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ENHANCING THE STABILITY OF UNDERGROUND COAL MINE WORKINGS USING POLYURETHANE INJECTIONS AND COMBINED SUPPORT SYSTEMS

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Underground coal mining at great depths is associated with increased rock pressure, floor heave, and gas hazards, which significantly complicate roadway stability. Traditional mechanical support systems (rock bolts, cable bolts, shotcrete, and wire mesh) often prove insufficient in soft and fractured strata. Over the past decade, polyurethane (PU) grouting and combined support systems have gained wide application as effective methods of reinforcement and sealing.

This review, based on 25 Scopus-indexed publications (2015-2025) and practical experience in the CIS coal basins, analyzes the properties of PU grouting materials, their injection technology, and their effect on roadway stability and gas drainage. Special attention is given to the role of thin spray-on liners (TSL) and hybrid solutions, as well as numerical modeling approaches (FLAC3D, RS2). The review highlights advantages of PU grouting such as high penetration and rapid strength gain, while also noting limitations including exothermic reaction, cost, and environmental concerns.

A synthesis of international research and industrial trials in Kazakhstan (Karaganda Coal Basin), Russia (Kuzbass), and Poland demonstrates the efficiency of combined systems in controlling floor heave and stabilizing roadway surroundings. Research gaps are identified in the fields of low-exotherm formulations, multi-physics modeling, joint design of support and gas drainage, and standardization of monitoring protocols.

Keywords: polyurethane grouting, combined support systems, roadway stability, floor heave, gas drainage, thin spray-on liner (TSL), permeability anisotropy, numerical modeling, Karaganda Coal Basin.

ПОВЫШЕНИЕ УСТОЙЧИВОСТИ ГОРНЫХ ВЫРАБОТОК УГОЛЬНЫХ ШАХТ НА ОСНОВЕ ПОЛИУРЕТАНОВЫХ ИНЪЕКЦИЙ И КОМБИНИРОВАННЫХ СИСТЕМ КРЕПЛЕНИЯ

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Разработка угольных пластов на больших глубинах сопровождается повышенными горными давлениями, пучением почвы и газоопасностью, что существенно осложняет поддержание устойчивости выработок. Традиционные механические схемы крепления (анкера, канатные элементы, набрызгбетон, металлическая сетка) во многих случаях оказываются недостаточными в условиях мягких и трещиноватых пород. За последнее десятилетие полиуретановые (ПУР) инъекции и комбинированные системы крепи получили широкое распространение как эффективные методы упрочнения и герметизации массива.

Настоящий обзор, основанный на 25 публикациях, индексируемых в Scopus (2015-2025 гг.), а также на практическом опыте угольных шахт стран СНГ, анализирует свойства ПУР-составов, технологию их нагнетания и влияние на устойчивость выработок и дегазацию пластов. Особое

внимание уделено применению тонкослойных напыляемых покрытий (TSL), гибридных решений и методам численного моделирования (FLAC3D, RS2). В обзоре подчёркиваются преимущества ПУР-высокая проникающая способность и быстрый набор прочности, а также указываются ограничения: экзотермия реакции, высокая стоимость и экологические риски.

Сравнение международных исследований и промышленных испытаний в Казахстане (Карагандинский бассейн), России (Кузбасс) и Польше подтверждает эффективность комбинированных схем в контроле пучения почвы и стабилизации массива. Выявлены исследовательские пробелы, связанные с разработкой низкоэкзотермичных рецептур, многофизическими моделями, совместным проектированием крепи и дегазации, а также стандартизацией методов мониторинга.

Ключевые слова: полиуретановые инъекции, комбинированные системы крепления, устойчивость выработок, пучение почвы, дегазация, тонкослойное напыляемое покрытие (TSL), анизотропия проницаемости, численное моделирование, Карагандинский угольный бассейн.

КӨМІР ШАХТАЛАРЫНДАҒЫ ТАУ-КЕН ҚАЗБАЛАРЫНЫҢ ТҰРАҚТЫЛЫҒЫН ПОЛИУРЕТАНДЫҚ ИНЪЕКЦИЯЛАР МЕН АРАЛАС БЕКІТУ ЖҮЙЕЛЕРІ НЕГІЗІНДЕ АРТТЫРУ

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Көмір пласттарын үлкен тереңдіктерде игеру жоғары тау қысымымен, табан жыныстарының көтерілуімен және газ қауіптілігімен қатар жүреді, бұл тау-кен қазбаларының тұрақтылығын сақтауды едәуір қиындатады. Дәстүрлі механикалық бекіту сұлбалары (анкерлер, арқанды элементтер, шашыратпа бетон, металл тор) жұмсақ және жарықшақты жыныстар жағдайында көп жағдайда жеткіліксіз болып шығады. Соңғы онжылдықта полиуретандық (ПУР) инъекциялар мен аралас бекіту жүйелері массивті нығайту мен герметизациялаудың тиімді тәсілдері ретінде кеңінен тарады.

