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Construction and Field Application Practice of Cement Slurry System Suitable for Ultra-Deep Wells with Ultra-Long Cementing Sections and Large Temperature Differences

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Abstract. Deep and ultra-deep resources have become an important replacement area for oil/gas exploration and development in China. However, the cementing engineering of deep and ultra-deep wells faces challenges, for example, high/ultra-high temperatures, high pressure, ultra-long cementing intervals, and large temperature differences, making it difficult to ensure the safety and quality of cementing operations. To address the challenge of slow strength development in cement slurry (CS) due to low temperatures at the top interval and the incorporation of a large amount of additives in the large temperature differential environment of ultra-long cementing intervals, this study relied on the self-developed inorganic salt-based early-strength agent DRA-2S to construct a series of CS systems suitable for large temperature differential environments, which were applied in the tie back liner cementing operation of Qingbei 1 Well (the temperature difference up to 120℃). The comprehensive performance evaluation of the CS indicates that it possesses good fluidity, low water loss, excellent settling stability, favorable rheological and thickening properties, and strong compatibility with other wellbore fluids. These characteristics meet the requirements for safe cementing operations. Most importantly, the compressive strength of the CS reaches 10 MPa after cuing for 72 h at a low temperature of 25℃, which helps to shorten the well construction time and reduce construction costs. Therefore, the self-developed early-strength agent and the constructed cementing CS system suitable for large-temperature-difference environments have broad application prospects.

Keywords: cement slurry, large temperature difference, ultra-deep well cementing.

1. Introduction

Oil/gas resources are the vital material foundation for the development of modern society, serving as the "lifeblood" for the operation of the industrial economy. Following the reform and opening-up, with the rapid economic development of our country, the demand for oil/gas resources has been increasingly growing. However, the medium and shallow resources in China, which are less difficult and costly to exploit, have entered the late stage of development and production. This has led to a year-on-year increase in China's dependence on foreign oil/gas resources in recent years, posing a severe challenge to energy security. With the continuous advancement of geological theories and engineering technologies, the proven reserves of deep and ultra-deep oil/gas have been

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increasing year by year, becoming a significant alternative energy source for China and even the world. In the practice of oil/gas exploration and development in China, deep and ultra-deep oil/gas resources account for 34% of the country's total oil/gas resources. These resources are characterized by high abundance, large scale, and substantial overall reserves, but they also present numerous world-class challenges in exploration and development. Notably, the Tarim Basin holds 83% of the nation's oil and 63% of its natural gas at depths exceeding 6000 meters, ranking first in the volume of ultra-deep oil/gas resources among all major basins in the country.

In the process of oil/gas exploration and development, well cementing is a critical engineering technology that supports the high-quality and smooth construction of wells and establishes a safety barrier for well production. The quality of cementing is an essential guarantee for the safe production throughout the lifecycle of "well assets" and for achieving profitable development. However, during the exploration and development of deep and ultra-deep oil/gas, the cementing engineering for deep wells (well depth over 4500 m) and ultra-deep wells (well depth over 6000 m) currently faces challenges such as high/ultra-high temperatures, high pressure, ultra-long cementing sections, and large temperature differences. These difficulties exponentially increase the complexity of cementing, making it hard to ensure the quality of cementing.

Currently, for cementing operations in long open-hole sections and long cementing intervals, the two-stage cementing technique is generally employed. However, this method carries risks such as the failure to successfully open the stage collar during the second stage of cementing, leading to operational hazards. Additionally, the prolonged construction time for two-stage cementing extends the well construction cycle and increases drilling costs. Moreover, to meet the performance requirements for cementing in ultra-long cementing intervals, a significant amount of additives such as retarders, fluid loss reducers, and dispersants are incorporated into the cement slurry (CS) system. However, the presence of these additives can lead to issues such as excessive retardation of the top CS and slow strength development at the top of the CS, which prolongs well construction time and jeopardizes the quality of cementing. Therefore, it is imperative to develop a large temperature differential CS suitable for ultra-deep wells with ultra-long cementing intervals, ensuring rapid strength development at the top of the cement sheath, shortening the well construction cycle, and enhancing cementing quality. This has significant practical implications for ensuring the safety of cementing operations and the efficiency of exploration and development in deep, ultra-deep, and wells with ultra-long open-hole sections and large temperature differentials.

