

Research Progress on the Permeability of Flexible Sealing Layer in Artificial Cavern for Compressed Air Energy Storage

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Abstract

Aiming at the permeability of flexible sealing layer in artificial cavern for compressed air energy storage, the engineering application cases of flexible materials as sealing layers are sorted out. The current research progress in experimental research, theoretical analysis and numerical simulation in this field is expounded, and the advantages and disadvantages of each research method are analyzed. On this basis, the future research direction in this field is prospected. It is believed that in the future, key variables such as air pressure, temperature, tension state and cycle times should be comprehensively considered in the penetration test to reveal the penetration law of flexible materials. At the same time, the penetration evolution model is constructed and numerical calculation is introduced to further explore the multi-field coupling response characteristics of flexible sealing layer.

Keywords

Flexible Sealing Layer; Permeability; Experimental Study; Theoretical Analysis; Numerical Simulation.

1. Introduction

Compressed Air Energy Storage (CAES) in artificial underground caverns has become one of the most promising large-scale energy storage technologies in China, as well as one of the most popular development paths for achieving the dual-carbon goals, owing to its outstanding advantages such as low carbon and environmental friendliness, large installed capacity, high system efficiency and good geological adaptability. The selection of appropriate sealing materials and sealing structures is one of the core factors determining the success or failure of the construction of artificial cavern gas storage reservoirs, and also a primary task for ensuring the reliability and economy of sealing structure design^[1-4]. According to the research of Allen et al.^[5], a daily air leakage rate of merely 2% will cause economic losses of millions of yuan per year for gas storage reservoirs. Even with the arrangement of synthetic rubber sealing layers and concrete linings, Japan's CAES demonstration project still suffered a daily air leakage rate of 0.2%, highlighting the difficulty of permeability control for flexible sealing materials. Relevant studies indicate that the sealing structure of artificial cavern gas storage reservoirs is required to possess excellent deformation adaptability, air tightness, fatigue resistance, and durability under high and low temperature cycles^[6].

At present, Yang et al.^[7] systematically summarized the construction status of underground artificial caverns for compressed air energy storage (CAES) at home and abroad, and concluded the main forms of sealing layers based on project overview. Xia et al.^[8] focused on the sealing performance of hard rock lined caverns and summarized several typical sealing materials adopted in current research as well as their characteristics. Starting from the airtightness problem, Jiang et al.^[9] compared the properties of different types of sealing materials and discussed whether they can meet the operational requirements of CAES gas storage caverns. In addition, Zhou et al.^[10] revealed the air leakage

mechanism inside rubber sealing layers, established a leakage calculation model coupling seepage and mechanical effects, quantitatively analyzed the influences of pressure, temperature, material properties and structural parameters on the leakage rate, and put forward optimization suggestions for sealing structure design.

The above studies have systematically covered the sealing layer forms in practical projects, the performance characteristics of various sealing materials, and the leakage analysis of engineering flexible sealing layers. However, the summary of experimental research on the permeability of flexible sealing materials remains relatively brief. On this basis, this paper conducts research and analysis on permeability tests of flexible sealing materials. Firstly, it sorts out the sealing structures adopted in existing CAES projects and summarizes the research methods of CAES artificial cavern sealing structures proposed by domestic and international scholars, including experimental investigation, numerical simulation and theoretical analysis. Secondly, it analyzes the working condition settings of existing permeability tests for flexible sealing materials, and explores the influencing factors of material permeability in combination with the actual operating environment of compressed air energy storage. Finally, the structural design of the permeability testing system for flexible materials is discussed. The research findings are expected to provide a reference for permeability testing, evolution law analysis and coupled response characteristic evaluation of flexible sealing layers in CAES artificial caverns.

2. Current Status of Construction of CAES Artificial Underground Caverns

The selection of sealing materials for existing CAES artificial cavern gas storage reservoirs mainly focuses on three categories: steel, low-permeability concrete, and flexible materials. Compared with steel liners and low-permeability concrete, flexible material sealing layers possess excellent flexibility and elasticity while featuring low cost. In recent years, numerous studies have begun to consider adopting flexible materials as the sealing layers for artificial cavern gas storage reservoirs [11-13].

The Skallen pilot gas storage cavern in Sweden^[14] adopts a large tank-type structure with a burial depth of 115 m and a cavern volume of 40000 m³. The interior is mainly lined with concrete, and steel plates are laid as the sealing layer, with a designed maximum internal pressure of 20–25 MPa.

