

Article

Development and Application of Film-Forming Nano Sealing Agent for Deep Coal Seam Drilling

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Abstract: To address the critical challenges of wellbore instability in deep coal seam drilling operations, this investigation developed an innovative organic–inorganic composite nanosealing agent (NS) through chemical modification of nano-silica. Advanced characterization techniques including Fourier Transform Infrared Spectroscopy, laser particle size analysis, and Scanning Electron Microscopy revealed that the optimized NS possessed a uniform particle distribution (mean diameter 86 nm) and enhanced surface hydrophobicity, effectively mitigating particle agglomeration. Systematic experimental evaluation demonstrated the material's multifunctional performance: the NS-enriched drilling fluid achieved an 88.7% reduction in sand bed invasion depth and 76.4% decrease in filtrate loss at optimal concentration. Notably, comparative inhibition tests showed the NS outperformed conventional KCl and KPAM inhibitors, achieving 91.2% shale rolling recovery rate and 65.3% lower swelling rate than deionized water baseline. Core flooding experiments further confirmed superior sealing capability, with 2% NS addition attaining 88% sealing efficiency for low-permeability cores (0.5 mD) and establishing a 10 MPa breakthrough pressure threshold. Field implementation in the SSM1 well at Shenmu Huineng Liangshui Coal Mine validated the technical efficacy, the NS-enhanced drilling fluid system achieved 86.7% coal seam encounter rate with zero wellbore collapse incidents, while core recovery rate improved by 32.6% to 90.4% compared to conventional systems. This research breakthrough provides a scientific foundation for developing next-generation intelligent drilling fluids, demonstrating significant potential for ensuring drilling safety and enhancing gas recovery efficiency in deep coalbed methane reservoirs.



Academic Editor: Qingbang Meng

Received: 18 February 2025

Revised: 6 March 2025

Accepted: 7 March 2025

Published: 11 March 2025

Citation: Duan, X.; Wang, W.; Ren, F.; Zhang, X.; Zhang, W.; Shan, W.; Ma, C. Development and Application of Film-Forming Nano Sealing Agent for Deep Coal Seam Drilling. *Processes* **2025**, *13*, 817. <https://doi.org/10.3390/pr13030817>

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Keywords: deep coalbed drilling; wellbore collapse; organic–inorganic composite nanoscale plugging agent; chemical modification

1. Introduction

With the continuous rise in global energy demand, deep coal seam gas, as a highly promising unconventional natural gas resource, is gradually becoming a research hotspot in the energy sector. The efficient exploitation of deep coal seam gas is not only crucial for ensuring national energy security and optimizing the energy structure but also plays a significant role in driving energy transformation and sustainable development [1]. However, deep coal seam drilling faces numerous severe challenges, with wellbore stability issues being particularly prominent. Deep coal seams are typically characterized by loose structures

and strong water sensitivity. During the drilling process, the wellbore is highly susceptible to collapse and rockfall, severely hindering the smooth progress of drilling operations and increasing drilling costs and safety risks [2]. Therefore, developing efficient wellbore stability technologies has become a key focus for deep coal seam gas development. Recent advances focus on developing comprehensive approaches to predict, prevent, and control instability issues. These strategies involve analyzing dominant instability mechanisms, considering factors such as shale type, in situ stress, and drilling fluid interactions [3]. Cloud-based solutions utilizing Mechanical Earth Models (MEMs) enable efficient trajectory planning and wellbore stability validation, optimizing azimuth and inclination to minimize risks [4]. Researchers emphasize the importance of integrating multiple parameters, including pore pressure, temperature, and chemical potential, into well planning and mud system selection [5]. Despite progress, the complexity of shale formations continues to present challenges, necessitating ongoing research and development of new technologies [6]. These advancements aim to reduce non-productive time and costs associated with wellbore instability in unconventional well construction. Nanoscale plugging agents stabilize wellbores through dual mechanisms: physical plugging and chemical inhibition. These agents, including nanosilica, nanoemulsions, and synthetic polymers, effectively seal microfractures and pores in shale formations [7]. They significantly reduce filtration loss and improve wellbore stability under various conditions, including high temperature and pressure [8].

In recent years, the application of nanosealing agents in drilling fluids has seen significant progress. Their unique physicochemical properties, such as high specific surface area, high surface energy, and excellent chemical stability, make them outstanding in addressing wellbore instability and fluid loss issues [9]. Studies by Chen Fuming [10] and Fu Yan [11] have demonstrated that nanosealing agents exhibit remarkable sealing effects in mudstone formations, with higher concentrations leading to enhanced sealing performance. Qiu Zhengsong [12] and Dai Feng [13] explored the application of micro-nano sealing technology in oilfields and found that it had a significant impact on resolving wellbore instability. Li Dan [14] and Wang Weiji [15] investigated the application of nano-expandable particles and modified nano-SiO₂ in sealing low-permeability reservoir fractures, showing excellent hydration swelling and sealing performance. Nie Xiaoxiao [16] and Lu Zhen [17] developed nanosealing agents suitable for oil-based drilling fluids and deep wells, effectively addressing wellbore instability. Additionally, Zheng Bin [18] and Gu Huan [19] further enhanced the performance of sealing agents through the synthesis and modification of nano materials. Xue Sen [20] and Teng Chunming [21] focused their research on salt-resistant and high-temperature-resistant nanosealing agents, effectively resolving wellbore instability and fluid loss issues in complex geological conditions. In the realm of composite nanosealing agents, Liu Lu [22] developed organic-inorganic composite nanofilm sealing agents and thermosetting nano-sealing agents, significantly improving the performance of drilling fluids and addressing shale wellbore instability. Overall, the application of nanosealing agents in drilling fluids has seen remarkable progress, providing new approaches and technologies for resolving wellbore stability issues.