2. Experimental Section

2.1 Materials

Oil well cement (OWC, Class G, highly sulfur resistant) was obtained from Shawan Tianshan Cement Co., Ltd. Reinforcing material (DRB-1S, DRB-2S), micro-silicon (3000mesh), Toughening material (DRE-3S), Elastic Material (DRT-1S), Early-strength agent (DRA-2S), Stabilizing agent (DRK-3S), Dispersant (DRS-1S), Fluid loss additive (DRF-1S, DRF-2L), Suspending agent (DRY-S3, DRY-S1), Defoamer (DRX-1L), Foam inhibitor (DRX-2L), Retarder (DRH-2L) , Flushing agent (DRY-1L, DRY-2L), Weighting Material (iron powder) were provided by CNPC Engineering R&D Co., Ltd. The above materials are all industrial grade and have not undergone any treatment before use.

2.2 Construction of CS System

Qingbei 1 Well is a key exploratory risk well deployed by PetroChina in the southern margin block of the Xinjiang Oilfield. The six-opening liner was run to a depth of 9056 meters, with the actual exploration depth of the bell mouth reaching 7711.33 meters. A composite casing (Φ193.7mm + 168.3mm) was reconnected to the wellhead, cementing the interval from 0 to 7711.33 m, thereby providing favorable conditions for well completion and testing. The schematic diagram of wellbore structure of Qingbei 1 well is depicted in Fig.1. The utilization of oil-based

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mud in this well has resulted in significant challenges in displacement, and the narrow annular clearance (12.7 mm of the unilateral gap) has led to high operational pressures. Notably, the temperature difference between the ground and the bell mouth of the well can reach over 120 ℃, which will result in slow development of the strength of the top CS. These conditions not only place stringent demands on the performance of the equipment but also introduce potential risks to the cementing operation, such as the risk of annular pressure during subsequent production phases. Therefore, to improve substitution efficiency, a displacement-type flushing spacer fluid is employed to thoroughly wet and reverse the removal of residual oil-based mud from the wellbore, thereby enhancing the quality of cement bonding. In addition, to ensure the rapid development of the strength of the top CS, the early-strength agent DRA-2S (inorganic salt) for large temperature differential environment was selected as the key material. And three CS systems (lead/middle/tail slurry) with different thickening times are designed by combining DRA-2S with other additives. Notably, the thickening time of the tail slurry is rationally controlled under safe construction conditions, and the construction displacement rate is properly designed to improve displacement efficiency and ensure the sealing integrity of the cement sheath during later production.

The spacer fluid (designed density 1.75 g/cm³) is composed of 100% clean water, 1.5% DRY-S1, 5% DRY-S3, DRK-3S, 5% DRY-1L, 10% DRY-2L, 150% iron powder, 0.5% DRX-1L, 0.5% DRX-2L, 3% DRF-2L, and 2% DRH-2L. The lead slurry system (designed density 1.90g/cm³) used for cementing the well section from 0 to 1500m is composed of 100% OWC, 5% DRB-1S, 10% DRB-2S, 4.2% micro-silicon, 4% DRE-3S, 4% DRT-1S, 3% DRA-2S, 5% DRF-1S, 2% DRS-1S, 2.5% DRK-3S, 2.5% DRY-S3, 0.5% DRX-1L, 0.5% DRX-2L, 4.6% DRH-2L, and 51.5% on-site water. The middle slurry system (designed density 1.90g/cm³) used for cementing the well section from 1500 to 5700m is composed of 100% OWC, 5% DRB-1S, 10% DRB-2S, 4.2% micro-silicon, 4% DRE-3S, 4% DRT-1S, 3% DRA-2S, 5% DRF-1S, 2% DRS-1S, 2.5% DRK-3S, 2.5% DRY-S3, 0.5% DRX-1L, 0.5% DRX-2L, 4% DRH-2L and 52% on-site water. And the tail slurry system (designed density 1.90g/cm³) used for cementing the well section from 5700 to 7711.33m is composed of 100% OWC, 47% DRB-2S, 3.5% micro-silicon, 4.5% DRE-3S, 3% DRA-2S, 4.5% DRF-1S, 2% DRS-1S, 3% DRK-3S, 3% DRY-S3, 0.5% DRX-1L, 0.5% DRX-2L, 3.7% DRH-2L, 61% on-site water.

