

Article

A Study on the Integrity Evaluation of Cement Sheaths for Deep Wells in Deep Water

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Abstract: The complex temperature and pressure conditions of deepwater wells have a serious impact on cementing quality. Therefore, the integrity of the cement seal becomes a critical factor that can restrict the safety of the wellbore, especially for wells ranging from the conventional deep water to deep water with more prominent deep stratum problems. The operating conditions of deep wells in deep water (referred as the dual-deep well) are complex and harsh. For the conventional evaluation device, it is difficult to accurately simulate the alternating HTHP conditions and to clarify the location and situation of the cement sheath leakage, which directly leads to the deviation of the evaluation results from the engineering reality. To solve this defect, based on the condition and structure characteristics of dual-deep wells, a device and method for casing/cement sheath/formation seal integrity evaluation for dual-deep wells at HTHP has been developed and established. Combined with the analysis of microstructure and micromorphology, the sealing ability and integrity of different cement slurry systems were evaluated. Through this study, a set of cement slurry systems suitable for dual-deep wells is selected that can satisfy the requirements of dual-deep wells with excellent isolation ability and seal integrity under temperature and stress changes. The research results provide a reference for deepwater wells' wellbore integrity evaluation and research.

Keywords: cement sheath; integrity evaluation; HTHP; dual-deep well

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1. Introduction

With the theoretical innovation and technical breakthrough of offshore oil industry in the field of deep water, dual-deep wells have become a hot spot of exploration and development. Dual-deep wells face more complex environmental conditions than conventional deepwater wells. The casing-cement-formation assembly formed after cementing can easily form micro-annulus under the temperature and pressure stress changes, resulting in cement sheath isolation failure. The formation fluid intrudes into the micro-annulus and migrates upward, which not only causes serious oil, gas, and water interflow and causes waste of resources but also easily causes annular pressure and threatens well quality and operator safety [1–4]. Conventional cement sheath integrity evaluation methods cannot simulate the cementing II interface under the combined effects of alternating temperature and pressure, internal pressure, and confining pressure, which makes the evaluation of integrity inaccurate, affecting the cementing quality and even leading to the risk of wellbore integrity [5].

Based on the well structure and working condition characteristics of dual-deep wells, this study developed and established a device and method for evaluating the integrity of the casing/cement sheath/formation seal in a dual-deep well. Based on the microstructure of the cement sheath, the sealing integrity of different cement slurry systems was analyzed and the failure of cementing interface I, cementing interface II, and the cement sheath was evaluated. The measures to improve the integrity of the cement sheath were put forward, and the cement slurry system suitable for a dual-deep well was optimized.

2. Evaluation Method of Cement Sheath Integrity in a Dual-Deep Well

The cement slurry is injected into the annulus through the casing string during the cementing. As the cement solidifies, it forms a cement sheath and binds the casing string to the borehole wall rock. The stress, the deformation, and the crustal stress of the string are also consolidated in the cement sheath. Therefore, the analysis of channeling, leakage, and internal defects of the casing/cement sheath/formation combination is an important basis for evaluating the sealing performance of a cement sheath [6].

2.1. Domestic and Overseas Research on the Integrity Evaluation of the Cement Sheath

According to their own characteristics and research content, domestic and foreign research teams have established a series of casing/cement sheath/formation combination simulation devices. The well-known company A takes the outer casing/cement sheath/inner casing three-layer structure through a plastic or rubber sleeve to achieve the purpose of applying a confining pressure test channel and observe the sealing of cement sheath after several temperature cycles.

The well-known company B adopts a three-layer structure of outer plastic/intermediate cement sheath/inner casing and observes the nucleation and propagation of cracks in the cement sheath after simulating alternating cycles of internal pressure several times. By testing the peel strength of the cementing I interface, the relationship between mechanical properties and fatigue properties of the cement sheath is obtained [6].

Based on the principle of approximate equivalent stress, Lin Yuanhua et al. [7] applied stress equivalent to that of the actual cement sheath to the simulated wellbore and detected the failure of the cement sheath by means of channeling, CT scanning, and SEM observation so as to develop an experimental device to evaluate the integrity of the cement sheath. The device fully considers the influence factors such as casing pressure, simulated formation confining pressure, annular pressure, and annular temperature, which can provide strong support for cement sheath evaluation and cement material modification research.

Cao Yanfeng et al. [8] considered the coupling effect of multiple factors, such as casing pressure, simulated formation confining pressure, annular pressure, and temperature, and developed a device consisting of a wellbore physical simulation system, a confining pressure application and control system, casing pressure, annular pressure, and a temperature control and sealing system.

The cement sheath integrity device designed by Liu Naiguang et al. [9] sets bubble detection holes in the upper and outer cylinder and connects the gas flowmeter so as to realize bubble detection and gas flow test when the cement seal is damaged.

The evaluation device designed by Yang Zhenjie et al. [10] evaluates the impact toughness and isolation reliability of cement by applying extrusion pressure on a steel pipe to simulate the formation of microcracks in the cement ring and, at the same time, ventilate the cement stone face or simulate the seepage effect of formation with water. However, the device only considers the damage deformation of cement stone and does not consider cement as a ring structure for simulation evaluation, which has limitations.

A three- or four-layer composite structure is widely used in casing/cement sheath/formation combination testing equipment domestically and overseas and rubber or a large size rock is used to simulate the formation. The evaluation device is unable to define the location and situation of the channeling leakage and unable to refine the simulation of cementing I and II interfaces and the complex working conditions of the wellbore. The material and experimental conditions of the composite sample are different from those of the actual wellbore, and the device is unable to simultaneously detect the cementation of the cementing I interface and the cementing II interface and their isolation ability. It is impossible to evaluate the integrity of the casing/cement/formation combination in a dual-deep well.

