Article

Synthesis and Evaluation of Highly Inhibitory Oil Well Cement Retarders with Branched-Chain Structures

Bin Lv, Jingfu Zhang,* Shuai Xie, Zishuai Liu, Jianjun Zhu, and Ming Xu

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ABSTRACT: Cementing at medium temperature and high temperature (90−150 °C) is facing challenges on account of the properties of the retarders. Except for the thermal stability, abnormal gelation, such as "bulging" and "stepping", often takes place and results in safety problems. In this article, the synthesis of a new retarder DRH-150 was introduced. First, a main chain with thermal-resistant groups, 2-acrylamido-2-methylpropanesulfonic acid-acrylic acid (AMPS-IA-AA) was prepared by free radical polymerization. Second, the retarder with a branched structure was synthesized by the grafting reaction. Evaluation of the construction performance showed that, within the temperature range from 90 to 150 °C, the initial viscosity of the cement slurry with DRH-150 was less than 15 Bc, exhibiting an adjustable thickening time and a dosage sensitivity of less than 20%. Meanwhile, no abnormal gelation phenomenon was observed. Referring to the static gelation, both the transition time and the starting strength time (1 MPa) were short. The overall results proved that the retarder DRH-150 might ensure the safety of well cementing and improve the wellbore sealing effect in deep wells, ultradeep wells, and complex wells.
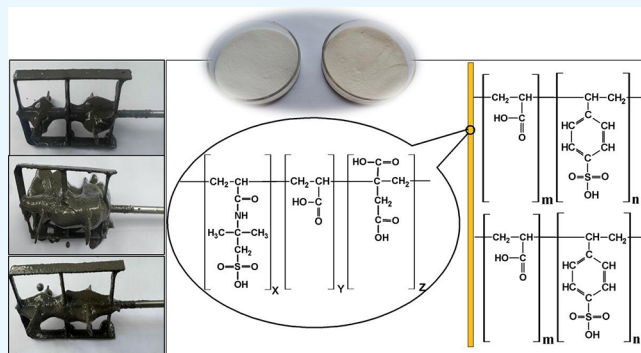
1. INTRODUCTION

With the continuous development of the oilfield and the gradually decreasing reserves, oilfield explorations have been conducted toward deep wells, ultradeep wells, and complex wells. However, it creates challenges to cementing. For example, retarders are often added to the cement slurry during cementing operations to guarantee the injection and safety. Although various types of industrial products have been developed since the 1950s, design and investigation of new-type retarders are still necessary to meet the requirements of the above unconventional wells.

As an indispensable additive in cementing, retarders mainly include lignosulfonate, hydroxycarboxylic acid, polysaccharide, polyol, etc.[1−5] However, in the medium to high-temperature range of 90 to 150 °C, the biomaterials exhibit poor thermal stability due to their small molecular weight and weak chemical bonds. Besides, some other cement retarders are temperature-sensitive with an exponential relation between the thickening time and the concentration. As a result, an ultraretardation of cement slurry would easily take place in the top low-temperature region of the cementing section. Furthermore, these thermally sensitive retarders may be too sensitive to their usage. Even slight fluctuations of the concentration would lead to significant differences in the thickening time, which are not conducive to formulation debugging and safe construction. In particular, although few cement retarders show satisfying temperature resistance and long-lasting retarding properties,

thickening mutations would appear at 110 to 130 °C; several or even dozens of Bc "bulging" and "stepping" are generated in the silicate oil well.[6−9] As the existing study reported, polymeric retarders might overcome the above insufficient conventional retarders. However, most research on polymeric retarders has focused on the adjustment of the functional group and molecular weight. New insight into the micro-structure of polymers and the design of retarder systems is still challenging and has potential.[10−12]

In this article, the molecular structure of polymer-based retarders and the abnormal gelation phenomenon were adequately investigated. All these work were conducted by combining the recent tendency in materials science, chemistry, and polymer synthesis technology.[13−17] A highly inhibitory medium-high temperature cement retarder with a branched chain structure was synthesized and named DRH-150. First, the 2-acrylamido-2-methylpropanesulfonic acid-acrylic acid chain was prepared by free radical polymerization under experimental conditions at 50 °C. Second, sodium styrenesul-

fonate and acrylic acid were grafted onto the polymer main chain under a radiation dose of 30 kGy. Analysis of the infrared spectroscopy and nuclear magnetic resonance spectroscopy showed that the polymer branch chains in the DRH-150 had been successfully grafted onto the main chain. The construction performance evaluation showed that, with a grafting rate of 27.8% and a temperature range of 90 to 150 °C, the initial consistency of the slurry with the DRH-150 retarder was <15 Bc. The thickening time was adjustable and the dosage sensitivity was less than 20%. The consistency curve was standard, and there was no abnormal gelation phenomenon. Besides, the static gelling strength time (1 MPa) could be controlled within 480 min when the thickening time was longer than 300 min. The achievement helps ensure the safety of drilling and construction completion as well as improve the wellbore sealing effect.

2. MATERIALS AND METHODS

2.1. Materials. Acrylic acid (AAc), itaconic acid (IA), 2-acrylamido-2-methylpropanesulfonic acid (AMPS), and sodium styrenesulfonate (SSS) were purchased, which were all commercial products. Deionized water (H_2O) was used as a reaction solvent. Isopropyl alcohol (IPA) was purchased and used as a chain transfer agent. Acetone (Ac) was used for extraction. Ammonium persulfate (APS) was used as an initiator. Sodium hydroxide (NaOH) was used to adjust the pH of the solution. Silica powder with 200 mesh was bought from Hebei Hongrun Quartz Silica Powder Co., Ltd. A kind of polymer dispersant, which was obtained from a polycondensation reaction of aldehyde and ketone, was also bought and used in the preparation of the cement slurry.

2.2. Synthesis of the Retarder. Synthesis of the retarder mainly included two steps: First, the main chain of the retarder was prepared by monomer polymerization. Second, a retarder with branched-chain, named DRH-150, was further synthesized by grafting based on the main chain.

2.2.1. Synthesis of the Main Chain. For preparation, 45 g of AMPS, 7.2 g of IA, and 200 g of deionized water were weighed in a 500 mL reaction flask and stirred thoroughly. Then, 10.35 g of AAc was added and stirred. The pH of the mixture solution was adjusted to 6.8 by 30 wt % NaOH solution and 4 mol/L dilute hydrochloric acid. Afterward, a certain amount of IPA was added, and the total concentration of the monomer was diluted to 15 wt % by deionized water. Finally, 0.13 g of APS was added as an initiator. The synthesis was conducted at 50 °C and N_2 atmosphere. The reaction lasted for 6~8 h, and the production was cooled to room temperature. An excess of Ac solution was added for precipitation. After filtration and drying, the main chain of the high-molecular-weight retarder was obtained.

