RSC Advances

ROYAL SOCIETY OF CHEMISTRY

PAPER

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Cite this: *RSC Adv.*, 2026, **16**, 21286

A study on the performance effects and mechanism of a drilling fluid wellbore stabilizer on cement slurry

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Received 8th March 2026
Accepted 15th April 2026

DOI: 10.1039/d6ra01989g

rsc.li/rsc-advances

Cementing slurry and drilling fluids are critical to wellbore operations in oil and gas exploration and production, with their performance directly determining cementing quality and long-term well productivity. This study investigates contamination of cementing slurry by individual drilling fluid treatment agents, focusing on a wellbore stabilizer to clarify the underlying mechanisms. At the macro scale, they examined variations in key parameters of cementing slurry, including thickening duration, compressive strength, and rheological behaviors. The findings indicate that while this stabilizer modifies the rheological features of the cementing slurry, it also exerts adverse effects on strength development and thickening capabilities. To explore the intrinsic pollution mechanisms more thoroughly, advanced microscopic testing methods were employed. These methods include Fourier Transform Infrared Spectroscopy (FTIR), thermogravimetric analysis (TG), scanning electron microscopy (SEM), X-ray diffraction (XRD) analysis, and mercury intrusion porosimetry (MIP). The results demonstrate that the contaminated cement paste exhibits a microstructure with elevated porosity and altered crystalline forms of hydration products. This research provides a robust theoretical basis for addressing drilling fluid-induced cementing slurry contamination and guides the optimization of drilling fluid and cementing slurry formulations in engineering practice.

1 Introduction

In oil and gas drilling operations, drilling fluid and cement slurry are two critical working fluids. Drilling fluid plays a role in carrying cuttings, cooling the bit, and stabilizing the wellbore during drilling. Cement slurry is used for cementing operations to firmly seal the casing to the wellbore, ensuring normal production and long-term stability of oil and gas wells. However, in actual drilling processes, due to the inevitable contact between drilling fluid and cement slurry during downhole operations, various treatment agents in the drilling fluid often contaminate the performance of the cement slurry. This problem is now one of the main things preventing cementing quality from improving, attracting extensive attention and in-depth research from many scholars both domestically and internationally.[1–4]

Li *et al.*[5] believed that the main reason for cement slurry contamination was the chemical reaction between treatment agents in drilling fluid and cement slurry, which led to cement slurry gelation and greatly affected thickening time and strength. In addition, a large number of calcium and magnesium ions in cement slurry also caused serious damage to the performance of drilling fluid. Feng *et al.*[6] found through the study of cement slurry properties and the structure of cement paste that cement particles and hydration particles in the cement paste generally exist in a non-permanent connection state. As the hydration reaction progresses further, various high-valence metal ions will form in the cement paste. These high-valence metal ions will cross-link with polymers in the drilling fluid to form gels, which can severely affect the flowability of the slurry.[7] Xie *et al.*[8] studied the extremely poor compatibility between organic salt drilling fluids and cement slurry in their article, finding that the nitro, sulfonic acid, carboxyl, amide, hydroxyl, amino, ether, methyl groups, and the high molecular structure chains formed in the high-temperature filtration loss agent in the drilling fluid can contaminate the cement slurry. They solved the contamination problem between the cement slurry and the organic salt drilling fluid by adding a pollution inhibitor. The main directions of foreign research on the compatibility between drilling fluid and cement slurry mainly include adjusting[9,10] and optimizing the formula and performance of drilling fluid and cement slurry,[11–13] designing the replacement scheme suitable for cement slurry replacement, and injecting isolation fluid to solve the compatibility problem between the two.[14–18] Since 1940, P.

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H. Jones and D. Berdine have made pioneering research on the mechanism of cement injection replacement, and gradually put forward some theories to effectively improve and enhance the efficiency of cement injection replacement.[19–21] A. Salihu *et al.*[22] studied the effects of sodium chloride, cement and silica sand on the physical properties of water-based drilling fluid, and found that with the increase of cement concentration, the plastic viscosity, apparent viscosity, yield point and gel strength of the mud, as well as pH value, density and temperature all increased. Soares *et al.*[23] found that after cement slurry is mixed with oil-based drilling fluid, its plastic viscosity and dynamic shear force increase, which may reduce the maximum pumpability of cement slurry during cementing. The micro-pores formed after cement curing can decrease the compressive strength of the hardened cement matrix, affecting the stability of hydraulic seals and causing well control issues. Ahdaya *et al.*[24] studied a new high-performance material based on Class C fly ash, a geological polymer. The study found that drilling fluid enhances the rheological behavior of the geological polymer by increasing its viscosity and reducing fluid loss, thus promoting pumping during cementing. Moreover, under the same conditions, the geological polymer has stronger resistance to drilling fluid contamination compared to traditional Portland cement.