Scopus базасында индекстелген 25 жарияланымға (2015-2025 жж.), сондай-ақ ТМД елдерінің көмір шахталарының практикалық тәжірибесіне негізделген осы шолуда ПУР-құрамдардың қасиеттері, оларды айдау технологиясы және олардың қазбалардың тұрақтылығы мен пласттарды дегазациялауға әсері талданады. Ерекше назар жұқа қабатты бүркелетін жабындарды (TSL), гибридті шешімдерді және сандық модельдеу әдістерін (FLAC3D, RS2) қолдануға аударылған. Шолуда ПУР-дың артықшылықтары-жоғары өтімділік қабілеті мен беріктіктің жылдам өсуі-көрсетіліп, сонымен қатар оның шектеулері де атап өтіледі: реакцияның экзотермиялығы, жоғары құны және экологиялық тәуекелдер.

Қазақстандағы (Қарағанды бассейні), Ресейдегі (Кузбасс) және Польшадағы халықаралық зерттеулер мен өндірістік сынақтарды салыстыру аралас сұлбалардың табан жыныстарының көтерілуін бақылауда және массивті тұрақтандыруда тиімді екенін растайды. Төмен экзотермиялық рецептураларды әзірлеу, көпфизикалық модельдер, бекітуді және дегазацияны бірлесіп жобалау, сондай-ақ мониторинг әдістерін стандарттау салаларындағы зерттеу олқылықтары анықталды.

Түйінді сөздер: полиуретандық инъекциялар, аралас бекіту жүйелері, қазбалардың тұрақтылығы, табан жыныстарының көтерілуі, дегазация; жұқа қабатты бүркелетін жабын (TSL), өтімділіктің анизотропиясы, сандық модельдеу, Қарағанды көмір бассейні.

Introduction. Modern underground coal mines are increasingly facing challenges related to the stability of mine workings under conditions of deep mining, elevated gas content, and tectonic disturbance of the rock mass. As mining depth increases, rock pressure rises, the stress–strain state of the rock mass changes, and the likelihood of dynamic phenomena and floor heave increases. Collectively, these factors reduce the safety of mining operations and complicate roadway maintenance [1-3].

Traditional mechanical support systems-rock bolts, cable bolts, steel mesh, and shotcrete-have proven effective at shallow and medium depths. However, under conditions of “three soft” strata (soft roof, weak floor, and weak sidewalls), their load-bearing capacity becomes insufficient. Significant plastic deformations, loss of structural integrity, and accelerated deterioration of support elements are commonly observed [4,5].

In response to these challenges, combined technologies integrating mechanical and chemical reinforcement of the rock mass have been активно developed in recent decades. A key role is played by polyurethane (PU) grouting, which enables the formation of a reinforced zone around the excavation through fracture filling, adhesion to rock surfaces, and the expansive effect of foaming [6]. Complementary methods include thin spray-on liners (TSL), which provide rapid formation of a surface layer, increasing the overall stiffness of the excavation boundary [7].

The combination of PU grouting, rock and cable bolting systems, and TSL is gradually becoming a new standard for ensuring stability in deep coal mining conditions. However, several issues remain unresolved, including the selection of optimal PU formulations, control of exothermic reactions and long-term durability, assessment of the impact of injections on gas drainage efficiency, and the standardization of monitoring methods [8].

The aim of this review is to systematize global experience in the application of PU grouting, TSL, and combined support systems in underground coal mine workings based on an analysis of publications indexed in the Scopus database for the period 2015-2025. The study examines the chemical and mechanical properties of the materials used, injection parameters, their influence on rock mass stability and gas drainage efficiency, as well as practical case studies from China, Kazakhstan, Poland, and other countries. Particular attention is given to numerical modeling approaches (FLAC3D, RS2) and the identification of research gaps requiring further investigation.

Visual examples of polyurethane resin behavior and the formation of reinforced rock mass are presented in Figures 1-2, while large-scale deformations and manifestations of rock pressure are illustrated in Figure 3.



a) **b)**

Fig.1 - Interaction of fine (a) and mixed coarse and fine (b) rock fractions during resin bonding

Materials and Methods. The methodological framework of this review combines a systematic analysis of international publications with a generalization of practical experience in roadway operation in CIS countries.

From the international perspective, the Scopus database was used as the primary source, enabling coverage of leading journals in engineering, materials science, and mining. The search covered the period from 2015 to 2025 and included the following keywords: polyurethane grouting, PU injection, roadway stability, soft rock, coal mine support, floor heave, permeability anisotropy, thin spray-on liner. The analysis included studies reporting laboratory tests, field experiments, and numerical modeling. At the initial stage, approximately 180 publications were identified; after filtering based on relevance and data completeness, 32 sources were retained, representing the current state of research.