2.2.2. Synthesis of Retarder DRH-150. The prepared main chain of retarder was dissolved at the concentration of 50 wt %. The solution was placed in a radioactive source for 30 min under a radiation intensity of 30 kGay[18−21] as a prepolymerization solution. The active monomers SSS and AAc were then dissolved in a mass ratio of 1:0.33, and the pH of the solution was adjusted to 7. The above two reaction solutions were mixed and diluted to a concentration of 17 wt %. Similarly, the following synthesis was conducted at 50 °C for 6~8 h at N_2 atmosphere. The product was precipitated by the Ac solution and purified after filtration and drying.

The AMPS-IA-AA intermediate products and DRH-150 are displayed as Figure 1.

AMPS-IA-AA (left), DRH-150 (right)

Figure 1. Photograph of the AMPS-IA-AA polymer main chain and the DRH-150 product.

2.3. Characterization of the Retarder. *2.3.1. Molecular Weight.* The intrinsic viscosity (η) was measured by a Ubbelohde viscometer with an internal diameter of 0.55 mm. The viscosity-average molecular weight $\overline{M_\eta}$ of the sample was calculated according to formula 1:

$$[\eta] = K\overline{M_\eta}^\alpha \tag{1}$$

where K and α are parameters of the Mark−Houwink equation, and $K = 4.75 \times 10^{-3}$, $\alpha = 0.8$ for the aqueous polyacrylamide system.

2.3.2. Grafting Rate. The grafting rate G of the branched retarder DRH-150 was calculated according to formula 2:

$$G = (W_2 - W_1)/W_1 \times 100\% \tag{2}$$

where W_1 is the mass of the grafted main chain AMPS-IA-AA, and W_2 is the mass of the DRH-150 sample obtained after the polymerization reaction. It should be noted that not all the monomers could be grafted to the main chain. Therefore, the grafting rate G in this study represents the maximum grafting ratio of this reaction.

2.3.3. Viscosity. The rheology of the polymer solution was measured using a Brookfield DV-III Ultra rheometer. Experiments were conducted at 25.0 ± 0.1 °C. After the temperature remained constant, the apparent viscosity was obtained at a shear rate of 7.34 s^{-1}.

2.4. Formulation of DRH-150 Cement Slurry. Two cement slurries were prepared referring the National Standard of the People's Republic of China, "GB/T 19139−2012 Oil Well Cement Test Methods", and the Oil and Natural Gas Industry Standard of the People's Republic of China, and "SY/T 5504.1−2013 Evaluation Method for Oil Well Cement Admixture Part 1: Retarder". The specific details are shown as follows:

Formula 1: G-grade cement, DRH-150 retarder, tap water, water-cement ratio = 0.44, ρ = 1.90 g/cm³;

Formula 2: G-grade cement, DRH-150 retarder, 35% silica flour, water-cement ratio = 0.56, ρ = 1.90 g/cm³.

3. RESULTS AND DISCUSSION

3.1. Structure and Characterization of DRH-150. The preparation process of the polymeric main chain and the molecular structure of the retarder DRH-150 are shown in Figures 2 and 3, respectively.

Figure 4 displays the FTIR result of the main chain of the retarder and retarder DRH-50, represented by the blue and red line, respectively. Referring to the blue line, the peak around 3340 cm^{-1} was the stretching vibration of the O−H bond on the oxhydryl group (−OH). The peaks at 2980 and 2930 cm^{-1} were due to the stretching vibration of the methyl group (−CH_3) and methylene (−CH_2−CH_3) on the polymer chain, respectively. The characteristic peak at 1548 cm^{-1} was
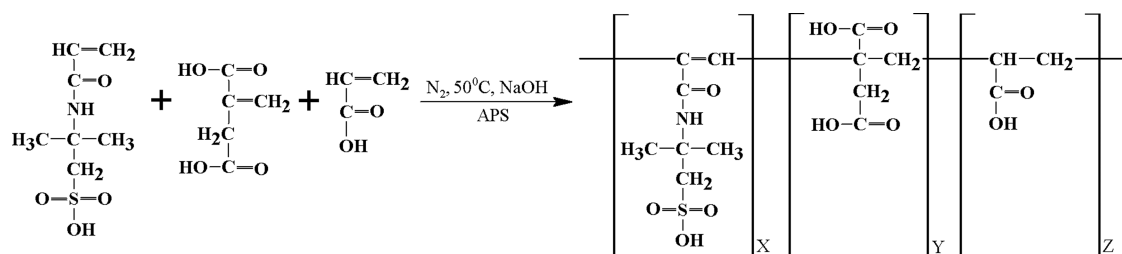
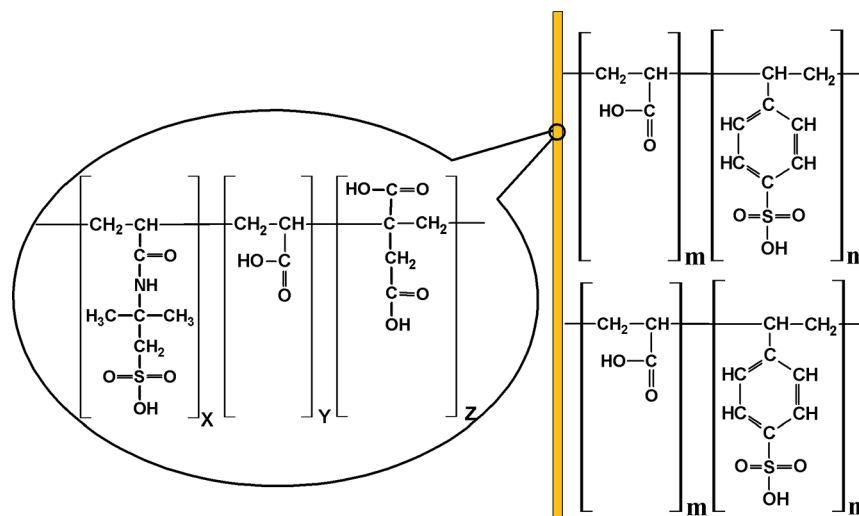**Figure 2.** Schematic diagram of the polymeric main chain of the DRH-150 retarder.