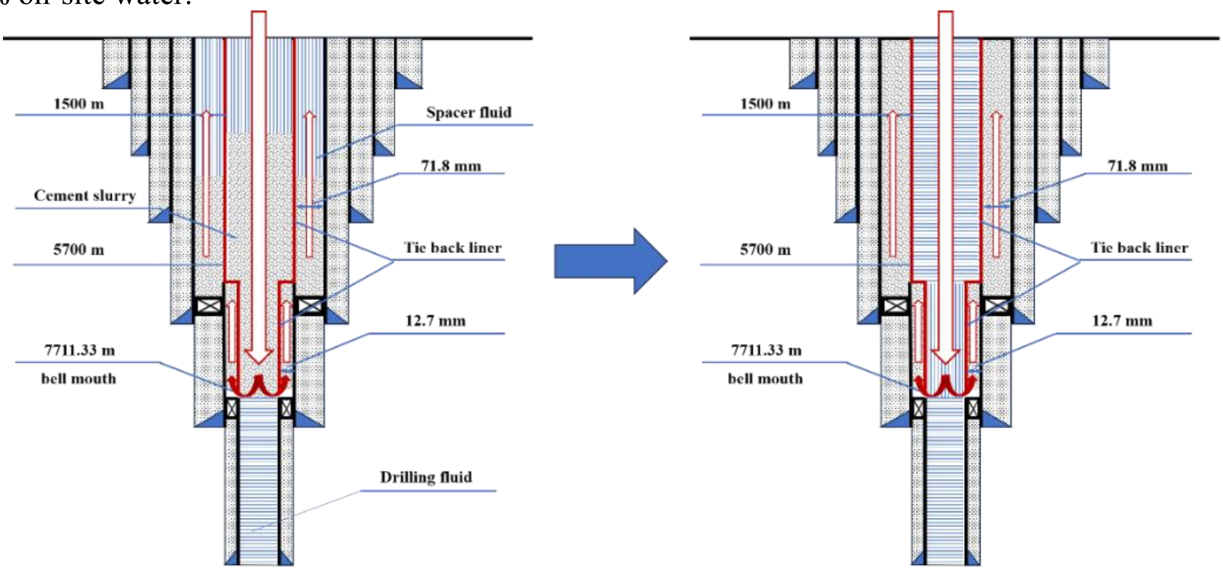

Fig. 1 Schematic diagram of cementing construction of Qingbei 1 well.

2.3 Application Performance Evaluation of Constructed CS

The preparation and performance evaluation of CS were conducted in accordance with the methods recommended in GB/T 19139-2012. The overall properties including density, fluidity, API fluid loss volume (FL_{API}), free liquid volume, stability, thickening performance, rheological

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properties, development of mechanical properties and compatibility with drilling fluid and isolation fluid of prepared CS were measured.

3. Experimental Section

3.1 Comprehensive Performance of CS

The basic properties of the lead/middle/tail cement slurries (CSs) are presented in Table 1. As shown in Table 1, the lead/middle/tail CSs exhibit good fluidity (greater than 18 cm), low API fluid loss volume (less than 100 mL/30min), no free liquid, and excellent sedimentation stability ($\Delta\rho$ < 0.03 g/cm^3). The above results indicate that the constructed CS systems have superior basic properties, meeting the basic requirements for on-site cementing operations [1].

Table 1. The basic properties of lead/middle/tail CSs.

CS	Fluidity (cm)	FL_{API} (mL)	Free liquid volume (%)	Stability ($\Delta\rho$, g/cm^3)
lead	21	42	0	0
middle	21	42	0	0.01
tail	20	40	0	0.01

The rheological properties of the lead/middle/tail CSs were characterized using a six-speed rotational viscometer. The rheological curves and parameters of the CS obtained through fitting the Herschel-Bulkley (H-B) rheological model are shown in Fig. 2. The yield stress (τ_y) of lead/middle/tail CSs were 2.08, 1.81 and 1.57 Pa, respectively. This indicates the formation of a dynamic mesh structure within the CS, which helps to suspend solid particles during static setting [2, 3]. The liquidity indexes (n) of CSs were 0.89, 0.85 and 0.84, respectively. And viscosity coefficient (K) of CSs were 0.49 Pa·s$^{0.89}$, 0.61 Pa·s$^{0.85}$ and 0.68 Pa·s$^{0.84}$. The above results demonstrated that the constructed CSs exhibits typical flow characteristics of plastic fluid. The appropriate value of n and K can reduce construction pressure and improve displacement efficiency during pumping. Therefore, the constructed CSs exist the excellent rheological properties and settlement stability at high temperatures.

