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Laboratory Development and Field Application of Novel Cement System for Cementing High Temperature Oil Wells

X. Wan, H. Zhang, Y. Li, Y. Yang, SINOPEC; H. Shan, Z. Xiao, SPE, OPT Co.

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Abstract

Cementing high temperature exploration wells present a number of challenges to well construction engineers. High bottom hole static temperature (above 100^{o}C), very low pump rates and excessively long job times due to the constraints imposed by tight annular clearances and the use of heavy, viscous drilling muds and cement slurries, and formation complexities (salt layer, high leakoff, unstable formations) all contribute to the operational risks not only during placement of the cement slurry in the wellbore, but also later to the set cement sheath during the life of the well. Various cement systems have been applied with unsuccessful results.

A new cement formulation developed has helped to resolve the problems encountered in cementing these exploration wells and eight jobs have been completed in the field with great success. Synergistic effect between the new retarder and fluid loss control additive improve the system performance significantly such as low fluid loss rate, minimal free water, proper rheology, predictable thickening time, high resistance to salt contaminations, and no adverse effect on set cement strength. An effective laminar flow spacer was also developed and used to displace drilling muds effectively to enhance its placement and improve the cementing bond.

This paper will describe details of thorough and systematic laboratory development of the new cement system and present case histories to document its effectiveness for cementing high temperature exploration wells.

Introduction

Deep and ultra-deep wells have been drilled in recent years with improvement of drilling technologies and equipment. Cementing mid-to-high temperature exploration oil and gas wells brings chanllemges to well construction engineers [1]. First of all, it is difficult to design cement slurries because most cement additives are not stable at high temperatures. Secomdly, excessively long placement time, low pump rate, and unstable cement slurry properties due to complex well properties such as long interval, tight annular clearance, small hole diameter, heavy and viscous drilling fluids and cement slurries introduce significant operational risks in cementing mid-to-high temperature oil and gas wells. Additionally, salt layer, high leakoff, unstable formations, and production of H_2S and CO_2 are generally encountered in cementing high temperature oil and gas wells. These formation complexities bring a number of challenges to well construction engineers not only during placement of the cement slurry in the wellbore, but also later to the set cement sheath during the life of the well.

Researchers [2] reported technical strategies in cementing deep oil and gas wells. The procedures in cementing deep oil and gas wells are basically the same as those for shallower wells. However severe and complex well and formation conditions cause great engineering risks especially in cement slurry design. Proper formulation of dispersants, retarders, fluid loss agents, and other additives becomes critical in cementing high temperature oil and gas wells. Meanwhile, efficient displacement of mud by chemical wash and spacer is also important to enhance cement placement and improve the cementing bond.

Excessively long pumping time (at least 4 to 5 hours) is generally required in cementing high temperature oil and gas wells [3]. Sufficient retarders must be added into cement slurry to provide adequate placement time at bottom hole circulating temperature. However, such cement slurry might be over-retarded at the top of the cement column, resulting in excessively long wait-on-cement (WOC) time. Therefore, development of novel retarders is critical for cementing high temperature oil and gas wells. Organic acids [4] and saccharide derivatives [5] are reported being successfully used in cementing high temperature oil wells. Meanwhile, development of fluid loss agents being stable at high temperature and pressure is also important for proper slurry design at high circulating temperature. Particulates [6] and high temperature water soluble polymers [7] have been used effectively as high temperature fluid loss control additives in high temperature cement slurries. In general, higher circulating temperature causes mugh higher sensitivity of cement additives. Therefore, compatibility tests between additives, mixing water, and cement should always be performed to ensure successful cementing jobs.

Efficient mud displacement is another key factor in cementing high temperature oil and gas wells. Turbulent-Flow displacement technique with chemical washes or spacers has been approved to be effective in mud removal [8]. However, there are certain well conditions such as low pump rate, and viscous cement slurries that can make this technique impractical or impossible. Viscous Laminar-Flow displacement is therefore accepted as major displacement technique in cementing high temperature oil and gas wells.