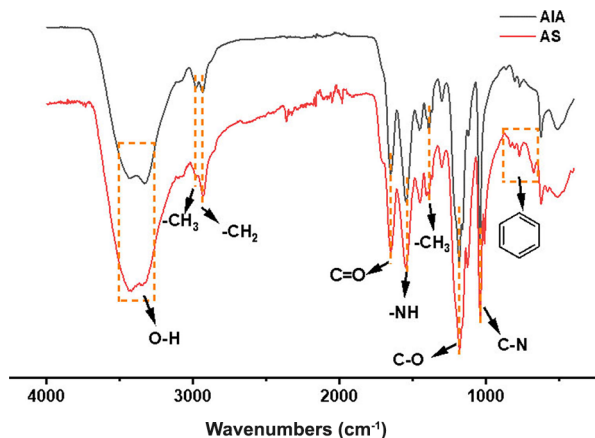**Figure 3.** Schematic diagram of the molecular structure of DRH-150.

Figure 4. Infrared spectrum of DRH-150.

attributed to the vibration of the secondary amine functional group (−NH−) of the AMPS unit, and the characteristic peak at 1708 cm^{-1} should be the carboxyl (−COOH) peak. The results indicated that the polymer main chain was a copolymer of AMPS, IA, and AA.[22,23]

On the other hand, in the spectrum of the retarder DRH-150, the double peak at 1380 cm^{-1} was a characteristic peak of two methyl groups (−CH$_3$) attached to the same carbon. The peak at 1,180 cm^{-1} was the C−O stretching vibration peak on the carboxyl group (−COOH). The peak at 1040 cm^{-1} was the C−N stretching vibration peak on AMPS. The peak between 600 and 800 cm^{-1} was the stretching vibration of H on the benzene ring. The results show that there were AMPS and SSS units in the polymer molecular structure of the

retarder, indicating that SSS was grafted to the polymer molecular chain.

Furthermore, the molecular structure of DRH-150 was described by NMR, as shown in Figure 5.

As shown in Figure 5a, 7.5 and 6.5 ppm were the peaks of H on the benzene ring. 5.5−6.1 ppm were probably the peaks of H on the unsaturated olefins in the sample that had not fully reacted. 4.8 ppm was the solvent peak of water. 3.0−3.7 ppm were peaks generated by H on the methylene group connecting the sulfonic and carboxylic acid groups. The peak around 2.1 ppm was due to methylene hydrogen on the polymer chain. 1.45 ppm was the methyl peak on the AMPS, indicating the presence of the structural unit of styrene sulfonic acid in the grafted side chain in the retarder structure. The ^{13}C NMR analysis in Figure 5b also showed that 175 to 180 ppm were the resonance peaks of different carboxylic acid and ester carbonyl groups in the AMPS structure. 140, 132, 128, and 124 ppm were the carbon peaks on the benzene ring. 58 ppm was the carbon peak attached to the sulfonic acid group on AMPS. 53 ppm was the quaternary carbon peak on the AMPS. 32 to 45 ppm were the carbon peaks on the polymer chain. Twenty-seven ppm was the methyl carbon peak on the AMPS. The results showed that the DRH-150 had a distinct graft structure.[24]

3.2. Effect of the Microstructure on Thickening Performance. *3.2.1. Molecular Structure.* Traditional polymer-based oil well cement retarders were mainly linear polymer,[25−27] which were prone to abnormal gelation or slurry thickening at the medium-high temperature (90 to 150 °C) range. In this research, high-temperature resistant monomers, AMPS and SSS, were used to synthesize polymeric

a. ^{1}H NMR spectrum
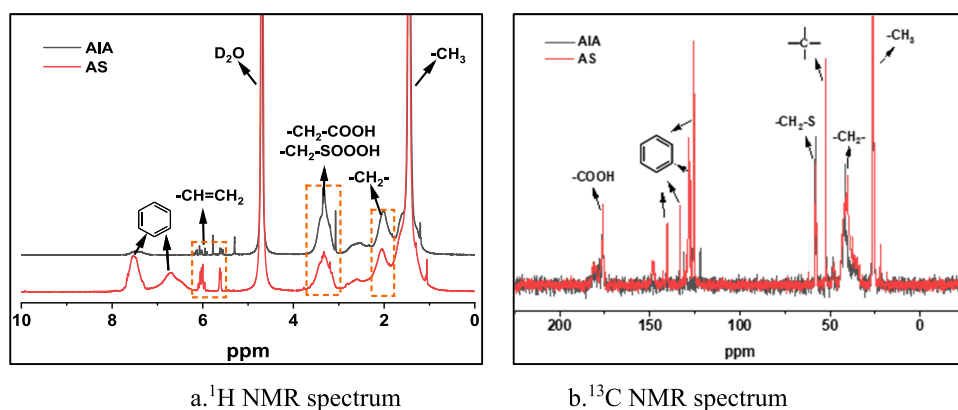

b. ^{13}C NMR spectrum

Figure 5. NMR spectra of the polymer main chain and DRH-150.

a. Consistency curve and encrustation conditions of 1.5wt%BWOC retarder LL-DRH-15

c. Consistency curve and encrustation conditions of 4wt%BWOC LH-DRH-150

b. Consistency curve and encrustation conditions of 1.5wt%BWOC retarder LH-DRH-150

