dispersions to increase the resistance of concrete coatings to aggressive environments. The reduction in the thickness of the shotcrete layer from 8 cm to 4 cm, while maintaining strength and increasing the useful cross-section of the workings by 5%, has been experimentally substantiated. It corresponds to models of increased plasticity [41-43]. However, unlike previous studies, this work demonstrates the impact of such optimization on economic indicators: the total costs of using the new shotcrete composition are reduced by 39%, despite a 22% increase in the cost per 1 m³ compared to the traditional composition. This effect is achieved by reducing the volume of material applied by 50% and reducing technological losses to 10%, which was previously limited.

4.5. Development of a New Polymer-Cement Composition of Shotcrete, considering Technological Efficiency and Economic Feasibility Based on Previously Developed Rational Traditional Compositions

Following the determination of rational compositions for binary and ternary formulations of traditional shotcrete mixtures, these mixtures were modified by introducing a special accelerating additive in amounts ranging from 2 to 10% of the cement weight. A hardening gas pedal was used with latex modifier SKS-65 GP grade "B", which has improved adhesion and plasticizing properties.

The purpose of creating a new polymer-cement shotcrete based on synthetic latex SKS-65 GP mark "B" and its application for fixing underground mine workings is to enhance the material's strength characteristics and improve its operational and technological properties. The increased physical and mechanical properties of polymer-modified shotcrete contribute to the enhanced reliability and durability of rock supports, thereby providing a higher level of safety for underground mining operations and increased productivity in mining production.

Compared to traditional compositions, polymer-cement shotcrete is characterized by increased elasticity (reduced modulus of deformation), enhanced crack resistance, higher density, improved water resistance, high adhesion to rock, and improved tensile strength characteristics. The complex of these properties makes this composition promising for use in complex mining and geological conditions.

4.5.1. Materials of New Polymer-Cement Latex Shotcrete

Polymer-cement shotcrete, based on synthetic latex, is a construction composite prepared using a water-latex emulsion as the setting fluid. The mixture consists of cement, fine and coarse aggregates, and is applied to the rock contour of the mine workings using specialized shotcrete equipment of various types. This technology is designed to enhance the performance characteristics of the material, particularly in underground construction environments.

As a polymer additive, synthetic latex SKS-65 GP grade "B" is used, which is obtained by the joint polymerization of butadiene and styrene in a mass ratio of 35:65. The process is carried out in an aqueous medium using a mixture of sulfanol NP-3 and synthetic fatty acid soaps (SFA) as emulsifiers. As mentioned above, the results confirm the higher performance characteristics of latex-modified shotcrete, including a strength of up to 46 MPa and a reduction in rebound to 10%. This is consistent with Wang et al. [11], and the excess adhesion and crack resistance can be attributed to the complex interaction between the multi-fractional aggregate and the polymer dispersion. Deviations from previous data are due to differences in sample geometry, surface preparation, curing conditions, and exposure. The observed behaviour is explained by the formation of a dense polymer-cement matrix with improved adhesion, reduced porosity, and resistance to microcracks, which is confirmed experimentally by a combination of technological factors.

Latex is a material that does not have explosive properties, has no odor, and does not support combustion. Latex complying with the requirements of TU 38103111-83 is used in construction. Transportation is carried out by road and rail transport in hermetically sealed containers. The shelf life of the material is 12 months from the date of manufacture. Latex SKS-65 GP is widely used in the production of water-dispersion paint and varnish materials, in the light and paper industry, as well as in the production of construction materials [18, 20].

Rhoximat is a latex dispersion powder, which is a dried aqueous dispersion of polymer. When added to water and subsequently stirred, the powder recovers its properties, forming an aqueous dispersion similar to the original latex emulsion. Such material is used as a modifying additive to increase the strength, elasticity, and water resistance of mortars and concrete mixtures [20].

The selection of cement, as well as fine and coarse aggregates, in the development of new polymer-cement compositions was carried out with consideration for requirements similar to those used in traditional shotcrete technology. A detailed description of these requirements is presented above in the section devoted to the study of shotcrete composition by the traditional method. It is also worth noting that the moisture content of aggregates (sand and crushed stone) used in the preparation of polymer-cement shotcrete mixtures should be within the range of 4% to 7% by weight. In compliance with this range, partial suppression of dust formation is achieved, which contributes to reducing the dustiness of the working area, as well as providing uniform moistening of the mixture, necessary for the stable supply of the material through the hose. Exceeding the moisture content of aggregates causes the mixture to clump and adhere to the inner surfaces of the shotcrete machine's parts and hoses, necessitating frequent equipment stops for cleaning, which reduces productivity and increases the labor intensity of the process. Thus, compliance with the regulated indicators of moisture content in aggregates is a prerequisite for the reliability, stability, and manufacturability of the shotcrete process. This approach ensures the accuracy of the comparative analysis, enabling us to objectively evaluate the impact of the latex additive on the physical, mechanical, and technological properties of the developed mixtures [18].

Water used for the preparation of water-latex emulsions should meet the requirements of GOST 23732-79 "Water for concrete and mortars. Technical conditions", ensuring the chemical stability and reliability of solutions and mixtures. It is allowed to use water from the mine water supply, provided that its hydrogen index (pH) is not less than 4, and the content of sulfates (in terms of SO4) does not exceed 1% of the water weight. Non-compliance with these requirements can lead to a violation of dispersion stability in latex emulsions, acceleration of coagulation processes in polymer particles, and, consequently, a reduction in the strength, elasticity, and water resistance of polymer cement compositions. Thus, water quality is a crucial factor that directly impacts the performance characteristics of the resulting building materials [18, 20].