Many slurry systems and spacer techniques have been used in cementing mid-to-high temperature exploration wells in Shengli oilfields of SINOPEC with unsuccessful results. A novel cement system and an effective laminar-flow viscous spacer developed have helped to resolve the problems encountered in cementing these exploration wells and eight jobs have been completed in these oilfields with great success. This paper will describe details of thorough and systematic laboratory development of the new cement system including an effective laminar-flow spacer and present case histories to document its effectiveness for cementing high temperature exploration wells.

Experimental

Apparatus and Materials

Standard experimental equipment is used and listed in Table 1. Except for special additives (from OPT Co.) and hollow microspheres (from 3M), cement, weighing agents, and cement extenders are provided by local suppliers, who supply the same materials to field operations.

Table 1 Experimental Apparatus and Equipment

Properties	Equipment	Model	Provider
Compressive Strength	Programmable Hydraulic Press	YAW-300B	S.G. Instrument
	High Temperature High Pressure Curing Chamber	HTD7370	Haitongda Instrument Co.
Viscosity	Fann Viscometer	35SA	Fann Instrument
Fluid Loss	Static Fluid Loss Cell	HTD7169	Haitongda Instrument Co.
	Atmospheric Consistometer	HTD1200	Haitongda Instrument Co.
Thickening Time	High Temperature High Pressure Consistometer	HTD8040	Haitongda Instrument Co.
Rheology	High Temperatute High Pressure Rheometer	GRACE7500	GRACE Instrument

Table 2 Experimental Materials

Name	Function	Provider
Oilwell cement, G	Cement	Local suppliers
Microsilica	Extender	
Hematite	Weighing Agent	
Silica Flour	Anti-retrogression Agent	
Hollow Microspheres	Extender	3M
KCM002	Dispersant	OPT Co.
KCM008	Fluid Loss Agent	
KCM007	Retarder	
KCM003	Anti-foaming Agent	
KCM004	Spacer	

Experimental Procedures

API RP10B Procedures

Testing cement slurries follows procedures described in API RP10B. Tests include slurry preparation, free water, density, compressive strength, viscosity, thickening time, and fluid loss.

Spacer Preparation and Rheology Stability Testing

Viscous spacer preparation (1.40 g/cc, 20 kg/m^3 KCM004 loading) follows procedures described in Q/OPT0005-2008 [9]. Load the slurry into GRACE7500 rheometer after 1 hour static aging. Raise temperature from 25^{o}C to 150^{o}C at rate of 6^{o}C/min, and then test the slurry rheology at 1000psi, 150^{o}C and shear rate of 40 sec^{-1}, 100 sec^{-1}, and 170 sec^{-1}for 6.5 hours.

Density Stability Testing

Measure density of the spacer slurry right after preparation as procedures described in Q/OPT0005-2008. Then pour the spacer slurry into a 600ml graduated cylinder and statically age for 7 days at ambient conditions. Measure the density of top and bottom part of the slurry without disturbing the slurry after aging and take pictures. Repeat same procedures to measure the density after dynamic aging in atmospheric consistometer at 85^{o}C for 20 minutes.

Results and Discussions

API Properties of Mid-to-high Temperature Cement Systems

API properties of high temperature cement slurries (listed in Table 4) at three densities (1.89 g/cc, 1.95 g/cc, and 2.00 g/cc) and bottom hole static temperarture 130-150°C are summarized in Table 3. Slurries have plastic viscosity and yield point of 100-150cp and 10-30 lb/100ft^2 respectively. Fluid loss varies in the range of 10-150ml and normally less than 0.5% free water is observed for these slurries. High compressive strength (24 hours, 35 to 45MPa) is obtained with these slurries at bottom hole static temperature.