d. Consistency curve and encrustation conditions of 1.5wt%BWOC DRH-150
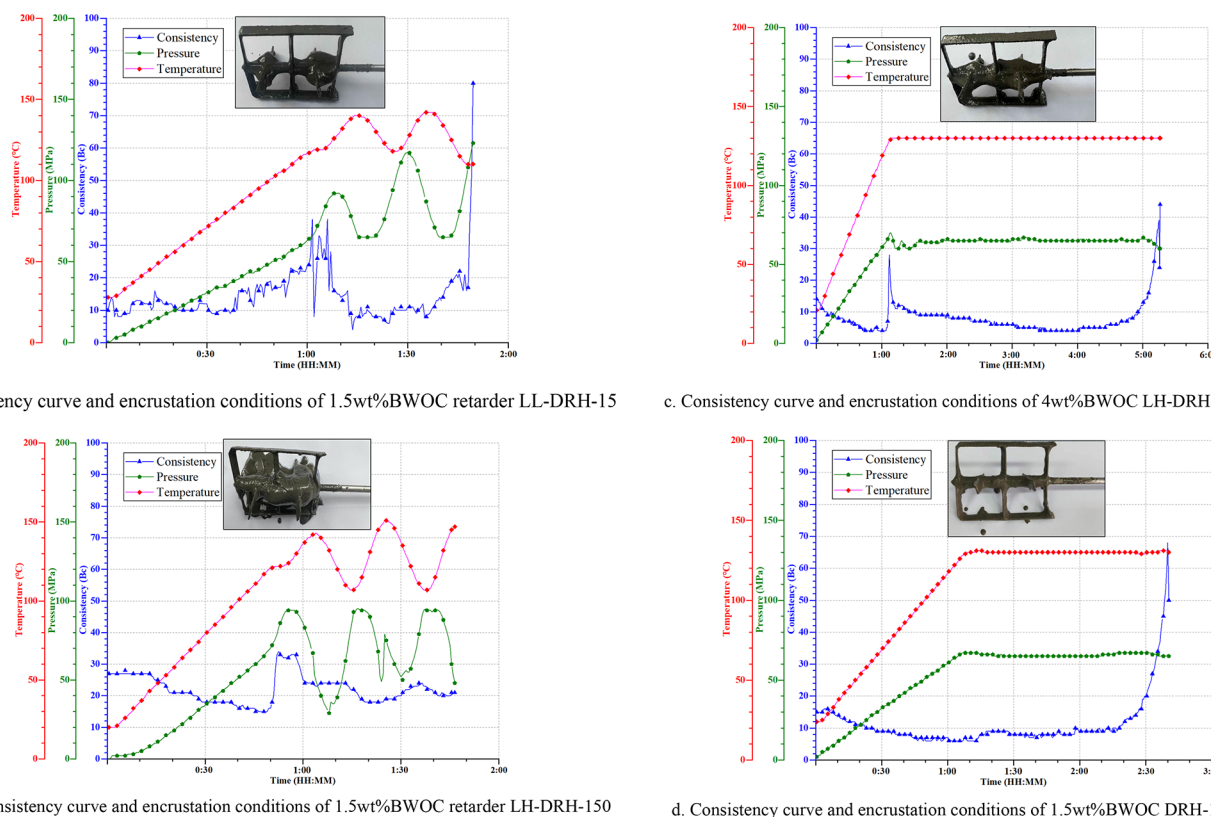
Figure 6. Effect of three different retarders on the thickening properties of cement slurry.

retarders with linear and branched structures, respectively. Among them, LH-DRH-150 and LL-DRH-150 were linear structure retarders with high and low molecular weights, respectively, and DRH-150 referred to retarders with branched-chain structures. The molecular weight of retarders was controlled by adjusting the dosage of the chain transfer agent.[28−30] For comparison, the ratio of the monomers of these samples was the same, and the total concentration was 18%. Besides, by the adjustment of the chain transfer agent, the viscosities of their solutions were closed. Specifically, the viscosities of LH-DRH-150 and LL-DRH-150 were 717 and 663 mPa s, respectively, at 15% concentration.
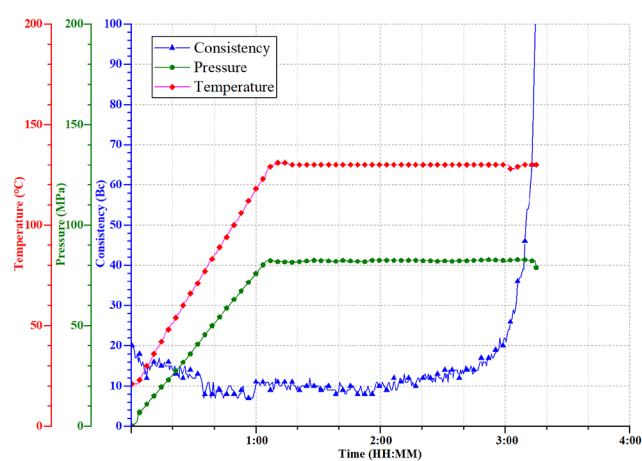
Thickening performances of the cement slurry system with three retarders were investigated under 130 °C. As shown in Figure 6, there was a "bulging" phenomenon on the consistency curve of the cement slurry system when retarder

LL-DRH-150 was added, with the maximum consistency reaching 38 Bc for 27 min. The temperature and pressure curves fluctuated continuously between 118 and 142 °C and 65−117 MPa, with a thickening time of 109 min. When the thickening experiment was running for 65 min, the temperature was quickly lowered to 93 °C and the cement slurry in the cup was found to be in a liquid state. However, there were two small pieces of gel with a diameter of 2.1 cm adhering to the paddle rod (Figure 6a).
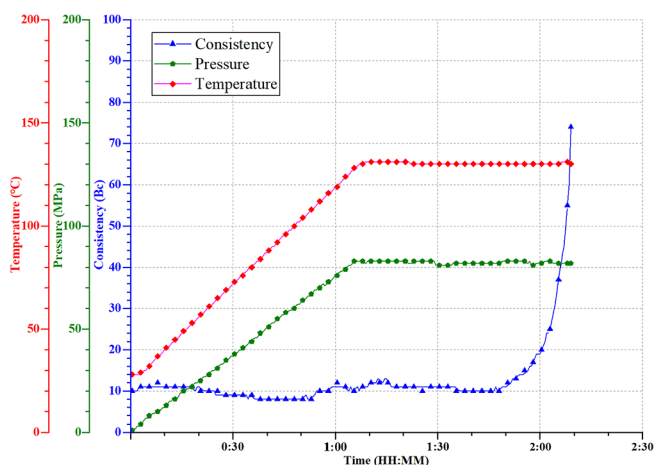
The consistency curve of the cement slurry system added retarder LH-DRH-150 showed a rapid increase from 48 min/15 Bc to 52 min/32 Bc and maintained for seven minutes, presenting a "plateau" and remained stable after 60 min, while the temperature and pressure curves fluctuated from 107 to 151 °C and 65 to 117 MPa, respectively. When the thickening experiment ran for 65 min, the temperature was quickly
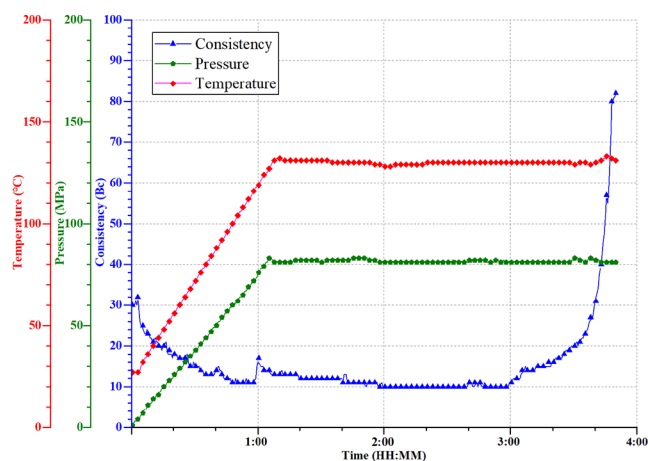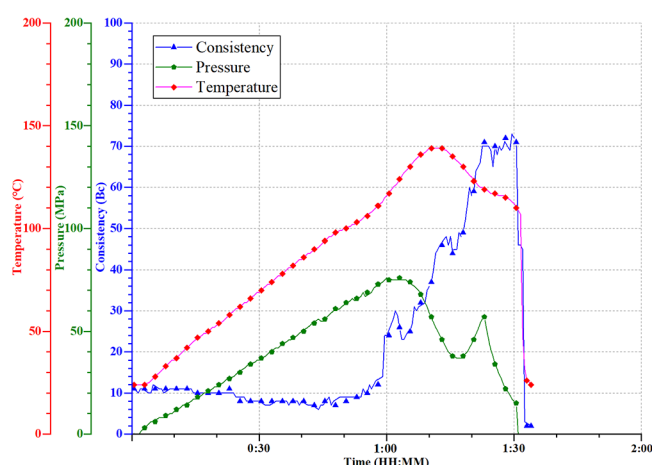
a. Consistency curve of 2% IPA retarder

