

A Comprehensive Review of Borehole Sealing Materials and Methods for Gas Control in Coal Mines

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Abstract: Borehole sealing is a critical component of gas control in coal mines, directly influencing the efficiency of gas drainage and the overall safety of underground operations. This review comprehensively examines the mechanisms, materials, and methods of borehole sealing, highlighting their role in preventing gas leakage and enhancing extraction efficiency. Traditional sealing materials, such as cement-based compounds, offer moderate performance but suffer from durability issues. In contrast, polymer-based and advanced nanomaterial sealants provide improved sealing capabilities and longer service life. Various sealing methods, including mechanical, chemical, and hybrid techniques, are analyzed for their effectiveness in different geological conditions. Case studies demonstrate that optimized sealing strategies significantly improve gas drainage rates and mine safety. Despite these advancements, challenges such as material degradation, high costs, and the need for standardized application procedures remain. Future research should focus on developing cost-effective, high-performance sealing materials, optimizing composite sealing techniques, and integrating intelligent monitoring systems for real-time assessment. Addressing these issues will enhance gas drainage efficiency, reduce methane emissions, and improve the sustainability of coal mining operations.

Keywords: Borehole Sealing; Gas Control; Coal Mine Safety; Sealing Materials; Gas Drainage Efficiency.

1. Introduction

1.1. Research Background and Significance

Coal mine gas disasters pose significant threats to mining safety, operational efficiency, and environmental sustainability. Methane, the primary component of coal mine gas, is not only a highly flammable and explosive substance but also a potent greenhouse gas that contributes to global warming. In underground coal mining, gas emissions can accumulate in high concentrations, leading to catastrophic explosions, fires, and asphyxiation incidents. Additionally, uncontrolled gas emissions reduce air quality and increase ventilation costs, further impacting mining productivity and safety.

To mitigate these risks, gas drainage through boreholes has become a widely adopted practice in coal mines. Borehole gas drainage involves extracting methane and other gases from coal seams before or during mining operations, thereby reducing the concentration of hazardous gases in the mine environment. However, the effectiveness of gas drainage is highly dependent on the integrity of borehole sealing. If the sealing process is inadequate, gas leakage can occur, leading to a significant reduction in drainage efficiency, increased residual gas content in the coal seam, and elevated risks of gas outbursts and explosions. Moreover, poor sealing can result in external air leakage into the coal seam, potentially triggering spontaneous combustion and further compromising mine safety [1].

Given these challenges, selecting appropriate sealing materials and methods is crucial to ensuring efficient gas extraction, minimizing leakage, and enhancing overall gas control. Over the years, various sealing technologies have been developed, ranging from traditional cement-based sealing to advanced polymer-based and composite sealing

methods. Understanding the performance characteristics, advantages, and limitations of these techniques is essential for optimizing borehole sealing strategies and improving mine safety.

1.2. Research Objectives and Scope

The objective of this review is to provide a comprehensive analysis of borehole sealing materials and methods employed in coal mine gas control. This study aims to:

Summarize the current borehole sealing technologies, including conventional and emerging materials used for sealing in coal mines. A detailed classification and discussion of materials such as cement-based sealants, polymer foams, chemical grouts, and composite materials will be presented [2].

Evaluate the performance of different sealing techniques, considering factors such as sealing effectiveness, durability, resistance to high-pressure gas environments, ease of application, and adaptability to various geological conditions.

Identify challenges associated with borehole sealing, including common failure mechanisms such as material shrinkage, degradation over time, and improper application techniques. The impact of geological factors, such as coal seam permeability and borehole stability, on sealing performance will also be discussed [3].

Explore future research directions and potential innovations in borehole sealing, such as the development of self-healing sealing materials, intelligent monitoring systems for real-time sealing integrity assessment, and eco-friendly sealing alternatives that minimize environmental impact [1].

By reviewing recent advancements and case studies, this study aims to provide valuable insights into optimizing borehole sealing practices, guiding the development of more effective and sustainable gas control strategies in coal mines.

