

Research Status and Development Trends of Sealing Materials for Coal Mine Gas Drainage

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Abstract

Gas drainage is crucial for coal mine safety and clean energy use, with sealing material performance directly affecting drainage efficiency and mine safety. This paper reviews the research and trends of sealing materials for coal mine gas drainage. It categorizes and details traditional (cement-based, polyurethane-based) and new (inorganic expansive, nano-modified, self-healing, composite) sealing materials. The paper also identifies key issues with current materials, such as expansive stability, durability, and environmental adaptability. Considering smart material technology and green mining needs, it proposes four development trends: high performance, functional compositeness, intelligence, and cost-effective environmental friendliness. Research highlights nano-modified inorganic flexible materials and self-healing composites as key solutions for sealing failures in complex geological conditions. Future efforts should focus on improving material-geology adaptability and establishing a full life-cycle quality evaluation system.

Keywords

Coal Mine Gas Drainage; Sealing Materials; Nano-modification; Self-healing; Development Trends.

1. Introduction

As coal mining extends to depths of one kilometer or more, the gas pressure and content in coal seams increase significantly, exacerbating the risk of gas outbursts[1]. Gas drainage has thus become a mandatory technical measure to ensure safe mine production. Drilling hole sealing, serving as the "last line of defense" in the gas drainage system, has its sealing quality directly influencing the gas drainage concentration, drainage cycle, and utilization efficiency[2-3]. Statistical data reveals that approximately 60% of coal mines in China have a gas drainage concentration below 15%, with over 40% of these cases attributed to sealing failures, primarily manifested as cracks between the sealing material and the coal-rock wall, as well as material aging and degradation. Traditional sealing materials, such as cement mortar with high shrinkage rates and polyurethane with poor durability, struggle to meet the sealing demands under deep and complex geological conditions[4].

In recent years, extensive research has been conducted by scholars both domestically and internationally on the performance optimization and innovation of sealing materials, leading to the development of novel systems such as nano-diffusion expansive agents and self-healing cement-based materials, along with the formulation of supporting techniques like the "two-plug and one-pressure" method and "bag-type grouting." The "NBT 11028-2022 Technical Specification for Sealing Abandoned Gas Drainage Boreholes in Coal Mines," implemented in 2022, clearly defines the core performance indicators and selection principles for sealing materials, providing a standard basis for technological upgrades[5-6]. This paper systematically reviews the development history, performance evolution, and engineering

applications of sealing materials, analyzes current technical bottlenecks, and anticipates future development directions, offering theoretical support and practical references for the innovation and promotion of sealing technologies for coal mine gas drainage.

2. Research Status of Sealing Materials for Coal Mine Gas Drainage

2.1. Traditional Sealing Materials and Their Application Characteristics

(1) Cement-based Sealing Materials

Cement-based materials, including cement mortar and ordinary cement slurry, were the earliest materials used for sealing in gas drainage. They offer advantages such as a wide range of raw material sources, low cost (approximately 150~300 yuan per ton), and high compressive strength (compressive strength ≥ 30 MPa at 28 days). These materials are mainly used to fill boreholes through manual or mechanical grouting, forming a rigid sealing structure through hydration reactions. Their action mechanism involves the physical adsorption and chemical bonding between products generated from cement hydration, such as calcium hydroxide and calcium silicate hydrate gel, and coal-rock particles, resulting in a dense sealing layer.

However, cement-based materials have significant drawbacks: 1) High setting shrinkage rate (usually 0.5%~1.2%), which leads to the formation of micro-cracks between the sealing layer and the borehole wall, serving as channels for gas leakage. 2) Low early strength (initial setting time of 4 ~6 hours, with the strength at 7 days being only 60% of that at 28 days), making it difficult to resist stress disturbances after borehole construction. 3) Poor deformation resistance, with a high elastic modulus of 20 ~ 30 GPa, which does not match the elastic modulus of coal-rock (1 ~ 5 GPa), making it prone to fracture due to rock stratum movement.

(2) Polyurethane-based Sealing Materials

Polyurethane sealing materials are two-component polymer materials (Component A: isocyanate. Component B: polyols, catalysts, etc.). After mixing, they undergo a foaming reaction with a volume expansion rate of 100% ~ 300%. They can quickly fill borehole cracks and bond tightly to the borehole wall (bonding strength ≥ 1.5 MPa), with adjustable initial setting time (3~30minutes), significantly improving sealing efficiency. Their sealing mechanism includes physical blocking (foam filling pores) and chemical bonding (formation of chemical bonds through the reaction between isocyanate and hydroxyl groups on the coal-rock surface), making them suitable for sealing medium-deep boreholes (50 ~ 200 m) and coal seams with developed cracks.