2.2. Integrity Evaluation of the Cement Sheath

To get closer to the actual situation, the influence of a wellbore casing pressure test on the assembly was simulated and the casing pressure was pressurized until the pressure

in the inner cavity reached the internal pressure determined by deepwater wells and the inner pressure of the casing cavity was maintained during the evaluation experiment. The cement system to be evaluated was formulated and continuously and smoothly injected into the annular space of the casing/cement sheath/formation assembly. After the bubbles were eliminated by vibration, the combination was slowly and smoothly placed in a high-temperature autoclave body. The environmental medium was added to the kettle, and the kettle was kept sealed. The temperature and pressure of the kettle body reached the cement sheath curing temperature of 250 °C and curing pressure of 70 MPa. After the end of maintenance, the internal steel wire was pulled out of the channeling pipeline and the pressure gauge connected to allow the assembly to invade the water and boost the channeling step by step. Finally, industrial CT was used to comprehensively analyze the integrity evaluation of the cement sheath body, the cementing I interface, and the cementing II interface, and the morphology and size of defects such as microcracks and bubbles in cement sheath were detected by scanning electron microscope (SEM). Comprehensive analysis of the cementing I interface between the casing and the cement sheath, the cementing II interface between the cement sheath and formation rock, and its cementing ability was carried out so as to analyze and evaluate the sealing integrity of the casing/cement sheath/formation assembly.

2.3. Development of a Cement Sheath Integrity Evaluation Test Device

2.3.1. Design Ideas

To evaluate the cement slurry system more accurately, a cement sheath integrity evaluation test device was developed according to the characteristics of temperature and pressure conditions in a dual-deep well and combined with the requirements of field cementing technology, as shown in Figure 1. The design ideas are as follows:

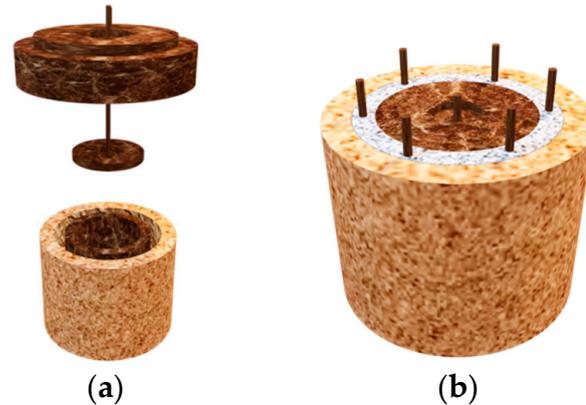


Figure 1. The 3D structure of a cement sheath seal integrity evaluation device: (a) cement slurry curing and maintenance; (b) posteriori channeling after disassembly.

1. Accurate wellbore simulation:

According to the well structure, petrophysical property, and wellbore operating parameters of the dual-deep well to be evaluated, the composite sample is determined. The compact size of the assembly is calculated according to the similarity principle, and the optimal Euclidean distance is reasonably designed to obtain the outer diameter, the inner diameter, and the wall thickness of the formation rock, the cement sheath, and the casing.

2. Error check:

The compact size seal integrity evaluation device designed by finite element analysis is similar to the casing and the cement sheath of an actual dual-deep well. It is confirmed that the stress and the strain of each component of the device are consistent with those of the actual deepwater well under the condition of simulated formation condition and the error meets the requirements of the simulation test.

3. Clear environmental variables:

The cement sheath curing temperature, pressure, and time and the casing and formation, respectively, under internal pressure, confining pressure, environmental media, and test channeling pressure are determined. According to the requirements of the size, temperature, pressure, and medium for the material of the assembly, the integrity evaluation device for the formation seal of the HTHP casing cement sheath is processed.

4. Check device performance:

A pressure test is carried out on a high-temperature autoclave and casing/cement sheath/formation combination, respectively, to confirm the reliability of the device performance and integrity performance to meet the requirements of experimental temperature and pressure.

2.3.2. Device Introduction

The assembly sample is designed in a compact way, and the developed seal integrity evaluation device includes three parts, a high-temperature autoclave, a temperature and pressure control system, and a simulated casing/cement sheath/formation assembly, as shown in Figures 2 and 3.

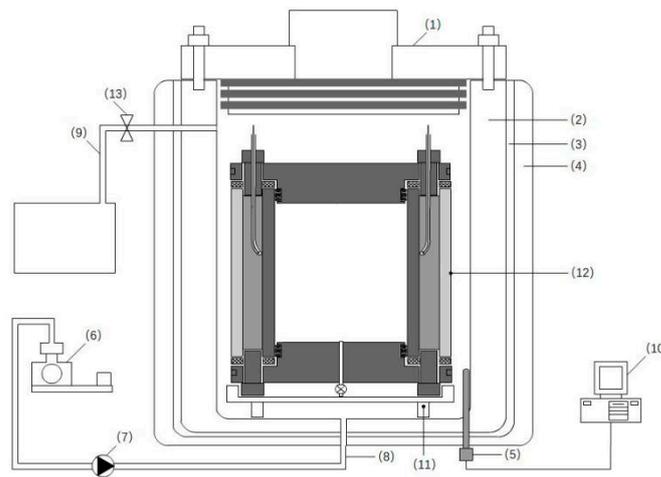


Figure 2. Casing/cement sheath/formation seal integrity evaluation device.