Despite these advancements, existing research has primarily focused on the application of single nano materials, with relatively fewer studies on composite nano materials. The unique geological conditions of deep coal seams require sealing agents not only to possess excellent sealing performance but also to have superior inhibitory properties to prevent hydration swelling-induced wellbore instability. Furthermore, as drilling depths increase and geological conditions become more complex, higher demands are placed on the high-temperature resistance and salt tolerance of sealing agents. Therefore, this study focuses on the wellbore stability issues in deep coal seam drilling. Using nano-silica as the raw

material, a novel organic–inorganic composite nanosealing agent (NS) was synthesized through chemical modification. The goal is to leverage its unique nanostructure and chemical properties to enhance the anti-collapse performance and sealing capabilities of drilling fluids in deep coal seams. Through systematic experimental studies on the inhibitory, rheological, filtrate, and sealing properties of this sealing agent, and through its application in actual drilling projects, this research aims to provide new technical support for the efficient development of deep coal seam gas resources.

2. Main Mechanisms and Functions of Nanosealing Agents

Nanosealing agents are broadly classified into three categories—inorganic, organic, and organic–inorganic hybrid materials—based on their composition and functional mechanisms [23]. Inorganic nanomaterials, such as nano-SiO₂ and nano-Al₂O₃, utilize their nanoscale particle size, high mechanical strength, and thermal stability to achieve physical sealing through pore-filling and particle accumulation mechanisms. Organic nanomaterials, exemplified by polymer-modified nanoparticles like silane-functionalized SiO₂, employ chemical adsorption, wettability alteration, and stimuli-responsive behaviors (e.g., temperature- or pH-triggered structural adaptations) to enable dynamic, adaptive sealing. Hybrid agents, such as SiO₂/polymer composites, synergistically combine the rigidity of inorganic cores with the flexibility of organic shells, facilitating composite mechanisms that integrate physical blocking with chemical bonding. This classification underscores the versatility of nanosealing agents in addressing diverse geological challenges.

In recent years, nanotechnology has gained significant traction in oil and gas exploration, particularly for enhancing drilling fluid performance. For example, the Engineering Technology Research Institute of China Petroleum Group Co., Ltd. released the standard Q/SPCP YJ120083-2022 for Nano-Sealing Agent for Oil-Based Drilling Fluids. Owing to their unique physicochemical properties—including high specific surface area, elevated surface energy, and robust chemical stability—nanomaterials have proven effective in optimizing key drilling fluid characteristics. These improvements encompass enhanced rheological properties, superior sealing capacity, and strengthened inhibitory capabilities, all of which contribute to improved wellbore stability and operational efficiency in complex formations.

In terms of enhancing sealing capability: nanosealing agents achieve sealing through physical, chemical, and composite mechanisms [24–27]. Physically, their nanoscale particle size allows them to enter micro-fractures, accumulate to form a dense layer, and slow down pressure transmission. Chemically, the organic components of nanoparticles can adsorb onto the surface of the formation, forming a stable sealing layer through aggregation or chemical bonding. Composite sealing combines organic and inorganic materials, utilizing the strength of inorganic materials and the flexibility of organic materials to form a compact sealing layer. Some nanosealing agents also possess self-adaptive functions, such as temperature or concentration responsiveness, enabling them to adjust their particle size or properties according to environmental changes and achieve more precise sealing effects, effectively reducing permeability and maintaining wellbore stability. For example: nano-SiO₂, due to its advantages such as wide availability, low cost, and ease of modification, has become the most commonly modified inorganic nanomaterial.

In terms of enhancing inhibitory properties: the superhydrophobic nanomaterials in the nanosealing agent (such as SiO₂ modified with silane coupling agents) can adsorb onto the shale surface, altering its microstructure. This adsorption changes the wettability of the shale surface from hydrophilic to superhydrophobic, thereby reducing the invasion of water from the drilling fluid and effectively inhibiting the hydration and swelling of the shale [28]. For example, grafting cationic polymers onto the surface of nano-SiO₂

imparts positive charges to the nano-SiO₂ particles, improving their dispersibility in water and enabling them to have both chemical inhibition and physical blocking effects. The polymers grafted onto the surface of modified nano-SiO₂ strongly adsorb onto the clay surface through electrostatic forces and hydrogen bonding, effectively suppressing the hydration and swelling of the shale.

In terms of improving rheological properties, on the one hand, the nanoparticles in the nanosealing agent have small and uniformly distributed particle sizes, which allows them to disperse better in the drilling fluid, reducing particle aggregation, thereby lowering the viscosity of the drilling fluid and improving its flowability [29]. On the other hand, the nanosealing agent enables the drilling fluid to exhibit better shear-thinning characteristics under shear action, maintaining higher viscosity at low shear rates to prevent settling and reducing viscosity at high shear rates to improve flowability [30]. For example, nanoparticles (such as silica, alumina, etc.) can enhance the viscosity and shearability of the drilling fluid, thereby improving its carrying capacity and cleaning ability in the wellbore [31].