Fig.2 - Adhesion to metallic surfaces of arch support and profiled sheet lagging

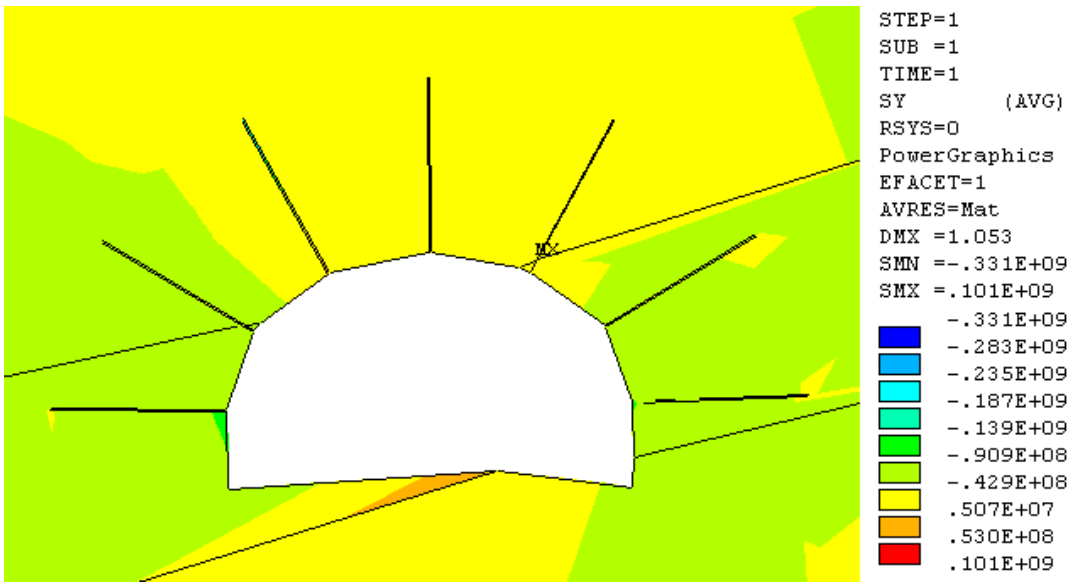


Fig.3 - Manifestations of rock pressure in a conveyor roadway under longwall mining with a return airflow ventilation scheme

In addition, the review relies on the experience of applying injection technologies in coal mines of the CIS. In Kazakhstan (Kuzembaev, Kostenko, and Abayskaya mines), Russia (Raspadskaya, Yubileinaya, Komsomolets in Kuzbass; Vorgashorskaya in Vorkuta), and Ukraine

(Zasyadko, Skochinsky, and Butovskaya mines in Donbas), extensive industrial experience has been accumulated in the use of polyurethane resins and combined support systems. These data are presented in research institute reports, dissertations, and monographs, which are not always indexed in Scopus but possess high practical value. The inclusion of such experience made it possible to expand the geographical scope of the analysis and demonstrate how global trends are adapted to regional mining and geological conditions.

Thus, the review methodology is based on two key directions:

1. systematization of global scientific publications, ensuring academic completeness and comparability;

2. integration of practical CIS experience, reflecting real results of technology implementation in the Karaganda Coal Basin, Kuzbass, and other regions.

This approach made it possible not only to trace the evolution of PU injection and combined support technologies at the international level but also to critically assess their effectiveness under industrial conditions in post-Soviet mining regions.

Polyurethane Materials. Polyurethane (PU) resins have become the primary injection material for stabilizing fractured rock in coal mines in recent years. Their key properties include low viscosity prior to gelation, controllable expansion ratio, high adhesion to coal and surrounding rock, and rapid strength development [1–3]. As a result, they are capable of penetrating microfracture systems and forming a reinforced zone around the excavation (Figures 1–2). Foaming upon contact with moisture produces an additional expansion effect, which contributes to void filling and reduces air leakage into gas drainage boreholes [4,5].

Micromechanisms of Reinforcement. The reinforcement mechanism of PU resins can be conditionally divided into three levels:

- Microscale - filling of pores and fractures, forming “bridges” between coal and rock

particles.

- Mesoscale - increase in local stiffness due to the formation of a cellular polymer structure,

redistributing stresses in the near-boundary zone.

- Macroscale - formation of a ring-shaped reinforced shell that reduces plastic deformation

concentration and prevents floor heave.

This multiscale effect has been confirmed by experimental studies in China [6–8] and industrial trials in the Karaganda Coal Basin, where the use of “BlockPUR S” resin resulted in more than a 20% reduction in deformation at roadway intersections and a decrease in convergence rate [9].

Comparison with Cementitious and Hybrid Materials. Ultrafine cement suspensions (UCS), modified with fly ash or microfillers, are also used for injection. These materials exhibit more stable rheology and higher durability; however, their penetration ability is lower than that of PU resins, particularly in fractures smaller than 0.1 mm [10].

In the CIS, cement-based mixtures have been more commonly used in main roadways where long-term stability is required, whereas PU resins have been applied in emergency and gas-hazardous conditions where rapid reinforcement is needed [11].

In recent years, hybrid systems have been developed, including PU + cement combinations, as well as PU formulations with mineral additives that reduce exothermicity and improve fire resistance [12].

Limitations and Prospects. The main limitation of PU resins remains their high exothermicity (up to 140–160 °C during reaction), which may lead to thermal stresses and localized rock degradation [13].

To mitigate these risks, low-exotherm formulations with phase-change additives are being developed worldwide [14]. In the CIS, such developments are mainly carried out within local projects aimed at adapting foreign resins to the conditions of the Karaganda Coal Basin and Kuzbass [11].

Injection Technology and Parameters.

1. Main Process Factors.

The technology of polyurethane injection is determined by several parameters:

- injection pressure, which defines the penetration depth into the fractured rock mass;

- viscosity of the composition prior to gelation and its time-dependent variation;

- gel time (from tens of seconds to 10-15 minutes depending on formulation);

- temperature conditions of the rock mass, significantly affecting reaction kinetics;

- packer arrangement scheme (advance, local, or circumferential).

According to Chinese studies, the optimal pressure for soft coal is at least 3-4 MPa, ensuring an impregnation radius of up to 1.2-1.5 m [1,2]. At lower pressures, the reinforcement zone becomes uneven, reducing sealing effectiveness.