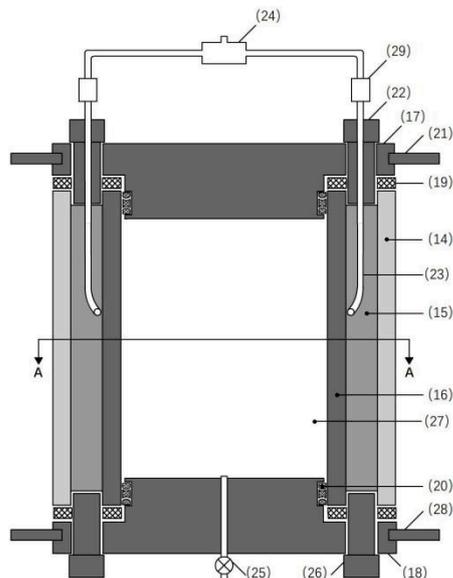


Figure 3. Profile of the simulated sample of the casing/cement sheath/formation assembly.

HTHP environment conditions for simulating seal integrity evaluation in a high-temperature autoclave:

(1) The kettle cover; (2) the kettle body; (7) the inlet check valve; (8) the intake pipeline; (9) the gas outlet pipeline; (11) the stent; and (13) the exhaust valve.

Temperature and pressure control system to monitor temperature and pressure during sheath seal integrity evaluation:

(3) The heating sleeve; (4) the thermal insulation layer; (5) the temperature pressure probe; and (6) the booster pump.

Simulation of the casing/cement sheath/formation assembly to simulate the HPHT well assembly:

(14) Stratigraphic rocks; (15) the cement sheath; (16) the casing; (17) and (18) the assembly upper/lower cover plate; (19) and (20) the combination/casing seal sheath; (21) and (28) the combined upper/lower cover handle; (22) and (26) the assembly upper/lower cover plug; (23) checking channeling pipelines; (24) checking channeling manifold; (25) the casing valve; (27) the casing cavity; (29) the straight connector; and (30) steel wire.

2.3.3. Installation Feasibility Verification

The ANSYS finite element was used to analyze the stress and strain changes of the actual wellbore, the casing, and the cement sheath in the designed evaluation device when working condition A changed to working condition B, so as to verify the reliability of the seal integrity evaluation device, as shown in Figures 4 and 5.

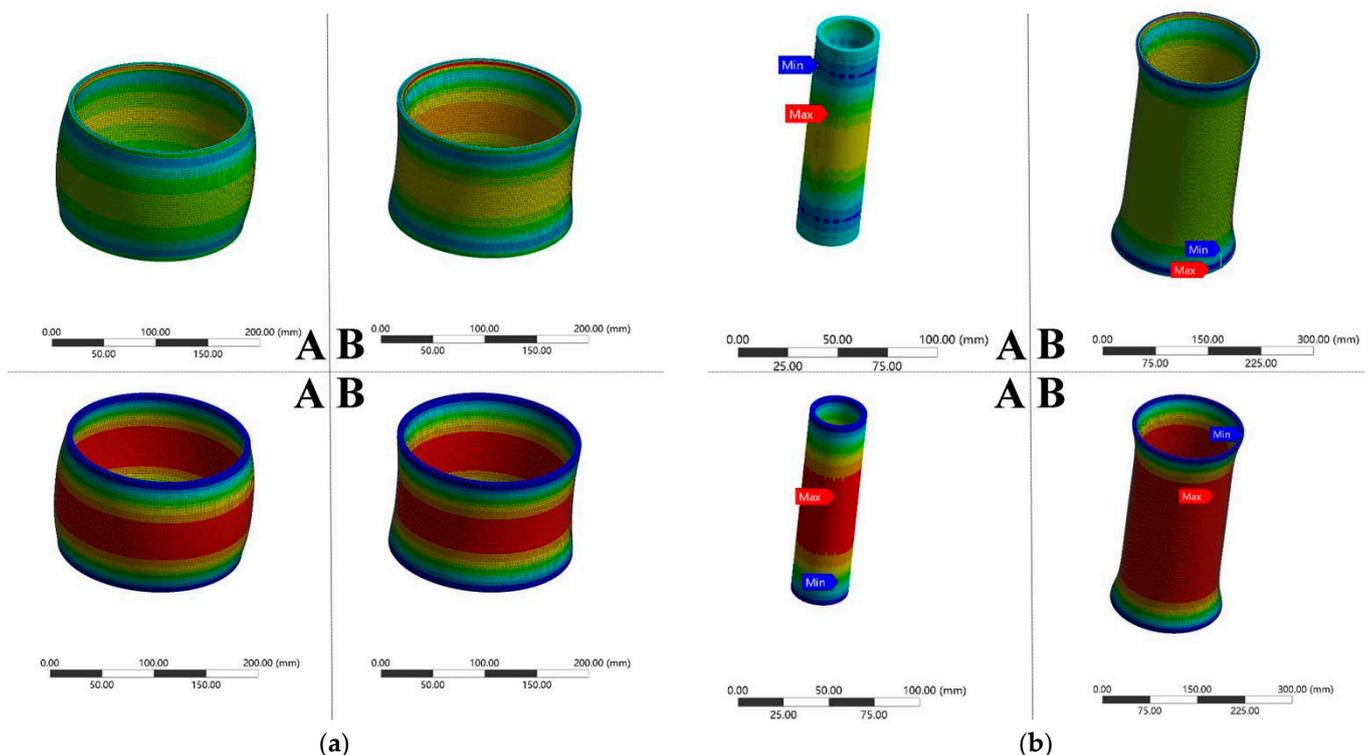


Figure 4. Comparison of casing stress and strain distribution under different conditions: (a) wellbore casing stress/strain distribution changes and (b) evaluate the variation in casing stress/strain distribution.