In terms of improving the mudcake, on the one hand, the nanoparticles in the nanosealing agent have small sizes, enabling them to enter the micro-pores and micro-fractures in the mudcake. Through physical accumulation and chemical adsorption, they form a dense mudcake structure. This dense mudcake can effectively prevent the infiltration of drilling fluid filtrate, reducing the permeability of the mudcake [32,33]. On the other hand, the organic and inorganic components in the nanosealing agent can form a tough thin film on the surface of the mudcake, enhancing its mechanical strength. This strengthened mudcake not only can better resist formation pressure but also reduce its peeling and wear [34].

In terms of improving lubricating performance, on the one hand, the nanoparticles in the nano-sealing agent can form a uniform lubricating membrane on the surface of the drilling tool, reducing the friction between the tool and the wellbore. For instance, the chemically modified nano-silicon dioxide sealing agent, with its excellent dispersibility and oleophilicity, can form a stable lubricating layer on the tool surface, thereby reducing the friction coefficient [35]. On the other hand, the nanoparticles in the nano-sealing agent have a high specific surface area and good dispersibility, enabling them to act as “rolling bearings” between the drilling tool and the wellbore. This reduces direct contact and significantly lowers the friction coefficient [36]. This mechanism is similar to forming a low-friction interface at the microscale.

3. Synthesis of Film-Forming and Anti-Collapse Nano-Sealing Agents

3.1. Synthesis Approach

Nano-silica possesses a unique three-dimensional network structure, with its surface rich in hydroxyl groups of different bonding states. These hydroxyl groups interact with each other through hydrogen bonding, resulting in an extremely high surface energy. This leads to a thermodynamically unstable state and manifests as highly chemical activity. However, this high activity also causes nano-silica to easily aggregate in drilling fluids, limiting the full realization of its performance. To address this issue, this study employs specific chemical substances to modify the hydroxyl groups on the surface of nano-silica. By reducing the number of surface silicon hydroxyl groups, the material's wettability is transformed from hydrophilic to hydrophobic, while also increasing the steric hindrance between nanoparticles, effectively inhibiting particle aggregation and significantly improving its dispersion stability. Additionally, polymers, due to their unique toughness, processability, and nodal characteristics, provide a solid foundation for the compounding of nanoparticles with polymer matrices. By incorporating nanoparticles into polymer matrices, it is expected to fully leverage the complementary and synergistic effects of inor-

ganic and organic materials, leading to the preparation of polymer nanocomposites with exceptional performance.

This study modifies nano-silica using silane coupling agents, introducing double bonds onto the nanoparticle surface. Subsequently, monomers such as styrene (St) and methyl methacrylate (MMA) are grafted onto the nanoparticle surface through polymerization reactions, successfully preparing nanosealing agents. The mechanism of action is primarily reflected in two aspects: on the one hand, the alkoxy groups in the silane molecules undergo condensation reactions with the hydroxyl groups on the silica surface, forming stable Si-O-Si covalent bonds. This significantly reduces the number of hydrophilic hydroxyl groups on the surface and weakens the hydrogen bonding forces between particles. On the other hand, the hydrophobic groups of the silane chains (such as $-\text{CH}_3$) are exposed on the particle surface. Through steric hindrance effects (steric hindrance) and hydrophobic interactions (hydrophobic interaction), particle aggregation is effectively inhibited (see Figure 1). According to DLVO theory, the surface potential of the modified particles is significantly reduced, and the formation of a hydrophobic layer weakens the balance between van der Waals forces and double-layer repulsion, making the particles more likely to remain in a monodisperse state in the drilling fluid. Additionally, the grafted polymers (such as MMA and St) further enhance steric hindrance through the flexibility of their molecular chains and improve dispersion stability due to their good compatibility with drilling fluid components.

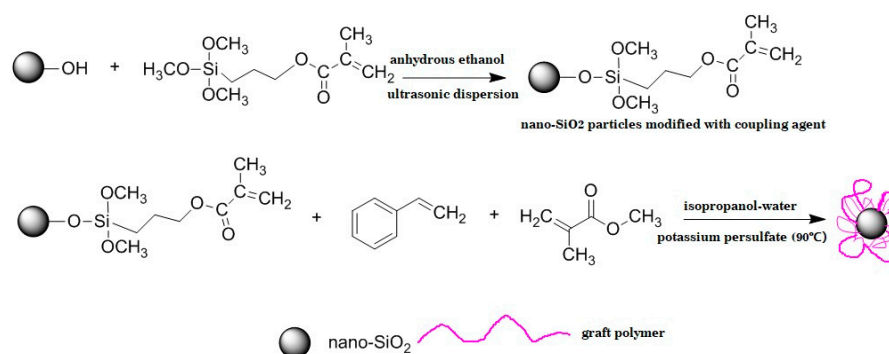


Figure 1. Schematic diagram of nano sealant modification.