2. Viscosity-Time Characteristics.

A key feature of PU compositions is the sharp increase in viscosity during gelation. At the initial stage, the mixture behaves as a quasi-Newtonian fluid with low flow resistance, facilitating penetration into fracture systems. This is followed by a rapid viscosity increase, fixing the material within pores and voids.

This “workability window” ranges from 30 seconds to 5 minutes depending on the resin type [3]. In the CIS, extended pot-life compositions (up to 7-8 minutes) have been used in Karaganda coal mines, allowing better control of penetration depth in extended fractures [14].

3. Zoning by Stiffness and Sealing.

International experience shows that a fully rigid shell is not always optimal. Excessive reinforcement may hinder methane filtration, reducing gas drainage efficiency [5].

Therefore, a zonal approach is applied:

- the collar and near-borehole zone are reinforced with rigid sealing materials;

- at greater distances, a more permeable “soft” zone is maintained.

This strategy has been successfully implemented in China for gas drainage borehole sealing [2] and in Kazakhstan (Kuzembaev and Kostenko mines), where high-density PU was used near the collar and lower-expansion PU deeper in the rock mass [12].

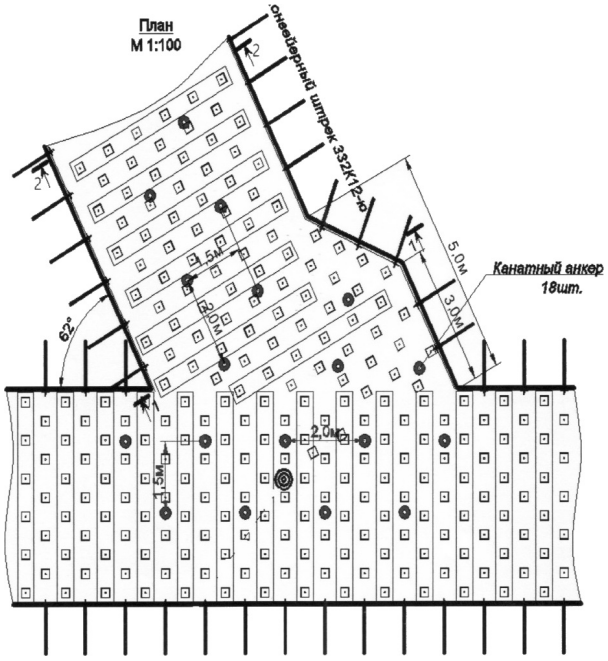


Fig.4 - Industrial trials and implementation of composite rock bolts in supporting the junction of conveyor roadway 332k12-s with ventilation incline K10 at the Abayskaya mine of «Karaganda Komir» JSC

4. CIS Practice.

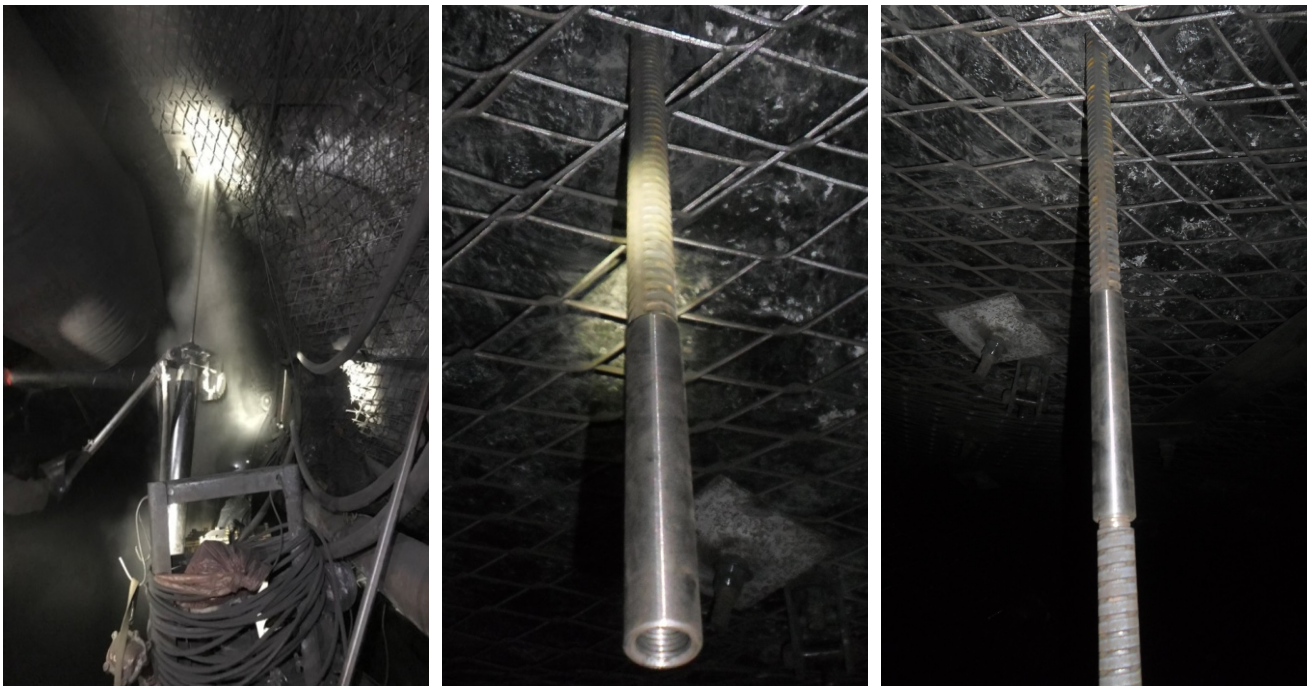
In the CIS, the use of malleable anchors with mixed bonding has demonstrated high efficiency in operational workings, improving load transfer and stability of the surrounding rock mass [15].