Table 3 API Properties of High Temperature Cement Systems

Slurry	Density g/cc	BHCT °C	PV/YP* cp, lb/100ft^2	Fluid Loss ml/30min	Free Water %	Thickening Time min	Compressive Strength	
							BHST, °C	24hr, MPa
1	1.89	110				300	130	
2	1.89	110				278	130	
3	1.89	110				143	130	
4	1.89	115	148/23 (52/10)	120	0.4	363	138	39.2
5	1.89	115	133/20 (68/5)	116	0.8	191	138	41.8
6	1.89	115	207/10 (97/6)	66		229	138	
7	1.89	120				217	145	
8	1.89	120				197	145	
9	1.89	120				271	145	
10	1.95	110				147	130	
11	1.95	110				309	130	
12	1.95	115				100	138	
13	1.95	115				141	138	
14	1.95	115	216/36	103	0.2	164	138	
15	1.95	115	199/40	126		310	138	
16	1.95	115	205/28			356	138	42.0
17	1.95	115	237/39	66	0.2	202	138	43.7
18	1.95	120		64		189	145	
19	1.95	120				280	145	
20	2.00	110				368	130	
21	2.00	110				194	130	
22	2.00	115				248	138	
23	2.00	115				108	138	
24	2.00	115				166	138	
25	2.00	120	159/28	98	0.8	287	145	34.8
26	2.00	120	165/30	50		135	145	

* Note: data in parenthesis are PV and YP values after dynamic aging at 85°C for 20 min.

Thickening Time and Retarder Concentrations

Relationship between thickening time and retarder concentration is shown in Figure 1. Data shows that thickening time increases monotonically with increasing retarder concentration. We also notice that thickening time is not sensitive to retarder concentration. As shown in Figure 1, about 0.2 gps KCM007 is required to extend thickeining time from 200 min to 260 min at 120°C. However, most retarders such as organic acids or saccharide derivatives are sensitive to subtle concentration variation.

As discussed earlier, enough retarder is generally added into cement slurry to minimize operational risks in cementing high temperature oil wells. Consequently, slurry on top of the cement column is over-retarded due to much lower temperature at top of casing string or liner, resulting in excessively long WOC (wait-on-cement) time and risks of formation fluid migration if high gas pressure presents. Therefore, retarder KCM007 is advantageous for cementing high temperature oil wells compare to other retarders because of its insensitivity to subtle concentration variation at high temperature.

Effect of Fluid Loss Control Additive on Thickening Time

Fluid loss control additive has to be compatible with retarder and dispersant in cement slurry in addition to minimizing fluid loss of cement slurry at circulating temperature. Slurries 15 and 16 listed in Table 4 are basically the same except for the difference in fluid loss agent concentration. Data in Figure 2 shows that thickening time increases with increasing KCM008 conventration. That is, synergistic interaction between retarder KCM007 and fluid loss agent KCM008 exists in high temperature cement systems, which makes the system to be more efficient.

Table 4 Formulation of Mid-to-high Temperature Cement Systems

Slurry	BHCT °C	Density g/cc	Cement BWOC%	Silica Flour BWOC%	Weighing Agent BWOC%	KCM002 gps	KCM003 gps	KCM008 gps	KCM007 gps
1	110	1.89	100	35		0.075	0.05	0.6	0.9
2	110	1.89	100	35		0.075	0.05	0.6	0.7
3	110	1.89	100	35		0.075	0.05	0.6	0.5
4	115	1.89	100	35		0.075	0.05	0.6	1.15
5	115	1.89	100	35		0.075	0.05	0.6	1.05
6	115	1.89	100	35		0.1	0.05	0.6	0.35
7	120	1.89	100	35		0.075	0.05	0.6	1.15
8	120	1.89	100	35		0.075	0.05	0.6	1.1
9	120	1.89	100	35		0.075	0.05	0.6	1.3
10	110	1.95	100	35		0.05	0.05	0.6	0.95
11	110	1.95	100	35		0.05	0.05	0.6	1.15
12	115	1.95	100	35		0.1	0.05	0.7	0.8
13	115	1.95	100	35		0.1	0.05	0.7	1.0
14	115	1.95	100	35		0.15	0.05	0.5	1.1
15	115	1.95	100	35		0.15	0.05	0.5	1.2
16	115	1.95	100	35		0.15	0.05	0.6	1.2
17	115	1.95	100	35		0.05	0.05	0.6	1.1
18	120	1.95	100	35		0.05	0.05	0.6	1.1
19	120	1.95	100	35		0.05	0.05	0.6	1.2
20	110	2.00	100	35	20	0.1	0.05	0.4	0.6
21	110	2.00	100	35	20	0.1	0.05	0.4	0.3
22	115	2.00	100	35	20	0.1	0.05	0.4	0.7
23	115	2.00	100	35	20	0.1	0.05	0.4	0.5
24	115	2.00	100	35	20	0.1	0.05	0.4	0.6
25	120	2.00	100	35	20	0.15	0.05	0.7	1.22
26	120	2.00	100	35	20	0.1	0.05	0.6	1.2

