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# *Review on Research of Lining and Seepage Control Materials for Compressed Air Energy Storage Underground Caverns*

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***Abstract.*** Against the background of global carbon peaking and carbon neutrality strategies, Compressed Air Energy Storage (CAES) has become a key technology for large-scale energy storage. This study takes the lining and seepage control materials of underground CAES caverns as the research core, which directly determine the operation safety and airtight performance of energy storage systems. Underground caverns, as mainstream gas storage structures, operate under harsh conditions including cyclic high pressure and drastic temperature changes, which put forward strict performance requirements for supporting and sealing materials. On the basis of sorting out domestic and foreign research results, this paper classifies common lining and seepage control materials, evaluates their engineering adaptability, and summarizes the latest progress in performance testing methods. Meanwhile, this work points out the technical defects and application bottlenecks of existing materials, and puts forward targeted research directions combined with engineering practice. The results prove that the innovation and optimization of key materials are the core driving force to promote the commercialization and large-scale application of CAES engineering.

***Keywords:*** Compressed air energy storage, Underground cavern, Lining material, Seepage control material, Research progress

## 1. Introduction

Research background and significance Under the global transition toward sustainable energy and the dual-carbon goals, there is an urgent demand for large-scale, long-duration energy storage technologies to support renewable energy accommodation and maintain grid stability. Compressed Air Energy Storage (CAES) technology has emerged as a highly promising solution due to its large capacity, long cycle life, and high efficiency. As the core component of CAES systems, underground caverns—such as salt caverns, lined artificial caverns, and abandoned mine shafts—offer significant advantages in site selection flexibility, construction cost, airtightness, and structural stability. Underground lined caverns, in particular, demonstrate outstanding potential as large-scale gas storage carriers. To ensure the long-term safe service of these caverns and the efficient operation of CAES systems, lining and seepage control materials play a critical role. Lining materials are essential for bearing high internal pressure and resisting environmental erosion, while seepage control materials are critical for preventing high-pressure air leakage, directly supporting the application of rigid-flexible combined sealing technologies [1].

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Overview of research status Globally, various engineering practices and studies have been conducted on CAES underground caverns, encompassing lined caverns, shallow-buried artificial caverns, and abandoned mines. Significant research achievements have been made regarding the temperature-pressure responses and structural heat transfer characteristics of these underground spaces. However, the research and development of specific materials are still in a phase of technological accumulation. Current studies on lining materials primarily focus on the design theories and cracking characteristics of lined caverns, while seepage control materials mostly borrow technologies and materials from related engineering fields. A mature material system fully adapted to the extreme working conditions of CAES has not yet been formed, though the emerging application of artificial intelligence provides a novel pathway for advanced material research and monitoring.

Research content and logical framework Focusing strictly on CAES underground caverns, this paper systematically bounds its research scope around the performance requirements, classifications, research progress, and synergistic working mechanisms of lining and seepage control materials, while carefully considering the severe impact of underground service environments [2]. The overall logical structure of this review follows a clear progression: analyzing the service environment, defining material performance requirements, reviewing the specific research progress of lining and seepage control materials, discussing their synergistic mechanisms, identifying current problems and challenges, and finally outlining future prospects.

## 1.1. Research background and significance

With the large-scale grid connection of renewable energy such as wind and solar power, the power grid has an increasing demand for long-term and large-capacity energy storage equipment to stabilize power fluctuation and improve energy utilization efficiency. CAES technology stands out among various energy storage schemes because of its long service life, large energy storage capacity and reliable operation efficiency. As the core gas storage unit of CAES systems, underground caverns include salt caverns, artificial lined caverns and abandoned mine shafts. These structures have obvious advantages in construction economy, airtightness and structural stability, and lined artificial caverns have the most extensive application prospect in practical projects. Lining and seepage control materials are the core components to ensure the long-term stable operation of caverns. Lining structures bear internal pressure and resist geological erosion, while seepage control layers prevent high-pressure gas leakage, and the two jointly form a mature rigid-flexible composite sealing system.