b. Consistency curve of 4% IPA retarder

c. Consistency curve of 7% IPA retarder

d. Consistency curve of 10% IPA retarder

Figure 7. Effect of IPA addition on the thickening performance of cement slurry.

lowered to 93 °C. The cement slurry in the cup was found to be in a liquid state when the rheometer cup was opened, and the paddle rod was covered with a sticky gel of about 3.5 cm in diameter, as shown in Figure 6b.

After significantly increasing the dosage of LH-DRH-150 (Figure 6c) to 4.0 wt % BWOC, the thickening time reached 316 min. However, the consistency curve still showed a sharp peak with a height of 28 Bc and a duration of 8 min. When the thickening experiment ran for 65 min, the temperature was quickly lowered to 93 °C. The cement slurry in the cup was found to be in a liquid state when the rheometer cup was opened, and the paddle rod was covered with a sticky gelling substance of about 1.8 cm in diameter, which was smaller than that of LH-DRH-150 with 1.5 wt % BWOC (as shown in Figure 6c).

In contrast, the experiment with the addition of 1.5 wt % BWOC DRH-150 showed that the thickening time was 161 min, and there was no apparent fluctuation. When the thickening experiment ran for 65 min, the temperature was quickly lowered to 93 °C. After the experiment, there was no adhering material on the paddle rod (Figure 6d).

3.2.2. Length of the Grafted Main Chain. By adjusting the amount of chain transfer agent IPA, branched retarders with different lengths of the main chain were prepared. In the

synthesis, the ratio of SSS to AAc was 1:0.33, and the ratio of the main chain to the branched chain was 1:0.6. As shown in Figure 7, the properties of cement slurry systems at a dosage of 1.5% BWOC with different concentration of IPA were evaluated.

When the IPA dosage was 2% (relative to the mass of the main chain), the system thickening time was 227 min. The initial consistency of the slurry was slightly higher, and a peak with a height of 5Bc had appeared on the consistency curve at the 59th minute. The "bulging" phenomenon was suppressed (Figure 7a). As the IPA addition increased to 4%, the thickening time was 193 min. The consistency curve was expected and in good conditions (Figure 7b). However, when the IPA addition was further increased to 7%. The thickening time was shortened to 129 min (Figure 7c). After continuing to increase the IPA addition to 10%, the consistency of the cement slurry system increased rapidly after rising to 130 °C and the retarding effect was poor (Figure 7d).

It was indicated that as the concentration of IPA was increased, the length of the main chain was decreased, therefore improving the probability of complexation between the retarder and the salt in the cement.[31−33] As a result, the hydration regulation of the cement would be reduced. However, if the length of the main chain was too large, the
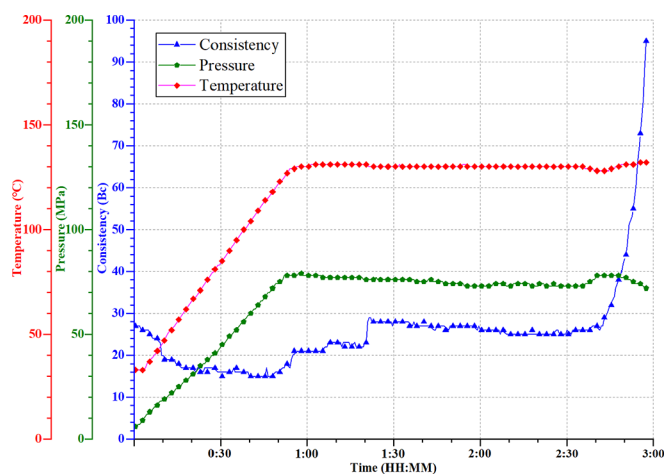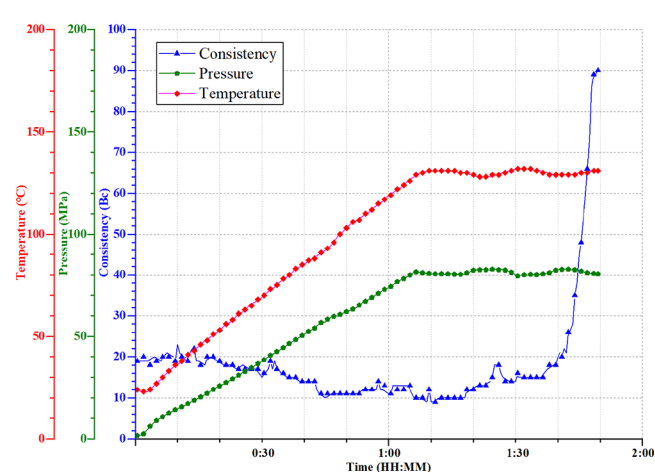
a. Consistency curve at 7.5% grafting rate
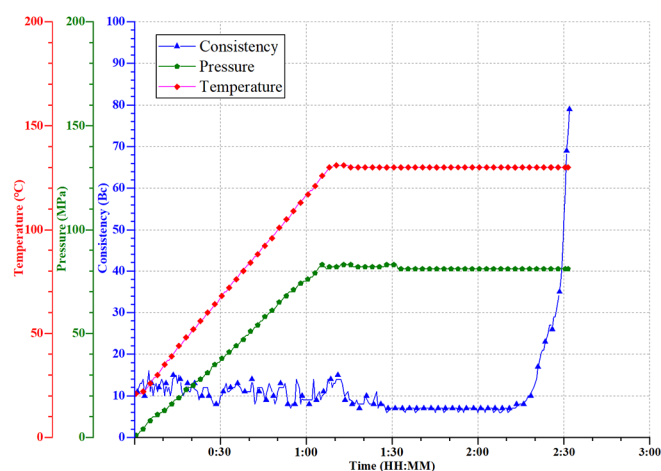
b. Consistency curve at 15.3% grafting rate
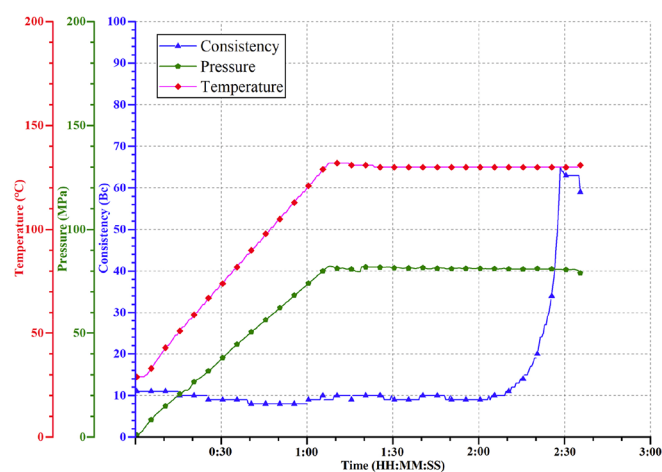
c. Consistency curve at 27.8% grafting rate