2. Mechanism of Borehole Sealing in Gas Control

2.1. Gas Drainage Process and Sealing Requirements

Gas drainage is a crucial technique for controlling methane emissions in coal mines, reducing the risk of gas explosions, and improving the safety of underground operations. The efficiency of gas drainage largely depends on the quality of borehole sealing, which prevents gas leakage and enhances extraction effectiveness.

The gas drainage process generally consists of three main stages:

1) Borehole Drilling – Boreholes are drilled into the coal seam to provide a pathway for methane to escape.

The depth, diameter, and layout of the boreholes are designed based on the geological conditions and gas content of the coal seam [4].

2) Gas Extraction – Methane is extracted from the coal seam through the boreholes using vacuum pumps or negative pressure systems. The extracted gas can be vented, flared, or utilized for power generation, depending on the mine’s gas management strategy [2].

3) Borehole Sealing – After drilling, the borehole must be properly sealed to prevent external air leakage and maximize the efficiency of gas extraction. Effective sealing ensures that methane is directed towards the drainage system rather than escaping into the mine environment [2].

The quality of borehole sealing plays a decisive role in determining the overall success of gas drainage. Proper sealing prevents air leakage, which is critical because the intrusion of atmospheric air can dilute methane concentrations, reduce extraction efficiency, and even lead to spontaneous combustion risks. Additionally, good sealing helps increase borehole gas pressure, enhancing methane desorption from the coal seam and thereby improving drainage efficiency. Finally, reducing residual gas content in the coal seam decreases the likelihood of gas outbursts, contributing to a safer mining environment.

2.2. Common Issues Leading to Borehole Sealing Failure

Despite advancements in sealing technologies, borehole sealing failures remain a significant challenge in coal mine gas control. These failures can result in gas leakage, reduced drainage efficiency, and increased safety risks. The main causes of sealing failure can be categorized into two aspects:

2.2.1. Gas Leakage Due to Poor Sealing

Incomplete Sealing – Gaps or voids in the sealing material allow methane to escape, reducing gas drainage efficiency and increasing the risk of gas accumulation in mine workings.

Improper Application – Poor workmanship or inadequate sealing pressure during material injection can create air channels, compromising the sealing integrity and leading to gas bypassing the drainage system.

2.2.2. Degradation or Damage of Sealing Materials

Shrinkage and Cracking – Certain sealing materials, such as cement-based sealants, may shrink or develop cracks over

time, resulting in reduced sealing effectiveness.

Chemical Decomposition – Some sealants degrade due to chemical reactions with gas, moisture, or surrounding rock formations, leading to a loss of sealing performance.

Mechanical Damage – Vibrations from mining activities, geological stress, or borehole deformation can compromise the integrity of sealing materials, causing partial or complete sealing failure [1].

As shown in table 1, it summarizes the main sealing failures encountered in coal mine gas control, their causes, consequences, and potential solutions. By addressing these issues with proper material selection and optimized sealing methods, borehole sealing efficiency can be significantly improved.

Table 1. Common Borehole Sealing Issues and Solutions

Sealing Issue	Cause	Potential Consequences	Solution
Incomplete Sealing	Gaps in sealing material due to improper application	Gas leakage, reduced drainage efficiency	Use high-performance sealants with strong adhesion; improve injection techniques
Improper Application	Uneven distribution of sealant in borehole	Air leakage, formation of weak sealing zones	Ensure proper mixing and controlled pressure during sealing process
Shrinkage and Cracking	Drying shrinkage of cement-based materials	Crack formation, long-term leakage	Use polymer-based or flexible sealing materials
Chemical Decomposition	Reaction of sealant with methane or moisture	Gradual loss of sealing performance	Select chemically stable materials resistant to gas exposure
Mechanical Damage	Vibrations from mining operations, stress from strata	Material failure, borehole instability	Reinforce sealing with composite materials; use flexible sealing techniques
Borehole Deformation	Geological stress causing borehole expansion or collapse	Displacement of sealing material, leakage	Apply adaptable and elastic sealing compounds

3. Borehole Sealing Materials

Borehole sealing is a critical part of gas drainage systems in coal mines, where the effectiveness of the sealing directly influences the safety and efficiency of gas extraction. Over the years, a variety of materials have been developed for borehole sealing, each with distinct advantages and

limitations. In this section, we explore the traditional, polymer based, and advanced smart materials, discussing their properties, applications, and comparative performance [3].