The gas storage cavern of the Kamisunagawa CAES demonstration project in Japan^{[15],[16]} adopts a tunnel-type structure with a burial depth of 450 m and a volume of approximately 1600 m³. The inner lining is composed of 0.7 m thick concrete, while the sealing layer adopts a lining structure consisting of three layers of 3 mm thick butyl rubber combined with nylon reinforcement mesh. The joints are reinforced with 3.2 mm steel plates, and the maximum internal pressure is 8 MPa.

The gas storage cavern of the pilot CAES power plant project in South Korea^[13] adopts a cylindrical tunnel-type layout with an inner diameter of 5 m and concrete lining. The two caverns are sealed with butyl rubber sheets and 300 mm thick steel plates, respectively. The internal operating pressure of the caverns ranges from 5 to 8 MPa.

The U.S. Soyland project^[17] consists of a series of parallel tunnels located in hard dolomite at a burial depth of 600 m. The caverns have a total volume of 245000 m³ and a total length of 1830 m. Rubber materials are fixed on the inner side of the concrete lining to form the sealing layer, with a planned storage pressure of 5.86 MPa.

To verify the feasibility of shallow-buried underground gas storage caverns, Jiang Zhongming's research team constructed a shallow-buried hard rock test cavern in Pingjiang^[18]. The cavern adopts a tunnel-type structure with a burial depth of 110 m and a net volume of 28.8 m³. Its main sealing layer is made of Fiber Reinforced Plastic (FRP), with a designed working pressure of 10 MPa.

The Underground Artificial Cavern Laboratory for Compressed Air Energy Storage of China Energy Engineering Group owns two super-large test caverns. With a maximum burial depth of 110 m, the caverns adopt a rigid-flexible composite multi-layer sealing structure and feature a maximum test

pressure of 20 MPa. Experimental verification shows that the laboratory has successfully withstood high pressure of 18 MPa, 500 hours of continuous operation and tens of thousands of cyclic loadings. A summary of the general conditions of artificial underground caverns in each project is presented in Table 1. Although various economical and effective sealing methods have been adopted in these underground cavern projects, existing studies indicate that the permeability issue of flexible sealing materials under high-pressure environments still cannot be ignored^[17].

Table 1. Overview of Underground Artificial Cavern Projects

Project Name	Structural form	Sealing layer type	Construction status
Skallen Gas Storage Cavern, Sweden ^[14]	Large tank type	Steel plate	Completed in 2002
Kamisunagawa Project, Japan ^{[15],[16]}	Tunnel-type	Butyl rubber and nylon reinforced mesh	Completed in 2001
CAES Power Station, Korean ^[13]	Tunnel-type	Butyl rubber / steel plate	Completed in 2011
Soyland Project, USA ^[17]	Tunnel-type	Rubber	Cancelled due to site selection
Pingjiang Test Cavern ^[18]	Tunnel-type	FRP	Completed high-pressure charge-discharge cycle tests in 2018
China Energy Engineering Laboratory	Tunnel-type	Rigid-flexible composite sealing layer	Test successfully completed in August 2025

3. Research Methods

3.1 Experimental Study

Under extreme working conditions such as high pressure, variable temperature and complex mechanical deformation, the long-term gas tightness of flexible sealing materials remains the key factor determining the operational reliability of underground gas storage reservoirs. Accordingly, numerous scholars at home and abroad have carried out extensive systematic research on the development of test devices and permeability testing for flexible sealing materials.

3.1.1 Development of Test Apparatus

Perez et al.^[19] designed a high-pressure sealing test system for the gas tightness of polymer materials, with a maximum working pressure of 3 MPa and a maximum temperature of 300 °C. To simulate the actual working conditions of opening fractures in gas storage caverns, Nakata et al.^[20] developed an annular sealing box with base fractures, which can conduct high-pressure sealing tests on sealing specimens made of rubber, asphalt, emulsion and other materials. Zhou et al.^[21] developed a permeability testing device for flexible materials and measured the gas permeability coefficient of materials such as butyl rubber under 10 MPa. According to the requirements of different pressure scenarios, Flaconnèche et al.^[22] separately designed test systems applicable to medium pressure conditions (1–14 MPa) and high-pressure conditions (100 MPa). Campion et al.^[23] adopted a high-pressure sealing box to test the permeability of thermoplastic materials to carbon dioxide and methane under the conditions of 17 MPa and 65 °C ~ 240 °C. Liang et al.^[24] designed and fabricated a sealing box to meet the gas tightness test requirements of rubber materials under the pressure of 5–10 MPa. The sealing box has a maximum bearing pressure of 20 MPa, which can satisfy the pressure demand of compressed air energy storage (CAES). Briscoe et al.^[25-27] adopted the high-low dual-chamber method to measure the sorption coefficient and diffusion coefficient of polymer materials. The