From the perspective of construction, the best method is to use an isolation fluid to avoid direct contact between drilling fluid and cement slurry. However, it is necessary to analyze the mechanisms of interaction between drilling fluid treatment agents and cement slurry. This is crucial for formulating effective control measures, effectively controlling and reducing the contamination of cement slurry by drilling fluid treatment agents, further improving cementing quality, and ensuring the efficient and safe development of oil and gas wells. This paper focuses on the issue of cement slurry contamination caused by a wellbore stabilizer, conducting a comprehensive and in-depth study aimed at accurately analyzing its mechanism of action, with the hope of providing a more solid theoretical foundation and technical support for the development of oil and gas drilling engineering technology.

2 Experimental

2.1 Experimental materials

In this experiment, grade G (high sulfate-resistant type) oil well cement produced by Jiahua Special Cement Co., Ltd was used as cement material, and its chemical composition, major mineral composition, and particle size distribution are shown in Tables 1, 2, and Fig. 1, respectively. The formula of blank cement slurry is: 100% G grade cement + 35% quartz sand (600 mesh) + 1.5% water loss reducer (G33S) + 0.3% dispersant (USZ) + 1.4% retarder (SD210), water to cement ratio is 0.44. The density of cement slurry is 1.90 g cm^{-3}, and the flowability at room temperature is 23 cm. G33S was procured from Henan Weihui Chemical Co., Ltd, USZ from Tianjin Youfu Technology Development Co., Ltd, potassium polyacrylate (WD-1) was procured from Shandong Hengke Biotechnology Co., Ltd, and the SD210 from Sichuan Chuanqing Downhole Technology Co., Ltd.

Table 2 Mineral composition of cement for G-Class (high sulfate-resistant type) oil wells

Mineral composition	C_3S	C_2S	C_3A	C_4AF
Content (%)	62.11	14.89	0.91	15.04

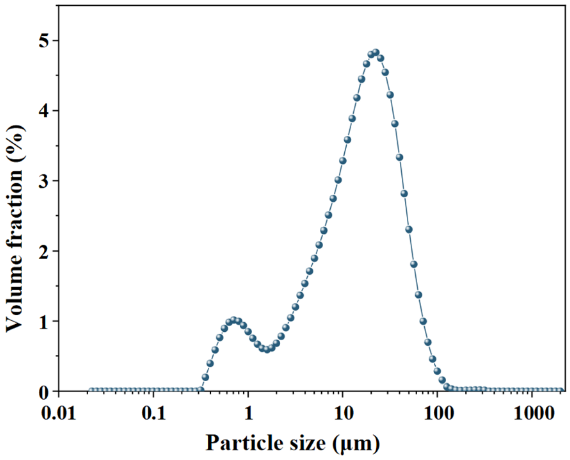


Fig. 1 Particle size distribution.

Table 3 Thickening time of WD-1 cement slurry with different additions

Amount (%)	0	0.01	0.02	0.04	0.06	0.07	0.08
Thickening time (min)	304	288	266	223	172	110	—

WD-1 is non-toxic and non-corrosive, appearing as a light yellow or white powder. It has excellent heat resistance and is widely used in deep well engineering as a wellbore stabilizer and shale dispersant. It effectively controls formation overflow slurry while reducing water loss, increasing lubricity, and improving the rheological properties of drilling fluid systems.[25,26] This study primarily investigates the contamination issues of cement slurry caused by WD-1 from both macroscopic and microscopic perspectives.

2.2 Experimental method

2.2.1 Effect of drilling fluid treatment agent on cement slurry performance. The drilling fluid treatment agent WD-1

Table 1 Chemical composition content of cement for G-Class (high sulfate-resistant type) oil wells

Oxide	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	SO_3	Loss
Content (%)	63.74	22.48	3.41	4.01	1.47	0.9	1.55	1.40	1.04

Table 4 Effect of different dosage of WD-1 on water loss of cement slurry

Amount (%)	0	0.01	0.02	0.04	0.06	0.07	0.08
Water loss (mL)	62	59.4	57.2	51.5	40.2	35.4	27.6

Table 6 Influence of WD-1 on cement slurry flow ability

Amount (%)	0	0.01	0.02	0.04	0.06	0.07	0.08
Mobility (cm)	23	22	16	15	—	—	—

was added to cement slurry at different concentrations (0, 0.01%, 0.02%, 0.04%, 0.06%, 0.07%, 0.08%) for high-temperature and high-pressure thickening, cement slurry loss of water, and cement slurry settling stability tests. The effects of the treatment agent on the performance of the cement paste were analyzed.

Thickening time and fluid loss of cement slurry were tested according to GB/T 19139-2012.[27]

2.2.1.1 Settling stability. Transfer the prepared cement slurry into a pressurized thickener and maintain constant temperature under target conditions for 20 minutes. After motor shutdown, allow 30 minutes at target temperature. Restart the motor and record the concentration rebound value. Terminate the process by cooling below 90 °C and collect the slurry. Remove upper oil contaminants using absorbent paper, transfer to a graduated cylinder, seal with plastic wrap, and incubate in a 90 °C water bath for 2 hours. Finally, measure the density of both upper and lower layers of the cement slurry.

Additionally, the treatment agent was prepared as an aqueous solution and mixed with different metal ion solutions to observe the reaction phenomena between the treatment agent and various metal ions: deionized water was used to prepare a 0.06% WD-1 aqueous solution, and then 0.5% KCl, $CaCl_2$ and $AlCl_3$ aqueous solutions were added to the aqueous solution respectively.