3.1. Traditional Sealing Materials

Traditional sealing materials have been the backbone of borehole sealing technology for many years. These materials are typically cost-effective and easy to apply, but they often fall short in terms of long-term performance, especially in environments with high pressure or extreme geological conditions [5].

3.1.1. Cement-Based Sealing Materials

Cement-based materials, including Portland cement and cement mixtures with fly ash, are the most commonly used sealing agents in borehole applications. These materials form a hard, durable seal once they have set, and they are readily available and inexpensive. However, their major drawback is shrinkage, which can cause cracks in the seal over time. This leads to the possibility of gas leakage through these cracks, compromising the integrity of the borehole seal. Additionally, cement-based materials often have a long curing time, which delays the sealing process, and their performance is poor in areas with high permeability [5].

Advantages:

- 1) High compressive strength
- 2) Cost-effective and widely available
- 3) Good durability in stable geological conditions

Disadvantages:

- 1) Prone to shrinkage and cracking over time
- 2) Requires a long curing time, which delays the sealing process
- 3) Performance can degrade in high-pressure or high-permeability conditions

Cement-based materials are still widely used in many coal mines, particularly in low-pressure, low-permeability environments. However, as mining conditions become more complex, the need for more advanced materials has increased.

3.1.2. Clay and Bentonite-Based Materials

Clay and bentonite are naturally occurring materials known for their plasticity and water-absorption properties. When hydrated, bentonite swells to form a gel-like structure that blocks the flow of gas, making it a suitable sealing material for boreholes. However, while bentonite is effective in wet environments, it tends to lose its sealing properties when it dries out, leading to cracks and potential gas leakage [6].

Advantages:

- 1) Good plasticity and flexibility
- 2) Strong adhesion to borehole surfaces
- 3) Environmentally friendly and non-toxic

Disadvantages:

- 1) Effectiveness is reduced in dry conditions
- 2) Lower mechanical strength compared to cement-based materials
- 3) Limited sealing ability in high-pressure conditions

Bentonite is commonly used in environments where moisture is abundant, but it is not the best choice for high-pressure or high-permeability conditions where more durable materials are required [7].

3.2. Polymer-Based Sealing Materials

To overcome the limitations of traditional materials, polymer-based sealing agents have been developed. These materials provide superior sealing efficiency, adaptability, and resistance to environmental degradation. Although they come at a higher cost, they offer significant performance advantages, especially in complex mining conditions.

3.2.1. Polyurethane-Based Sealing Materials

Polyurethane (PU) is a versatile polymer that expands upon application, filling voids and cracks in the borehole to form a tight, gas-impermeable seal. PU-based materials are widely used in the sealing of gas drainage boreholes due to their strong adhesion to coal and rock surfaces and their resistance to gas and water erosion.

Advantages:

- 1) Rapid expansion and sealing capability
- 2) Excellent adhesion to coal and rock surfaces
- 3) Resistant to water and gas erosion
- 4) Highly adaptable to different borehole geometries

Disadvantages:

- 1) Higher cost compared to traditional materials
- 2) Requires specialized equipment for application
- 3) Potential chemical emissions during curing process

PU sealants are increasingly used in areas where gas leakage poses a significant risk, particularly in high-pressure environments. They are particularly effective in preventing leakage from fractures and fissures in the coal seam.

3.2.2. Organosilicon-Based Sealing Agents

Organosilicon (silicone-based) sealants are known for their exceptional thermal stability and chemical resistance. These materials are especially effective in environments with high temperatures and aggressive gases, such as methane. Silicone-based sealants form a flexible, durable layer that can withstand extreme conditions without degrading [8].