In the Karaganda Coal Basin, technological regulations were developed: packer spacing of 0.8–1.2 m, injection pressure up to 5 MPa, and control of resin outflow through adjacent boreholes to assess impregnation radius [7].

In Kuzbass, combined schemes were implemented: preliminary injection of cement suspensions to fill large fractures, followed by PU injection for sealing fine fractures. This approach reduced the consumption of expensive polymers by 20-30% while maintaining reinforcement efficiency [8].

5. Visualization.

Schemes of packer placement, injection sequences, and radial impregnation zones are shown in Figures 4 and 5, illustrating the actual technological process.



a) **b)** **c)**

Fig.5 - Drilling of a borehole using an SBR roof bolter (a) and installation of a composite rock bolt into the borehole (b, c - corresponding to the middle and lower parts of the rod) in the roof at the junction of conveyor roadway 332k12-s with the ventilation incline $к_{10}$

***Mechanisms of Floor Heave and Integrated Support Solutions*.**

1. Nature of Floor Heave.

Floor heave is one of the most critical problems in deep underground coal mines. It is associated with stress redistribution under conditions of “three soft” strata and active fracturing in the near-boundary zone. This leads to plastic extrusion of floor rocks into the excavation, accompanied by increased convergence and accelerated deterioration of support systems [1-3]. Typical deformation patterns and manifestations of floor heave are shown in Figure 6.

2. Limitations of Mechanical Support Systems.

Traditional methods of controlling floor heave-extended rock bolts, cable bolts, and advance support systems-reduce the rate of deformation but do not eliminate the process itself. Observations in

the Karaganda Coal Basin and Kuzbass show that even when bolt length is increased to 3-4 m, the plastic zone continues to develop, affecting the floor and sidewalls [4].

3. Combined Support Systems

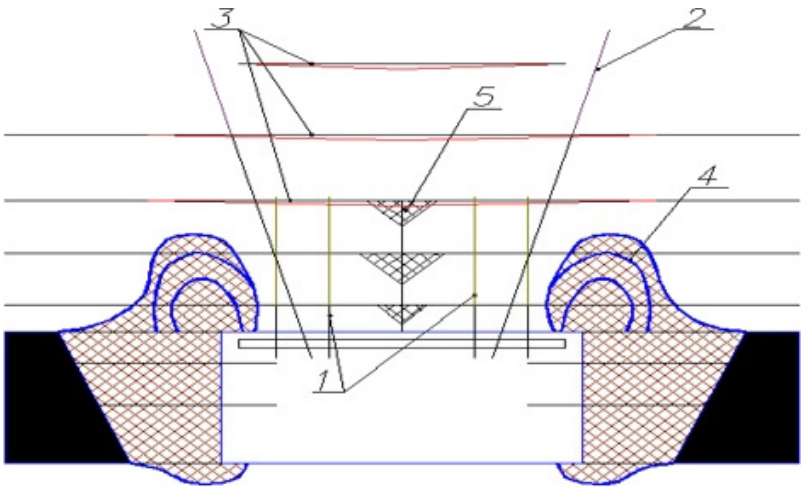
The highest efficiency is demonstrated by combined solutions that include:

- short rows of bolts (to stabilize the near-boundary zone);

- long cable bolts (to support the roof and sidewalls);

- local PU injections in zones of maximum floor deformation.

This approach forms a “reinforced-injection belt” that redistributes stresses and reduces displacement amplitude [5,6]. In China, this solution resulted in a 30-40% reduction in the rate of floor heave [7], while in the Karaganda Coal Basin it led to stabilization of roadway junctions and a reduction in maintenance work volumes [8].



1-standard-length steel-polymer rock bolts; 2-deep-seated anchors; 3-bedding separation cracks; 4-zone of shear stress concentration and roof rock disintegration; 5-plastic hinge.

Fig.6 - Diagram of the deformed state of the near-boundary rock mass of a development roadway

4. Role of TSL Coatings.

An additional element of the combined system is the thin spray-on liner (TSL), used for rapid stabilization of rock surfaces. A thin layer of polymer or modified cement increases the overall stiffness of the excavation boundary and prevents detachment of small rock fragments. Experiments in mines in Poland and Kazakhstan have shown that TSL reduces local delamination and improves roadway stability at early stages [9].

5. Modeling and Field Data.

Numerical simulations (FLAC3D, RS2) confirm that the combination of rock bolts and PU injections reduces the width of the plastic zone and lowers stress concentration in the floor [10]. Field verification using acoustic monitoring systems (e.g., “Mikon-GEO”) and deformation markers has demonstrated good agreement between model predictions and actual measurements [11].

Thus, effective control of floor heave requires a comprehensive approach: mechanical support systems (bolts, cables) stabilize the rock mass, chemical injections increase its stiffness, and TSL provides rapid surface support. This synergy reduces the risk of support failure and extends the service life of mine workings.

Numerical Modeling of the Reinforced Zone.