3.2. Methods and Characterization

Surface modification of nano-silica: First, a certain amount of nano-silica is accurately weighed and placed in a vacuum drying oven for drying to remove moisture adsorbed on the surface. Subsequently, the dried nano-silica is dispersed in an appropriate amount of anhydrous ethanol, and ultrasonic treatment is performed using an ultrasonic disperser for 0.5 to 1.5 h to ensure uniform dispersion in ethanol. Next, an appropriate amount of silane coupling agent KH550 is dissolved in anhydrous ethanol and mixed evenly with the nano-silica ethanol dispersion. Ultrasonic treatment is continued for 1 to 2 h to promote full contact between the silane coupling agent and the surface of the nano-silica. Finally, the mixture is transferred to a reaction flask, nitrogen is introduced to remove oxygen, and then ultrasonic reaction is carried out at 95 °C for 4 to 6 h. After the reaction is completed, the product is collected by centrifugation and washed multiple times with anhydrous ethanol to remove unreacted substances. The washed product is placed in a vacuum drying oven at 60 °C for drying and reserved for later use.

Preparation of polymer nanosealing agent: In a reaction flask, KH550-modified nano-silica (KH550-nano-SiO₂), methyl methacrylate (MMA), and styrene (St) are added in a predetermined ratio, with isopropanol-water as the dispersion medium. The mixture is stirred by magnetic stirring for 30 min to ensure thorough mixing of all components. Sub-

sequently, an appropriate amount of initiator is added to the mixture, and polymerization is carried out at 90 °C until the reaction is complete. After the reaction, the crude product is dissolved in an appropriate amount of benzene, and methanol is used for precipitation and washing to remove impurities. Finally, the purified product is placed in a vacuum drying oven for drying, yielding the final nanosealing agent product, denoted as NS.

Characterization of structure and performance: Fourier Transform Infrared Spectroscopy was used to analyze the functional groups of the nanosealing agent NS, and the results are shown in Figure 2. From the figure, it can be clearly observed that the characteristic absorption peaks have changed, indicating that silane coupling agents and polymer chains have been successfully introduced onto the surface of nano-silica, achieving effective surface modification. Furthermore, Scanning Electron Microscopy (SEM) was used to analyze the surface structure of the sealing agent NS, and the results are shown in Figure 3. Before modification, the nano-silica particles were irregular in shape, with blurred boundaries, larger particle sizes, and uneven distribution, exhibiting severe aggregation and adhesion, forming block-like clusters. After surface modification and polymer grafting, the particles of the sealing agent sample were uniformly dispersed, with regular morphologies and concentrated particle size distributions. Additionally, a laser particle size analyzer was used to test the particle size of the nanosealing agent, and the results (Figure 4) show that the particle size distribution is relatively concentrated, in a monodisperse state, with a distribution range of 20 to 150 nanometers and an average particle size of approximately 86 nanometers. Unlike conventional plugging materials whose micron-scale dimensions ($>1\text{ }\mu\text{m}$) lead to poor nanopore accessibility, the chemically modified nanoscale silica developed in this work demonstrates precise size matching with coal seam nanopores. As evidenced by laser particle size analysis (Figure 4), the engineered nanoparticles exhibit a monodisperse distribution that enables effective sealing of 50–300 nm scale fractures prevalent in deep coalbed methane reservoirs.

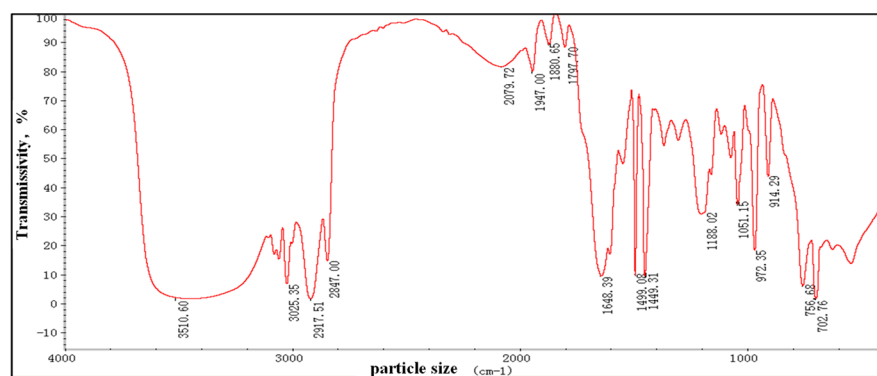


Figure 2. Infrared spectrum of the sealing agent.

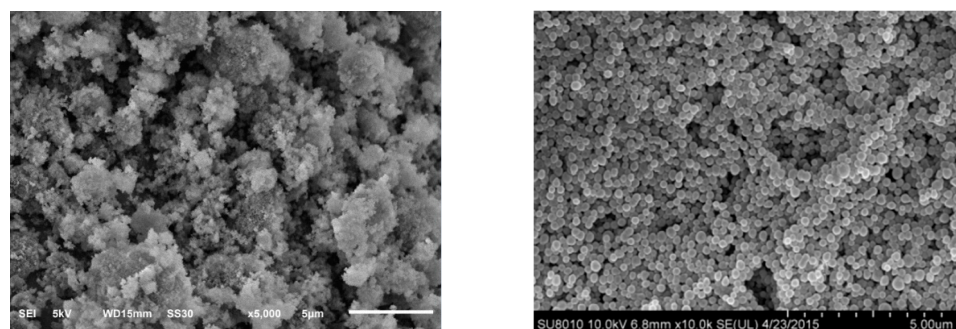


Figure 3. SEM images of nano-SiO₂ before and after modification (Left: nano-SiO₂; Right: nanosealing agent).