2.2.2 Pollution mechanism analysis

2.2.2.1 Preparation of cement paste. The preparation process of cement paste is based on standard GB/T 19139-2012.[27] The mixed cement slurry is poured into the corresponding compression molds for water bath curing and high-temperature high-pressure oil bath curing, with curing temperatures of 90 °C and 150 °C, respectively. The reason for choosing 90 °C is that it is the common extraction temperature for shale gas wells today. Selecting 150 °C is based on the actual temperature measured at the site, aiming to further investigate the evolution of hardened cement matrix mechanical properties under different temperatures. The curing age at 90 °C was 1 d, 3 d and 7 d respectively. Because of the long heating and cooling time of the equipment, oil bath curing cannot be carried out for 1 d. Therefore, in order to investigate the evolution of cement slurry in the early stage of high temperature environment, curing age of 3 d and 7 d were selected at 150 °C.

2.2.2.2 Pollution mechanism research methods. After the curing of the samples, they were soaked in anhydrous ethanol to terminate hydration and dried in an oven for 24 h. After the drying, some intact pieces were taken and some were ground into powder for testing. XRD, TG, SEM and MIP were used to analyze the microstructure, structure and hydration products of cement paste. Among them, the XRD scanning rate is 6° min^{-1}, and the scanning range is 10–90°, hardened cement matrix's microstructure is seen using SEM, and its pore size distribution and porosity are described using MIP. The samples to be tested must first be cleaned to remove residual oils from the surface. Place the samples in anhydrous ethanol for three days to eliminate hydration reactions. After removal, dry them in a 60-degree oven for 48 hours to remove internal moisture and anhydrous ethanol. Once dried, crush the samples into uniform cubes weighing no more than 3 grams for mercury porosity testing. Conduct mercury porosity tests on blank cement slabs cured at 150 °C for three days and cement slabs containing 0.06% WD-1; TGA is nitrogen atmosphere, the experimental temperature range is 40–1000 °C, and the heating rate is 10 °C min^{-1}.

3 Results and discussion

3.1 Performance evaluation

3.1.1 Thickening time. Table 3 shows the thickening time of cement slurry with different amounts of WD-1 added. Table 3 illustrates that the cement slurry's thickening time typically exhibits a monotonically declining trend as the amount of WD-1 rises. Moreover, as the amount of WD-1 increases, the decrease in thickening time becomes faster. The cement slurry thickens in 63.8% less time when the adding rate reaches 0.07%. The cement slurry will become less fluid if this treatment agent is used in excess, making it impossible to perform thickening tests, indicating that WD-1 has caused severe contamination of the cement slurry. This sharp reduction is caused by the adsorption-bridging and Al^{3+} crosslinking of WD-1 with cement hydration products, which rapidly builds a flocculent network and accelerates slurry structuration.

3.1.2 Water loss. Table 4 displays the findings of a test that examined the impact of varying WD-1 addition amounts on the cement slurry's water loss. As the amount of WD-1 added gradually increased, the water loss of the cement slurry decreased, particularly significantly within the range of 0.04 to 0.06%. The reduction in water loss is mainly due to the formation of a network structure by potassium polyacrylate in the cement slurry. A significant proportion of free water is encapsulated by this structure, which lowers the amount of

Table 5 Settling stability of cement slurry with different added WD-1

Amount (%)	0	0.01	0.02	0.04	0.06	0.07	0.08
Density difference (g cm^{-3})	0.092	0.066	0.053	0.046	0.045	0.037	0.035

Table 7 Rheological properties of pure cement slurry and cement slurry with 0.06% WD-1 added

	3r/min	6r/min	100r/min	200r/min	300r/min	600r/min
Pure cement slurry	3	4	51	97	139	246
WD-1 cement slurry	—	—	—	—	—	—

unencapsulated free water in the cement slurry and, therefore, water loss.

3.1.3 Settling stability. The effects of different amounts of WD-1 on the settling stability of cement slurry were measured, and the results are shown in Table 5.

According to the above data, it is evident that as the WD-1 content gradually increases, the settling stability of the cement slurry improves. The cement slurry with 0.01% WD-1 exhibits better settling stability compared to the unadulterated cement slurry, showing an improvement of 28.2%. Improved stability results from polymer chain extension and particle flocculation induced by WD-1, which homogenizes cement particle distribution and reduces density segregation.

3.1.4 Flow properties. The changes of cement slurry flowability under different weighting drilling fluid treatment agents were investigated, and the results are shown in Table 6. Table 7 shows the shear stress of neat cement slurry and cement slurry with 0.06% WD-1 at different rotational speeds. The neat cement slurry shows stable and favorable rheological behavior. After adding WD-1, the slurry undergoes severe flocculation, leading to excessive thickening and loss of measurable rheological response. Loss of fluidity is attributed to strong bridging flocculation between WD-1 macromolecules and cement particles.