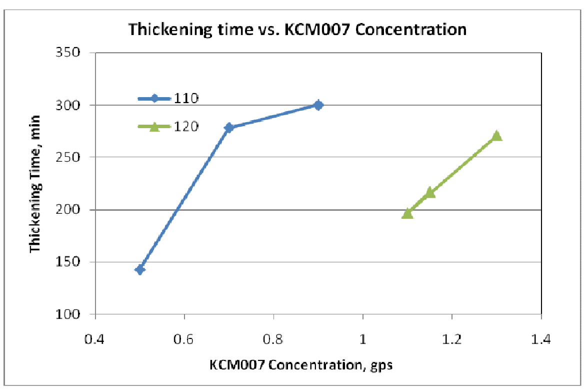


Figure 1—Relationship between Thickening Time and Retarder Concentration

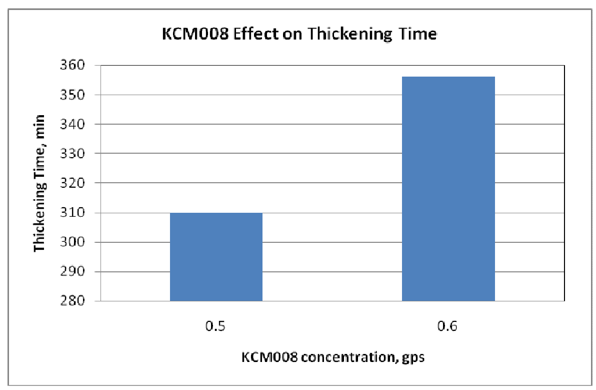


Figure 2—Effect of Fluid Loss Agent Concentration on Thickening Time

Temperature Effect on Cement Compressive Strength

As we described, over-retardation on top of the cement column generally takes place in cementing mid-to-high temperature oil wells, resulting in long WOC (wait-on-cement) time and high operational risks. Effect of temperature on compressive strength development of cement system is illustrated in Figure 3. Results indicate that high temperature cement systems not only develop their compressive strength rapidly, but also have no over-retardation on top of the cement column, which generally locate at low temperature zones. For example, 24 hours compressive strength of 19MPa is achieved at 95°C (top of cement column) when cement compressive strength reaches 28MPa at bottom hole static temperature (130°C) in 12 hours. The compressive strength development insensitivity to temperature variation not only reduces wait-on-cement time, but also minimizes any risks of formation fluid migration.

Properties of Effective Laminar-Flow Viscous Spacer

Since turbulent-flow displacement technique is impractical or impossible in cementing high temperatute exploration wells discussed in this paper, a high temperature laminar-flow viscous spacer has been developed to be used together with mid-to-high temperature cement systems for efficient displacement of drilling fluids prior to cement placement.

Rheological Stability of Viscous Spacer

As rule of thumb, density and viscosity values of laminar-flow spacer should be between those of drilling fluids and cement slurries at circulating temperature for efficient displacement. Therefore it is important for spacer to be stable at high temperature and pressure. Rheological property of viscous spacer (1.40 g/cc, 20.0 kg/m^3 KCM004 loading) at 150^{o}C and 1000psi is shown in Figure 4. Data shows that viscosity of typical viscous spacer is stable for 6.5 hours at shear rate of 170 sec^{-1}, which is normally accepted annular shear rate in most casing programs.