Condition A: The pressure in the casing is 20 MPa and the temperature is 25 °C.

Condition B: The pressure in the casing is 20 MPa, the confining pressure is 70 MPa, and the temperature is 250 °C.

A comprehensive comparison shows that when working conditions change, the increasing trend of stress and strain of the designed seal integrity simulation evaluation device is consistent with that of the actual wellbore and the casing stress and strain level of

the evaluation device is consistent with that of the actual wellbore under HTHP. It shows that the device can simulate the characteristics of increasing stress and the deformation of the casing and the cement sheath with the change in temperature and pressure when the temperature and pressure increase, which meets the basic requirements of cement seal evaluation in a dual-deep well.

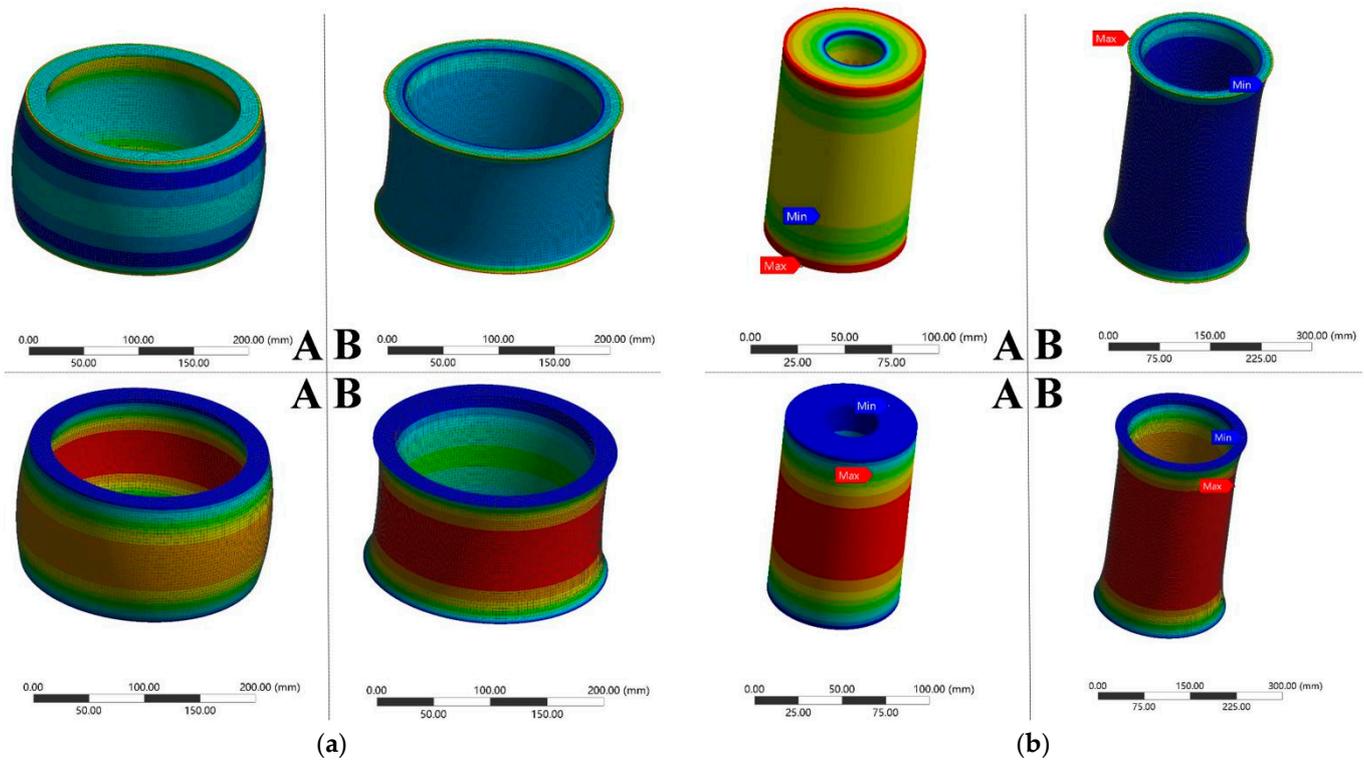


Figure 5. Comparison of stress and strain distribution of cement sheath under different conditions: (a) wellbore cement sheath stress/strain distribution changes and (b) evaluate the variation in cement sheath stress/strain distribution.

3. Experimental Study on Seal Integrity Evaluation of a Cement Sheath in a Dual-Deep Well

3.1. Basic Information of the Test

The designed seal integrity device was used to simulate the working conditions of a dual-deep well casing pressure test of 20 MPa, confining pressure of 70 MPa, and temperature of 250 °C. According to the formula of different cement slurry systems in dual-deep wells, as shown in Table 1, the composites SL I-1, SL II-1, SL II-2, SL II-3, and SL III-5 were prepared. After curing the composites at 250 °C for 4 days, the bonding status of interface I and interface II of the cement sheath was observed and whether cracks existed in the composite body was observed by the naked eye. The sealing integrity of the cement stone was evaluated by the 0–10 MPa differential pressure channeling method, as shown in Table 1.