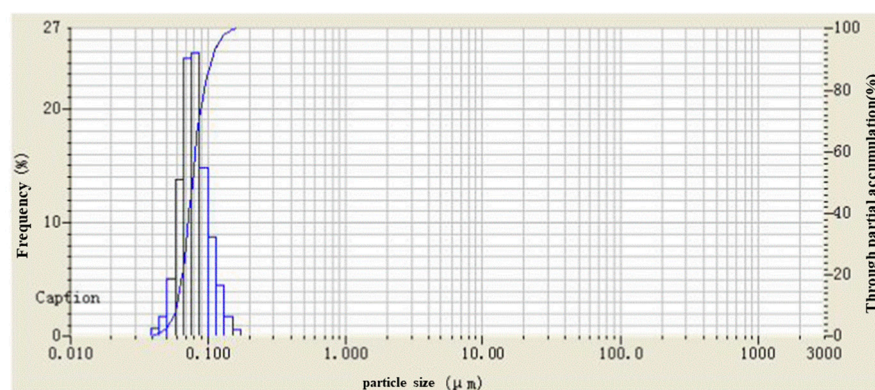


Figure 4. Particle size distribution graph of the sealing agent.

4. Performance Evaluation of Film-Forming and Anti-Collapse Nano-Sealing Agents

4.1. Compatibility and Filtrate Loss Performance Evaluation

To deeply investigate the compatibility of the nanosealing agent NS with the drilling fluid and its impact on filtrate loss, this study conducted a systematic experimental investigation. The experiment selected a 4% bentonite-based slurry and a drilling fluid formulation (2% bentonite + 1.5% rheological modifier + 0.2% filtrate reducer + 5% KCl + barite, density of 1.2 g/cm³) and tested the performance changes of the drilling fluid under hot rolling conditions (100 °C/16 h) before and after the addition of NS at a concentration of 2%. The experimental results are shown in Table 1.

Table 1. Performance evaluation of sealing agent NS in drilling fluid system (100 °C × 16 h).

Drilling Fluid Formula		AV (mPa.s)	PV (mPa.s)	YP (Pa)	GEL (Pa/Pa)	API (mL)	HTHP (mL)
4% Bentonite Slurry	before rolling	7.5	3	4.5	4/5.5	22	
	After rolling	12	7	5	5.5/7	25	
4% Bentonite Slurry + 2% NS	before rolling	18	9	9	5/8	12.8	
	After rolling	20	10	10	7.5/9	10.8	
Formula of weighting drilling fluid	before rolling	29	24	5	1/2	5.6	
	After rolling	19	15	4	0.5/1.5	3.6	14.4
Formula of weighting drilling fluid + 2% NS	before rolling	34	26	8	1/2	4.8	
	After rolling	38	31	7	1.5/2.5	3.2 (film formation)	10.5

The data in Table 1 demonstrate that the addition of the nanosealing agent NS significantly improved the rheological properties of the drilling fluid. Its high specific surface area and surface energy enabled it to achieve uniform dispersion in the drilling fluid, effectively reducing particle aggregation, thereby significantly improving the stability of the drilling fluid. Additionally, the hydrophobic properties of NS allow it to interact synergistically with other components in the drilling fluid (such as bentonite and polymers), enhancing the thixotropy of the drilling fluid. This thixotropy helps maintain the suspension and carrying capacity of the drilling fluid during drilling, while forming a dense mudcake during static conditions, thereby significantly reducing the filtrate volume. Experimental results show that after the addition of NS, the drilling fluid system exhibited a significant reduction in API filtrate loss after high-temperature rolling, and the mudcake quality was notably improved, forming a thin and dense mudcake that effectively prevented the invasion of drilling fluid into the formation, thereby stabilizing the wellbore. Furthermore, the hydrophobic groups on the surface of NS reduced the interfacial tension between the mudcake and formation water, suppressing capillary action-driven filtrate invasion and further reducing filtrate loss (see Figure 5).

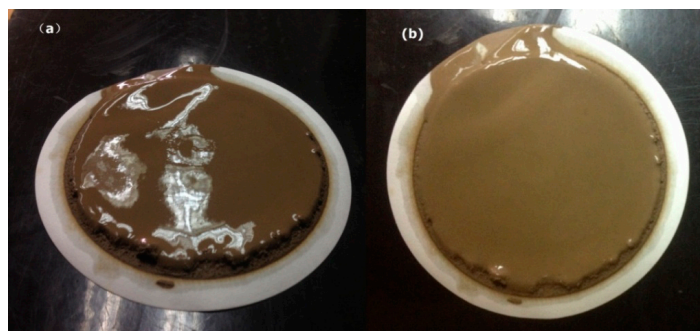


Figure 5. Comparison of mudcake quality before and after the addition of sealing agent in weighted drilling fluid formulation ((a) mudcake formed by API filtrate loss without sealing agent; (b) mudcake formed by API filtrate loss with 2% sealing agent).

4.2. Inhibitory Properties Evaluation

To comprehensively evaluate the inhibitory performance of the nanosealing agent NS, this study systematically assessed it using rolling recovery rate and linear expansion tests. The experiment utilized core samples from the No. 3-1 coal seam of the Liangshui Coal Mine in Shenmu, Huineng, under conditions of 100 °C/16 h. The results were compared with those of deionized water, a 5% KCl solution, and a 1% KPAM solution. The experimental results are shown in Figure 6.