4.5.2. Laboratory Studies on the Development of a Novel Polymer-Modified Shotcrete Composition

Within the framework of this work, comprehensive laboratory studies were conducted to develop and justify the rational composition of new polymer-cement shotcrete mixtures. The experiments covered both binary and ternary formulation compositions formed based on traditional formulations, which allowed for ensuring the correctness of the comparative analysis.

In the context of binary and ternary formulations of polymer-cement compositions for new-generation shotcrete, it has been determined that a cement consumption of 400 kg/m³ is optimal. The findings of research conducted on the conventional mixture indicate that the optimum blend of strength characteristics and financial viability is attained at this cement content level. Furthermore, the ideal water-cement ratio (W/C) is established, with an average of 0.43 for binary and 0.48 for ternary formulations.

As a modifying component, synthetic latex SKS-65 GP grade "B" was introduced into the composition in amounts ranging from 2% to 10% of the cement weight. The primary objective of the research was to investigate the impact of varying latex additive content on the material's strength characteristics, including compressive and tensile strength, as well as to assess the changes in the mixture's structure and homogeneity.

The test results enabled the identification of optimal ratios of components, resulting in a significant improvement in the mechanical and operational properties of sprayed concrete, including increased crack resistance, adhesion to the rock base, density, and water resistance. The obtained data formed the basis for further recommendations on the use of polymer-cement mixtures in underground construction.

The strength properties of samples made from modified latex compositions were experimentally investigated under laboratory conditions at KazNRTU named after K.I. Satbayev. The results of compressive strength tests of the obtained samples are presented in Tables 3 and 4.

Table 3. Results of laboratory tests of strength characteristics of specimens from binary and ternary formulations of shotcrete mixtures based on a new polymer-cement latex composition

Test number	Shotcrete formulations	Water-cement ratio	Amount of latex additive, from cement weight, %	Amount of cement consumed per 1 m^3 of shotcrete mixture, kg	Relative content of crushed stone, %	Compressive strength MPa at age (day)			
						1	3	7	28
Binary formulation									
1	1:2.4	0.43	2	400	-	1.9	5.1	13.8	24.5
2	1:2.4	0.43	4	400	-	2.5	7.1	21.7	37.5
3	1:2.4	0.43	6	400	-	2.7	7.3	22.1	38.1
4	1:2.4	0.43	8	400	-	2.9	7.6	22.9	39.2
5	1:2.4	0.43	10	400	-	3	7.9	23.1	39.5
Ternary formulation									
1	1:1.4:1.5	0.48	2	400	34	4.2	8.4	24.1	32.7
2	1:1.4:1.5	0.48	4	400	33.9	5.1	10.9	31.4	44.6
3	1:1.4:1.5	0.48	6	400	33.7	5.3	11.1	31.6	44.8
4	1:1.4:1.5	0.48	8	400	33.6	5.5	11.3	31.7	44.9
5	1:1.4:1.5	0.48	10	400	33.4	5.6	11.4	31.8	45.1

Table 4. Results of comparative economic analysis on determination of rational compositions of binary (Compositions - cement:sand:latex:water) and ternary (Compositions - cement:sand:crushed stone:latex:water) formulations of polymer-cement latex shotcrete

№	Concrete mix composition 1-5 (C:S:W:L) 6-10 (C:S:CS:W:L)	Cement, kg	Sand, kg	Crushed stone, kg	Latex, l	Water, l	Compressive strength, MPa	Compressive strength, MPa Cost, Tg (USD) (1 m^3 of concrete mix)
Binary polymer-cement compound (Component ratio: cement:sand:latex:water)								
1	1:2.4:0.43:0.02	400	997	-	5.1	112	24.5	56.3
2	1:2.4:0.43:0.04	400	992	-	10.3	111	37.5	64.1
3	1:2.4:0.43:0.06	400	986	-	15.4	110.5	38.1	72.6
4	1:2.4:0.43:0.08	400	982	-	20.4	109.9	39.2	80.8
5	1:2.4:0.43:0.10	400	977	-	25.4	109.4	39.5	88.9
Ternary formulations polymer-cement compound (Component ratio: cement:sand:crushed stone:latex:water)								
6	1:1.4:1.5:0.48:0.02	400	512	479.3	4.5	109	32.7	57.8
7	1:1.4:1.5:0.48:0.04	400	509	476	9	108	44.6	65.2
8	1:1.4:1.5:0.48:0.06	400	508	475	13.5	108.1	44.8	75.1
9	1:1.4:1.5:0.48:0.08	400	506,1	474	17.9	107.6	44.9	81.7
10	1:1.4:1.5:0.48:0.10	400	499	469	22.5	105.6	45.1	89.2

Note: Material prices: Cement M400=35000tg/t (70USD/ton); bulk density of cement -1500kg/m^3; Sand - 5000tg/t (10USD/ton); density of sand -1600kg/m^3; Crushed stone - 6000tg/t, (12USD/ton), density of crushed stone -1400kg/m^3; Latex emulsion - 800 tg/l (1,6USD/ liter); Average density of latex emulsion - 1000 kg/m^3; Water - 45 tg/m^3 (0,10USD/m^3); density of water - 1,000 kg/m^3. Prices for materials are based on the rates as of February 10, 2025.

4.5.3. Analysis of Strength Characteristics of Binary and Ternary Formulations of Polymer-Cement Shotcrete with Latex Additive

The strength characteristics of specimens made from binary and ternary polymer-cement-based shotcrete compositions with varying latex content, ranging from 2 to 10% by weight of cement, were analyzed (Table 3). The tests were conducted in laboratory conditions using the previously described methodology. The obtained results enabled us to conduct a comparative strength analysis for both types of mixtures, as presented in Figure 13.