sorption and diffusion coefficients were calculated by monitoring the gas consumption on the high-pressure side, while this method cannot directly obtain the permeability coefficient of polymer materials. According to the environmental characteristics of compressed air energy storage caverns, Terashita et al.^[1] designed a high-pressure sealing box and determined the permeability coefficients of various flexible material specimens under different thicknesses, air pressures and temperatures. Qin et al.^[28] developed a testing system for the permeability coefficient of flexible sealing materials, and investigated the effects of temperature, pressure and thermal aging on the permeability characteristics of flexible sealing materials using the established system.

3.1.2 Permeability Test

Hori et al.^[12] conducted field tests by laying polymer materials on the tunnel wall of compressed air energy storage (CAES) projects and carried out a 7-day sealing performance test, which verified the feasibility of flexible materials for storing high-pressure gas. Fialova et al.^[29] systematically investigated the gas permeation behavior in rubber materials under different experimental conditions, and calculated the concentration gradient and diffusion coefficient based on the steady-state adsorption capacity. Yao et al.^[30] performed experimental research on the transport characteristics of helium in rubber sealing materials. The pressure difference method was adopted to determine the key leakage parameters of rubber materials, including permeability coefficient, diffusion coefficient and solubility coefficient. Zhou et al.^[21] measured the permeability coefficients of four polymer materials, namely butyl rubber (IIR), ethylene propylene diene monomer (EPDM), natural rubber (NR) and glass fiber reinforced plastic (FRP), by using self-developed high-pressure airtight test equipment.

In the research on permeability tests of flexible sealing materials, although a number of test devices have been developed worldwide, relevant equipment and technologies are still dominated by foreign research. Domestic studies are still lacking in systematic and mature research achievements as well as complete experimental systems. Most existing researches focus on the influences of temperature, pressure, thermal aging and other factors on the permeability characteristics of materials. However, few studies have investigated the gas permeation behavior of sealing layers under the actual operating conditions of Compressed Air Energy Storage (CAES), particularly under the combined action of alternating loads and coupled thermo-hydro-mechanical multi-fields. Therefore, it is essential to develop a dedicated test system for permeability measurement of flexible sealing materials targeting the above complex working conditions. The system can provide technical support for in-depth research on the permeability performance evaluation, permeability evolution law and multi-field coupling response characteristics of sealing layers in CAES artificial caverns.

3.2 Theoretical Analysis

In addition to laboratory and field tests, the analytical solution method serves as another effective approach for air leakage assessment^[31]. Based on the fundamental physical laws of mass conservation and energy conservation, Kushnir et al.^[32] regarded CAES salt caverns as an adiabatic system and derived the governing equations describing the variations of internal air temperature and pressure. By combining these equations with three different forms of gas state equations, they established an ideal gas model, a real gas model, and a simplified self-developed gas model, respectively. Taking mass and energy conservation, the real gas state equation, and radial heat conduction of surrounding rock as the core framework, Kushnir et al.^[33] constructed a thermodynamic coupling model for the charging and discharging cycles of CAES caverns and derived its approximate analytical solution. The results revealed that wall heat transfer, thermal physical properties of rock, air injection temperature and pressure ratio dominate the fluctuations of temperature and pressure as well as gas storage capacity. On the basis of Kushnir's research, Zhou et al.^[34] first established governing equations for the variations of cavern temperature and air pressure considering heat transfer between air and each layer of surrounding rock. Subsequently, Laplace transform and the superposition principle were adopted to solve the temperature distribution around the cavern and the air pressure variation inside the cavern during operation. Finally, adopting an axisymmetric thermoelastic model, the solved temperature and air pressure were taken as known loading conditions to analytically

determine the induced stress field and displacement field. Xia et al.^[35] proposed a simplified unified analytical solution considering heat exchange between the cavern and surrounding rock, which can rapidly calculate the temperature and pressure evolution during the charging and discharging processes of CAES caverns. This method addresses the deficiencies of insufficient accuracy in traditional adiabatic or isothermal assumptions and the heavy computational cost of complex numerical solutions.