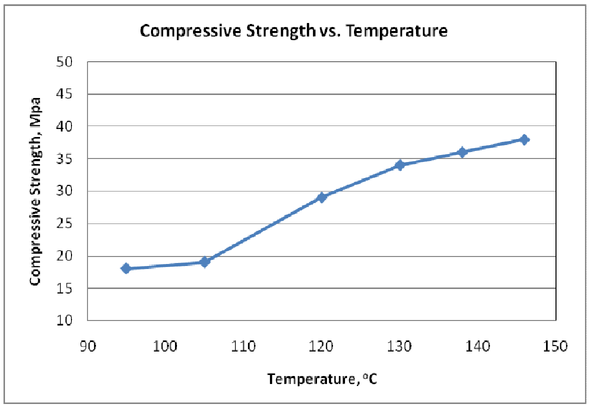


Figure 3—Temperature Effect on Compressive Strength Development

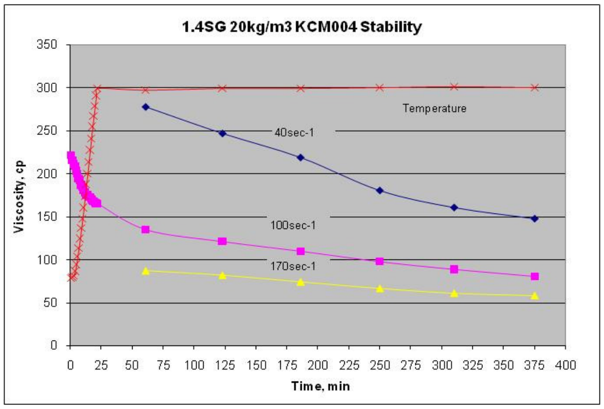
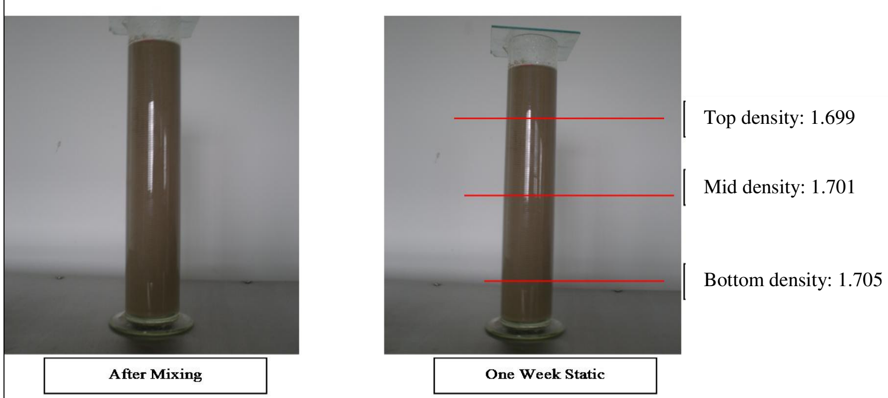


Figure 4—Rheology Stability of Spacer System at 1000psi and 150^{o}C

Density Stability of Viscous Spacer

Viscous spacer is generally batch-mixed on-site. As-prepared spacer is sometimes used a few days after preparation due to operational delay. It is therefore very important to have the viscous spacer to be stable for at least a few days. Density stability of a typical spacer system (1.7 g/cc, 10kg/m^3 KCM004 loading) after 7 days static aging at ambient conditions is summarized in Figure 5. Data shows that viscous spacer is stable after 7 days static aging with negligible density variation of 1.699 g/cc, 1.701 g/cc, and 1.705 g/cc at the top, middle, and bottom of the spacer respectively.



One week static aging at room temperature.

Density:	1.70sg	Measured Properties:	
KCM004 loading:	10kg/m^3	Fluid loss:	12ml
Weighing agent:	Barite	Density:	1.699 -1.705 sg
Antifoam agent:	KCM003		

Figure 5—Density Stability of Laminar-Flow Viscous Spacer

Field Application of Novel Cement System and Viscous Spacer

Novel cement system and viscous spacer have been successfully used in cementing ten exploration wells (listed in Table 5) in Shengli Oilfields of SINOPEC. Cementing programs include casing, liner, and plug at bottom hole static temperature ranging from 105°C to 173°C and density of 1.60-2.00 g/cc. A salt-bearing formation (well F) has also been successfully cemented using novel cement system and laminar-flow viscous spacer.