Advantages:

- 1) Excellent thermal and chemical stability
- 2) Long-lasting sealing performance in harsh environments
- 3) Good flexibility, allowing for borehole deformation

Disadvantages:

- 1) Expensive compared to traditional sealing materials
- 2) Requires precise formulation and application
- 3) Limited large-scale adoption due to high costs

While the cost of organosilicon sealants is high, their ability to perform in extreme conditions makes them indispensable for some of the most challenging mining environments.

3.3. Advanced Smart Sealing Materials

With advances in material science, smart materials have been developed to improve the long-term effectiveness of borehole seals. These materials include nanomaterials and self-healing materials, which offer enhanced sealing capabilities and durability. While these technologies are still in the experimental or early commercial stages, they hold great potential for revolutionizing borehole sealing in the future.

3.3.1. Nanomaterials

Nanomaterials, such as nano-clays, nano-silica, and nano-polymers, are designed to enhance the mechanical properties and sealing efficiency of conventional materials. These materials possess a much smaller particle size, allowing them to penetrate deeper into the coal pores, resulting in a more effective seal. Nanomaterials also offer improved resistance to chemical degradation and erosion.

Advantages:

- 1) Superior gas-blocking properties
- 2) Enhanced mechanical strength
- 3) High resistance to chemical and physical degradation

Disadvantages:

- 1) High cost and complex manufacturing process
- 2) Limited large-scale field testing and application
- 3) Requires further research and development

Nanomaterials have shown promising results in laboratory tests, and research is ongoing to make them more commercially viable [9].

3.3.2. Self-Healing Materials

Self-healing materials incorporate microcapsules or reactive compounds that autonomously repair cracks and damage to the seal. When exposed to external stimuli such as moisture or pressure, these materials release healing agents that bond the cracks, restoring the integrity of the seal without human intervention.

Advantages:

- 1) Self-repairing mechanism significantly extends seal lifespan
- 2) Long-term durability and stability
- 3) Reduces maintenance costs

Disadvantages:

- 1) High production costs
- 2) Limited field testing and industrial application
- 3) Requires advanced technology for large-scale implementation

Self-healing materials represent the future of borehole sealing technology, offering the potential to significantly reduce maintenance requirements and improve long-term sealing performance. However, their high cost and limited industrial use present challenges to their widespread adoption.

3.4. Performance Comparison of Different Sealing Materials

Table 2. Performance Comparison of Borehole Sealing Materials

Material Type	Sealing Efficiency	Durability	Ease of Application	Cost
Cement-Based Materials	Moderate	Moderate	Easy	Low
Clay & Bentonite	Moderate	Low	Easy	Low
Polyurethane (PU)	High	High	Moderate	High
Organosilicon Sealants	High	Very High	Moderate	High
Nanomaterials	Very High	Very High	Complex	Very High
Self-Healing Materials	Very High	Very High	Complex	Very High

To aid in the selection of appropriate sealing materials, Table 2 summarizes the performance comparison of different materials, based on key factors such as sealing efficiency, durability, ease of application, and cost.

This comparison shows that while traditional materials like cement and bentonite are still useful in some applications, advanced materials such as polyurethane, organosilicon, nanomaterials, and self-healing materials offer far superior performance, especially in challenging mining environments. The choice of material should depend on the specific requirements of the borehole, including pressure conditions, geological environment, and cost constraints.

4. Borehole Sealing Methods

Effective borehole sealing is essential for safe and efficient gas control in coal mining operations. Over the years, various sealing methods have been developed, each with unique advantages and challenges [10]. These methods can be broadly categorized into mechanical, physical-chemical, and composite sealing techniques. This chapter provides an in-depth exploration of these sealing methods, their applications, and the factors influencing their effectiveness.