None of the above analytical solutions take into account the air leakage of underground caverns during operation. To address this deficiency, Zhou et al.^[36] proposed an iterative analytical method for air leakage assessment of unlined compressed air energy storage (CAES) caverns. The reliability of this method was verified by comparison with field test data and numerical simulation results. Nevertheless, this analytical method involves more complicated calculation procedures and exhibits relatively low computational accuracy, which limits its practical engineering application^[31].

3.3 Numerical Simulation

Zhou et al.^[21] established the multi-field coupling governing equations for lined caverns of compressed air energy storage (CAES), and verified the equations using measured data from the Huntorf power station and the pilot cavern in Hokkaido, Japan. Combined with experimental data and the multi-field coupling governing equations, the gas tightness and mechanical properties of polymer sealing layers under typical operating conditions were calculated and analyzed. Qin et al.^[37] constructed a gas tightness model for CAES caverns based on laboratory high-pressure permeability tests, and validated the reliability of the model using field measured data from the Huntorf power station in Germany and the CAES test tunnel in Hokkaido, Japan. Liang et al.^[38] proposed a hyperelastic damage constitutive model to characterize the mechanical behavior of rubber sealing layers. Numerical simulation was adopted to investigate the performance of cavern lining structures with steel and rubber serving as sealing layers respectively. In view of the deficiencies existing in the current thermodynamic analysis models for compressed air energy storage, Liao et al.^[39] took the unsteady thermal convection effect of underground cavern walls into consideration and developed a modified model suitable for thermodynamic process analysis of underground caverns. The proposed model was verified based on the experimental data of the Huntorf power station and the test results of the ANGAS project. Based on the solution-diffusion model, Liang et al.^[24] established an improved air tightness calculation model for rubber sealing layers of CAES caverns. Numerical calculations were performed to evaluate the cavern leakage rate during the long-term operation of CAES, and a comparative analysis was conducted on the leakage results calculated by the pore flow model and the solution-diffusion model. Aiming at the permeation and accumulation characteristics of high-pressure air in linings and surrounding rocks after flowing through fractured sealing layers (FSL), Qin et al.^[40] established a corresponding air tightness calculation model. Taking the Yungang Mine CAES project as a case study, they analyzed the influence of high-pressure air permeation and accumulation on engineering safety and operation performance.

In the above numerical simulations, the pore seepage model is mostly adopted as the airtightness calculation model for flexible sealing layers of CAES caverns. However, flexible sealing materials are mostly polymers such as rubber, elastomers and flexible polymer membranes, whose gas permeation follows the solution-diffusion mechanism. Driven by pressure difference, gas completes transmembrane transport through three sequential processes: dissolution, diffusion and desorption. Therefore, prior to conducting numerical simulations, it is necessary to carry out corresponding permeability tests according to the actual permeation mechanism of flexible materials, and establish a matched airtightness calculation model for flexible sealing layers based on the solution-diffusion mechanism.

4. Conclusion

In view of the research on permeability and air tightness of flexible sealing layers in underground caverns for Compressed Air Energy Storage (CAES), the main conclusions and prospects are summarized as follows:

(1) At present, there is a lack of permeability testing devices for flexible sealing materials in China that can adapt to the actual operating conditions of compressed air energy storage (CAES), such as alternating loads and coupled thermal-hydraulic-mechanical multi-field effects. Therefore, it is necessary to independently develop a test system capable of simulating alternating loads and multi-field coupling conditions of CAES in the future, so as to provide equipment support for revealing the permeability evolution law of flexible sealing layers.

(2) The existing analytical models for air leakage in underground caverns (e.g., the iterative analysis method) suffer from complicated calculation procedures, low computational accuracy and poor engineering applicability. Therefore, it is necessary to break through the solving bottleneck of traditional complex analytical solutions and focus on establishing an efficient and high-precision air tightness evaluation model for underground caverns.

(3) In numerical simulations, existing studies commonly directly apply the pore seepage model applicable to porous media to polymer flexible sealing materials, which fails to truly reflect the transmembrane gas transport mechanism following the solution-diffusion principle. Therefore, future research should rely on novel test systems to conduct systematic permeability experiments based on the solution-diffusion mechanism of polymer materials, so as to obtain permeability parameters consistent with actual engineering conditions. On this basis, corresponding airtightness calculation and numerical simulation models should be established, providing solid theoretical support for the performance evaluation and engineering design of sealing layers in artificial compressed air energy storage (CAES) caverns.

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