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Solidifying Mud Cake to Improve Cementing Quality of Shale Gas Well: A Case Study

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Abstract: The purpose of this study is to improve the cementing quality of shale gas well by mud cake solidification, as well as to provide the better annular isolation for its hydraulic fracturing development. Based on the self-established experimental method and API RP 10, the effects of mud cake solidifiers on the shear strength at cement-interlayer interface (SSCFI) were evaluated. After curing for 3, 7, 15 and 30 days, SSCFI was remarkably improved by 629.03%, 222.37%, 241.43% and 273.33%, respectively, compared with the original technology. Moreover, the compatibility among the mud cake solidifier, cement slurry, drilling fluid and prepad fluid meets the safety requirements for cementing operation. An application example in a shale gas well (Yuanye HF-1) was also presented. The high quality ratio of cementing quality is 93.49% of the whole well section, while the unqualified ratio of adjacent well (Yuanba 9) is 84.46%. Moreover, the cementing quality of six gas-bearing reservoirs is high. This paper also discussed the mechanism of mud cake solidification. The reactions among $H_3AlO_4^{2-}$ and $H_3SiO_4^-$ from alkali-dissolved reaction, Na^+ and $H_3SiO_4^-$ in the mud cake solidifiers, and Ca^{2+} and OH^- from cement slurry form the natrolite and calcium silicate hydrate (C-S-H) with different silicate-calcium ratio. Based on these, SSCFI and cementing quality were improved.

Keywords: Cement-interlayer interface, mechanism, mud cake solidifier, shale gas well.

INTRODUCTION

Both the economy development and social stability greatly depend on energy, and energy needs are sharply increasing in these decades, which urge to find substitution energy. Unconventional gas, including shale gas, coal bed methane (CBM), low permeability (tight gas) reservoirs, etc [1-3], is attracting the world's view and is having an increasing impact on the world for its enormous resources potential and economic benefit. Compared with conventional gas, the reserves of unconventional gas are much larger. At a rough estimation, shale gas has great potentialities to account for 25% yield of natural gas till 2030 and one third till 2040 [4]. Hydraulic fracturing has been widely used to enhance the production of oil and natural gas in low-permeability formations all around the world, about 90% of gas wells and 70% of oil wells [5, 6]. The applications of hydraulic fracturing and horizontal well in production of unconventional gas improvement have been rapidly developed [7-9]. However, the gas channeling occurs after hydraulic fracturing which influences the shear strength at cement-interlayer interface (SSCFI) and hydraulic fracturing pressure [10]. Consequently, crushing and sloughing easily occur in the shale.

Previous researches have shown that the pathway for fluid channeling is the cement-interlayer interface [11, 12] and it has also been proved by the practice in oilfield. The cement sheath and the interlayer wall will peel off and form micro-fissure as long as there are mud cakes exist between them and no matter how thin they would be, which will lead to the decreasing SSCFI [13], offering the fluid which trapped in the interlayer a channeling path [14]. So the main factors that affect SSCFI are the interface defects and the bond strength [15]. The effective way to solve this problem is to achieve an integrated solidification and cementation of cement, mud cake and interlayer [16].

As a trail, the technology of mud to cement (MTC) emerged in the early 1990s [17, 18]. The integrated solidification and cementation of the cement- interlayer interface were achieved using multi-functional drilling fluid. However, the technology of MTC had been questioned by many scholars as early as in 1994 because MTC solidified body has a serious embrittlement problem [19-21]. So the MTC technology is only proposed in the cementing operation of surface casing and intermediate casing because MTC solidified body doesn't have the same properties as the traditional cement [21].

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Considering the limits of MTC method, a new method, mud cake to agglomerated cake (MTA) method was proposed to achieve the integrated solidification and cementation of cement-interlayer interface [22]. This method can solve the problem without changing the cement slurry [23-26], but it was also limited to shallow well operation because this method still required to add mud cake modifier to the drilling fluid. We improved this method to improve the deep well cementing quality without changing both drilling fluid and cement slurries. At present, this method has been used in Yuanye HF-1, a shale gas well, to solve the problem of gas channeling.

CEMENTING DIFFICULTIES OF WELL YUANYE HF-1

Well Yuanye HF-1, located in Guangyuan, Sichuan, China, is an important wildcat well for shale gas. Drilling results showed that there are multi sets of gas reservoir in this well. Due to its complicated geological structure, one-time cementing technology should be applied. Meanwhile, the gas channeling after well cementing is a severe problem [27, 28]. It is really a complex theoretical and technical problem in well cementing of gas well and the low SSCFI is one of the main reasons [10]. Several difficulties in well cementing of well Yuanye HF-1 are as follows [29, 30].