3.2. Integrity Test Evaluation Results

According to the seal integrity evaluation test, the bodies of the composite SL I-1 cement sheath, the cementing I interface, and the cementing II interface have completely lost sealing integrity. There is leakage between the cement sheath and the cementing I interface and between the cement sheath body and the cementing II interface, showing that the seal integrity is almost lost. The combination SL II-2 can suppress the pressure when the pressure is 10 MPa, and only small discontinuous bubbles appear locally, which shows a certain degree of sealing integrity. The SL III-5 cement sheath has channeling between

part of the body and the cementing I interface and the cementing II interface and has a certain degree of isolation ability. The test results of the seal integrity are shown in Table 2.

Table 1. Formulation system table of dual-deep well cement slurry.

Name	SL I-1	SL II-1	SL II-2	SL II-3	SL III-5
Cement	SD-G 50.37%	SD-G 46.74%	SD-G 46.97%	SD-G 46.44%	SD-G 47.2%
Thermal stabilizer	PC-C82 17.63%	C-Si80S 23.37%	C-Si80S 23.49%	C-Si80S 23.22%	TC-Si70S 23.61%
Water	19.64%	18.21%	20.15%	15.48%	22.41%
Defoaming agent	PC-X66L 0.5%	C-DF64L 0.47%	C-DF64L 0.47%	C-DF64L 0.46%	PC-X61L 0.47%
Drop water loss	PC-G80L 1.81%	C-FL80L 1.87%	C-FL80L 3.28%	C-FL80L 1.39%	C-FL80L 3.07%
The gas channeling agent	PC-GR5 3.02%	C-GR7 8.41%	C-GR7 4.70%	C-GR7 12.07%	PC-GS12L 8.32%
Retarder	C-R40L 0.08%	C-R40L 0.93%	C-R40L 0.94%	C-R40L 0.93%	C-R22L 1.81%

Table 2. Five cement sheath seal integrity test results.

Combination	The Surface State and Characteristics of the Combination	The Result of Channeling	Leakage and Seal Integrity
SL I-1	Numerous microcracks on the surface	The bubbles all originate from the crack site.	Complete channeling between the body, the cementing I interface, and the cementing II interface; loss of sealing.
SL II-1	Body crack	The channeling pressure is only 0.55 Mpa, and channeling leakage occurs.	The body, the cementing I interface, and the cementing II interface are completely channeling, with almost no sealing.
SL II-2	No obvious microcracks	There is no obvious leakage when the channeling pressure is 1 MPa, there is small channeling leakage when the pressure is 3 Mpa–5 Mpa, and there is discontinuous small channeling leakage when the pressure reaches 10 MPa, which can suppress the pressure.	There are small leakages between the cement body and the cementing I interface and between the cement body and the cementing II interface, which can contain pressure and provide a degree of seal integrity.
SL II-3	Cracks on the surface of the body	There is no obvious leakage when the channeling pressure is 1 MPa, there is small channeling leakage when the pressure is 3 Mpa–5 Mpa, and there is discontinuous small channeling leakage when the pressure reaches 10 MPa, which can suppress the pressure.	There is leakage between the cement sheath body and the cementing I interface and between the cement body and the cementing II interface. Seal integrity is almost lost.
SL III-5	Cracks on the surface of the body	At 1 Mpa–5 Mpa, discontinuous microbubbles appear in local areas, and discontinuous microbubbles appeared at 10 MPa.	There is a channeling between the cement sheath body and the cementing I interface and the cementing II interface, which has a certain degree of isolation ability.

In summary, the cement sheath of the composite SL II-2 has no obvious crack and can suppress pressure at 10 MPa test pressure and only small discontinuous bubbles appear locally. The cement sheath has a certain degree of sealing integrity at 20 MPa internal pressure, 70 MPa confining pressure, and 250 °C, which is the best group of sealing integrity among the five combinations.

3.3. Study on Cement Sheath Seal Integrity Cement Slurry Performance Requirements

Based on the test results of the cement sheath prepared by five kinds of cement slurry systems, suggestions on the selection of various additives are obtained, as shown in Table 3.

Table 3. Five cement sheath seal integrity test results.

Type of Admixture	Impact on Seal Integrity	Suggestions on Selection of Auxiliaries
Defoaming agent	The number and size of bubbles in the SL II-2 cement sheath were significantly reduced. The isolation capability and seal integrity are superior to that of SL I-1.	C-DF64L > PC-X66L C-DF64L dosage 1%
Dispersant	There was no aggregation of white additives in the upper part of SL I-1, and its dispersity was better than that of SL III-5.	PC-F41L > TC-F31L
Drop water loss	SL II and SL III-5 can resist certain test channeling pressure and the internal channeling is not complete; their sealing ability is superior to that of SL I.	C-FL80L > PC-G80L C-FL80L dosage 7%
The gas channeling agent	SL II series have a certain isolation ability, and their ability to inhibit gas migration and improve the isolation performance is superior to that of SL I series.	C-GR7 > PC-GR5/PC-GS12L C-GR7 dosage 10%
Retarder	The thickening time control of SL II and SL III-5 with C-R40L and C-R22L is more reasonable than that of SL I-1 with PC-H21L to achieve the best matching of early/late strength.	C-R40L > C-R22L > PC-H21L C-R40L dosage 2%
Thermal stabilizer	SL I-1 had better dispersion than SL II and SL III-5. No white additive was found in the high-temperature Cu sheath.	PC-C82 > C-Si80S PC-C82 dosage 50%

In summary, on the basis of SD-G, c-DF64L as a defoaming agent, PC-F41L as a dispersant, C-FL80L as a water-loss agent, C-GR7 as an anti-gas channeling agent, C-R40L as a retarder, and PC-C82 as a heat stabilizer are optimized for the cement slurry system. The composite prepared has a relatively excellent isolation ability and sealing integrity.