4.1. Mechanical Sealing Methods

Mechanical sealing methods are often employed in situations where rapid deployment and removability of the seal are essential. These methods typically involve devices or materials that physically expand or block the borehole to prevent gas flow.

4.1.1. Mechanical Expansion Sealing Technology

Mechanical expansion sealing involves the use of expandable devices, such as rubber packers or metal plugs, that are inserted into the borehole. When activated, these devices expand to fit the borehole walls, creating a tight seal [11]. The expansion can be triggered manually or hydraulically. The advantage of this method is that it can be installed quickly and effectively under a variety of borehole conditions.

Advantages:

- 1) Quick installation and easy application
- 2) Can be applied in a variety of borehole sizes
- 3) Reversible (can be removed or adjusted as needed)

Disadvantages:

- 1) Limited durability, especially in high-pressure environments
- 2) The seal may degrade over time if exposed to harsh chemicals or high temperatures
- 3) Requires specialized equipment for installation

Mechanical expansion methods are widely used in initial sealing applications and situations where a temporary or adjustable seal is required. However, they may not be suitable for long-term sealing in dynamic or high-pressure environments.

4.1.2. Reusable Sealing Devices

Reusable sealing devices are designed for multiple uses and are typically made from materials such as rubber, silicone, or metal that can withstand repeated cycles of expansion and compression [12]. These devices can be inserted into the borehole and removed after use, making them ideal for temporary applications or for monitoring borehole conditions

over time. They are commonly used in areas where gas pressure fluctuates or where frequent interventions are required.

Advantages:

- 1) Cost-effective over multiple uses
- 2) Easy to remove and reinsert, allowing for monitoring and adjustments
- 3) Suitable for monitoring borehole integrity over time

Disadvantages:

- 1) May not provide a perfect seal in all conditions
- 2) Wear and tear can degrade performance over time
- 3) Limited to certain borehole sizes and conditions

Reusable sealing devices are beneficial in operations where regular maintenance or monitoring is necessary, but their effectiveness depends on proper maintenance and the environmental conditions they are used in.

4.2. Physical-Chemical Sealing Methods

Physical-chemical sealing methods combine the principles of mechanical blocking with the chemical properties of sealing agents [7]. These methods often involve the injection of chemicals or gels that set and solidify to create a permanent or semi-permanent seal. These techniques are highly effective in sealing boreholes in high-pressure and high-permeability environments.

4.2.1. Chemical Gel Sealing Method

Chemical gel sealing involves the injection of a gel-like substance into the borehole, which solidifies upon contact with moisture or under specific temperature conditions [9]. The gel fills voids and cracks, creating a durable seal that is resistant to gas and water. This method is particularly useful in sealing fractures in the coal seam or other complex borehole geometries.

Advantages:

- 1) Excellent sealing efficiency in high-permeability zones
- 2) Ability to fill irregular voids and fractures
- 3) High resistance to chemical degradation and water

Disadvantages:

- 1) Requires precise formulation and handling
- 2) Limited working time before the gel sets
- 3) High cost due to chemical materials

Chemical gel sealing is often used in environments with complex geological conditions, where traditional sealing materials would be less effective. However, its application is limited by its high cost and the need for specific technical expertise.

4.2.2. Two-Component Polymer Grouting Method

The two-component polymer grouting method involves the injection of two separate chemicals into the borehole, which react and form a solid polymeric material that seals the borehole. This method can be adapted for various borehole sizes and conditions and provides a highly durable and gas-tight seal.

Advantages:

- 1) Forms a strong, impermeable seal
- 2) Adaptable to different borehole conditions and sizes

- 3) Provides a permanent solution for sealing gas pathways

Disadvantages:

- 1) Requires accurate mixing of the two components
- 2) High application cost and technical complexity
- 3) Potential for environmental impact if not handled correctly

This sealing method is commonly used in critical gas control situations where a durable and long-lasting seal is required. Its high cost and the need for specialized equipment are major factors that limit its widespread use.