3.1.5 The compressive strength of hardened cement matrix. On the basis of the test results in 3.1.4, we selected 0.06% increased WD-1 cement slurry to test its compressive strength at 90 °C, and blank cement slurry was used as the control group. The results are shown in Fig. 2. From the graph, it can be seen that within 7 days of hydration, the compressive strength increases with rising temperature and curing age. When only 1 day of curing is applied, the cement paste mixed with WD-1 shows no strength, indicating that WD-1 has a significant negative impact on the early hydration of the cement paste, which is not conducive to meeting the strength requirements for cement paste during logging. Increasing the curing time to 3 days or 7 days, the compressive strength of the cement paste system mixed with this treatment agent remains lower than that of normal cement paste systems, suggesting that adding WD-1 is detrimental to the development of cement paste strength.

To investigate the strength development of the treatment agent at underground temperatures, it was cured for 3 days and 7 days in a high-temperature and high-pressure curing chamber

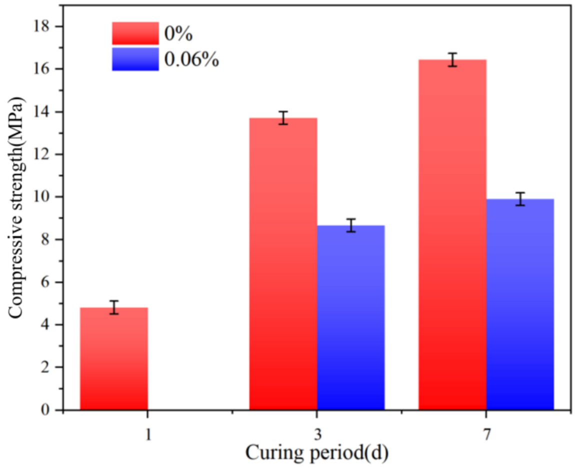


Fig. 2 Compressive strength of different hardened cement matrixs.

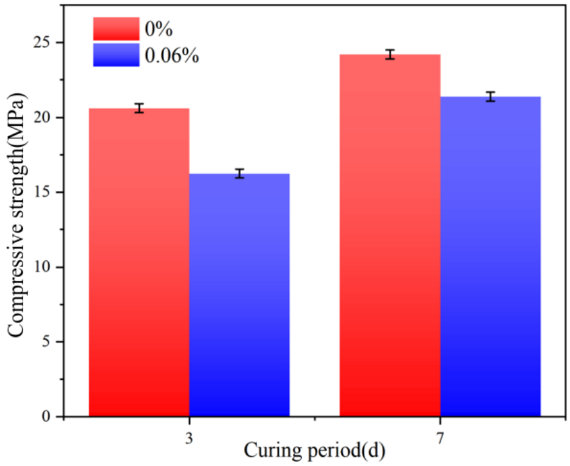


Fig. 3 150 °C strength development of different hardened cement matrixs under curing.

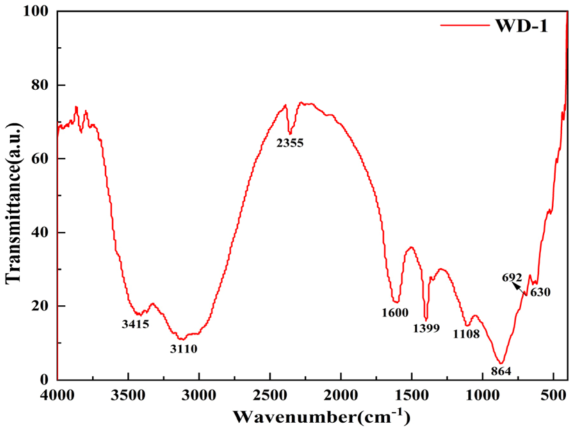
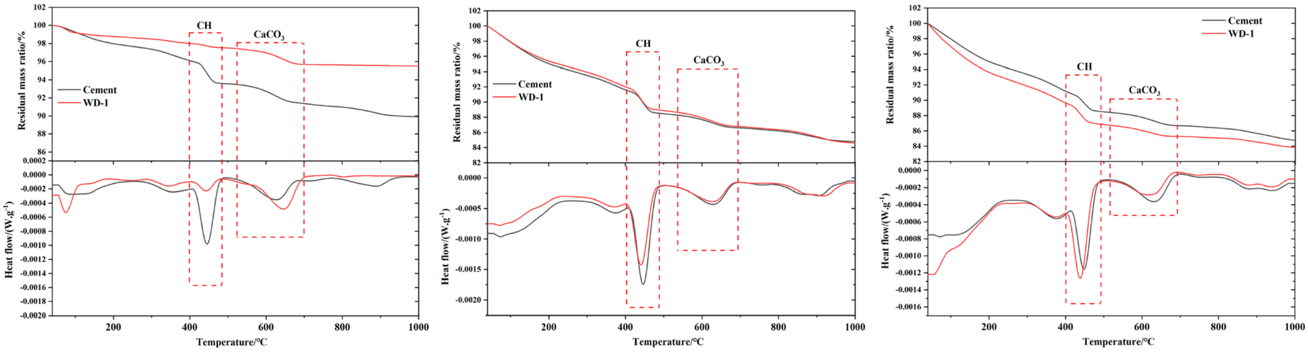