## 1.2. Overview of research status

At present, scholars at home and abroad have carried out a lot of research and engineering tests on different types of CAES underground caverns, and have mastered the temperature-pressure response law and heat transfer characteristics of cavern structures during cyclic operation. However, the research on supporting and sealing materials lags behind the development of structural design. Most existing lining material studies only focus on crack control and structural design theory, and seepage control technologies are mostly transplanted from hydraulic tunnel and water conservancy projects. So far, there is no complete material system that can fully adapt to the extreme working conditions of CAES caverns. In recent years, the introduction of artificial intelligence technology has provided a new technical path for material performance monitoring and intelligent optimization [3].

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### 1.3. Research content and logical framework

Aiming at the extreme service environment of underground CAES caverns, this paper focuses on the performance requirements, classification characteristics, research progress and cooperative working mechanism of lining and seepage control materials. Different from conventional review papers, this work combines engineering practice to analyze the matching degree between materials and working conditions. The full text is organized as follows: firstly, the multi-field coupling service environment of caverns is analyzed, and the performance indexes of core materials are defined; secondly, the research progress of lining and seepage control materials is reviewed respectively; then the cooperative working mechanism of composite structures is discussed, and the existing technical problems are summarized; finally, the future research focus and engineering application prospect are prospected.

## 2. Environment and material performance requirements of CAES underground caverns

### 2.1. Complex service environment of underground caverns

CAES underground caverns are in a harsh multi-field coupling environment for a long time. In terms of mechanical properties, the charging and discharging cycles of the system cause continuous high-pressure cyclic loads on the cavern wall, and the superposition of surrounding rock stress seriously threatens the stability of the sealing structure [4]. In terms of thermodynamic properties, the operation of the system leads to frequent temperature changes inside the cavern, forming an uneven high-temperature distribution area. The coupling effect of stress, temperature and seepage changes the seepage characteristics of rock mass, and groundwater erosion and fracture penetration will further reduce the service life of materials.

### 2.2. Performance requirements of lining materials

In order to adapt to the above harsh working conditions, lining materials must have excellent comprehensive mechanical properties. High strength, good toughness and fatigue resistance are the basic indexes to resist cyclic load and control crack propagation [5]. In terms of thermal properties, materials need to have good high temperature resistance and freeze-thaw stability to adapt to rapid temperature changes. In addition, lining materials must have strong corrosion resistance and aging resistance to cope with long-term groundwater and chemical erosion. From the perspective of construction, materials should have good pouring performance and be compatible with intelligent grouting technology to ensure coordinated deformation with surrounding rock.

### 2.3. Performance requirements for seepage control materials

The core function of seepage control materials is to ensure the airtightness of caverns, so ultra-low gas permeability is the primary performance index to avoid high-pressure gas leakage. Meanwhile, such materials need high flexibility and mechanical compatibility, which can deform synchronously with lining structures and surrounding rock to prevent cracking under temperature and pressure cycles [6]. Durability is also a key index, including aging resistance, corrosion resistance and temperature stability, to ensure long-term stable service in underground environment. In construction, materials should have strong adhesion and be suitable for complex cavern sections, so as to improve construction quality and work efficiency. The specific performance requirements are listed in Table 1.

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Table 1. Performance requirements for lining and seepage control materials in CAES caverns

| Material Category | Core Properties | Specific Requirements |
|---|---|---|
| Lining Materials | Mechanical | High strength, high toughness, fatigue resistance, and crack resistance under high-pressure cyclic loads |
| | Thermodynamic | High-temperature resistance, freeze-thaw resistance, and excellent thermal stability |
| | Durability | High resistance to chemical and groundwater erosion to extend operational lifespan |
| | Construction | Ease of pouring and molding, highly adaptable to intelligent grouting processes |
| | Airtightness | Extremely low gas permeability to effectively prevent high-pressure air leakage |
| | Mechanical | High flexibility and strong capability for synergistic deformation with surrounding structures |
| | Durability | Strong resistance to aging, corrosion, and severe temperature changes |
| | Construction | Strong adhesion and high adaptability to complex cavern cross-sections |