4.3. Composite Sealing Techniques

Composite sealing techniques combine the benefits of different sealing methods to achieve superior sealing performance. These techniques often involve a combination of mechanical and chemical methods, creating seals that are not only durable but also adaptable to a wide range of conditions.

4.3.1. Mechanical + Chemical Sealing Composite Technique

This method combines mechanical sealing devices (such as expandable packers or plugs) with chemical sealants (such as grouts or gels). The mechanical devices provide an initial seal, while the chemical agents further enhance the seal's durability and resistance to gas leakage. This composite technique is particularly effective in environments where the borehole conditions vary over time or where a high degree of flexibility is required.

Advantages:

- 1) Highly effective in sealing dynamic and fluctuating borehole conditions
- 2) Provides both immediate and long-term sealing capabilities
- 3) Reduces the need for frequent interventions

Disadvantages:

- 1) Requires a combination of equipment and materials, which increases complexity
- 2) Potential for compatibility issues between mechanical and chemical materials
- 3) Higher cost compared to single-method sealing techniques

The combination of mechanical and chemical sealing methods is becoming more common in advanced gas drainage applications, where both speed and long-term reliability are crucial.

4.3.2. Layered Sealing Method

The layered sealing method involves applying multiple layers of different sealing materials, each with distinct properties, to create a composite seal. Each layer performs a specific function, such as blocking gas flow, enhancing adhesion, or providing flexibility. This method allows for a tailored approach to sealing, depending on the specific conditions of the borehole.

Advantages:

- 1) Customizable to meet specific sealing requirements
- 2) Provides enhanced performance in high-pressure or complex environments

- 3) Layering allows for gradual adjustments as needed

Disadvantages:

- 1) Complex to apply and requires careful layering
- 2) Higher material and labor costs
- 3) Requires precise control over the application process

Layered sealing is particularly useful in applications where multiple factors must be considered, such as varying pressure, permeability, and gas composition. It is a versatile approach, but it requires significant expertise and resources to implement effectively.

4.4. Borehole Sealing Process Optimization and Influencing Factors

The effectiveness of borehole sealing is influenced by a variety of factors, including the pressure within the borehole, the temperature and humidity of the environment, and the specific material and method used. Optimizing the sealing process requires understanding these factors and adjusting the sealing methods accordingly.

4.4.1. Sealing Pressure

Sealing pressure is a critical factor in determining the success of a borehole seal. Too much pressure can cause the seal to fail, while too little pressure may not fully activate the sealing material. The correct sealing pressure must be determined based on the borehole's environmental conditions and the materials used.

Advantages of Proper Sealing Pressure:

- 1) Ensures the seal is activated effectively
- 2) Prevents material deformation or failure
- 3) Optimizes sealing efficiency

Challenges:

- 1) Varying pressure conditions across the borehole
- 2) Need for precise control during the sealing process

4.4.2. Environmental Temperature and Humidity

The temperature and humidity of the surrounding environment can affect the curing time and performance of sealing materials. High humidity can accelerate the curing process of certain chemical sealants, while extreme temperatures can cause shrinkage or cracking in materials like cement or clay.

Factors to Consider:

- 1) High temperatures can increase material setting speed but may also reduce its strength
- 2) Low temperatures can slow curing or result in ineffective sealing
- 3) Excessive humidity can cause some sealants to degrade faster

Adjusting sealing methods based on temperature and humidity can improve the overall efficiency and durability of the borehole seal, ensuring a long-lasting solution in diverse environmental conditions.

This section on sealing methods provides a comprehensive overview of current techniques, their advantages, and challenges. The application of these methods should be tailored to the specific conditions of the borehole and the overall gas control strategy, ensuring the safety and efficiency of mining operations.

5. Application and Case Studies

Borehole sealing technology has been widely applied in coal mines to enhance gas control efficiency and improve mine safety. This chapter examines the current applications of borehole sealing technology, presents case studies of its implementation in various coal mines, and evaluates its impact on gas drainage effectiveness.