1. Modeling Approaches.

The use of numerical methods (FLAC3D, RS2, UDEC) has become standard practice in assessing the effectiveness of injection-based reinforcement. Three main approaches are commonly applied:

- Equivalent reinforcement - mechanical properties of the rock mass (elastic modulus,

cohesion, internal friction angle) are increased in injection zones, allowing simulation of reinforcement effects without explicitly modeling the grout structure [1,2].

- Explicit modeling of the “bolt–grout–rock” system-contact elements are introduced

between the bolt, bonding material, and rock mass, enabling analysis of pull-out mechanisms and stress distribution [3].

- Parameterization of impregnation radius and heterogeneity-variable thickness of the

reinforced zone is modeled, reflecting real conditions where the penetration radius depends on pressure, viscosity, and fracture characteristics [4,5].

2. Model Verification.

The key objective of modeling is to ensure agreement with field measurements. For this purpose, the following data are used:

- deformation measurements (convergence, contour displacement);

- acoustic monitoring (e.g., “Mikon-GEO” systems) to detect microfracture development;

- drilling observations (gas emission rates, resin outflow from boreholes).

Studies in China and the CIS have shown that equivalent reinforcement models closely match the actual distribution of plastic zones observed during PU injection applications [6-8].

3. Modeling of Bolts and Cables.

Special attention is given to modeling fully grouted bolts and cable bolts. Modern models incorporate nonlinear behavior of the “bolt-grout-rock” system and load transfer mechanisms. Pull-out tests are used to calibrate contact parameters [9].

In the CIS, such studies were conducted in the Karaganda Coal Basin, where the performance of conventional and composite bolts was compared, with stress distribution along the rod length being analyzed [10].

4. Scenario Modeling.

Numerical experiments allow prediction of:

- optimal bolt length and spacing at different depths;

- the effect of pre-injection and local injection treatments;

- the influence of fracture anisotropy on roadway stability.

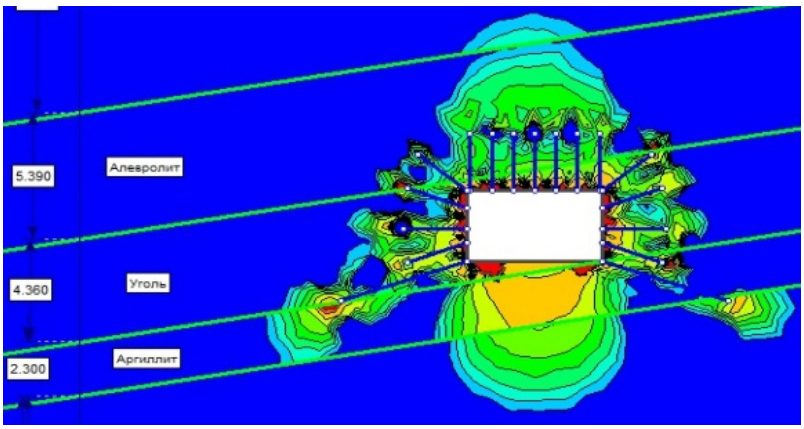


Fig.7 - Results of stress-strain state modeling for a roadway located in a coal seam with varying lengths of floor anchors from 5.0 to 6.4 m

For example, FLAC3D modeling showed that a combined system (bolts + PU injections) reduces the width of the plastic zone in the near-boundary rock mass by 25-30% compared to purely mechanical support [11].

Examples of stress distribution and plastic

deformation zones before and after injection reinforcement are presented in Figure 7. These illustrations allow comparison of numerical modeling results with field observations.

Thus, numerical modeling has become not only a predictive tool but also a means of calibrating injection parameters, thereby increasing the reliability of design solutions.

Influence on Gas Drainage and Permeability Anisotropy.

1. Role of Sealing.

One of the key effects of polyurethane resin application is the sealing of the collar and near-borehole zone of gas drainage wells. Dense filling of fractures prevents air leakage and ensures stable negative pressure within the borehole. This leads to an increase in methane concentration in the extracted gas and improves the efficiency of degasification [1-3].

2. Problem of Excessive Isolation

However, practice shows that an excessively rigid and continuous shell around the borehole may have a negative effect. The reinforced rock mass loses its filtration properties, reducing the radial gas inflow from deeper parts of the seam [4]. In some cases, a decrease in borehole productivity has been observed when using low-porosity compositions with a high expansion ratio [5].

3. Controlled Permeability Anisotropy.

To address this issue, the concept of controlled permeability anisotropy is applied. The essence of this approach is that the collar zone is reinforced as tightly as possible, while permeability is preserved in more distant zones of the rock mass by using “softer” compositions or reducing injection pressure [6,7].

This approach ensures a balance between mechanical reinforcement and maintaining pathways for methane filtration. Numerical models confirm that with isotropic sealing, the borehole quickly reaches a steady-state regime, but the overall gas flow rate is lower. In contrast, anisotropic permeability creates a more extensive drainage zone, increasing the total volume of extracted methane [8].