d. Consistency curve at 42.1% grafting rate

Figure 8. Effect of the grafting rate on the thickening properties of the cement slurry.

curling of individual polymer molecules and the entanglement between polymer chains would be exacerbated, therefore leading to adverse effects on the complexation ability of the functional groups. Overall, the retarder exhibited the best comprehensive properties at the concentration of IPA at 4%.

3.2.3. Effect of Grafting Rate on the Thickening Properties of the Cement Slurry System. The grafting rate is an essential parameter that significantly impacts the macroscopic performance of retarders. The grafting rate was controlled by adjusting the monomer ratio of the main chain and the side chain in this study. As shown in Figure 8a, a step of 15 to 29 Bc was observed at the graft rate of 7.5%. Meanwhile, the thickening time was about 175 min. While the grafting rate was increased to 15.3%, there was a fluctuation of 6 Bc in the consistency and it became stable after the temperature was increased to 130 °C, with a thickening time of 151 min (Figure 8b). As the grafting rate further increased to 27.8%, no fluctuation was observed in the curves. However, the thickening time was significantly decreased to 107 min while the grafting rate was 42.1% (Figure 8d).

It was implied that the content of the adhesion groups on the retarder molecule was decreased with the grafting rate.[34] Interaction between the cement particles and the slurry was improved when the grafting rate was low. Therefore, the initial viscosity of the slurry would be increased.[35,36] On the other hand, the retarding effect would be weakened if the grafting rate was too high since the rigid benzene group might hinder the interaction between the adhesion group and the particles.[37−41] Overall, a balance was achieved at a grafting rate of 27.8%, according to the experiment results.

3.3. Construction Performance Evaluation of DRH-150. *3.3.1. Thickening Properties.* The thickening properties of the DRH-150 cement slurry were evaluated in combination with the properties of cement hydration differences in the medium-high temperature zones, as shown in Figure 9. Experiments were conducted at a total of four temperatures, ranging from 90 to 150 °C, and the concentration of the retarder was increased with the temperature, ranging from 1.2 to 3.2%. The results showed that the cement slurry system could be pumped for a long time after adding DRH-150, and the consistency curve was standard with almost no fluctuations and no abnormal gelation phenomena. The performance was excellent, safe, and reliable, enabling the cementing construction to be carried out safely and smoothly.

Furthermore, the relation between the thickening time and the dosage of the retarder at different temperatures was
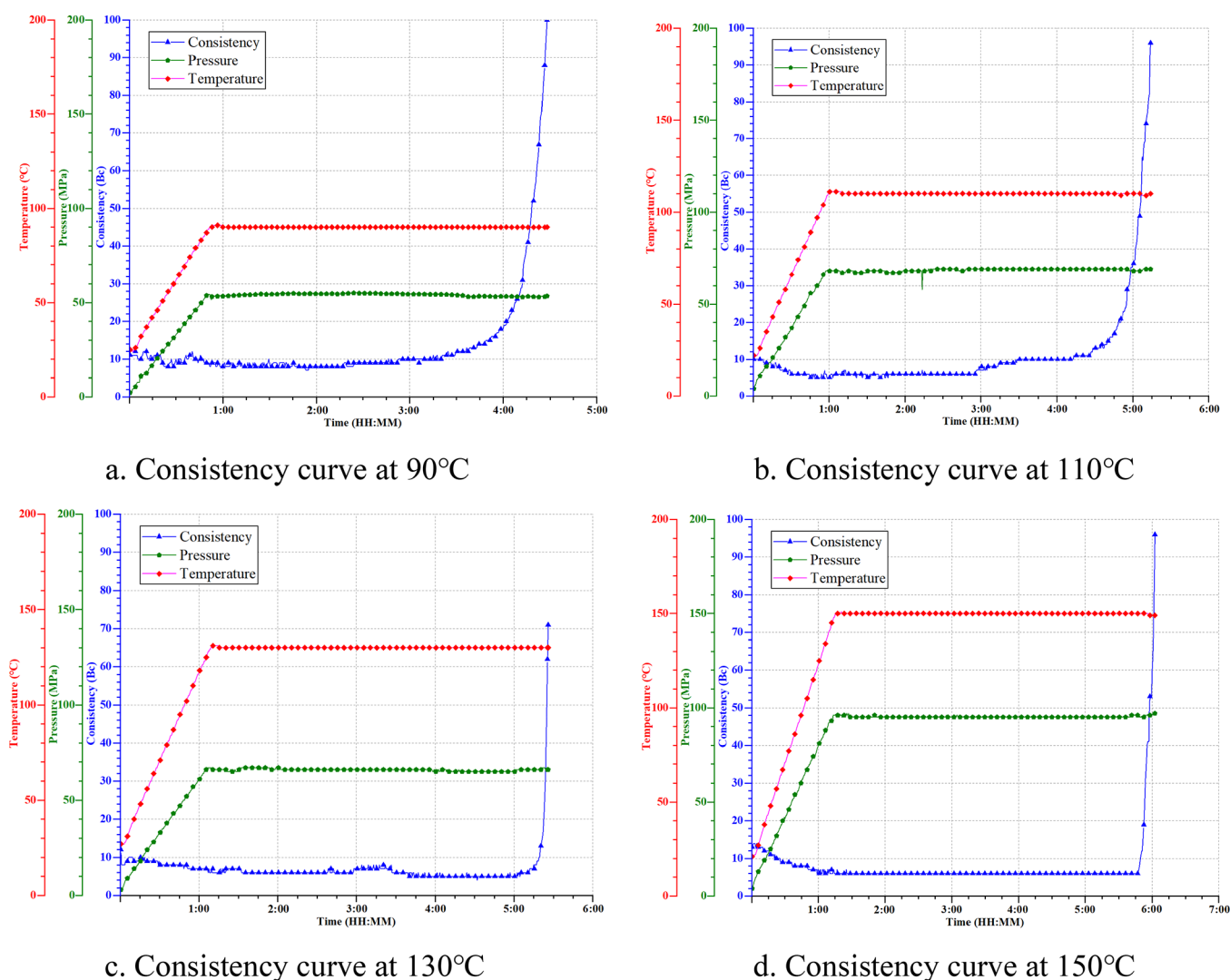
a. Consistency curve at 90°C