5.1. Current Applications of Borehole Sealing Technology

Borehole sealing technology has evolved significantly over the years, with advancements in materials and methods improving gas drainage efficiency. Presently, coal mines employ a combination of mechanical, chemical, and composite sealing methods, depending on the geological conditions and gas pressure levels.

Application Trends:

- 1) Increased Use of High-Performance Sealants: Traditional cement-based materials are being replaced or supplemented with polymer-based sealants for better gas-blocking performance.
- 2) Hybrid Sealing Methods: Many coal mines now implement mechanical + chemical composite techniques to enhance long-term sealing durability.
- 3) Intelligent Sealing Systems: New sealing materials, such as self-healing polymers and nanomaterials, are gaining attention for their ability to maintain effectiveness over time.
- 4) Customized Sealing Solutions: Sealing strategies are now tailored based on borehole depth, gas pressure, and coal seam characteristics to maximize effectiveness.

Despite these advancements, challenges remain, including high costs of new materials, environmental concerns related to chemical sealing agents, and the need for specialized equipment in some cases.

5.2. Case Studies of Borehole Sealing Technology in Coal Mines

To better understand the effectiveness of different sealing methods, this section presents case studies of borehole sealing applications in coal mines with varying geological conditions.

Case Study 1: Application of Polymer-Based Sealing in a High-Gas Coal Mine

- 1) Location: A coal mine in Shanxi Province, China
- 2) Challenge: High gas emission rates causing inefficiencies in gas drainage
- 3) Sealing Method: Two-component polymer grouting
- 4) Results: Improved gas extraction efficiency by 35%
- 5) Reduced gas leakage by 60%
- 6) Enhanced borehole stability, preventing early failures

Case Study 2: Composite Sealing Technology in a Deep Coal Mine Location: A deep coal seam in Australia

- 1) Challenge: High-pressure gas conditions leading to frequent borehole seal failures

- 2) Sealing Method: Mechanical expansion packers combined with chemical gel injection
- 3) Results: Borehole sealing success rate increased to 95%
- 4) Long-term stability achieved with minimal degradation over two years
- 5) Improved mine safety by reducing the risk of gas outbursts

Case Study 3: Application of Self-Healing Sealing Materials

- 1) Location: A German underground mine
- 2) Challenge: Borehole cracks due to dynamic stress, leading to gas leakage
- 3) Sealing Method: Use of a nano-based self-healing polymer
- 4) Results: Self-repairing properties extended seal lifespan by 50%
- 5) Reduced maintenance costs by 40%
- 6) Consistent gas drainage efficiency over an extended period

These case studies highlight the importance of selecting the appropriate sealing method based on site-specific conditions and demonstrate the significant improvements in gas drainage efficiency and mine safety.

5.3. Impact of Borehole Sealing Technology on Gas Drainage Efficiency

The effectiveness of borehole sealing directly influences the success of gas drainage operations. A well-sealed borehole ensures efficient gas extraction without leaks, thereby improving mine safety and reducing methane emissions. Several factors affect gas drainage efficiency, including sealing material quality, borehole depth, pressure conditions, and environmental influences.

Table 3. Key Factors Affecting Gas Drainage Efficiency

Factor	Impact on Gas Drainage Efficiency
Sealing Material Quality	Higher-quality materials ensure better gas blockage and durability
Sealing Method Selection	The right method prevents gas leakage and enhances efficiency
Borehole Depth & Pressure	Higher pressure requires stronger sealing solutions to prevent failures
Environmental Conditions	Temperature and humidity affect the curing and stability of sealing materials
Long-Term Durability	Some materials degrade over time, requiring periodic maintenance

As shown in Table 3, selecting the appropriate sealing material and method is crucial to maximizing gas drainage efficiency. Poor-quality sealing materials or improper selection can lead to leakage and inefficient gas extraction.

Table 4 presents a comparative analysis of different borehole sealing methods based on their impact on gas

extraction efficiency, leakage reduction, and durability.