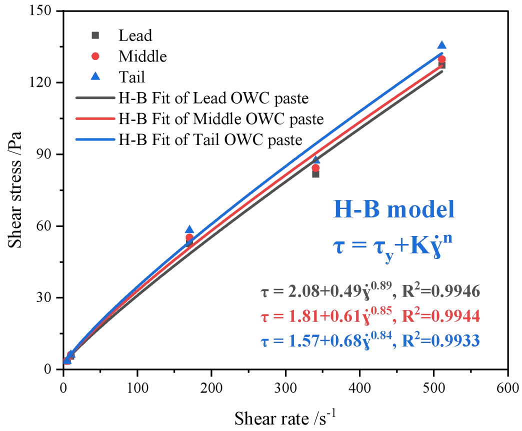

Fig. 2 The rheological curves of lead/middle/tail CSs.

The thickening performance of CS is directly related to construction safety. Therefore, the thickening time of lead/middle/tail CSs with normal point (1.90g/cm^3) and high point (1.93g/cm^3) of density at 120 ℃ and 125 ℃ were measured, the results are listed in Table 2. The thickening time of lead/middle/tail CSs with 1.90 g/cm^3 at 120 ℃ were 456, 377 and 301 min, respectively, which meets the time requirements for cementing construction. In addition, compared to 120 ℃, the thickening time of CSs with 1.90 g/cm^3 at 125 ℃ slightly reduced, which indicates that there is no inverted phenomenon (i.e., the thickening time prolongs as the temperature increases,) in the thickening performance of CS [4, 5]. Moreover, the thickening time of CSs with 1.93 g/cm^3 at

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120 ℃ was not significantly different from that of the CSs with 1.90 g/cm^3. This suggests that the fluctuation of density of CSs during on-site mixing has little effect on the thickening performance of CSs, which ensures the safety of cementing construction. Notably, the consistency evolutions of the thickening curves of lead/middle/tail CSs were relatively smooth and almost at a right angle, with no abnormal gelation phenomena such as consistency bulge [6].

Table 2. Results of thickening measurements of lead/middle/tail CSs.

CS	Density, Curing condition	Thickening Time (min/70Bc)
lead	1.90g/cm^3, 120℃×143MPa	456
	1.90g/cm^3, 125℃×143MPa	401
	1.93g/cm^3, 120℃×143MPa	415
middle	1.90g/cm^3, 120℃×143MPa	377
	1.90g/cm^3, 125℃×143MPa	311
	1.93g/cm^3, 120℃×143MPa	314
tail	1.90g/cm^3, 120℃×143MPa	301
	1.90g/cm^3, 125℃×143MPa	249
	1.93g/cm^3, 120℃×143MPa	261

As depicted in Fig. 3, the compressive strength at the top of middle CS after curing at 93 ℃ for 24 h reached to 11.4 MPa. In addition, the compressive strength of tail CS reached to 17.5 MPa and 21.6 MPa after curing 110 ℃ (the top of tail CS) and 150 ℃ (the bottom of tail CS) for 24 h, respectively. Notably, the compressive strength at the top of lead CS after curing at 25 ℃ for 72 h reached to 10.1 MPa. The compressive strength of constructed CSs meet the requirements of cementing construction, which is beneficial for subsequent drilling construction. The rapid development of compressive strength can be attributed to the addition of early-strength agent, which can accelerate the hydration of cement minerals and the generation of hydration products [7].