b. Consistency curve at 110°C

c. Consistency curve at 130°C

d. Consistency curve at 150°C

Figure 9. Consistency curves of the DRH-150 cement slurry at different temperatures.

investigated, as shown in Figure 10. It was indicated that the thickening time of cement slurry was linearly increased with the DRH-150 dosage at the same temperature. Meanwhile, the
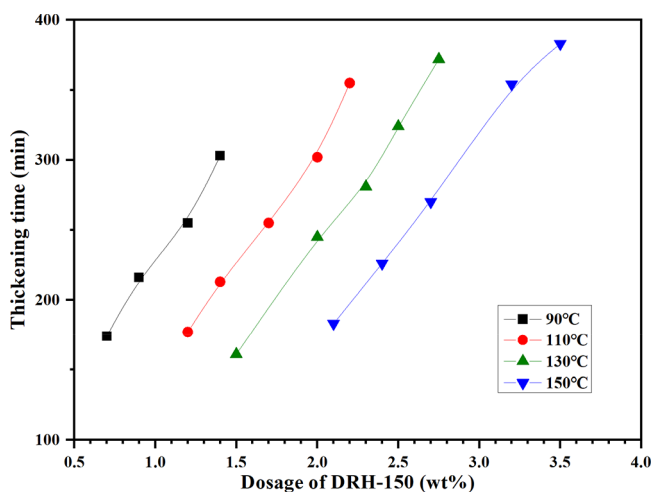

Figure 10. Effect of DRH-150 dosage on thickening times at different temperature points.

slopes of the curves in Figure 10 were slightly decreased with temperature. It was speculated that the hydration rate was improved at higher temperatures; therefore, more retarder was needed to ensure the contact probability with the cement particles.

3.3.2. Rheological Properties. The rheological properties of the cement slurry system were an essential parameter for the cement injection construction. As shown in Table 1, Q_c (critical discharge) was calculated based on a reasonable diameter of 220 mm and casing OD of 140 mm. P_f (friction) was calculated based on a seal height of 500 m and a return velocity of 1.5 m/s. It was observed that both Q_c and P_f increased slightly with the DRH-150 concentration. However, the G-grade raw slurry was the same with the addition of DRH-150, meaning that the retarder DRH-150 was sufficient to meet the construction requirements.

3.3.3. Other General Properties. Other properties, such as compressive strength and fluidity, were also evaluated, as shown in Table 2.

It was displayed that the dosage sensitivity was decreased from 20.00 to 8.19 while the temperature increased from 90 to 150 °C. Besides, referring to Formula 2, the compressive strength of the cement was increased with temperature. It should be noted that the compressive strength was 26.2 MPa

Table 1. Rheological Properties of Cement Slurry Added with DRH-150

DRH-150 dosage %	Φ 300	Φ 100	Φ 3	n	K Pa Sn	τ_s Pa	Q_c L/s	P_f MPa
0[a]	75	35	2	0.72	0.41	1.02	44.88	0.55
1.2[a]	84	36	3	0.82	0.25	1.53	45.20	0.56
2	90	39	3	0.80	0.30	1.53	48.43	0.61

[a]Formula 1, the rest is Formula 2.

Table 2. Conventional Properties of DRH-150 Cement Slurry

DRH-150, %		1.2[a]	2.0	2.5	3.2
flow rate, cm		26	26	25	25
circulation temperature, °C		90	110	130	150
thickening time, min		255	302	324	354
thickening time after increasing 10 wt %, min		303	355	372	383
dosage sensitivity, %		20.00	17.55	14.20	8.19
compressive strength (aging 24 h)	conservation conditions[aa]	113 °C	133 °C	154 °C	175 °C
	compressive strength, MPa	26.2	23.8	27.4	28.6

[a]Formula 1, the rest were Formula 2.