Fig. 4 Infrared spectrum of WD-1.



a) b) c)

Fig. 5 TG/DTG of cement samples at 90 °C: (a) hardened cement matrix is maintained for 1 day, (b) hardened cement matrix is maintained for 3 days and (c) hardened cement matrix is maintained for 7 days.

at 150 °C, and its strength was measured. The results are shown in Fig. 3. It can be observed that under 150 °C conditions, the cement paste with WD-1 added has lower strength after 3 d and 7 days curing compared to pure cement paste, with a difference of 2–3 MPa. WD-1 inhibits the hydration of dicalcium silicate (C_2S), reduces the formation of calcium hydroxide (CH) and C–S–H gel, and degrades the pore structure, all of which suppress early strength development.

3.2 Effect of drilling fluid treatment agent on cement microstructure

3.2.1 Infrared analysis. Fig. 4 displays WD-1's infrared spectrum. The N–H bending vibration absorption peak and the C=O bending vibration absorption peak of the amide group are located at 3415 cm^{-1} and 1600 cm^{-1}, respectively, in the WD-1 infrared spectrum. The $-CH_2$ stretching vibration absorption peak is located at 3110 cm^{-1}, the C–H bending vibration absorption peak is located at 1108 cm^{-1}, the asymmetric stretching vibration peak of –COO– is located at 1399 cm^{-1}, the O–H out-of-plane deformation coupling peak is located at 1108 cm^{-1}, the O–H out-of-plane deformation vibration peak is located at 864 cm^{-1}, and the in-plane bending vibration absorption peak of –COO– is located between 600 and 700 cm^{-1}. The main functional groups of WD-1 include carboxyl, hydroxyl, and amide groups, which have adsorption properties, with the adsorption capacity being $-COO- > -CONH_2 > -OH$. When WD-1 in the drilling fluid system interacts with cement slurry, it produces two distinct effects. First, WD-1's relatively high molecular weight and extended molecular chains enable each chain to simultaneously adsorb multiple cement particles, forming a hybrid cross-linked network structure. Second, calcium ions in the cement slurry system reduce the polymer's solubility, causing molecular chain coiling. Through dual mechanisms of adsorption bridging and electrical neutralization, this triggers flocculation reactions in the cement slurry, macroscopically manifesting as increased slurry viscosity and significant loss of fluidity.

3.2.2 Thermal weight test results. As shown in Fig. 5, the thermal weight analysis was carried out on the blank cement samples and the cement samples with WD-1 after 1 day, 3 days and 7 days of curing. From Fig. 5a, it can be observed that the cement samples with WD-1 added show almost no mass loss in the 400–480 °C range, indicating that WD-1 hinders the formation of CH in the early stage of cement paste and affects the hydration process of the cement paste. This is in line with the cement paste's compressive strength data after one day. The mass loss of the cement paste in both systems is essentially constant throughout the 400–480 °C range, according to an analysis of the curves in Fig. 5b and c, suggesting that the hydration of the cement paste after 3 days and 7 days without WD-1 has not been affected by the treatment agent. This indicates that the impact of the treatment agent on cement hydration decreases over time, which is also consistent with the strength data of the cement paste.

Fig. 6 shows the thermogravimetric analysis of cement paste with 0.06% WD-1 added under 150 °C for 3 days. It is evident from the figure that the mass loss points of the cured cement samples are mainly distributed in three regions. The first region ranges from 50 °C to 120 °C, where the primary mass loss occurs due to the hydration of C–S–H and calcium sulfoheptahydrate in the cement paste. The second region is from 400 °C to 480 °C, where the main cause of mass loss is the decomposition of $Ca(OH)_2$ at high temperatures in the cement slurry. This

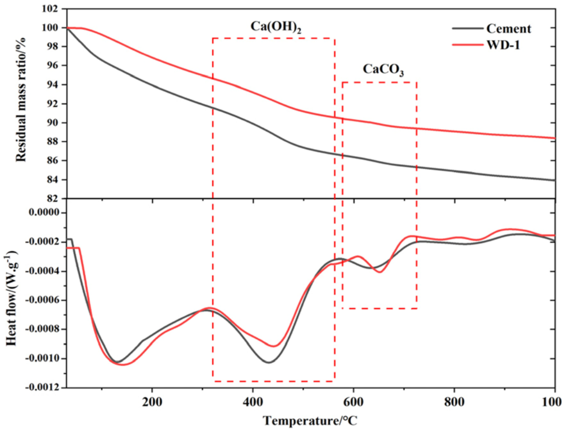


Fig. 6 TG/DTG of cement samples with WD-1 added at 150 °C.