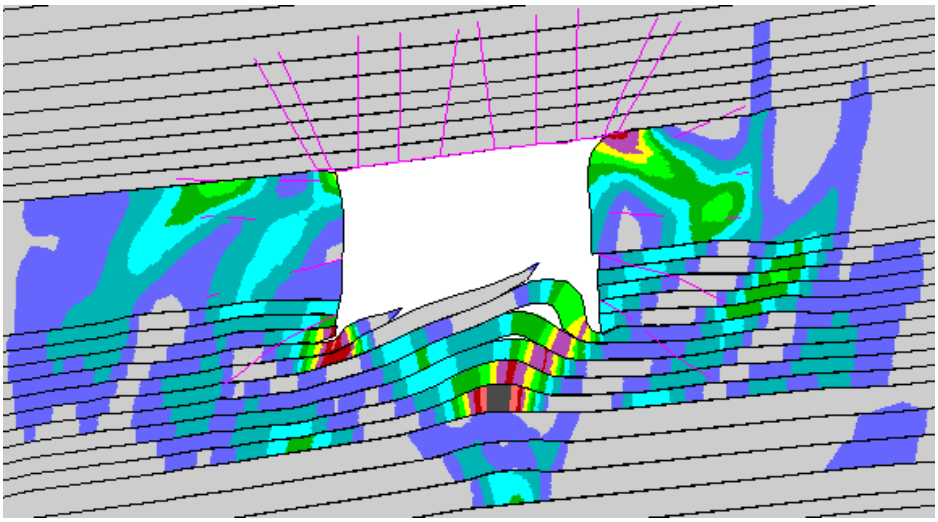


Fig.8 - Geomechanical model of the stress-strain state around the excavation

4. Application in the CIS.

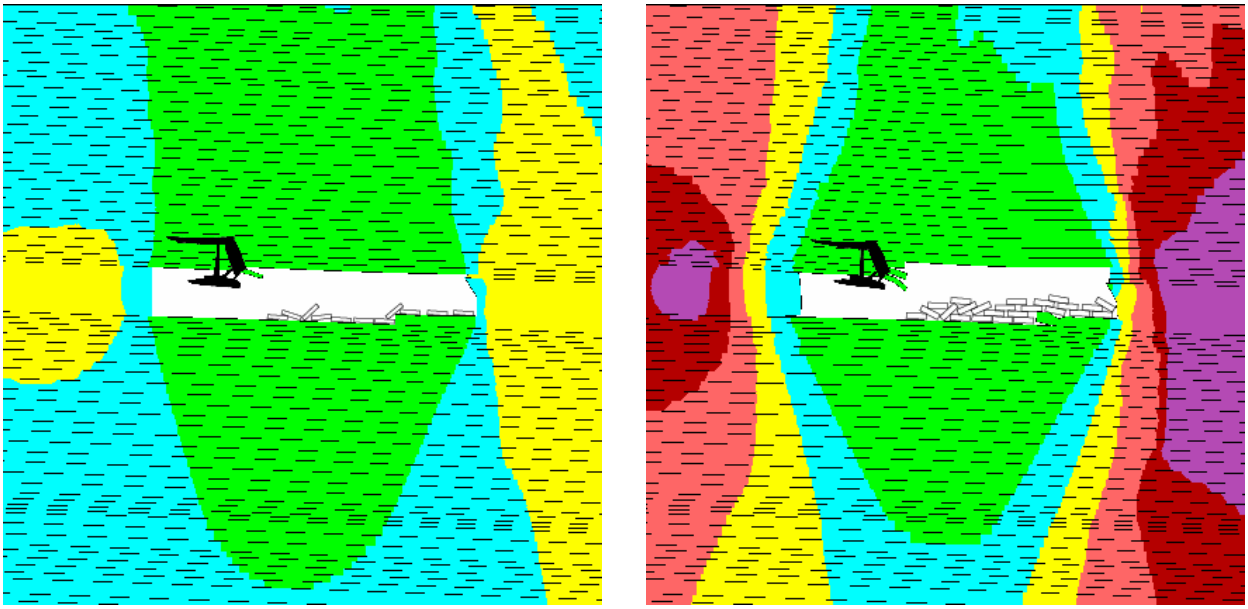
In the Karaganda Coal Basin, a combined sealing method has been developed: the borehole collar is sealed with a high-density PU composition, while at depths of 3–5 m, a lower-expansion injection is applied to preserve permeability [9].

In Kuzbass, “two-level” sealing schemes have been successfully implemented, where the upper zone performs a sealing function and the lower zone acts as a filtration barrier with controlled

conductivity.

5. Visualization.

A schematic distribution of sealing and filtration zones is shown in Figures 8 and 9. This illustration demonstrates the zoning of the rock mass around the gas drainage opening, achieving an optimal balance between strength and permeability.



Вентиляционный штрек **Конвейерный штрек**

Fig.9 - Stress distribution around roadways adjacent to the longwall face

Thus, the impact of PU injections on gas drainage is dual in nature: when properly applied, they increase methane concentration and stabilize the degasification regime, whereas excessive sealing reduces borehole productivity. Therefore, the key task is to control permeability anisotropy and to select compositions according to specific geological conditions.

Practical Case Studies and Alternative Solutions.

1. Chinese Experience.

China remains the global leader in the application of polyurethane injections in coal mines. Comprehensive technologies have been developed, including pre-injection for rock mass preparation, sealing of gas drainage boreholes, and combined support systems [1-3].

At mines in Shanxi Province, the implementation of PU reduced roof fall frequency by 35% and increased methane concentration in drainage boreholes to 80-85% [4].

2. Kazakhstan Experience.

In the Karaganda Coal Basin, polyurethane resins have been used since the early 2010s. The main sites include the Kuzembaev, Kostenko, and Abayskaya mines.