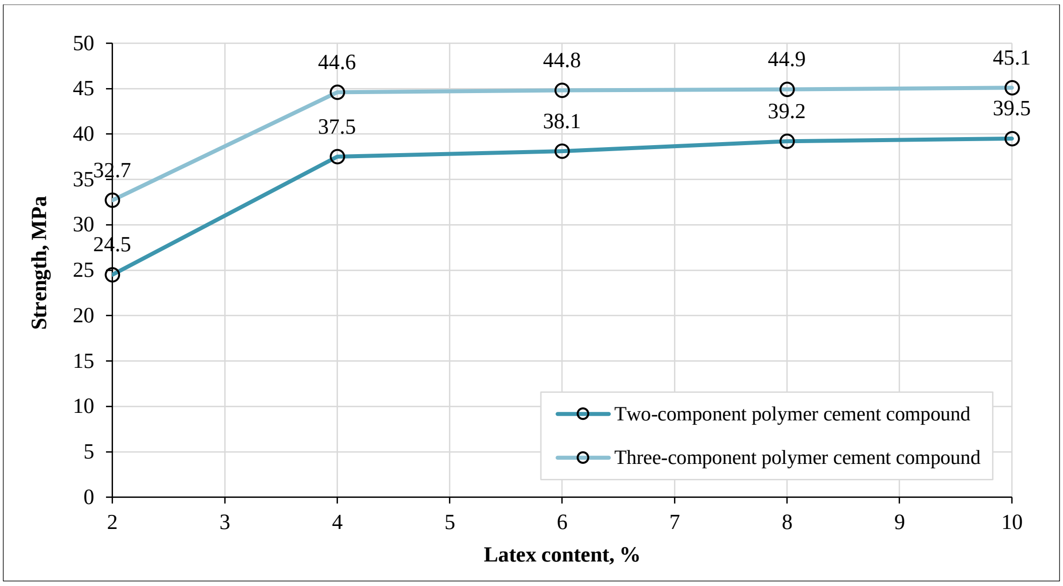

Figure 13. Graph comparing the strength of binary and ternary formulations of polymer-cement shotcrete as a function of latex content on the 28th day of hardening

Figure 13 shows the dependence of the compressive strength of polymer-cement shotcrete on binary and ternary formulations' compositions on the latex content at the 28th day of curing. The analysis of experimental data revealed a significant increase in the strength of both types of mixtures with the increase in latex content from 2% to 4%. In particular, for binary composition, the strength increases from 25 to 37 MPa, and for ternary composition, from 32 to 45 MPa.

At a further increase in latex content from 4% to 10%, stabilization of the strength characteristics is observed, with an insignificant increase in the indicators (Figure 13). Thus, for the binary composition, the strength at latex content of 8% is 39.2 MPa, and at 10% - 39.5 MPa, which corresponds to an increase of only 0.77%. If we compare the strength at latex content of 4% (37.5 MPa, 2-test) and 10% (39.5 MPa, 5-test), the increase is 5.33%.

A similar tendency is observed for the ternary formulation's composition: at a latex content of 8%, the strength reaches 44.9 MPa, and at 10%, it reaches 45.1 MPa, corresponding to an increase of only 0.45%. When comparing the strength values at a latex content of 4% (44.6 MPa, 7th test) and 10% (45.1 MPa, 10th test), the increase amounted to 1.12%, despite a 150% increase in latex dosage. Based on the analysis, it was found that the optimum strength gain is observed when the latex content is increased to 4%, after which its further introduction has a practically negligible effect on the strength characteristics of the material.

Comparative analysis of binary and ternary polymer-cement latex shotcrete compositions, carried out within the framework of this study, showed that over the entire range of latex concentrations studied, the ternary formulation's composition is characterized by higher compressive strength compared to the binary formulation. This dependence is due to the complex modifying effect of additional components included in the ternary formulation system, which contribute to the formation of a denser and more homogeneous structure of cement stone, as well as improving the contact zone "filler-binder".

The obtained results confirm the effectiveness of latex additives in enhancing the physical and mechanical properties of polymer-cement sprayed concrete. The greatest positive effect is achieved with the introduction of latex in an amount of approximately 4% of the cement weight in both binary and ternary formulations. Further increasing the dosage of the polymer additive results in only an insignificant increase in strength, indicating that the maximum rational latex content for the compositions under consideration has been achieved.

4.5.4. Economic Analysis of the Cost of Polymer-Cement Latex-Containing Shotcrete Mixtures of a New Composition

After analyzing the strength characteristics of binary (C:P:L:B) and ternary formulations (C:S:CS:L:W) polymer-cement shotcrete (shotcrete), in which the content of latex varied from 2 to 10% by weight of cement, a comparative economic analysis of the cost of these mixtures was performed. The analysis was conducted by considering the ratio of strength to cost, which enabled the determination of the optimal dosage of polymer additive to achieve a balance between physical-mechanical and economic indicators of the material. The obtained results are presented in Figures 14 and 15.