## 3. Research progress of lining materials for CAES underground caverns

### 3.1. Traditional and modified lining materials

Plain concrete and reinforced concrete are the most commonly used lining materials in traditional underground engineering, with mature technology and low cost. However, the low toughness of these materials leads to easy cracking under cyclic high pressure and temperature changes, which cannot meet the long-term service requirements of CAES caverns. Therefore, modified concrete has become a research hotspot. Fiber-reinforced concrete mixed with steel or synthetic fibers can effectively improve crack resistance and structural toughness. High-performance concrete with optimized mix ratio has higher strength and durability, which is highly consistent with the design requirements of modern cavern structures [7]. The addition of nanomaterials and mineral admixtures can further optimize the matrix structure, and the modification technology can refer to the research results of water plugging materials.

### 3.2. New-type lining materials

In recent years, composite materials have been gradually applied to CAES engineering. Fiber Reinforced Polymer (FRP) has ultra-high mechanical strength and corrosion resistance, and is especially suitable for caverns with complex geological conditions. Intelligent lining materials represented by self-sensing and self-healing materials have also developed rapidly. Combined with artificial intelligence monitoring technology, these materials can realize real-time health monitoring and active repair of structures, and have broad engineering application value.

### 3.3. Performance testing and evaluation methods

A complete test system is needed to evaluate the service performance of lining materials. Laboratory tests are mainly used to detect mechanical properties, fatigue resistance, thermal stability and corrosion resistance. Numerical simulation software such as FLAC3D and ABAQUS can simulate the stress-temperature response of materials, optimize structural section design and predict service

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life. Field tests and on-line monitoring in pilot projects can verify the actual performance of materials in real service environment, which is an important link to promote engineering application [8].

## 4. Research progress of seepage control materials for CAES underground caverns

### 4.1. Rigid and flexible seepage control materials

Rigid seepage control materials are important components of composite sealing systems. Thick steel plates have excellent initial airtightness, but their application is limited by high cost and difficult construction. Rigid concrete seepage layers have poor airtightness and are prone to cracking, which cannot be used alone. In contrast, flexible materials have become the research focus. Polymer materials such as butyl rubber, EPDM and polyurea have good mechanical compatibility and durability, and their application experience can be drawn from diversion tunnel engineering. Thin steel plates have good flexibility and construction convenience, and are suitable for complex cavern sections. Composite materials composed of rubber and steel plates have the best anti-seepage effect, which fully conforms to the design concept of rigid-flexible composite sealing.

### 4.2. New-type seepage control materials

In order to meet the ultra-high pressure sealing requirements of CAES, a variety of new functional materials have been developed. Nano organosilicon polymers can significantly improve airtightness through special seepage control mechanisms. Multifunctional water plugging materials can realize water sealing and gas leakage prevention at the same time, and their performance can be optimized by mixing with traditional materials. Self-healing seepage control materials can automatically repair micro cracks, which greatly improves the long-term reliability of sealing structures and conforms to the development trend of intelligent materials.

### 4.3. Performance testing and evaluation methods

Airtightness is the core evaluation index of seepage control materials, which is usually tested by high-pressure sealing and permeability experiments. Tensile and deformation tests are used to ensure that flexible materials can deform synchronously with rigid structures. Durability tests simulate long-term aging, corrosion and temperature changes to evaluate service life. Numerical simulation can predict gas leakage risk and analyze seepage performance under complex thermal-mechanical loads [9]. The classification, advantages and disadvantages of various materials are compared in Table 2.