a. 90°C static gelation curve

b. 110°C static gelation curve

c. 130°C static gelation curve
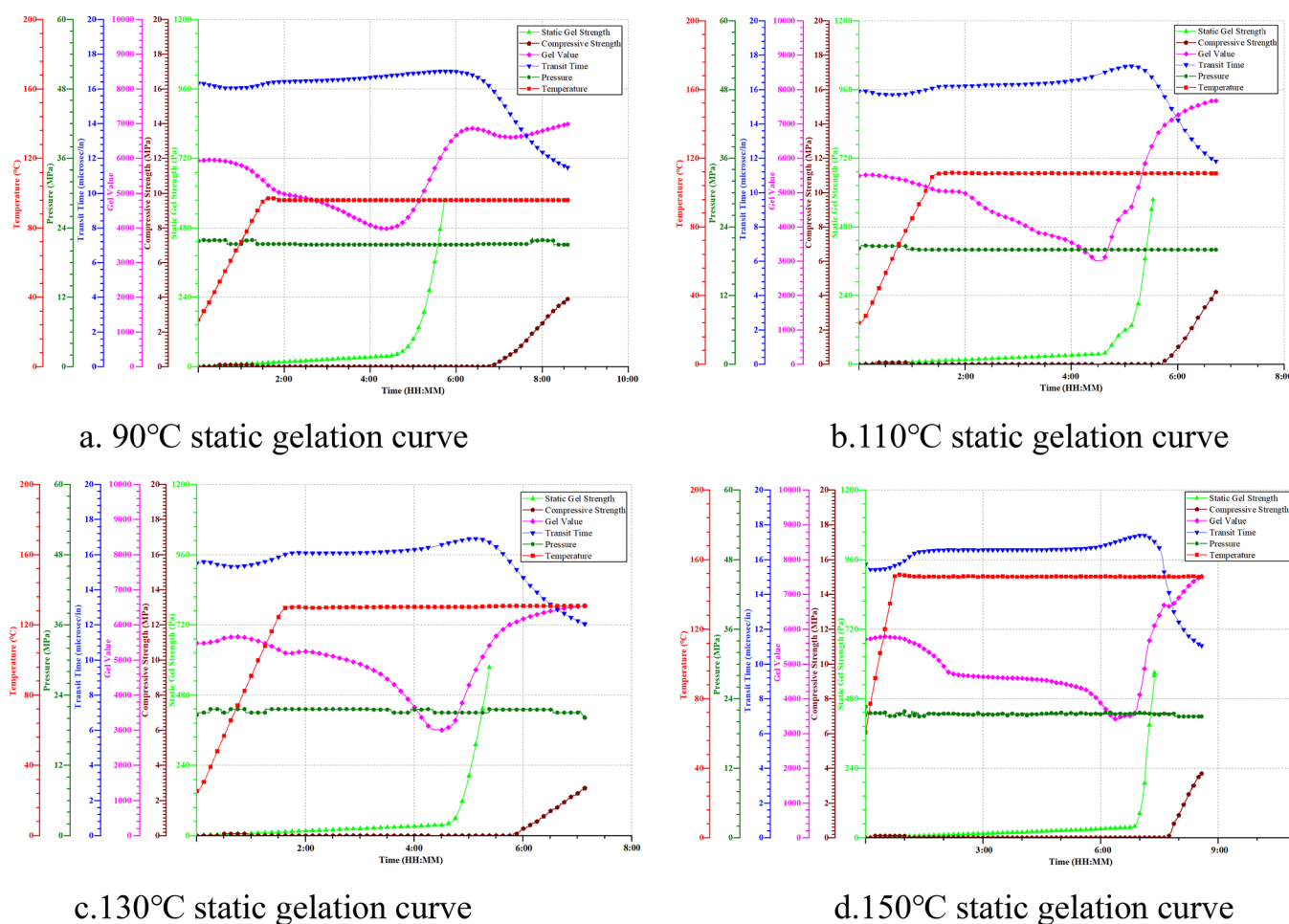

d. 150°C static gelation curve

Figure 11. Static gel curves of cement slurry at different temperatures.

aging at 113 °C, which was higher than 23.8 MPa that aged at 133 °C, which was on account of the different composition between the two formulas. Although silica flour was added to enhance the strength of the cement at elevated temperatures, the effective content of the cement was reduced simultaneously.

3.3.4. Static Gelation. After the injection of the cement slurry, gelation of the cement slurry initiated as the hydration

reaction proceeded, transforming from a liquid fluid state that could transmit hydraulic pressure to a solid state with measurable compressive strength.[42−44] When the static gel strength was less than 48 Pa, the cement slurry could transfer hydraulic pressure. Gas channeling would not occur in the wellbore under overbalanced pressure conditions. When the static gel strength became greater than 240 Pa, the strength of the hardened cement slurry was able to resist gas invasion.

However, in the transition range between 48 and 240 Pa, the fluidity of the cement slurry gradually decreased and created weightlessness, resulting in a pressure decrease of the liquid column on the lower wellbore, which would lead to the risk of annular gas channelling. As a result, the transition time of the gelation reaction from 48 to 240 Pa was supposed to be short.

Retarders could delay the hydration process of the cement by controlling the nucleation rate of the hydration products. Simultaneously, the static gel strength transition time of the cement slurry might also be affected. Related evaluation was performed for the retarder DRH-150 under different temperatures, using a 5265 static gel strength/ultrasonic compressive strength analyzer from the CHANDLER Company (USA). The results are displayed in Table 3 and Figure 11.

Table 3. Evaluation of Static Gel Strength of thw DRH-150 Cement Slurry System

S/N	experimental temperature °C	DRH-150%	48 to 240 Pa transition time min	1 MPa strength time min
1[a]	90	1.2	38	429
2	110	2.0	37	360
3	130	2.5	21	379
4	150	3.2	13	475

[a]Formula 1, the rest isFormula 2.

The evaluation results showed that the transition time of cement slurry from 48 to 240 Pa was 38 to 13 min, decreased with the temperature from 90 to 150 °C, while the starting strength time (1 MPa) fluctuated in the range of 360~475 min. In particular, the difference between the starting strength time (1 MPa) and the thickening time was not more than 80 min. It was conducive to resisting the intrusion of formation fluid and reducing the risk of annular channeling in the process of cement slurry weightlessness.

4. CONCLUSIONS

Synthesis and characterization of a new branched cement retarder were investigated in detail:

1. The cement retarder, DRH-150, was prepared by radiation graft polymerization, in which the mass ratio of AMPS-IA-AA main chain raw materials was 1:0.16:0.23, and the mass ratio of branched raw materials, SSS to AAc, was 1:0.33. When the grafting rate was 27.8%, there was good retardation and inhibition of encrustation.

2. From 90 to 150 °C, cement slurry with retarder DRH-150 exhibit good properties. The initial consistency was less than 15 Bc, the thickening time was adjustable by the dosage, and the additional sensitivity was less than 20%. There was no abnormal gelation phenomenon, with good rheology and fast static gelling time (1 MPa), and the overall performance could meet the cementing construction requirements.

■ AUTHOR INFORMATION

Corresponding Author

Jingfu Zhang − *Key Laboratory of Enhanced Oil Recovery, Northeast Petroleum University, Ministry of Education, Daqing 163318, China*; Email: zjf286@126.com

Authors

Bin Lv − *Key Laboratory of Enhanced Oil Recovery, Northeast Petroleum University, Ministry of Education, Daqing 163318, China; CNPC Engineering Technology R&D Company Limited, Beijing 102206, China;* ◉ orcid.org/0009-0004-5090-5008

Shuai Xie − *Key Laboratory of Enhanced Oil Recovery, Northeast Petroleum University, Ministry of Education, Daqing 163318, China*

Zishuai Liu − *CNPC Engineering Technology R&D Company Limited, Beijing 102206, China*

Jianjun Zhu − *Key Laboratory of Enhanced Oil Recovery, Northeast Petroleum University, Ministry of Education, Daqing 163318, China*

Ming Xu − *CNPC Engineering Technology R&D Company Limited, Beijing 102206, China*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.3c05692

Notes

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