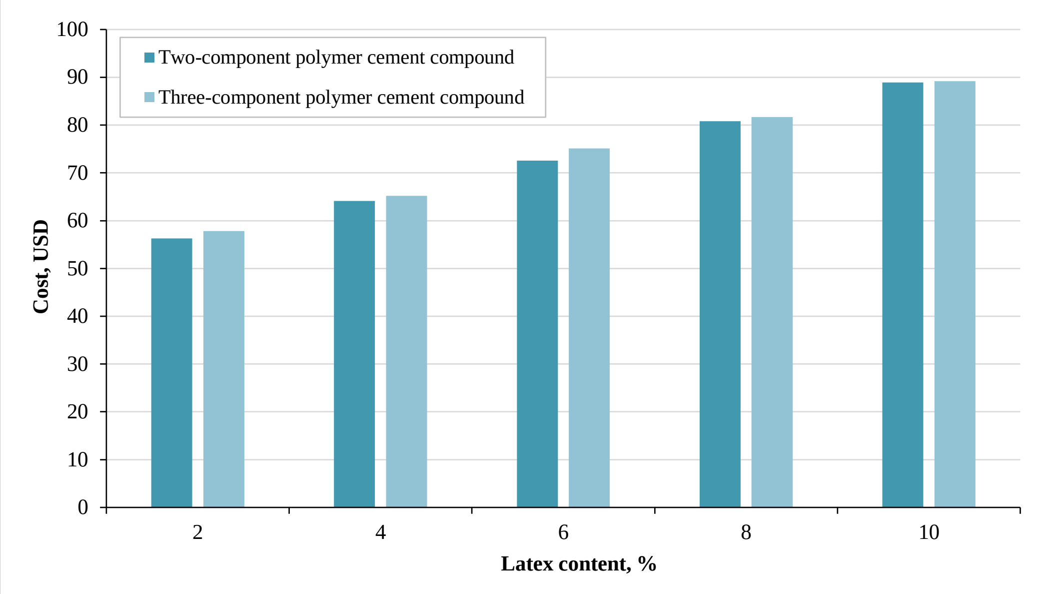

Figure 14. Graph of dependence of the cost of 1 m³ of binary and ternary formulations compositions of polymer-cement shotcrete on the latex content within the range from 2 to 10%

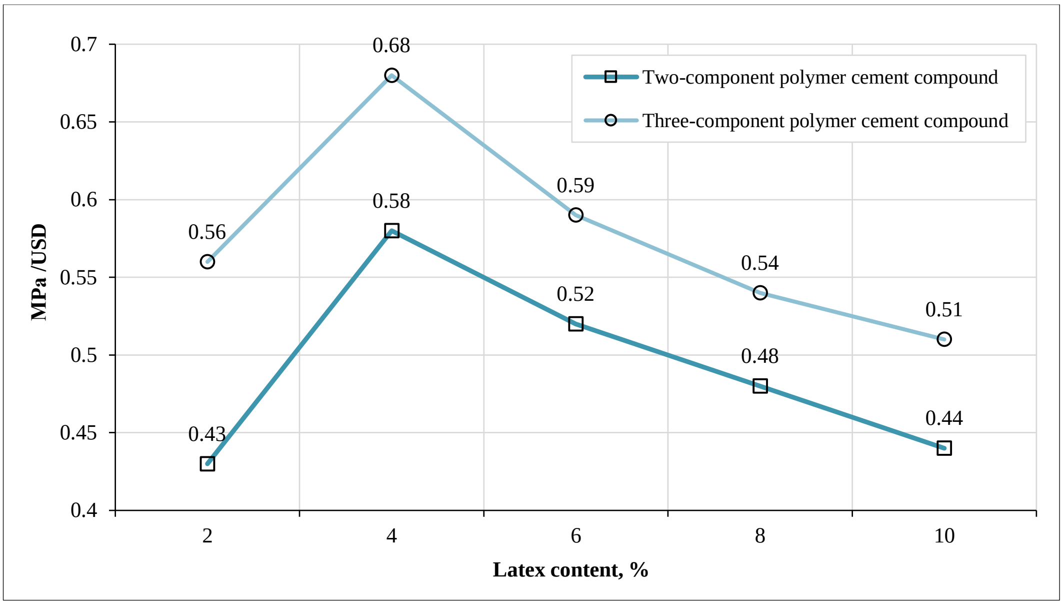

Figure 15. Comparative analysis of the efficiency of rational compositions of binary and ternary formulations of polymer-cement shotcrete in terms of strength/cost depending on the latex content

Based on the data in Table 4, as well as graphs presented in Figures 14 and 15, it was found that the cost of 1 m³ of polymer-cement shotcrete mixtures increases linearly with increasing latex content. For binary compositions, the cost varies from 56.3 to 88.9 USD, and for ternary formulation compositions, from 57.8 to 89.2 USD.

The analysis of the economic efficiency of binary compositions revealed that increasing the latex content from 2 to 10% (from the first to the fifth test) results in a 58% increase in the mixture's cost. In comparison, the strength gain is 61.2%. When comparing the second and fifth trials, the cost increases by 38%, while the strength gain reaches only 5.3%. Similarly, the cost difference between the fourth (80.8 USD/m³) and fifth (88.9 USD/m³) formulations is 10.1%, while the strength increase is only 0.77%. These results indicate the ineffectiveness of further increases in latex dosage above 4% by weight of cement from the perspective of economic efficiency.

A similar analysis for the ternary formulations showed that the cost of 1 m³ of mix increases from $57.80 at a 2% latex content to $89.20 at 10%. The cost increase between the sixth and tenth tests is 54.3%, while the strength increase reaches 37.6%. When comparing the seventh (64.9 USD/m³) and tenth (89.2 USD/m³) tests, the cost increases by 37.4%, while the strength increases by only 1.12%. In addition, when going from the ninth (83.5 USD/m³) to the tenth (89.2 USD/m³) formulations, the cost increase is 6.8%, while the strength increase is only 0.45%.

Moreover, the efficiency of latex shotcrete application was evaluated by the ratio of compressive strength (MPa) to the cost of 1 m^3 of concrete mix (USD) (Figure 15). The maximum efficiency value is achieved at a latex content of 4%, with binary composition at 0.58 MPa/USD and ternary formulation at 0.68 MPa/USD.