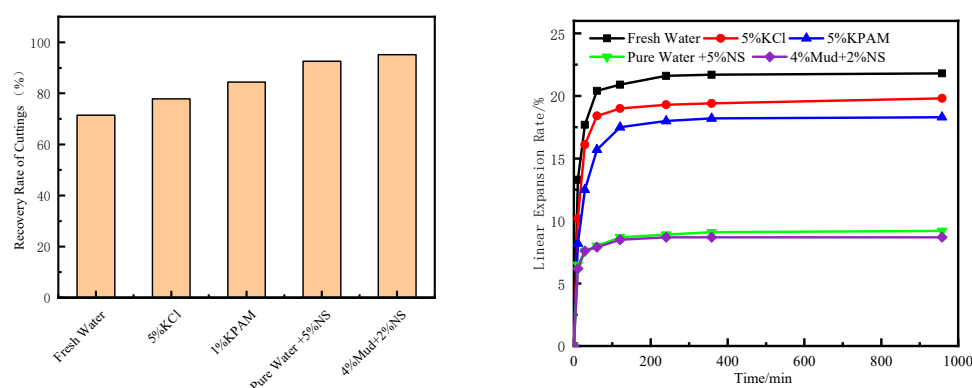


Figure 6. Rolling recovery rate and linear swelling rate experimental results of shale.

As shown in Figure 6, the rolling recovery rate of the nanosealing agent NS exceeds 90%, significantly higher than that of the conventional inhibitors KCl and KPAM. Additionally, the linear expansion rate of the core samples treated with NS is reduced by 65% compared to deionized water, demonstrating superior inhibitory performance. During the initial stage of the linear expansion test, the expansion rate of NS-treated core samples is similar to that of other inhibitors; however, as time progresses, the expansion rate of NS-treated core samples decreases significantly, showing its excellent long-term inhibitory effect. The inhibitory properties of the nanosealing agent NS are primarily attributed to its hydrophobicity and high surface energy after surface modification. The modified NS particles can form a dense protective membrane on the formation surface through chemical adsorption and physical sealing. This protective membrane effectively prevents free water in the drilling fluid from entering the formation pores, thereby significantly reducing formation hydration and swelling. Furthermore, this protective membrane prevents the dispersion and detachment of formation particles, further enhancing wellbore stability. Compared to conventional inhibitors, NS shows significant advantages in inhibiting formation swelling and protecting the wellbore, providing a new solution for improving the performance of drilling fluids and wellbore stability.

4.3. Sealing Performance Evaluation

To evaluate the sealing effect of nanosealing agent NS on low-permeability shale microfractures, this study selected low-permeability artificial core samples with a permeability of 15 mD for simulation experiments. The experiment utilized a core permeability test instrument to evaluate the sealing effect on fractures and pores in the shale ranging from 0.4 to 1 μm . The microfractures (0.1–1 μm width range) were engineered under controlled laboratory conditions using a custom-built fracture induction apparatus [37]. Before the experiment, the core samples were vacuumed and saturated with standard saline solution for 24 h to ensure complete internal wetting. Under a pressure difference of 3.5 MPa and a confining pressure of 5 MPa, standard formation water was used for forward displacement, and the initial displacement pressure and initial permeability of the core were recorded. Subsequently, both blank base slurry and drilling fluid containing 2% nanosealing agent NS were used for 120 min of contamination treatment on the core samples. Standard formation water was then used for forward displacement again, and the displacement pressure and permeability of the core at this time were recorded. Finally, standard formation water was used for reverse displacement, and the displacement pressure and final permeability of the core were recorded. The pressure difference, permeability, and flow rate were calculated based on Darcy's law:

$$Q = k \cdot \frac{\Delta P \cdot A}{\mu \cdot L} \quad (1)$$

$$R_p = \left(1 - \frac{K_1}{K_0}\right) \times 100\% \quad (2)$$

where Q is the displacement fluid flow rate (mL/min), K is the core permeability (mD), ΔP is the displacement pressure difference (MPa), A is the cross-sectional area of the core (cm^2), μ is the fluid viscosity (mPa·s), L is the core length (cm), and R_p is the plugging efficiency.

Figure 7 demonstrates the sealing performance of nanosealing agent NS on low-permeability core samples. The tested drilling fluids include the weighted drilling fluid formulation in Table 1 and the weighted formulation with 2% NS added. From Figure 7a, it can be observed that the water-based drilling fluid without a sealing agent had a forward displacement pressure peak of only 1.1 MPa before contamination; after contamination, the forward displacement pressure peak was approximately 3.9 MPa. Figure 7b shows the displacement pressure curve for the water-based drilling fluid with 2% NS added. The forward displacement pressure peak before contamination was 1.2 MPa, and after contamination, the forward displacement pressure peak exceeded 10 MPa, significantly higher than the maximum breakthrough pressure of the formulation without a sealing agent. Calculations revealed that the sealing efficiency of the water-based drilling fluid increased from 71.8% to 88% after the addition of 2% sealing agent. From this, it can be seen that the synthesized nanosealing agent NS exhibits remarkable sealing capability, effectively reducing the permeability damage caused by the drilling fluid to low-permeability core samples. This provides strong support for improving the sealing performance of drilling fluids.