4. Microstructure Evaluation of Cement Sheath Integrity in a Dual-Deep Well

According to the evaluation results of the sealing integrity of the casing/cement sheath/formation assembly in a dual-deep well, SL I-1 and SL II-2 with different sealing integrity values were selected. CT scanning and electron microscopy were used to observe the microstructure of the cement sheath, and the damage to the cementing I interface, the cementing II interface, and the cement sheath body was evaluated. The sealing integrity test result of the casing/cement sheath/formation assembly was further defined and validated.

4.1. Microstructure Analysis Method

4.1.1. CT Scanning Analysis of Microstructure of the Cement Sheath

1. Microstructure analysis

After inspecting the leak, the samples were tested by high-resolution CT scanning to obtain the three-dimensional structure data volume of the cement sheath inside the sample. Different substances were extracted by using gray difference for three-dimensional rendering, and cracks, channeling, and leakage in the cement sheath were displayed in three dimensions.

2. Analysis of interface characteristics

The interfacial characteristics of the cementing I interface formed by cementing with casing and the cementing II interface formed by cementing with formation rock were observed by slice pictures of the cement sheath in all directions.

3. Pore extraction

Through slicing and segmentation of the cement slurry system, the pores were extracted and the sealing integrity of the cement sheath was evaluated comprehensively by calculating porosity, crack length, and segment size.

4. Pore–throat analysis based on the maximum sphere algorithm

The principle of maximum ball algorithm: The larger pores are equivalent to balls, and the channels connecting the larger pores are equivalent to throats. Through the analysis of the pore–throat structure, the connectivity of pores was understood and the curve variation rules of throat radius, pore radius, pore–throat ratio, coordination number, throat length, pore shape factor, and throat shape factor were calculated to reveal the sealing integrity of casing/cement sheath/formation combination.

4.1.2. SEM Analysis of Microstructure of the Cement Sheath

The cement sheath in the casing/cement sheath/formation combination was cut into small samples by modified wire cutting equipment, and the microstructure and structure of the cement sheath as well as the location, size, and propagation direction of the internal crack were further analyzed and observed by scanning electron microscopy. The focus was on the microstructure characteristics of the cement sheath body; the interface; and the cross section and longitudinal section of the pipeline, including internal structure uniformity, defect shape and size, crack morphology, and size and propagation direction.

4.2. Microstructure Evaluation and Analysis Results

Based on the evaluation results of cement sheath seal integrity, comprehensive analysis of the microstructure, interface characteristics, pores, and the pore throat of the cement sheath was carried out as follows:

1. Microstructure analysis

Circumferential cracks are evenly distributed in the cement sheath SL I-1, and small size bubbles are distributed along the crack propagation direction. There are large radial cracks and gaps in the cementing II interface. A small number of circumferential cracks appear in the cement sheath SL II-2 body near the cementing II interface, and the interface between the pipeline and the body is clear. Compared with SL I-1, SL II-2 has fewer circumferential cracks and no penetrating microcracks, which obviously has better sealing performance, as shown in Figure 6.

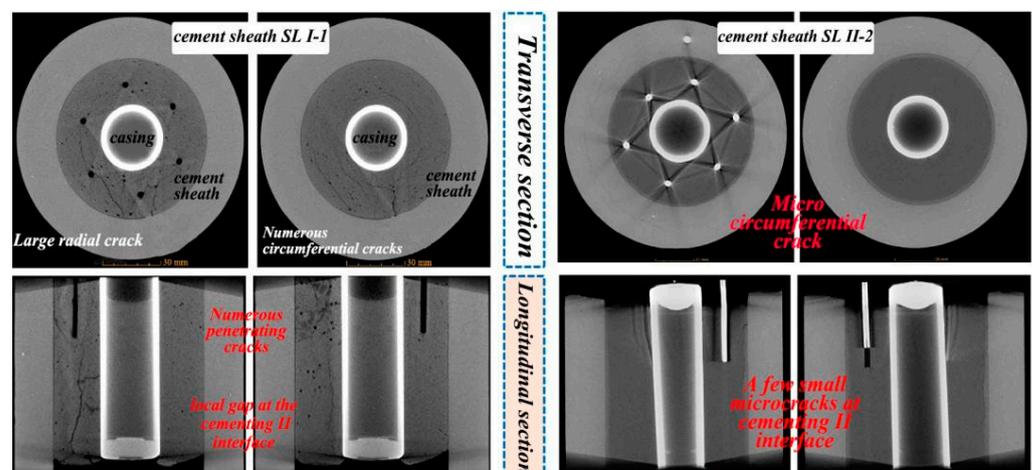


Figure 6. Transverse/longitudinal section of the CT scan.

2. Analysis of interface characteristics

The cement sheath SL I-1 cementing I interface is tightly fitted. Circumferential cracks in the cement sheath squeeze the outer rock, causing it to crack and form a large-size crack that creates a gap at the cementing II interface. The cement sheath SL II-2 cementing I interface is tightly fitted, and only a few microcracks are generated in the process of temperature rise and pressure boost and cooling and pressure relief, but no large cracks are formed. Only a few microcracks are generated in the cement sheath SL II-2 cementing I interface, which has certain sealing integrity, as shown in Figure 7.