Thus, the conducted comparative analysis demonstrates that the most rational latex content, from the perspective of strength characteristics ratio and economic feasibility, for both studied systems is 4% of the cement mass. A further increase in latex content leads to a disproportionate increase in the cost of the mixture, with a minimal increase in strength, which reduces the overall economic efficiency of using such compositions.

As a result of studies on the strength characteristics of polymer-cement latex shotcrete, as well as an analysis of its economic efficiency, rational compositions of both binary and ternary formulations were determined. These compositions offer an optimal balance of performance properties and production costs. The obtained data are presented in Figures 16 and 17.

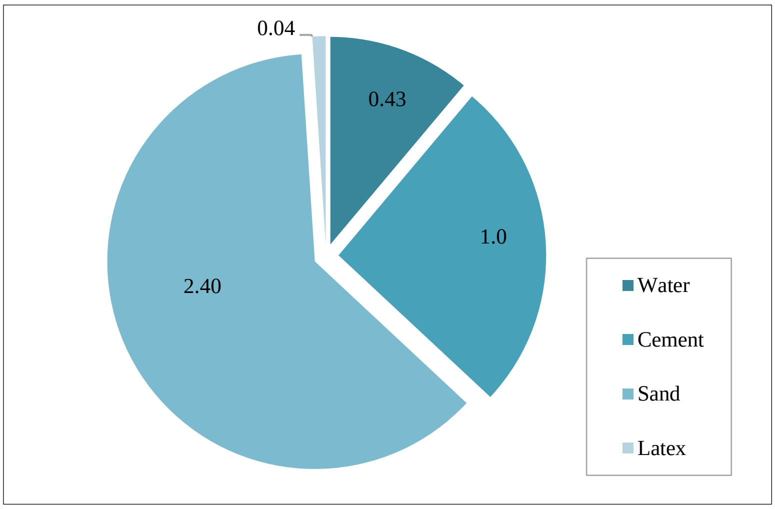

Figure 16. Rational composition of binary polymer-cement latex shotcrete, determined by the results of the conducted research

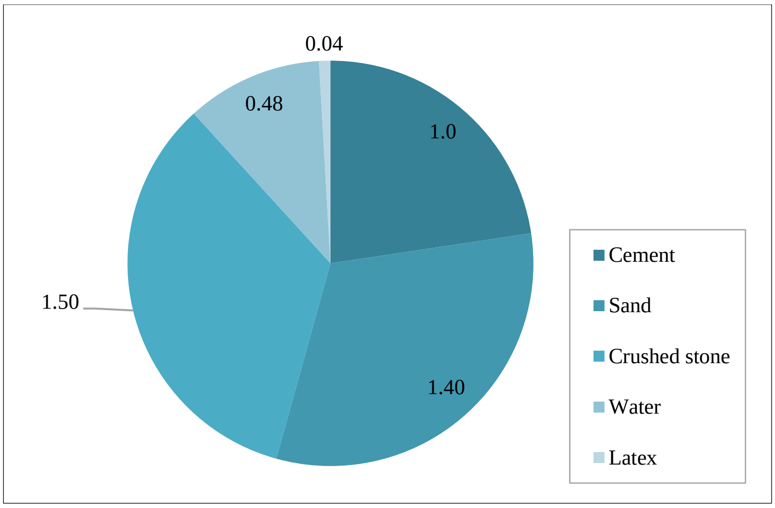

Figure 17. Rational composition of ternary formulations polymer-cement latex shotcrete, determined by the results of the conducted research

The following composition of binary polymer-cement latex shotcrete is recognized as rational for use:

- Cement:sand:water:latex = 1:2,4:0,43:0,04.

For ternary formulations of polymer-cement latex-sprayed concrete, the optimal composition with the ratio of components is:

- Cement:sand:crushed stone:water:latex = 1:1,4:1,5:0,48:0,04.

These compositions provide the required strength characteristics at economically justifiable material costs, which confirms their feasibility for use in underground construction.

4.5.5. Research on the Technology of Polymer Cement Shotcrete Fastening Construction

As mentioned in the previous sections, the erection of shotcrete support structures involves applying a concrete mixture to the surface of the mine workings with the aid of a directed air flow. In this case, the mixture is supplied at high pressure, with the jet exit velocity from the nozzle ranging from 60 to 80 m/s. This method of application enables the formation of a protective concrete layer with enhanced strength characteristics and improved adhesion to the rock mass surface compared to traditional concrete placed in formwork.

The mechanism of formation of the shotcrete layer is as follows. At the initial stage, finely dispersed cement particles moistened with water adhere to the surface of the mine workings to form a thin bonding film. Then fine fractions of sand aggregate are embedded in this film, and as the coating thickness increases, larger grains of crushed stone are added. The result is a strong, evenly compacted concrete coating with high adhesion to the substrate and reliable performance characteristics.

Depending on where the concrete mixture is prepared and how it is transported to the nozzle, there are two basic methods of shotcrete spraying: "dry" and "wet". In the dry method, a dry mixture of cement and aggregate is conveyed by hose to the nozzle, where it is wetted with water just before spraying. In the wet method, the ready-moistened mixture is transported to the application site. Despite the development of technologies, the dry method of shotcrete spreading remains the most widespread in modern underground construction practice, primarily due to its technological mobility, the ability to quickly adjust the moisture content of the mixture during application, and economic feasibility [18].

The technology of erecting polymer-cement shotcrete is generally similar to traditional shotcrete and includes the following set of operations:

- Preparation of the roof and sides of mine workings for shotcreting, including cleaning, moistening of the surface, and, if necessary, installation of anchoring and supporting elements;
- Application of polymer-cement shotcrete on the prepared surface in a layer corresponding to the design thickness by shotcrete.