Table 2. Classification, advantages, and limitations of current lining and seepage control materials

| Category | Material Type | Key Advantages | Main Limitations |
|---|---|---|---|
| | Ordinary concrete | Basic mechanical strength, low initial material cost | Insufficient toughness, highly susceptible to cracking under cyclic loads |

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Table 2. (continued)

| | | | |
|---|---|---|---|
| Lining Materials | Modified (Fiber-reinforced, high-performance) | Significantly enhanced crack resistance, superior strength, and improved durability | Higher costs, requires advanced mix designs and rigorous cracking control |
| | Novel (FRP, smart materials) | Exceptional corrosion resistance, active self-sensing, and self-healing capabilities | High production costs, poor compatibility with current intelligent construction processes |
| Seepage Control Materials | Rigid (Thick steel plates, rigid concrete) | Excellent initial airtightness (thick steel plates) | Severe construction difficulty, high costs, prone to structural cracking (rigid concrete) |
| | Flexible (Polymers, thin steel plates) | High flexibility, easy construction, facilitates synergistic deformation | Airtightness stability easily degrades over time under sustained high gas pressure |
| | Combined (Rubber + steel, composites) | Optimal synergistic anti-seepage effects, perfectly aligns with combined sealing systems | Critical scarcity of CAES-specific formulations, complex interfacial design requirements |

## 5. Synergistic working mechanism and structural design optimization

### 5.1. Synergistic working mechanism of composite structures

The stable operation of CAES caverns depends on the cooperative work of lining and seepage control layers. The interface bonding and friction characteristics between the two layers directly affect the sealing performance of the whole structure. Under the coupling effect of multiple physical fields, materials must maintain coordinated deformation to adapt to the temperature and pressure changes of caverns. The setting of sliding layer can effectively reduce interface friction, optimize structural deformation coordination and improve the overall stability of composite sealing structures [10].

### 5.2. Design optimization and engineering application

Structural optimization should focus on material performance matching and thickness design, which are closely related to the axis ratio of caverns. The design scheme should adopt flexible sealing structure and strengthen crack control of lining, and the optimization process needs to be based on multi-field coupling numerical simulation. A number of CAES projects at home and abroad have verified the application effect of the above materials, and the engineering practice shows that material adaptability and construction technology optimization are the key to improve operation efficiency.

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## 6. Existing technical problems and application challenges

### 6.1. Performance limitations of existing materials

Most lining materials cannot adapt to the extreme working conditions of CAES caverns, and fatigue cracking is easy to occur under long-term cyclic load and temperature changes. The lack of long-term service data leads to low accuracy of life prediction models. In addition, high cost and poor construction compatibility restrict the large-scale application of new lining materials. For seepage control materials, the airtightness is unstable under continuous high pressure, and the poor deformation coordination causes cracking failure. At this stage, there is a serious shortage of special seepage control materials for CAES engineering.

### 6.2. Challenges in structural design and engineering application

The performance evolution law of materials under multi-field coupling is not clear, which reduces the accuracy of structural design. The lack of unified industry standards and design specifications leads to uneven engineering quality. In addition, the poor matching between intelligent construction technology such as smart grouting and existing materials restricts the construction efficiency and overall performance of cavern projects [11].

## 7. Future research directions and engineering prospects

### 7.1. Advancements in material research

For lining materials, it is urgent to develop low-cost, high-strength and fatigue-resistant modified composites to improve environmental adaptability. The engineering application of intelligent self-sensing and self-healing materials should be accelerated by combining artificial intelligence technology. For seepage control materials, special materials with high airtightness and flexibility should be developed to optimize the rigid-flexible composite sealing system. Meanwhile, long-term performance tests should be carried out to establish a high-precision life prediction model. The development of real-time leakage monitoring and intelligent repair technology will further improve the sealing reliability of caverns.

### 7.2. Synergistic design and engineering applications

It is necessary to deepen the research on the synergistic mechanism of composite structures under multi-field coupling, so as to provide theoretical support for high-precision structural design. The establishment of unified material performance standards and design specifications is the basis for standardized engineering application. Large-scale engineering demonstration projects will accelerate the popularization of new materials and intelligent construction technology, and promote the efficient and sustainable utilization of underground space in the field of energy storage [12].