However, polyurethane materials have three major technical bottlenecks: 1) High cost (approximately 8,000~12,000 yuan per ton), resulting in poor economic viability for large-scale applications. 2) Intense heat generation during the foaming process (with a maximum temperature reaching 80 ~ 120 °C), posing a risk of explosion in high-gas environments. 3) Insufficient durability, as they are prone to aging and degradation in the humid and acid-base environments underground, with a more than 50% decline in sealing performance after 2~3 years, leading to a continuous decrease in gas drainage concentration. In addition, polyurethane materials release toxic gases when burned, which does not meet the environmental protection requirements of green mines.

2.2. New Sealing Materials and Technological Breakthroughs

(1) Inorganic Expanding Sealing Materials

Inorganic expanding sealing materials are based on inorganic minerals (such as silicates and aluminates) and are compounded with nano-scale expanding agents and binders. They achieve expansion sealing through physical complexation and chemical reactions, offering advantages such as environmental friendliness, non-toxicity, anti-aging properties, and moderate cost (approximately 1,500 ~ 3,000 yuan per ton). They have been a research hotspot in recent years.

Their core performance characteristics include: 1) Micro-expansion, with a volume expansion rate of 0.3% ~ 0.8% during setting, effectively compensating for shrinkage and avoiding crack formation. 2) High permeability, with low slurry viscosity (200 ~ 500 MPa·s) and low grouting resistance, allowing penetration into micro-cracks in coal-rock (width \geq 0.1 mm). 3) Strong bonding, with a bonding strength to coal-rock \geq 2.0 MPa and excellent water erosion resistance. The advantage of inorganic expanding materials lies in their strong environmental adaptability, stable performance in underground environments with a water content of 20% ~ 40% and a temperature of 5 ~ 40 °C, and no release of toxic and harmful substances, meeting the environmental protection requirements of the "Coal Mine Safety Regulations."

(2) Self-healing Sealing Materials

In response to the problem of crack formation in sealing materials under stress disturbances, researchers have developed self-healing sealing materials. Their core principle is to introduce self-healing agents (such as microcapsules, microbial spores, and rehydratable components) into the material system. When cracks occur, the self-healing agents are activated and generate repair products through chemical reactions to fill the cracks and restore sealing performance. Currently, self-healing cement-based materials are the most widely used, achieving crack self-healing by adding 3% ~ 5% of self-healing agents (such as ettringite-type expanding agents and nano-silica sol).

(3) Nano-modified Composite Sealing Materials

The introduction of nanotechnology provides a new path for breakthroughs in the performance of sealing materials. By incorporating nanoparticles (such as nano-SiO₂, nano-Al₂O₃, and nano-calcium carbonate) into traditional materials or new systems, the microstructure and macroscopic properties can be significantly optimized. The action mechanisms of nanoparticles include: 1) Filling effect, where nanoparticles (with a particle size of 1~100 nm) fill the internal pores of the material, reducing porosity and improving density. 2) Interface strengthening effect, where nanoparticles form strong chemical bonds with the substrate, enhancing bonding strength and anti-aging properties. 3) Catalytic effect, accelerating hydration or polymerization reactions, shortening setting time, and improving early strength.

(4) Composite Sealing Material Systems

Composite sealing material systems refer to the combined use of two or more different types of materials to leverage their respective advantages and achieve multiple functions such as "rigid support + flexible sealing + crack filling." They mainly include composite modes such as "inorganic + organic," "rigid + flexible," and "surface + deep." For example, in the "cement-based material + polyurethane" composite system, polyurethane is used to fill cracks in the deep part, while cement-based materials are used for reinforcement in the shallow part, balancing sealing performance and structural stability. In the "inorganic expanding material + self-healing agent" composite system, the environmental protection and durability of inorganic materials are utilized, and the problem of crack failure is solved through self-healing agents.

The "rigid + flexible" composite process recommended by the "NBT 11028-2022" standard is widely used for sealing boreholes near mined-out areas: a rigid supporting layer (thickness of 50 ~ 100 mm) is formed on the outer side of the borehole wall using cement-based materials, and a polymer flexible material (such as nano-diffusion expanding agent) is used on the inner side to adapt to rock stratum movement. The sealing length exceeds the mining influence range by 1 ~ 2 m, and 5% ~ 10% of deformation compensation space is reserved during grouting. The core advantage of composite sealing material systems is their strong adaptability, allowing flexible adjustment of material combinations according to geological conditions (such as water-rich areas, fault zones, and high-gas areas). However, their construction process is complex, and they have high requirements for operational skills.