The incorporation of polymeric latex into shotcrete formulations fundamentally alters its microstructure. As the emulsion coalesces during hydration, it forms a continuous polymer network that markedly enhances bond strength, hydrophobicity, crack-bridging capacity, and long-term durability under aggressive geomechanical and hydrothermal stresses. Such improvements are critical for underground excavations subject to elevated in situ pressures and water ingress, where structural reliability is non-negotiable. Polymer-cement shotcrete can be applied using standard dry- and wet-mix shotcreting equipment, including chamber, rotary, and auger-type delivery systems, without modification [28, 18]. Both domestic machines (BSM 601/603/605; C-630A; BM-60/68; SB-66/67/67A; VO, No 1, VSA-1) and international models (BT5-1/BT5-2; Torkret S-3; OM-57; TM-63; Aliva B5-12/M5-2; Meyco Piccola, GM, Repjet, Robojet, Robojet Modula, Spraymobile, Dosa/Mix) have proven compatible with polymer-modified mixtures [6, 20].

All application procedures must conform to SNiP III-15-76 Section 8 ("Shotcrete Works and Equipment") [6, 18, 28] and the manufacturers' operational protocols. To ensure safe and efficient nozzle access and positioning, it is recommended that operators use self-propelled working platforms (e.g., SP-8A, SP-18A) during shotcrete application. Prior to initiating shotcrete application, a rigorous pre-operation inspection shall be conducted, which includes verification of the electrical grounding system's continuity, functional testing of all valves (service and safety relief), calibration checks for pressure gauges, and examination of auxiliary instrumentation mounted on both the shotcrete delivery unit and the water-latex emulsion mixing tank (Figure 18). Subsequently, the material-delivery hose must be purged with compressed air, maintained at no more than 0.1 MPa, to evacuate residual moisture and ensure unobstructed flow.

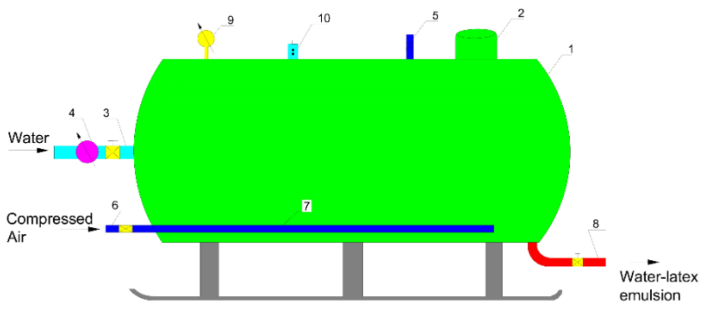

Figure 18. Tank for preparation of water-latex emulsion (1-Tank; 2-Neck for filling latex into the tank, equipped with a hermetic lid; 3-Nutrient of 52 mm diameter with a tap for filling the tank with water; 4-Water meter; 5-Nutrient of 25 mm diameter with a tap for venting the tank during its filling with water; 6-Nipple diameter 25 mm with a cock for compressed air supply to the tank; 7-Pipe diameter 25 mm with holes in the bottom part; 8-Nipple diameter 25 mm with a cock to which the hose going to the nozzle is connected; 9-Gauge; 10-Safety valve).

Prior to the compressed air supply, the nozzler (fixer) shall warn people located in the work area, indicating a safe place, and put up warning signs at a distance of at least 20 m on both sides of the working area. At the signal of the nozzle man, the operator of the shotcrete machine supplies compressed air into the material hose, after which the water-latex emulsion is supplied. It is recommended to hold the nozzle with the nozzle tip pointing downwards to prevent the emulsion from entering the hose before the air supply. Before applying sprayed concrete, it is recommended to moisten the rock surface of the mine with water-latex emulsion. It promotes consolidation of the contact layer and increases the adhesion of the shotcrete coating to the substrate. The application of polymer-cement shotcrete is performed immediately after the rock mass is moistened.

At the nozzle operator's signal, the operator feeds dry concrete mix into the material hose. The nozzle man adjusts the supply of water-latex emulsion, matching its flow rate with the value of compressed air pressure on the shotcrete machine. To select the optimal application modes, it is recommended to conduct a trial spraying of the material on the lower section of the mine workings. The order of application of shotcrete coating along the contour of the mine working is as follows: from the bottom of the vertical wall to the top, then from the top of the vault to its axial part. When applying the coating, it is necessary to ensure uniform movement of the nozzle with an overlap of at least 20 cm of the previous layer. On vertical surfaces, the coating is applied in horizontal or vertical strips from bottom to top. It is advisable to treat vaults with circular movements of the nozzle.

During the application of shotcrete, the jet should be directed strictly perpendicular to the concreted surface, and the distance from the nozzle to the base should be 0.8-1.3 m (Figure 19). Prolonged holding of the nozzle in one place is inadmissible to avoid the formation of buildup and coating defects.

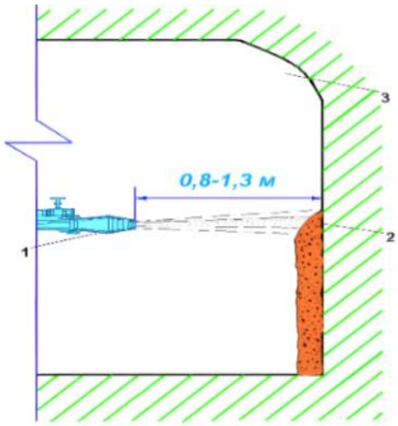

Figure 19. Optimal distance from the nozzle to the surface of the rock mass of the mine working (1-nozzle; 2-fixed shotcrete; 3-internal space of the mine)

The emulsion feed is adjusted to obtain a mixture of optimal consistency, ensuring minimal material loss during application. A high-quality applied coating with a correctly selected water-cement ratio (W/C) is characterized by the absence of sagging, dry spots, and excessive dust formation. It is recommended to control the thickness of the applied shotcrete layer using special beacons made of cement dough, installed in characteristic sections of the mine workings. When erecting a combined support, additional control is exercised over the height of the installed anchor heads.