Table 5 Field Cases Using Novel High-Temperature Cement System and Viscous Spacer

Summary of Field Cases									
ID	Well	Operation	Cementing program	Depth m	BHST °C	BHCT °C	Slurry density, g/cc Lead	Tail	Note
1	A	8-5-2009	7"Casing	4778	173	150	1.60	1.89	
2	B	9-3-2009	Plug	4778	173	150		1.89	
3	C	8-19-2009	Plug	4750	150	120		1.89	
4	D	8-21-2009	5-1/2" Casing	4330	150	120	1.89	1.89	
5	E	9-2-2009	5-1/2"Casing	4285	165	120	1.89	1.89	
6	F	9-21-2009	7"Liner	3853	130	100		2.00	18% NaCl
7	G	11-30-2009	5-1/2"Liner	4275	130	115		1.89	
8	H	12-19-2009	5-1/2" Liner	3900	130	105	1.75	1.95	
9	I	12-20-2009	5-1/2" Liner	4104	140	110		1.89	
10	J	1-9-2010	5-1/2" Liner	2890	105	80		1.89	

In order to quantitatively evaluate performance of novel cement system and viscous spacer, we define a cementing job with good bonding between cement and casing (Sonic signal at more than 85% of the cemented interval reads less than 20mV in CBL) as a successful job. Eight wells listed in Table 5 (excluding two plug jobs) were selected to compare with similar wells (similar BHST, depth, casing program, and slurry density in the same exploration areas) using conventional cement systems and displacement techniques. Results shown in Figure 6 indicate that job success rate increases from 29% to 82% by using novel cement system and viscous spacer.

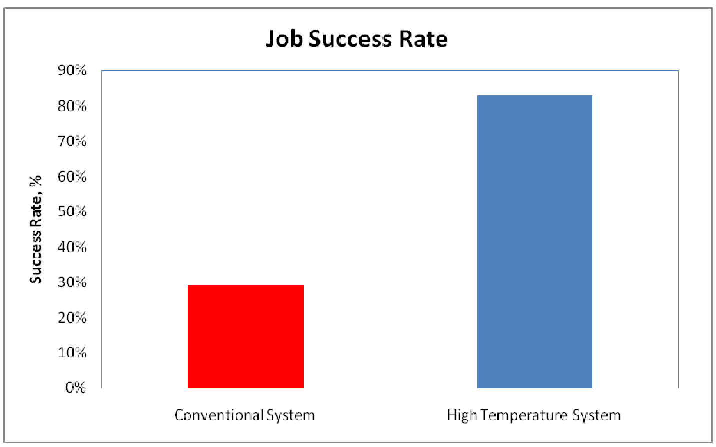


Figure 6—Comparison of Job Success Rate Before and After Using Novel Cement System and Viscous Spacer

Conclusions

(1) Both experimental and field application results indicate that novel cement system can be successfully used at density and temperature (BHST) ranging from 1.60 to 2.00 g/cc, and 105 to 173°C respectively. Novel cement systems have typical plastic viscosity of 100-150cp, and yield point of 10-30 lb/100ft^2. Fluid loss is adjustable in the range of 10-150ml. Less than 0.5% free water and 24 hours compressive strength 35-45MPa is normally obtained for these slurries.

(2) Thickening time of novel cement system not only increases monotonically with increasing retarder concentrations, but also is insensitive to retarder loading. Such retarder insensitivity to subtle concentration variation not only favors the formulation of cement systems, but also reduces the risks of high temperature cementing operations.
(3) Less retarder and fluid loss agent is required to obtain the same slurry performance due to synergistic interactions between fluid loss agent and retarder.
(4) Novel high temperature cement system not only develops its compressive strength rapidly, but also has no over-retardation on top of the cement column. Strength development insensitivity to temperature variation not only reduces wait-on-cement time, but also minimizes risks of formation fluid migration.
(5) Effective laminar-flow viscous spacer developmed is stable at both surface and bottom hole conditions. Both rheological and density stability of the spacer system helps in efficient mud displacement and ensure good bonding between formation, cement sheath and casing.
(6) Results of field cases indicate successful application of novel cement system and viscous spacer in eight mid-to-high temperature exploration wells. Job success rate increases from 29% to 82% using novel cement system and viscous spacer.

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SI Metrc Conversion Factors

gal	×	3.785238	E–03	=	m^3
ft	×	0.333333	E+00	=	m
°F		(°F-32)/1.8		=	°C
lb	×	4.535924	E–01	=	kg
psi	×	6.894757	E+00	=	kPa

*Conversion factor is exact