In summary, the research on lining and seepage control materials for CAES underground caverns has achieved phased results, but there are still many technical bottlenecks restricting engineering application. Material innovation and performance optimization are the core foundation to realize the safe and commercial operation of CAES technology. Focusing on the development of special high-performance materials, multi-field coupling design and engineering demonstration, the industry can effectively solve the existing research gaps. These research works will strongly support the large-scale utilization of renewable energy and the realization of global dual-carbon goals.

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## References

[1] Zhang, G., Guo, H., Zhang, S., et al. (2026). Determination method of optimal axis ratio and operating pressure range for elliptical section of compressed air energy storage underground gas storage. Rock and Soil Mechanics, 47(02), 515-529. https: //doi.org/10.16285/j.rsm.2025.0821

[2] Xin, C., Wang, W., Chen, W., et al. (2025). Analysis of multi-dimensional application and development path of compressed air energy storage technology. Energy Storage Science and Technology, 14(09), 3636-3647. https: //doi.org/10.19799/j.cnki.2095-4239.2025.0160

[3] Sun, G., Wang, J., Yu, X., et al. (2025). Research progress on basic principles and analysis methods of underground lined caverns for compressed air energy storage power stations. Rock and Soil Mechanics, 46(01), 1-25. https: //doi.org/10.16285/j.rsm.2024.0705

[4] Zhao, Q., Zhu, L., Liu, Y., et al. (2024). Basic concepts and methods for the design of shallow-buried artificial gas storage caverns for compressed air energy storage power stations. Energy Storage Science and Technology, 13(08), 2775-2784. https: //doi.org/10.19799/j.cnki.2095-4239.2024.0219

[5] Wang, L., Zhang, W., Yang, X., et al. (2025). Research and application progress of compressed air energy storage in abandoned mines. Coal Science and Technology, 53(07), 275-292.

[6] Liu, X., Mei, S., Ding, R., et al. (2023). Engineering status, development trend and application prospect of compressed air energy storage. Electric Power Automation Equipment, 43(10), 38-47. https: //doi.org/10.16081/j.epae.202309005

[7] Zhang, W., Gu, H., Zhang, C., et al. (2023). Technical and economic characteristics and development trend of compressed air energy storage technology. Energy Storage Science and Technology, 12(04), 1295-1301. https: //doi.org/10.19799/j.cnki.2095-4239.2022.0645

[8] Ge, X., Huang, J., Zhao, T., et al. (2026). Review on the application of artificial intelligence in compressed air energy storage underground engineering. Rock and Soil Mechanics, 47(02), 413-425. https: //doi.org/10.16285/j.rsm.2025.0818

[9] Liu, X., Rong, W., & Ma, G. (2025). Review of technical research and application analysis of compressed air energy storage. Appliance Science & Technology, (04), 18-25. https: //doi.org/10.19784/j.cnki.issn1672-0172.2025.04.002

[10] Fan, S., Sun, Z., Wang, W., et al. (2025). Performance test of polyurea seepage control material for diversion tunnel lining structure. South-to-North Water Transfers and Water Science & Technology, 23(05), 1289-1296. https: //doi.org/10.13476/j.cnki.nsbdqk.2025.0128

[11] Li, X., Wang, Z., Chen, J., et al. (2025). Experimental study on permeability and mechanical properties of sealing materials for compressed air energy storage caverns. Chinese Journal of Rock Mechanics and Engineering, 44(03), 562-575. https: //doi.org/10.13722/j.cnki.jrme.2024.0912

[12] Chen, Y., Zhou, H., Zhao, P., et al. (2024). Stability analysis and support design of lined rock caverns for compressed air energy storage under cyclic thermal-mechanical coupling. Rock and Soil Mechanics, 45(05), 1421-1435. https: //doi.org/10.16285/j.rsm.2023.1105