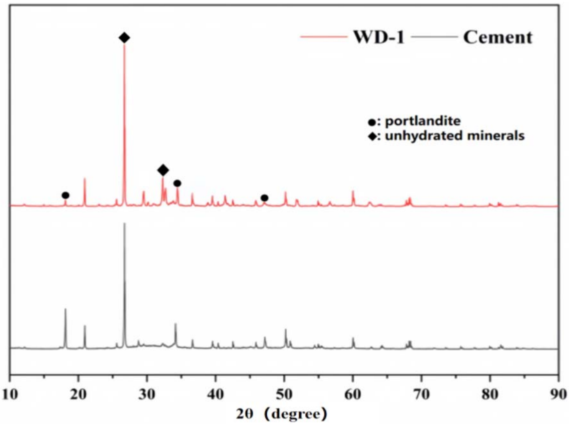


Fig. 7 XRD spectra of pure cement samples and cement samples with WD-1.

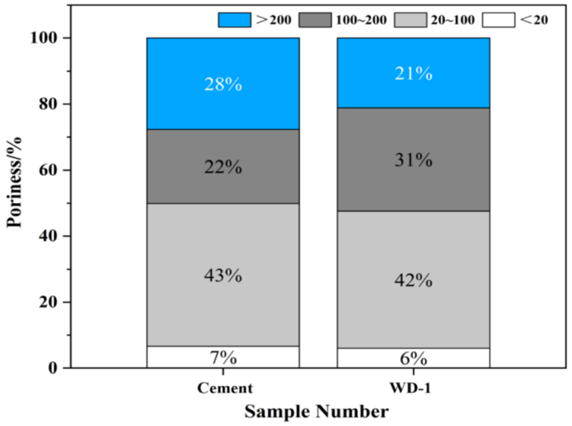


Fig. 9 Porosity distribution.

indicates that the mass loss in both systems is roughly consistent within this range. The third region is from 540 °C to 720 °C, where there is virtually no decomposition of carbonate materials.

3.2.3 X-ray diffraction test results. In XRD testing, changes in diffraction peaks of unhydrated minerals and calcium hydroxide crystals are commonly used to characterize the cement hydration process. Fig. 7 presents the X-ray diffraction patterns of two cement paste systems after 3 days of curing in a 90 °C water bath. With the addition of WD-1, the intensity of CH diffraction peaks ($2\theta = 18°, 34.1°, 47.1°$) in the cement paste system decreases, while the intensity of diffraction peaks corresponding to unhydrated mineral (C_2S) at 28.7° and 32.2° increases. This phenomenon occurs because after adding WD-1, the molecular chains wrap and adsorb a large number of cement particles, thereby retarding the hydration reaction of C_2S in the cement paste. Except for the characteristic peaks of CH and C_2S, the characteristic peaks of other phase structures remain essentially consistent, indicating that no new phase structure is generated after the addition of WD-1. Fig. 8 presents the XRD spectra of two cement slurry systems after 3-day curing in a 150 °C water bath. The characteristic peaks of cement phase structures in both systems under high-temperature curing conditions showed fundamental consistency, indicating that the hydration product types remained similar and the hydration reaction pathways remained largely unchanged under these conditions. The introduction of WD-1 did not contribute to the formation of new crystalline phases, nor did it significantly affect the crystal structure or crystallinity of the primary hydration products.

3.2.4 MIP test result. Fig. 9 displays the pore distribution graphs, and Table 8 lists the particular values. The probability distribution function of pores is illustrated in Fig. 10, and the most probable pore sizes are provided in Table 9. It can be seen

Table 8 Porosity content of different systems

Porosity/%	Cement	WD-1
Total porosity	37.7706	36.2097
<20 nm	2.46356	2.17555
20–100 nm	16.13379	15.05177
100–200 nm	8.34526	11.32896
>200 nm	10.32808	7.65302

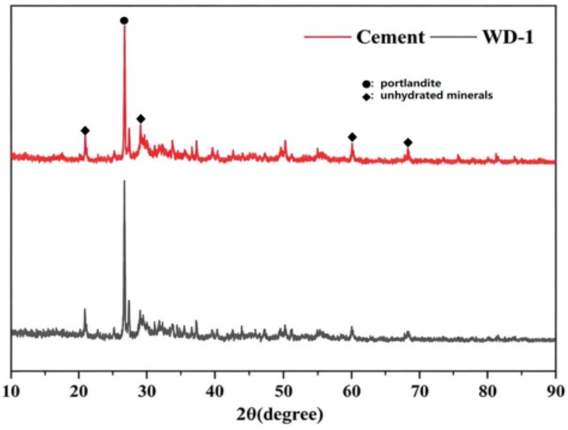


Fig. 8 XRD spectra of samples cured at 150 °C for 3 days.

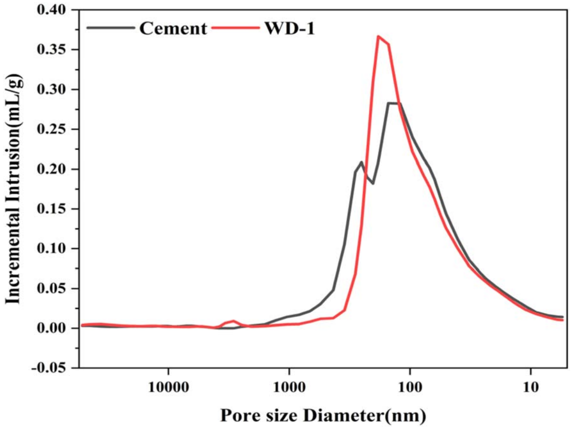


Fig. 10 Porosity probability distribution function.