Field tests have shown that the use of “BlockPUR S” resin in junctions and conveyor roadways reduces convergence rates by 20-25% and stabilizes the roof in fractured sandstones and siltstones [5].

A separate direction involves sealing gas drainage boreholes, where a combined approach (rigid collar zone + permeable filtration zone) has demonstrated a 15-20% increase in gas flow rate [6].

3. Russian Experience.

In Kuzbass, polyurethane injections are actively used for local stabilization in tectonically disturbed zones. Combined schemes have been developed, involving preliminary injection of

cement suspensions to fill large fractures, followed by PU injection for fine crack sealing.

This approach reduced polymer consumption by 25-30% while maintaining strength levels [7].

In Vorkuta, PU injections have also been applied for sealing old workings, where they act as anti-filtration barriers.

4. Polish and European Experience

In Poland and Germany, polyurethane resins are widely used as emergency technologies for rapid rock mass stabilization in cases of sudden collapses or water inrushes [8].

Polish researchers активно apply TSL coatings as part of combined support systems. These thin-layer materials reduce support cycle time and improve safety during roadway development [9].

5. Alternative Materials.

In addition to polyurethane, the following materials are used:

- ultrafine cement suspensions (UCS)-for long-term stabilization of main roadways;

- acrylate resins-for local sealing in water inflow conditions;

- TSL coatings-for rapid surface reinforcement of roof and sidewalls.

In the CIS, cement-based materials are traditionally used for long-term stabilization, while polyurethane is applied in emergency and gas-hazardous conditions. In Europe, TSL has become widely adopted as part of standard mechanical support systems.

Thus, practical case studies confirm that no universal material exists: polyurethane is optimal for rapid response and fine fracturing, cement mixtures for durability, acrylates for waterproofing, and TSL for surface stabilization. The choice depends on geological conditions and operational priorities.

Results and Discussion.

1. Exothermicity and Durability.

Despite the high efficiency of polyurethane resins, the issue of exothermic reactions remains unresolved. Reaction temperatures can exceed 140-160 °C, leading to thermal stresses and localized coal degradation [1].

Internationally, low-exotherm formulations with heat-reducing additives are being developed; however, their widespread adoption is limited by cost and synthesis complexity [2]. In the CIS, adaptation of such materials is slower, and foreign resins are often used without proper adjustment to local geological conditions.

2. Insufficiency of Multiphysics Models.

Modern numerical models typically consider either mechanical effects (increase in stiffness) or filtration processes (permeability anisotropy). However, the coupling between **mechanics-filtration-chemistry** remains insufficiently studied [3].

In particular, the influence of PU microstructure (porosity, cellular structure) on long-term filtration properties is not fully understood. Multiphysics models could provide deeper insight but require significant computational resources and experimental calibration data.

3. Integrated Design of Support and Degasification.

Support systems and degasification measures are often designed separately. However, practice shows that excessive sealing may reduce gas extraction efficiency [4].

Therefore, an integrated approach is required, considering that support systems must both stabilize the rock mass and maintain its filtration capacity. Experiments with “two-level” sealing schemes are already being conducted in China and Kazakhstan, although standardized approaches are not yet established.

4. Need for Monitoring Standardization.

Different studies use non-comparable methods to assess injection effectiveness: some measure deformation, others gas flow, and others acoustic signals. This complicates cross-regional comparison.

A standardized protocol is required, including integrated monitoring using deformation markers, acoustic sensors, and gas flow measurements [5].

This would enable the creation of a unified database for comparative analysis.

5. Economic and Environmental Aspects.

The cost of PU resins remains a significant barrier to widespread adoption in the CIS. Meanwhile, in Europe and China, efforts are underway to develop lower-cost formulations based on recycled polymers [6].

Environmental concerns are also important: cured resins are практически non-degradable, raising issues of disposal and long-term environmental safety.

Thus, the current state of research highlights several unresolved challenges: control of exothermic reactions, development of multiphysics models, integration of support and degasification systems, standardization of monitoring, and reduction of costs alongside environmental adaptation of PU materials. Addressing these issues will determine the future development of the technology.

Conclusion. Analysis of global literature and CIS experience shows that polyurethane injections and combined support systems have become an important tool for ensuring the stability of coal mine workings under conditions of deep mining and high gas content. Their application allows the formation of a reinforced zone around the excavation, reduction of plastic zone width, stabilization of roof and floor, and improved degasification efficiency through sealing of the near-borehole space.

The key advantages of polyurethane resins remain their high penetration ability and rapid strength gain. However, their use is associated with challenges such as exothermic reactions, high cost, and the lack of standardized monitoring methodologies.

Significant practical experience has been accumulated in the CIS (e.g., “BlockPUR S” in the Karaganda Coal Basin and combined systems in Kuzbass), confirming the feasibility of adapting international technologies to local conditions.

Future research directions include:

- development of low-exotherm and environmentally safe formulations;

- implementation of multiphysics models integrating mechanics, filtration, and chemistry;

- integrated design of support and degasification systems considering controlled

permeability;

- development of unified monitoring protocols combining deformation, acoustic, and gas

measurements.

Thus, polyurethane injections and combined technologies occupy a strategically important position in improving the safety and efficiency of coal mining, and their further development remains a priority direction in mining science and practice.

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