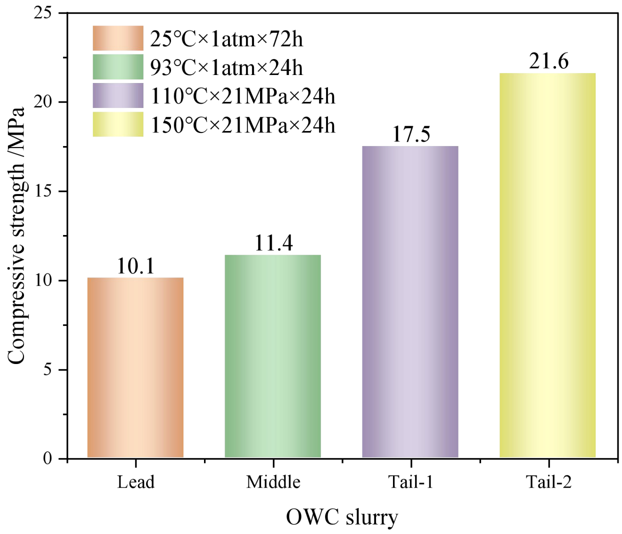

Fig. 3 The compressive strength of lead/middle/tail CSs.

Moreover, the development of static gel strength and compressive strength of tail CS curing at 110 ℃ and 130 ℃ were monitored in real by ultrasonic method using a static gel strength analyzer, results are presented in Fig .4. As depicted in Fig .4(a), for the top of tail CS, the transition time of static gel strength from 48 Pa to 240 Pa was 72.5 min, and the time of 0.1 MPa and 1.0 MPa for compressive strength were at 362 and 393 min, respectively. Additionally, for the entire tail CS, the transition time was 9 min, and the time of 0.1 MPa and 1.0 MPa for compressive strength were 201 and 211 min, respectively. Notably, a short transition time is beneficial for reducing the risk of gas migration and avoiding annular pressure during later production [8, 9]. The rapid development of

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tail slurry strength is beneficial for performing the subsequent cementing construction and shortening cementing construction time.

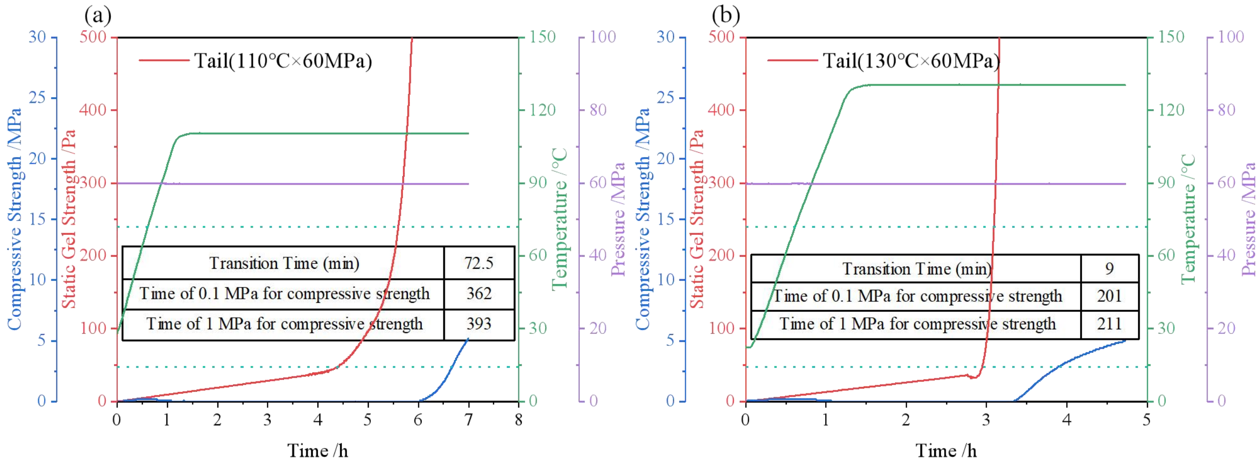

Fig. 4 The development curve of static gel strength and compressive strength of tail CS.

3.2 Anti-Pollution Performance of CS

Since Qingbei 1 Well utilizes oil-based drilling fluid, it is prone to forming an oil film on the casing wall and Wellbore surface, leading to displacement difficulties and affecting the quality of cement interface bonding. To ensure displacement and cleaning efficiency, a highly efficient oil-displacing flushing spacer fluid was constructed. Since the rheological properties of the spacer fluid are directly related to displacement and cleaning efficiency, the rheological properties of the spacer fluid were tested using a six-speed rotational viscometer. The rheological curve and parameters of the spacer fluid were obtained by fitting the test results using the Herschel-Bulkley (H-B) rheological model, and the results are presented in Fig. 5. The spacer fluid exhibits the flow characteristics of a non-Newtonian plastic fluid with shear-thinning properties. And the yield stress (τ_y), liquidity indexes (n) and viscosity coefficient (K) were 1.67 Pa, 0.83, and 0.22 Pa·$s^{0.83}$. These results suggest the constructed spacer fluid has excellent rheological properties and settling stability, which helps to improve the displacement and flushing efficiency of the spacer fluid.