To further investigate the sealing effect of nanosealing agent NS on low-permeability core samples, this study utilized the SEM to observe the cross-section of the core samples before and after sealing, with results shown in Figure 8. The unsealed low-permeability core exhibited a loose and porous structure, with numerous microfractures and pore throats internally, which provided pathways for fluid infiltration. In contrast, the cross-section of the core samples treated with NS sealing became significantly denser, forming a distinct sealing layer. The sealing mechanism of nanosealing agent NS primarily involves the synergistic effects of physical filling and chemical adsorption. On the one hand, the

nanoparticles (with an average particle size of approximately 86 nm) can enter the shale microfractures (0.4–1 μm) and pore throats due to their smaller size, forming a “bridging-filling” structure (see Figure 8b), thereby significantly reducing the connectivity of the pores and obstructing fluid infiltration. On the other hand, the surface-modified NS particles possess hydrophobic properties, enabling them to physically adsorb onto the mineral surface of the formation through van der Waals forces. Simultaneously, the siloxane bonds (such as Si-O-Si bonds) on their surface can chemically bond with the mineral surface of the formation, further enhancing the mechanical stability and durability of the sealing layer. This synergistic sealing mechanism of physical and chemical effects allows NS to achieve efficient and stable sealing in complex formation environments.

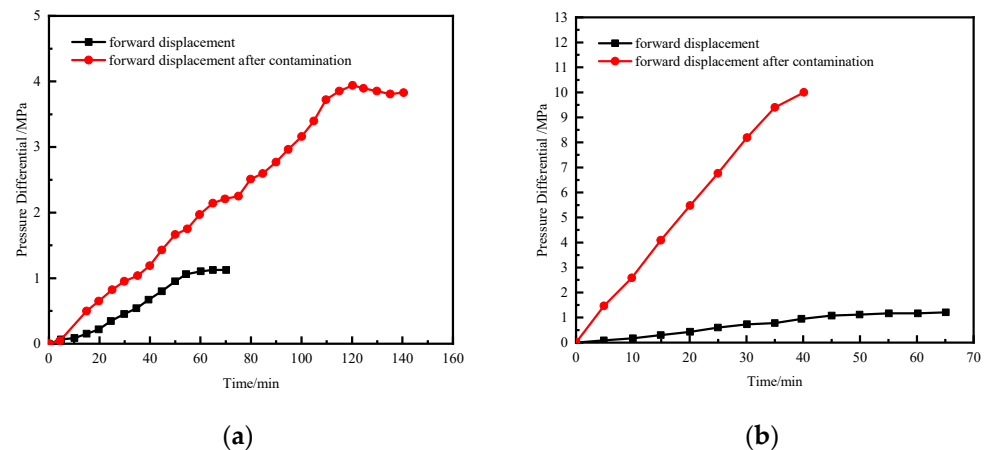


Figure 7. Nano sealant NS low-permeability core sealing performance ((a) displacement pressure curve of drilling fluid without sealing agent; (b) displacement pressure curve with 2% NS sealing agent).

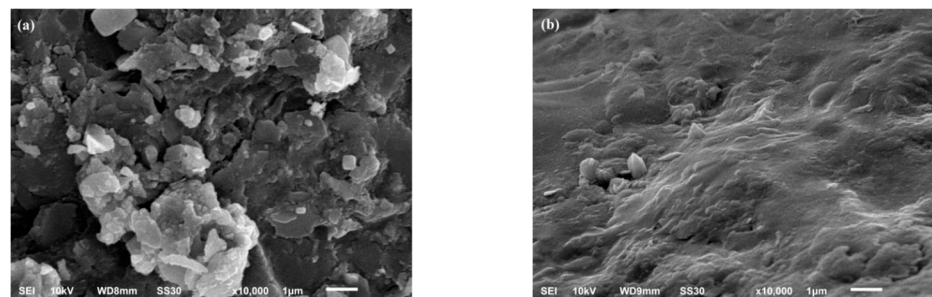


Figure 8. Cross-sectional SEM comparison of low-permeability core before and after sealing ((a) cross-section of the unsealed core; (b) cross-section of the sealed core).

5. Construction of Film-Forming Anti-Collapse Drilling Fluid System

Based on the aforementioned nanosealing agent NS with film-forming and anti-collapse properties, this study developed a high-efficiency film-forming anti-collapse drilling fluid system. The key treatment agents in this system include filtrate reducers, sealing agents, and anti-collapse agents, among others. The specific formulation is as follows: 3% bentonite + 0.2% soda ash + 0.1% caustic soda + 3% SP (sodium polyacrylate) + 0.2% fluid loss reducer DSP + 3% anti-collapse agent + 1.5% SO-1 + 0.3% salt-tolerant polymer + 0.5% film-forming agent B + 0.5% nano-sealing agent + barite. By rationally compounding these components, this system demonstrated excellent performance in deep coal seam drilling.

The experimental test results indicate that the funnel viscosity of this film-forming anti-collapse drilling fluid system is maintained between 30 and 60 mPa·s, the dynamic

shear force ranges from 4 to 20 Pa, the static shear force ranges from 0.98 to 3.92 Pa, and the dynamic plastic viscosity ratio is between 0.20 and 0.48. These performance indicators all meet the strict requirements for deep coal seam drilling, ensuring the stability and efficiency of the drilling fluid under complex geological conditions. The addition of nanosealing agent NS significantly enhanced the sealing performance of the drilling fluid while synergizing with other treatment agents to further optimize the rheological properties and filtrate control capabilities of the drilling fluid. The development of this system provides a highly efficient and reliable drilling fluid solution for deep coal seam drilling, with broad application prospects.