The working pressure of compressed air in the chamber of the shotcrete machine is selected based on the distance of transportation of the concrete mixture. The optimal distance from the shotcrete machine to the coating location is 30-40 meters. When applying shotcrete, the rebound value of the material should be no more than 15%. If the normative values are exceeded, it is recommended to reduce the aggregate size to 8 mm.

Upon completion of work with dry mix, it is necessary to: switch off the electric motor (or pneumatic drive); stop supplying water-latex emulsion; close the compressed air supply valves; depressurize the working chamber and open the bell (for chamber machines). After completing the process of shotcreting, it is required to: clean the loading valve, dosing device and outlet pipe from cement buildup; blow the installation and material hose with compressed air; wash with water the container for the preparation of water-latex emulsion; disassemble and wash the nozzle, including the sleeve with spraying holes; close the working chamber with a wooden shield or tarpaulin to prevent foreign objects and water from getting inside the installation.

4.5.6. Study of Comparative Economic Indicators of Application of Traditional Composition Shotcrete and Polymer-Cement Latex New Composition

The newly developed polymer-cement latex shotcrete was applied for lining a 400 m long mine adit at the Zholbarysty mine, with a cross-sectional area of 15 m². Compared to traditional shotcrete, laboratory and field tests demonstrated that the compressive strength of the new composition was, on average, 40% higher. This increase in mechanical performance justified reducing the design thickness of the support layer from 8-10 cm (applied in two layers) to 4-5 cm, without compromising the load-bearing capacity or protective function.

Tables 1 to 3 and Table 5, as well as Figures 20 and 21, present detailed technical and economic results.

Table 5. Comparative technical and economic indicators of application of shotcrete of traditional composition and polymer-cement latex shotcrete of new composition

№	Indicators	During the construction of mine support with traditional composition shotcrete	During the erection of mine support with a new polymer cement composition shotcrete
1	Cross-sectional area of the mine workings during sinking (rough cut), (design cross-section), m^2	15	15
2	Length of the mine, m	400	400
3	Thickness of shotcrete layer (average thickness of support), cm	8	4
4	Cross-sectional area of mine workings in clear view (after bracing), m^2	13,8	14,4
5	Consumption of shotcrete mixture including 15% losses (material rebound), m^3	552	276
6	Cost of 1 m^3 ofshotcretemix, USD ($)	53,48	65,2
7	Total cost of supporting 400 m of mine, USD ($)	29521	17995

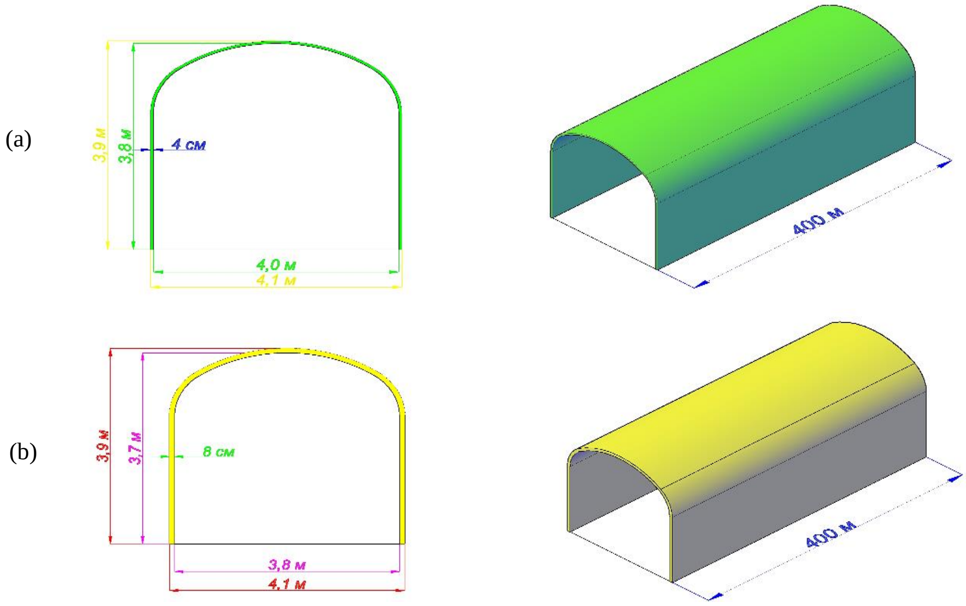

Figure 20. Comparative scheme of fixing the mine with a length of 400 m and a cross-sectional area of 15 m^2 using traditional shotcrete composition and polymer-cement latex shotcrete of new composition. 18A: fixing scheme with application of traditional shotcrete composition with an average design layer thickness of 8 cm; 18B: fixing scheme with the use of polymer-cement latex new composition shotcrete with an average layer thickness of 4 cm.