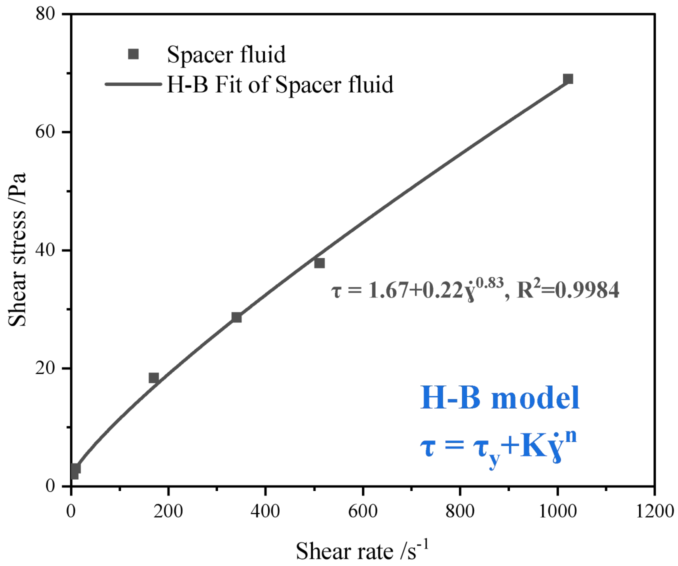

Fig. 5 The rheological curve of spacer fluid.

The severe contamination of the CS by the drilling fluid (manifested as an increase in CS consistency and a shortening of thickening time) poses significant risks to cementing operations. Therefore, the compatibility evaluation between lead CS, drilling fluid, precursor slurry and

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isolation fluid is extremely important. The compatibility evaluation results are listed in Table 3. As presented in Table 3, the thickening times of mixed slurry with different proportions of lead CS, drilling fluid, spacer fluid and precursor slurry were longer than the cementing construction time. And the mixing of other wellbore fluids has a relatively small impact on the thickening time of CS, effectively ensuring the safety of cementing construction.

Table 3. Compatibility evaluation results of lead CS with spacer fluid and drilling fluid.

Mixing types and proportions by volume of slurries (v/v%)	Thickening Time
lead CS: spacer fluid = 9:1	500 min/70Bc
lead CS: spacer fluid = 7:3	425 min/70Bc
lead CS: drilling fluid: spacer fluid = 7:2:1	466 min/70Bc
lead CS: drilling fluid: spacer fluid = 7:1:2	500 min/21Bc
lead CS: precursor slurry = 7:3	373 min/70Bc
lead CS: precursor slurry: spacer fluid = 7:2:1	452 min/70Bc
lead CS: precursor slurry: spacer fluid = 7:1:2	490 min/70Bc
lead CS: spacer fluid: precursor slurry: drilling fluid = 7:1:1:1	413 min/70Bc

4. Summary

Relying on the self-developed inorganic salt-based early-strength agent DRA-2S for large temperature differential environment, a series of CS systems suitable for the large temperature differential environment of ultra-deep wells with ultra-long cementing intervals were constructed and applied during the cementing construction of the tie back liner of Qingbei 1 Well. This study can draw the following conclusions:

(1) The constructed CS systems feature high fluidity, low fluid loss, no free liquid, strong sedimentation stability, and excellent rheological and thickening properties. Notably, the constructed CS systems have a rapid development of early compressive strength at low temperatures (reaching 10.1 MPa after curing at 25 ℃ for 72 h) and a short transition time for static gel strength development at high temperatures.

(2) The constructed CS system has good compatibility with wellbore fluids such as drilling fluid, spacer fluid and precursor slurry. The mixing of wellbore fluid has almost no effect on the thickening performance of CS, meeting the requirements of cementing construction.

In summary, the constructed CS system for large temperature differential environment exhibits superior comprehensive performance, can meet the requirements for field construction performance, and is expected to shorten the well construction cycle and save drilling costs.

Acknowledgements

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