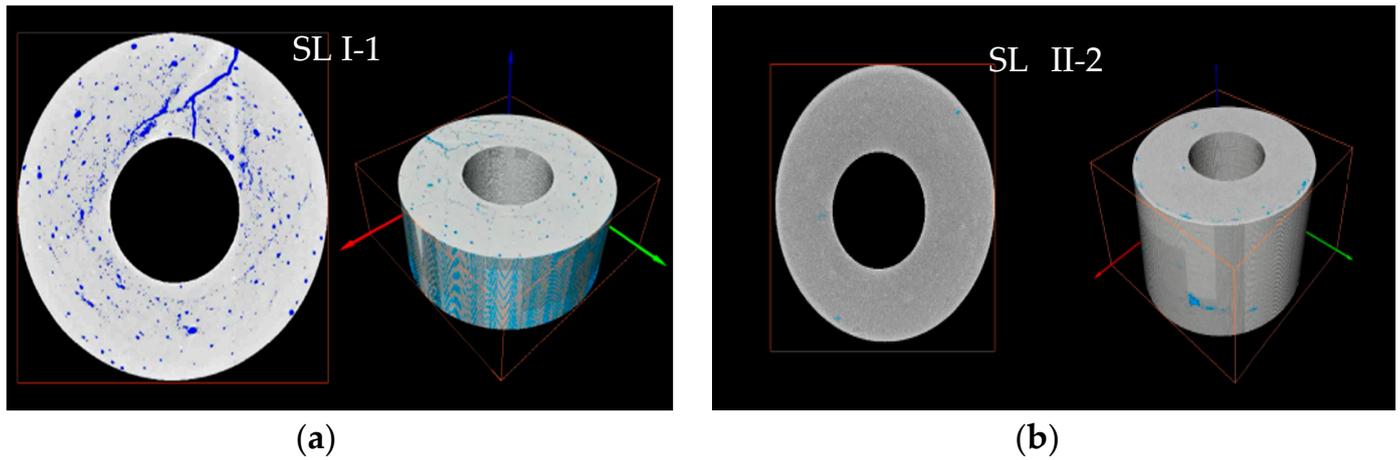


Figure 7. Interface characteristics of the cement sheath by CT scanning: (a) SL I-1; (b) SL II-2.

3. Pore extraction/pore-throat analysis

The cement sheath SL I-1 has a porosity of 2.31%, a maximum pore radius of 1.35 mm and an average of 221.807 μm , and a distribution range of 50–400 μm . The cement sheath SL II-2 has a porosity of only 1.40%, with a maximum pore radius of 302.737 μm and an average of 102.182 μm , and a distribution range of 40–160 μm . The pore equivalent diameter is small, the number of pores is small, and there is no channeling-leakage channel, as shown in Figure 8.

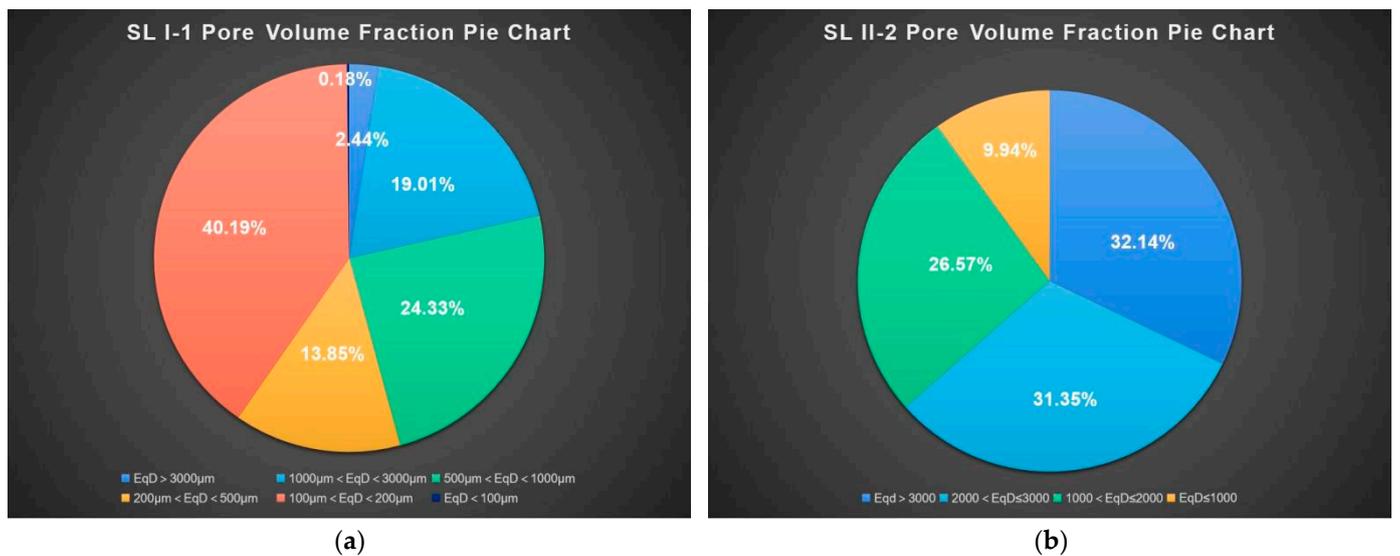


Figure 8. Pie chart of the pore volume fraction of the cement sheath scanned by CT: (a) SL I-1; (b) SL II-2.