Table 9 Porosity content of different systems

	Cement	WD-1
The most compact aperture/nm	149.498089	183.168162
Maximum aperture distribution probability (mL g^{-1})	0.28297	0.36650

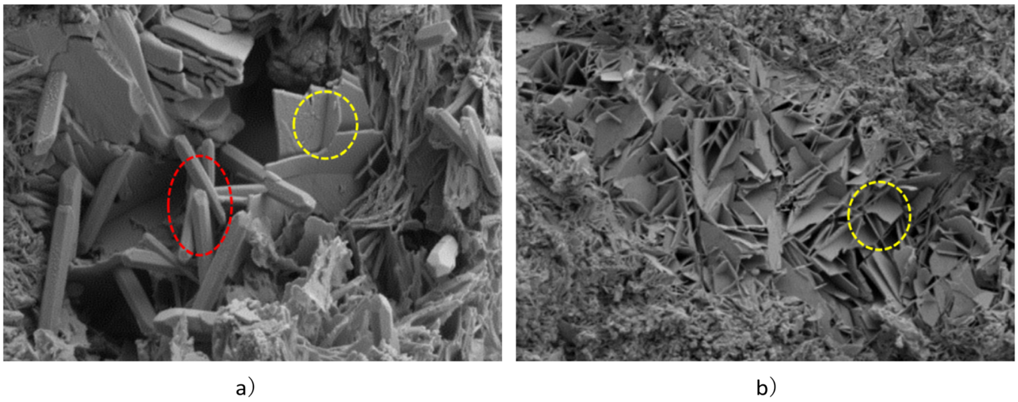

a) b)

Fig. 11 SEM images of blank hardened cement matrix and hardened cement matrix with WD-1 added: (a) pure hardened cement matrix, (b) hardened cement matrix mixed with WD-1.

from the Fig. 9 that with the addition of treatment agent, the total porosity in the system decreases, and the gel pores in the system decrease, the capillary pores increase, and the unhydrated particles in the system increase, indicating that the addition of treatment agent delays the early hydration rate and reduces the content of C–S–H gel in the cement matrix.

From the pore probability distribution function in Fig. 10, it can be seen that with the addition of WD-1, the most probable pore size of the cement paste increases from 149.498089 nm to 183.168162 nm, and the distribution probability also increases. This indicates that the addition of WD-1 slows down the early hydration rate, leading to a slower waterization process without forming sufficient three-dimensional structure. As a result, there are more capillary pores in the early stage of cement paste hydration, resulting in low hydration degree and weak system strength.

3.2.5 Results from scanning electron microscopy. The microstructure images of pure cement and cement with 0.06% WD-1 after 150 °C curing are shown in Fig. 11. It can be observed that in pure cement, many needle-like columnar crystal of calcium aluminite (AFt) and flake-like calcium hydrated monosulphoaluminate (AFm) are embedded in the cement matrix, with fibrous C–S–H attached to the surface serving as a connecting agent between them and filling some voids. Fig. 11b shows the microstructure of hardened cement matrix with WD-1 addition, revealing abundant sheet-like AFms that act as structural support and interconnective components.

3.2.6 Reaction of drilling fluid treatment agent with metal ion. As can be seen from Fig. 12, the WD-1 solution reacts with $AlCl_3$ solution to produce flocculation substances, but does not react with KCl and $CaCl_2$ solutions, indicating that WD-1 only reacts with Al^{3+} in water, but does not react with Ca^{2+} and K^+,

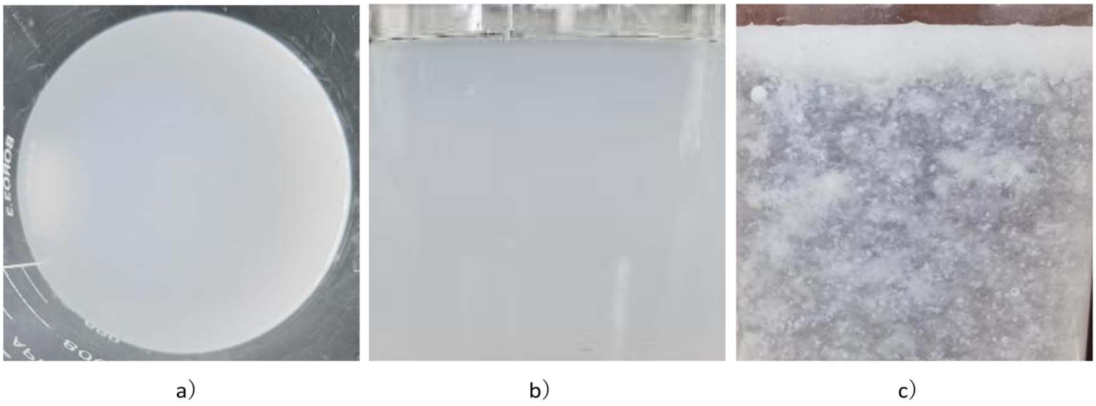

a) b) c)

Fig. 12 The WD-1 aqueous solution reacts with different metal salt solutions: (a) Join KCl, (b) Join $CaCl_2$, (c) Join $AlCl_3$.