3. Key Technical Issues with Current Hole-Sealing Materials

3.1. Inadequate Synergistic Optimization of Performance

Existing hole-sealing materials struggle to simultaneously meet the synergistic requirements of "high strength, low shrinkage, high elasticity, and high permeability". Rigid materials (e.g., cement-based ones) offer high strength but poor resistance to deformation, while flexible materials (e.g., polyurethane) exhibit good elasticity but insufficient strength. Although nanomodified materials demonstrate excellent performance, they face challenges in balancing cost and performance. For instance, when the nanoparticle content exceeds 5%, the material's viscosity increases significantly, leading to a decrease in permeability and affecting grouting effectiveness. Conversely, when the content is less than 3%, the modification effect is insignificant. Additionally, the environmental adaptability of materials needs improvement. Under high humidity (relative humidity > 85%) and high salinity water (salt content > 5%) conditions, the swelling stability of some inorganic materials decreases, and organic materials are prone to aging and degradation.

3.2. Poor Compatibility between Hole-Sealing Processes and Materials

The effectiveness of hole sealing depends not only on material performance but also closely on process parameters. However, there is currently a disconnect between material selection and process design. For example, when a one-time grouting process is used for deep holes (depth \geq 50 m), the hole-sealing material is prone to loss, resulting in inadequate sealing in the deep sections. In water-rich areas, the failure to use impermeable materials increases the risk of coupled water damage and gas leakage. Although the "NBT 11028-2022" standard outlines material selection principles for different geological conditions, blind material selection still occurs during on-site construction. For instance, the use of rigid materials in mining-affected areas can lead to fracture and failure of the sealing layer. Furthermore, non-standard construction operations (e.g., incomplete hole cleaning, insufficient grouting pressure) can also affect material performance. For example, residual coal and rock powder from incomplete hole cleaning can reduce the material's bond strength by more than 30%.

3.3. Incomplete Quality Inspection and Evaluation System

Currently, hole-sealing quality inspection primarily relies on post-event evaluation, lacking real-time monitoring throughout the process. Laboratory testing struggles to simulate complex underground geological environments (e.g., stress disturbances, temperature variations), leading to discrepancies between test results and actual application effects. On-site inspection mainly relies on indirect indicators such as gas extraction concentration, which cannot directly reflect the integrity and durability of hole-sealing materials. For example, some boreholes initially exhibit high extraction concentrations but experience a sharp decline after three months due to material aging, a problem that is difficult to detect through initial inspections. Additionally, the lack of unified standards for evaluating the lifespan of hole-sealing materials makes it challenging to quantitatively compare the service lives of different materials, affecting the decision-making process of coal mining enterprises.

3.4. Challenges in Balancing Environmental Protection and Cost-Effectiveness

The increasing environmental requirements for hole-sealing materials in green mine construction have led to the phase-out of traditional polyurethane materials due to their release of toxic and harmful substances. However, the high cost of new environmentally friendly materials (e.g., nanoscale inorganic materials, self-healing materials) limits their large-scale promotion. For instance, the cost of nanoscale diffusion swelling agents is 5~10 times that of cement mortar. Although some of these costs can be offset by improving extraction efficiency and reducing construction costs, economic pressure remains for small and medium-sized coal

mines. Furthermore, the complex production processes and high energy consumption of some new materials, such as the 3–5 times higher energy consumption in nanoparticle preparation compared to conventional materials, do not align with low-carbon development goals.

4. Development Trends of Hole-Sealing Materials for Coal Mine Gas Extraction

4.1. High Performance: Synergistic Optimization of Multiple Properties

Future hole-sealing materials will evolve towards a synergistic combination of "high strength, low shrinkage, high elasticity, high durability, and high environmental friendliness". Key technological pathways include: 1) Upgrading nanomodification technology by adjusting nanoparticle size (10~50 nm) and surface modification processes to balance material density and permeability. For example, composite addition of nano-SiO₂ and nano-Al₂O₃ can simultaneously enhance material strength and resistance to deformation. 2) Innovating self-healing mechanisms by developing new systems such as microbial self-healing and light-responsive self-healing. For instance, encapsulating urease-producing microbial spores in porous carriers allows spore activation upon crack formation, leading to urea decomposition and calcium carbonate precipitation to fill cracks, with repair efficiency exceeding 90%. 3) Optimizing environmental adaptability by compounding salt-resistant, acid-resistant, and high-temperature-resistant additives to develop specialized hole-sealing materials suitable for deep high-temperature (>60 °C), high-salinity, and high-pH environments, meeting the needs of kilometer-scale mining.