6. Field Application

The SSM1 well in the No. 3-1 coal seam of Shenmu Huineng Liangshui Coal Mine began triple-opening operations on 8 September 2024 and was successfully completed on 11 October. The No. 3-1 coal seam of Shenmu Huineng Liangshui Coal Mine features geological diversity. During construction, this section passes through two faults (F226 fault with a displacement of 15–40 m and FB70 fault with a displacement of 0–7 m). The rock types in this area, such as lump coal, powdered coal, and sandstone interbedded with mudstone, exhibit water-sensitive formation characteristics. Additionally, the sandstone section in this area has aquiferous formation characteristics and contains fissure water. Furthermore, the middle part of this coal seam contains crushed coal and powdered coal, which have a loose structure. Once exposed, they are prone to falling blocks and collapse, making it highly susceptible to accidents such as stuck drill pipe and buried drill.

During the drilling operations, an enhanced inhibitory film-forming anti-collapse drilling fluid system was employed, achieving significant results. The coal seam encounter rate for this well reached 86.7%, indicating the efficiency and adaptability of the drilling fluid system in complex geological conditions. Throughout the drilling process, the drilling fluid system containing nanosealing agent NS demonstrated outstanding anti-collapse performance, effectively preventing coal seam collapse and rockfall. The film-forming agent B could quickly form a dense protective membrane around the wellbore, effectively blocking free water from entering the formation and reducing the risk of hydration swelling and collapse. The synergistic action of nanosealing agent NS with anti-collapse materials precisely sealed and firmly bonded the formation pores, significantly improving the stability of the formation and ensuring the stability and safety of the wellbore during drilling.

Compared to the previously used bentonite-based drilling fluid system, the adoption of the film-forming sealing drilling fluid system containing nanosealing agent NS led to a significant improvement in core recovery. Previously, the core recovery rate with the bentonite system was below 60%, while with the new system, the core recovery rate was significantly increased to over 90%. The retrieved core samples had intact surfaces and clear structures, providing high-quality samples for subsequent geological analysis. Additionally, the funnel viscosity of the drilling fluid remained stable between 45 and 60 s, ensuring good cuttings suspension capability, further improving drilling efficiency and hole cleanliness.

7. Conclusions

This study successfully developed a novel organic–inorganic composite nanosealing agent (NS) specifically designed for deep coal seam applications and conducted a systematic investigation into its performance and application effects, yielding the following key conclusions:

1. The NS sealing agent exhibited outstanding dispersibility, compatibility, inhibitory properties, and sealing performance within the film-forming drilling fluid system. In terms of inhibition, NS proved far more effective than traditional inhibitors in suppressing

shale hydration swelling and dispersion. Regarding sealing performance, the sealing efficiency of NS for low-permeability core samples reached 88%, significantly surpassing the performance of drilling fluid systems without sealing agents and highlighting its remarkable advantages in enhancing drilling fluid performance.

2. The mechanism of action of NS involves multiple aspects. Surface modification based on DLVO theory was used to control particle dispersibility, while hydrophobic chains and steric hindrance acted synergistically to effectively inhibit particle aggregation. Nanoparticles optimized the rheological properties of the drilling fluid through colloidal interactions and improved filtrate reduction performance according to the Kozeny–Carman model. The physical–chemical synergistic sealing mechanism utilized size matching and interfacial adsorption to reduce formation permeability and enhanced breakthrough pressure based on capillary pressure models, thereby achieving effective sealing and stabilization of the formation.

3. The laboratory tests conclusively demonstrated the superior performance of the nanosealing agent (NS): a 91.2% shale rolling recovery rate was achieved in inhibition tests, significantly exceeding conventional inhibitors, while core flooding experiments revealed an 88% sealing efficiency and a 10 MPa breakthrough pressure threshold for low-permeability cores.

4. In the field application at the SSM1 well of Shenmu Huineng Liangshui Coal Mine, the drilling fluid system incorporating NS demonstrated highly significant anti-collapse effects. The coal seam encounter rate for this well was high, with excellent wellbore stability during drilling and no occurrences of rockfall or collapse. Additionally, the drilling fluid system exhibited good carrying capacity and lubrication performance, effectively improving drilling efficiency. This provides a highly efficient and reliable drilling fluid solution for deep coal seam drilling.

Author Contributions: Conceptualization, X.D.; methodology, W.W.; formal analysis, F.R.; investigation, X.D. and W.W.; data curation, W.S.; writing—original draft preparation, W.S. and C.M.; writing—review and editing, X.D. and C.M.; visualization, X.Z. and W.S.; supervision, W.Z. All authors have read and agreed to the published version of the manuscript.

Funding: The work was funded by Science and Technology Innovation Capability Support Project of Shaanxi Provincial Coalfield Geology Group Co., Ltd. “Research on Wireline Coring Tools and Environmentally Friendly Drilling Fluid Technologies for Deep and Complex Strata” Project Number: SMDZ-2023CX-3; National Natural Science Foundation of China (NSFC), Project Number: 41802196; Sponsored by CNPC Innovation Found: 2024DQ02-0149.

Data Availability Statement: All our data has already been displayed in the article; there is no additional information to provide.

Conflicts of Interest: Authors Xiaoqing Duan, Fujian Ren, Xiaohong Zhang and Weihua Zhang was employed by the company Shaanxi 185 Coal Field Geology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

NS Nanosealing agent
SEM Electron Microscopy

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