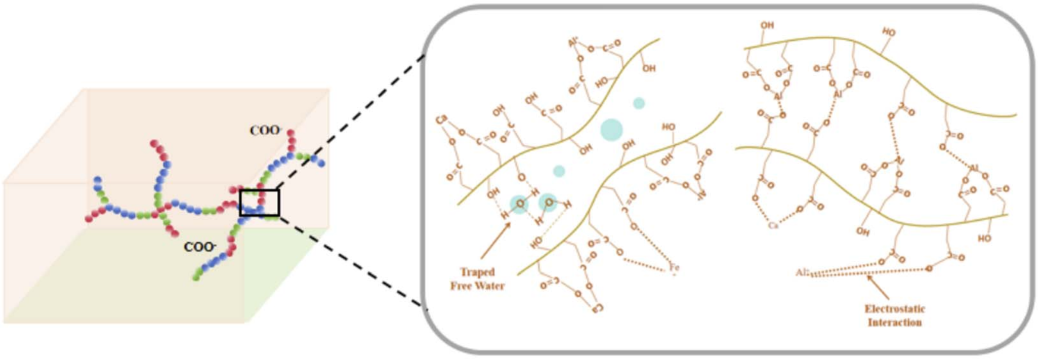


Fig. 13 Schematic diagram of the action between drilling fluid treatment agent and Al^{3+}.

indicating that WD-1 will react with Al^{3+} in cement slurry to form flocculation structure.

3.2.7 Pollution mechanism. Based on the above analysis, the mechanism of potassium polyacrylate's contamination of cementing slurry is summarized as follows: the main chain of potassium polyacrylate molecules contains many functional groups with adsorption properties, such as carboxyl, hydroxyl, amino, amide, and sulfonic acid groups. In terms of adsorption capacity, these functional groups have the following order: $-SO_3-$ > –COO– > $-CONH_2-$ > –OH > –O–. They can adsorb onto different cement particles. When WD-1 from the drilling fluid comes into contact with the cementing slurry, on one hand, due to the large molecular weight and long molecular chains of WD-1 polymers, multiple cement particles often adsorb onto a single molecular chain, forming a mixed network structure; on the other hand, Ca^{2+} in the cementing slurry reduces the solubility of the polymer, causing the molecular chains to curl, form adsorption bridges, and undergo electro-neutralization. These two effects lead to flocculation of the cementing slurry, characterized by increased viscosity, formation of flocculent clumps, and loss of fluidity. The schematic diagram of this mechanism is shown in Fig. 13.

4 Conclusion

This study primarily investigates the impact and mechanism of potassium polyacrylate as a drilling fluid treatment agent on cement slurry pollution. Through macroscopic performance testing and microscopic structural analysis, the following conclusions were drawn: as the amount of WD-1 increases, the thickening time of the cement slurry shows a monotonically decreasing trend. When the addition reaches 0.07%, the thickening time is reduced by 63.8%. Further addition leads to the loss of fluidity in the cement slurry, indicating that WD-1 has a significant negative effect on the thickening performance of the cement slurry. This is due to the fact that the carboxyl and hydroxyl functional groups on the WD-1 molecular chain physically adhere to the cement particles' surface. The high molecular chains promote the formation of a flocculent network structure through the "bridging effect," leading to increased viscosity and loss of fluidity in the slurry. On the other hand, under both 90 °C and 150 °C curing conditions, the compressive strength of cement paste containing WD-1 is lower than that of the blank samples, especially with almost zero early strength, indicating that the addition of WD-1 inhibits the early hydration of cement. This result can be confirmed by infrared spectroscopy, XRD, and mercury porosimetry tests. Early hydration products are decreased as a result of WD-1's suppression of calcium hydroxide production and delay of C_2S hydration. Additionally, WD-1 increases capillary pores and decreases gel pores in the cement paste, with the pore size increasing from 149.5 nm to 183.2 nm, exacerbating pore structure degradation and reducing strength.

A theoretical foundation for the design of cement slurry and drilling fluid compatibility is provided by this study. It will be able to replicate high-temperature and high-pressure conditions in ultra-deep wells in the future, exploring the impact of treatment agent thermal stability on the long-term performance of cement slurry. On the other hand, it is also necessary to study the synergistic pollution effects of different treatment agents under various conditions, establishing a multi-factor coupled pollution prediction model.

Author contributions

Yong Zhang: conceptualization, writing – original draft preparation, data curation, writing – review and editing. Simeng Liu: conceptualization, writing – original draft preparation, data curation, writing – review and editing. Sibin Li: conceptualization, data curation, writing – original draft preparation. Mingjia Mei: conceptualization, data curation, writing – original draft preparation. Chenyang Wang: conceptualization, writing – review and editing. Ming Li: conceptualization, supervision, writing – review and editing.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Data availability

Data will be made available on request.

Acknowledgements

The author would like to acknowledge the scientific assistance of Advanced Cementing Materials Research Center (SWPU, China).

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