4.2. Functional Integration: Material-Process-Geology Compatibility

Functional integration represents the core trend in addressing hole-sealing challenges under complex geological conditions, featuring a development model of "material compositing + process integration + intelligent adaptation". 1) Material compositing will evolve towards multi-component synergy, such as a quaternary composite system of "inorganic substrate + nanomodifier + self-healing agent + environmentally friendly additive", balancing strength, elasticity, self-healing, and environmental friendliness. 2) Process integration will deeply fuse with material properties, such as combining "bladder grouting + staged pressurization" processes with high-permeability materials for precise filling of deep borehole fractures. After application in the Du'erping Mine, borehole sealing rates increased from 75% to over 95%. 3) Intelligent adaptation based on geological conditions will involve using geological radar and borehole imaging technologies to predict fracture distributions around boreholes, combined with big data analysis to optimize material formulations and process parameters. For example, high-elasticity composite materials can be used in fault-developed areas, while high-impermeability materials can be applied in water-rich zones, enabling personalized hole-sealing solutions tailored to specific conditions.

4.3. Intelligence: Integration of Self-Sensing, Self-Response, and Self-Repair

Intelligence represents the cutting-edge development direction of hole-sealing materials, achieving integrated functions of "self-sensing, self-response, and self-repair" in hole-sealing systems by integrating sensing and smart material technologies. 1) Self-sensing capabilities involve embedding optical fiber sensors and pressure sensors into materials to monitor stress changes and fracture development in the sealing layer in real time, with data transmitted to ground monitoring centers via the Internet of Things. 2) Self-response capabilities enable materials to automatically adjust their properties in response to environmental changes, such as accelerating setting speed with increasing temperature or enhancing strength under increased pressure. 3) Upgraded self-repair functions involve developing active self-repair systems that rapidly release repair agents through remote triggering (e.g., electromagnetic or

ultrasonic waves) for timely fracture repair. For example, the intelligent self-healing hole-sealing material developed by Henan Polytechnic University automatically initiates an electrochemical reaction to release repair agents when optical fiber sensors detect fracture widths exceeding 0.2 mm, achieving an 88% repair rate within 24 hours.

4.4. Environmentally Friendly and Low-Cost: Green and Sustainable Development

In line with the "dual carbon" goals and green mine construction requirements, hole-sealing materials will evolve towards environmental friendliness and cost-effectiveness. 1) Green raw materials will involve using industrial solid wastes (e.g., fly ash, coal gangue, slag) to replace some base materials, reducing resource consumption and carbon emissions. For example, preparing inorganic swelling materials with 30%~50% fly ash reduces costs by 20%~30% while improving material impermeability. 2) Low-carbon production processes will optimize nanoparticle preparation and material compositing to reduce energy consumption and pollutant emissions. For instance, using the sol-gel method instead of traditional high-temperature calcination to prepare nano-silica sol reduces energy consumption by over 40%. 3) Recycling technologies will involve developing recoverable and biodegradable hole-sealing materials, such as bio-based polyurethane materials that can be degraded by microorganisms after gas extraction, avoiding environmental pollution. Additionally, scaling up production and technological innovation will further reduce the costs of new materials, making the prices of high-performance materials like nanomodified and self-healing ones drop to 1/2~1/3 of those of conventional polyurethane, enhancing cost-effectiveness.

5. Conclusion

The development of hole-sealing materials for coal mine gas extraction has evolved from traditional single materials to novel composite systems. Nanomodified inorganic flexible materials, self-healing cement-based materials, and "rigid + flexible" composite systems have become the current technological mainstream, significantly improving hole-sealing quality and gas extraction efficiency. Industrial applications in enterprises such as Jinneng Holding Group and Yangquan Coal Industry Group demonstrate that new hole-sealing materials can increase gas extraction concentration by 2~3 times, extend extraction cycles to over 12 months, and reduce construction costs by 20%~30%.

However, current hole-sealing materials still face key challenges, including inadequate synergistic optimization of performance, poor process compatibility, incomplete quality inspection systems, and difficulties in balancing environmental protection and cost-effectiveness. Future development should focus on four directions: 1) Achieving multi-property synergy in materials through nanomodification and self-healing mechanism innovation. 2) Strengthening deep compatibility between materials, processes, and geology to develop personalized hole-sealing solutions. 3) Integrating intelligent sensing and response technologies to construct self-sensing, self-response, and self-repair integrated systems. 4) Utilizing industrial solid wastes and low-carbon processes to achieve environmental friendliness and cost-effectiveness in materials. And hole-sealing materials will advance towards "high performance, multifunctionality, intelligence, and greenness", providing core technological support for the safe and efficient extraction of deep coal resources and the utilization of gas resources. Future efforts should further strengthen basic theoretical research and engineering application demonstrations, establish a full lifecycle quality evaluation system for hole-sealing materials, and promote standardized and industrialized technological development.

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