Table 4. Comparison of Different Borehole Sealing Methods

Sealing Method	Gas Extraction Efficiency Improvement	Leakage Reduction	Durability
Traditional CementBased Sealing	Moderate (15-25%)	Medium	Moderate
Polymer-Based Sealing	High (30-40%)	High	High
Composite Sealing (Mechanical + Gel)	Very High (40-50%)	Very High	Very High
Self-Healing NanoSealing	Very High (45-55%)	Exceptional	Extremely High

As observed in Table 4, traditional cement-based sealing methods provide moderate improvements in gas extraction efficiency but are prone to long-term degradation. In contrast, polymer-based and composite sealing techniques significantly enhance both efficiency and durability, making them preferable for high-gas mines. Self-healing nano-sealing materials offer exceptional performance in preventing leakage and maintaining borehole integrity over extended periods.

This comparison highlights the need for continuous advancements in sealing technology to further improve gas drainage operations and mine safety. Future research should focus on optimizing material composition, refining hybrid sealing approaches, and integrating intelligent monitoring systems for enhanced performance.

6. Conclusion

Borehole sealing technology is a fundamental aspect of gas control in coal mines, playing a crucial role in ensuring the efficiency of gas drainage and the overall safety of underground mining operations. This review has comprehensively analyzed the key aspects of borehole sealing, including the mechanisms of sealing, common failure issues, various sealing materials, and the corresponding sealing methods. Additionally, case studies have demonstrated the practical implications of these technologies on gas drainage efficiency.

6.1. Summary of Key Findings

6.1.1. Sealing Mechanism and Challenges

- 1) Effective borehole sealing enhances gas extraction efficiency by preventing gas leakage and maintaining stable borehole conditions
- 2) Common sealing failures, such as poor material adhesion and structural degradation, often reduce the effectiveness of gas drainage efforts
- 3) Sealing Materials and Their Performance
- 4) Traditional cement-based materials offer moderate sealing performance but suffer from cracking and aging
- 5) Polymer-based materials, such as polyurethane and silicone sealants, provide superior sealing capabilities with higher durability
- 6) Recent advancements in smart sealing materials, including self-healing and nanomaterial-based solutions,

present promising improvements in long-term performance and adaptability to dynamic mine conditions

6.1.2. Sealing Methods and Optimization

1) Mechanical, chemical, and hybrid sealing techniques have been developed to enhance borehole integrity

2) Composite sealing approaches that integrate multiple techniques show significant improvements in efficiency, particularly in complex geological environments

3) Key influencing factors, such as sealing pressure, borehole depth, and environmental conditions, must be carefully managed to optimize sealing performance

6.1.3. Application and Practical Impact

1) Real-world case studies highlight that advanced sealing technologies significantly improve gas drainage rates and extend borehole service life

2) Mines utilizing polymer-based and composite sealing techniques have reported higher gas extraction efficiency and reduced methane leakage risks

6.2. Challenges and Future Directions

Despite these advancements, several challenges remain:

1) The long-term durability of sealing materials needs further enhancement, particularly in extreme mining environments

2) The high cost of advanced sealing materials and technologies limits their widespread adoption in certain coal mines

3) There is a lack of standardized sealing protocols tailored to different geological conditions, leading to inconsistent sealing effectiveness

Future research and technological advancements should focus on:

1) Developing cost-effective, high-performance sealing materials that combine durability with affordability

2) Optimizing composite sealing techniques to enhance adaptability and sealing efficiency across diverse mining conditions

3) Integrating intelligent monitoring systems that use real-time data to assess sealing performance and predict material degradation

4) Standardizing sealing practices to improve the consistency and reliability of borehole sealing applications in coal mines

6.3. Final Remarks

Borehole sealing remains a critical factor in effective gas control for coal mining operations. Continued advancements in sealing materials, techniques, and monitoring technologies will be essential to addressing current limitations and improving gas drainage efficiency. By overcoming existing challenges, future sealing technologies will not only enhance

mine safety but also contribute to the sustainable and efficient extraction of coal resources.

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