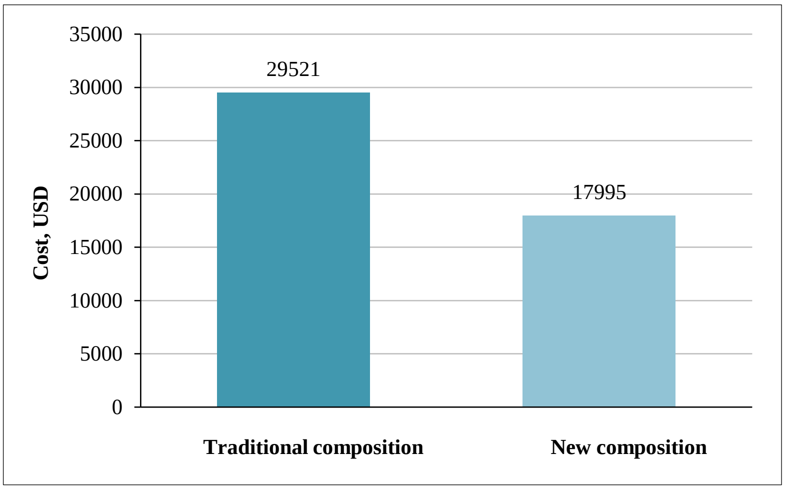

Figure 21. Comparative cost of supporting a 400 m mine working using traditional shotcrete versus polymer-cement-latex shotcrete (in USD)

As shown in Figure 20, reducing the shotcrete thickness from 8 cm to 4 cm using a polymer-cement latex composition results in increased tunnel clearance and reduced material consumption.

The reduction in lining thickness resulted in a twofold decrease in material consumption - from 552 m³ to 276 m³. Despite a higher unit cost of the modified shotcrete mix (65.2 USD/m³), which represents a 22% increase compared to the conventional composition (53.48 USD/m³), the total cost of lining a 400-meter section was significantly reduced, from $29,521 to $17,995. It yielded an overall savings of 11,526 USD, corresponding to more than 39%. Furthermore, the optimized lining configuration contributed to an increase in the effective cross-sectional area of the excavation, from 13.8 m² to 14.4 m², thereby enhancing ventilation efficiency and transportation conditions within the underground workings.

The results are consistent with earlier studies by Elbialy et al. [12] and Almenov et al. [22], who showed that polymer and fiber additives improve the mechanical strength and durability of shotcrete under laboratory conditions. However, most previous research focused on laboratory-scale specimens, without full-scale underground validation [8]. Our study not only confirms improved strength and adhesion but also demonstrates real-world economic benefits at the field scale, thereby validating the reproducibility and scalability of our findings.

Furthermore, Wang et al. [11] reported a 30% reduction in rebound losses using optimized nozzle systems. Our field results showed a similar loss reduction of 10%, aligning with their findings and confirming the role of both mix design and application technology. In contrast to studies limited to thermal or chemical durability [14, 18], our research provides a comprehensive cost-benefit assessment under dynamic mine conditions.

In summary, the introduction of the new polymer-cement latex shotcrete composition not only reduces material use and costs but also improves operational conditions underground. The economic feasibility, combined with the technical advantages demonstrated in both lab and field environments, supports the wide-scale adoption of this technology in underground mining. These findings fill an important gap in the literature by bridging microstructural insights, mechanical improvements, and validated economic impacts under real mining conditions.

5. Conclusion

The present study focuses on the development of an advanced shotcrete composition based on latex-modified mixtures and the justification of its application technology. Optimal proportions were proposed for binary (C:S:W:L = 1:2.4:0.43:0.04) and ternary (C:S:CS:W:L = 1:1.4:1.5:0.48:0.04) formulations, with cement consumption of 400 kg/m^3. The implementation of latex modification resulted in a substantial enhancement of compressive strength, with an observed increase of 45%. Concurrently, there was a reduction in rebound of 30%, a decrease in support thickness of 50%, an enlargement of the cross-section by 5%, and a significant reduction in support costs of 39%. The recommended dosage of latex is 4% of the cement mass. The efficiency of the composition was confirmed during the excavation of Tunnel No. 4 at the Zholbarysty mine, where an economic benefit of ≈11,526 USD was achieved. The developed polymer-cement latex shotcrete has high practical value and is suitable for underground mining and civil engineering applications. The present study makes a contribution to the scientific basis for shotcrete mix design, application technology, and understanding of material behavior under mining pressure.

However, the research is limited by scale, as tests were conducted in the laboratory and on-site using 10 formulations, and a measurement error of ±5–7% was observed. The load range was found to be incapable of accounting for temperature variations, humidity changes, or aggressive environments. It is recommended that future research endeavors concentrate on the micro- and nano-level interactions between polymers and cement stone. That should be achieved by utilizing electron microscopy and X-ray structural analysis techniques. Additionally, the development of eco-friendly mixtures comprising secondary materials, such as fly ash, microsilica, and construction waste, should be investigated. Furthermore, the behavior of these mixtures under impact, thermal, and vibrational loads should be thoroughly examined. Digital modelling of shotcrete-rock interaction is also showing promise.

6. Declarations

6.1. Author Contributions

Conceptualization, T.A.; methodology, T.A. and R.Zh.; software, M.S., D.Sh., B.S., and B.N.; validation, T.A., R.Zh., and M.S.; formal analysis, T.A., D.Sh., and B.S.; investigation, T.A., M.S., and B.S.; resources, T.A. and B.N.; data curation, T.A., R.Zh., and D.Sh; writing—original draft preparation, T.A., R.Zh., D.Sh., and B.S.; writing—review and editing, T.A., R.Zh., and D.Sh.; visualization, T.A. and M.S.; supervision, T.A. and R.Zh.; project administration, T.A.; funding acquisition, T.A.; All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in the article.

6.3. Funding

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6.5. Institutional Review Board Statement

Not applicable.

6.6. Informed Consent Statement

Not applicable.

6.7. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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