4. SEM microscopic morphology analysis

A large number of cracks with a large size, penetrating type, and irregular expansion are distributed in the cement sheath SL I-1, and local cracks rapidly expand and bifurcate more. The cement sheath SL II-2 cementing II interface is clear and smooth, and no obvious cracks or cracks are observed even when magnified to 1000 \times , indicating that the interface bond between the cement sheath and rock is in good condition, as shown in Figure 9.

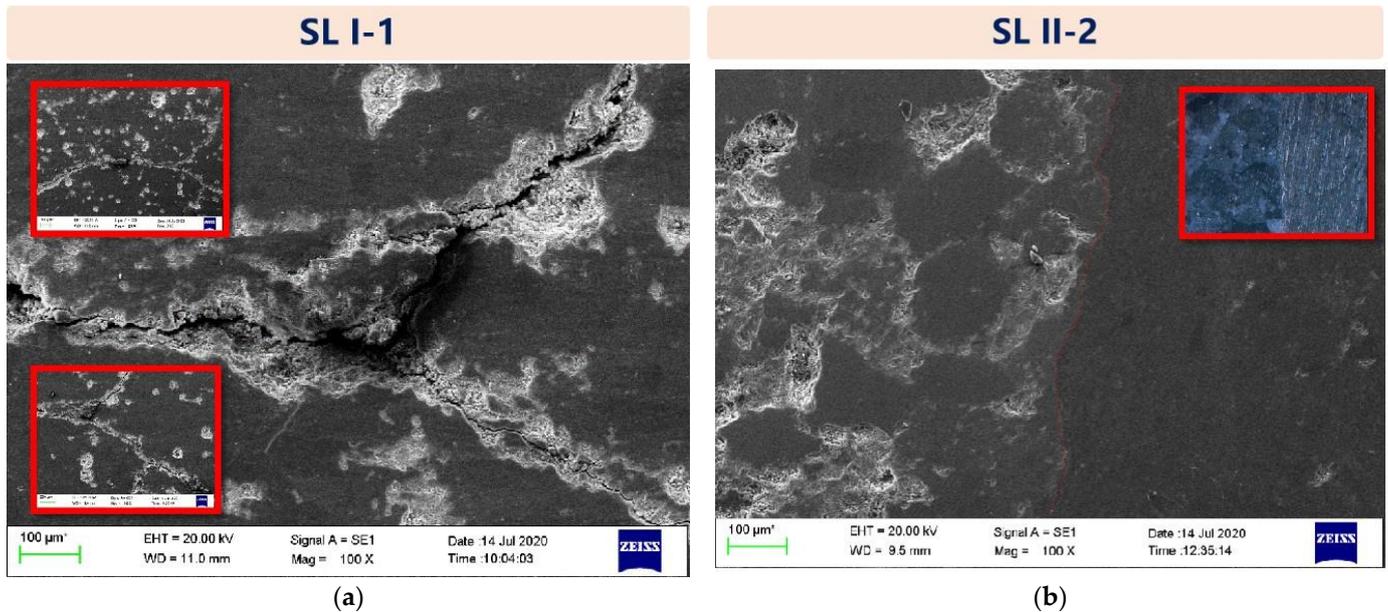


Figure 9. SEM micromorphology analysis of crack distribution characteristics: (a) SL I-1; (b) SL II-2.

In conclusion, there are a large number of circular deformation points about 100 μm in size in SL I-1, which firstly undergo elastic deformation, crack source nucleation, brittle fracture, and rapid propagation, showing a large number of large-size, penetrating, and irregular propagation cracks, which significantly affect the sealing ability of cement sheath SL I-1. The result is complete channeling between the cementing I interface, the body, and the cementing II interface, resulting in loss of seal integrity. Although the cement sheath SL II-2 also has a large number of deformation points, only elastic deformation occurs at the deformation point; a small number of cracks of 10 μm length appear locally, and not near the deformation point; the pressure is normal in the process of checking the channel; there is no obvious leakage; and the cement sheath has good sealing performance.

4.3. Study on the Microstructure of Cement Sheath Seal Integrity

The analysis results show that pores and pore throats are the main causes of leakage in a cement sheath, so controlling pores, pore throats, and cracks is a necessary condition to ensure the sealing ability and integrity of the cement ring. At the same time, when the cement sheath is exposed to extreme temperatures and pressure under the action of alternating thermal stress, such as load in the direction of microcracks, internal defects formed under the influence of outer load, the maximum principal stress along the β angle of an elliptical crack, and load that deform circular points into elliptical points, larger cracks are formed and negatively influence the integrity of the cement sheath seal.

5. Conclusions

1. A cement sheath seal integrity evaluation device suitable for a dual-deep well was developed.
2. The isolation ability and sealing integrity of casing/cement sheath/formation assemblies prepared by five kinds of cement slurry systems were analyzed and evaluated. The experimental results show that on the basis of SD-G, C-DF64L as a defoaming agent, PC-F41L as a dispersant, C-FL80L as a water loss reducing agent, C-GR7 as an anti-gas channeling agent, C-R40L as a retarder, and PC-C82 as a heat stabilizer are optimized. The composite prepared has relatively excellent isolation ability and sealing integrity.
3. The microstructure and morphology of composites with differing seal integrity were analyzed and evaluated. It is necessary to ensure sealing ability and seal integrity by strictly controlling the pore and pore throat of and cracks in the cement sheath.
4. Future research can further study the cement sheath toughness/flexibility lifting technology, cement sheath performance degradation under deep-well high-frequency vibration, cement sheath quality testing technology, and seal integrity improvement measures.

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