1. This horizontal well with big rig load, casing depth is 3728 m, building-up section ranges from 3318 to 3730 m, deviation angle increases from 1.2 to 71°. Cuttings bed tends to form in the high-angle directional section.
2. Sloughing and leakage probably happen in well cementing due to long isolation section and low formation bearing pressure. Simultaneously, the render replacement efficiency is hard to guarantee cementing quality because of the long open hole and large borehole. Besides, the drilling fluid contains approximately 5% crude oil and other organic treating reagents, and will influence well quality.
3. Hydrocarbon in the well section ranges from 3131 to 3611 m (3131 to 3133 m, 3136 to 3151 m, 3234 to 3241 m, 3378 to 3379 m, 3569 to 3570 m and 3608 to 3611 m), especially in the section ranges from 3136 to 3151 m. The lithology is grey fine sandstone, and the layer thickness is up to 15 m. And, the key point is how to avoid gas channeling at cement-interlayer interface.
4. Considering the big injection volume and long placement time of cement, the cement slurry in open hole section would dehydrate and thicken when flowing back, which threatens construction safety. Long-time construction requires high cementing equipment performance and good ground construction conditions.

SIMULATION EXPERIMENT

Experimental Materials and Instrument

Experimental materials. The drilling fluid is from well Yuanye HF-1 (Table **1**). The cement slurry system is composed of API class G oilwell cement (from Jiahua cement plant in China), 0.2% retarder, 2.5% fluid loss additive, 44% tap water, 0.1% defoamer (from Shandong Obot petroleum technology Co., Ltd. in China). The mud cake solidifier (GJ-I and GJ-II) is self-made [31]. The permeability and porosity of self-made simulated wellbores (SWB) [10] are $150 \times 10^{-3}\ \mu m^2$ and 18%, respectively.

Experiment instruments. TG-3060A constant speed agitator, TG-1280 atmospheric pressure curing box, WDW-Y10A electronic pressure testing machine and TG-8040D2 high temperature and high pressure thickening apparatus (Shenyang Tiger petroleum equipment Co., Ltd. in China). ZNN-D6 six kinds of speed rotary viscometer and ZNS water loss instrument under middle pressure (Qingdao Hisense optical communication Co., Ltd. in China).

Test of SSCFI

To verify the effect of mud cake solidifier (GJ-I and GJ-II) on the mud cake solidification, the SSCFI of self-made SWBs were tested. The SWBs (Fig. **1**) share the similar physical properties and compaction law of Yuanye HF-1 formation.

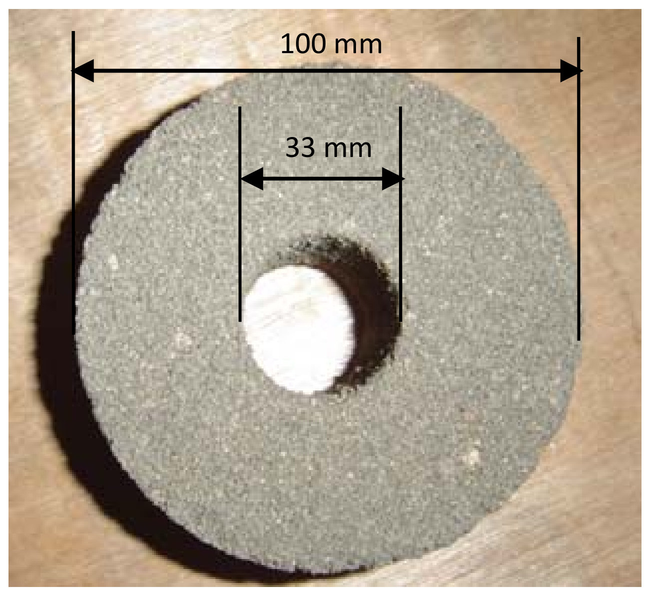

Fig. (1). SWB based on physical properties and compaction law of interlayer.

Experiment procedures. Firstly, inject drilling fluid into SWBs and ensure the whole annular space is filled with

Table 1. Properties of the drilling fluid in well Yuanye HF-1.

Density ($g \cdot cm^{-3}$)	Marsh Viscosity (s)	Plastic Viscosity (mPa·s)	Shear Force (Pa)			Mud Cake Thickness (mm)	API Fluid Loss (ml)	pH
			Initial	Final	Yield Point			
1.55	62	28	4	16	10	0.3	2.5	10

drilling fluid. Wait for 4 h until a certain thickness of mud cake form. Remove the false mud cake with glasses rods gradually (simulating the activity of bore) until a dense mud cake forms. Secondly, divide all SWBs into two groups. In the first group, use conventional technology (not MTC or MTA) where water is used as prepad fluid to treat the mud cake. In the second group, use the mud cake solidification method to treat the mud cake where both GJ-I solution and GJ-II solution are used. The contact durations of GJ-I solution and GJ-II solution are 70s and 140s respectively. Thirdly, prepare the cement slurry according to API RP 10B. Inject the cement slurry into the SWBs. Stir the cement slurry several times with a stirrer bar to ensure that the cement slurry has a good consistency. Fourthly, put them into a curing box for 3, 7, 15 and 30 days at 90 °C (the downhole temperature of well Yuanye HF-1). Fifthly, test the shear force at cement-interlayer interface and record the height of SWB. At last, calculate SSCFI according to Eq. (1) [10].

$$p = \frac{10F}{\pi h D} \tag{1}$$

where p is SSCFI (MPa), F is the shear force at cement-interlayer interface (KN), h is the height of SWB (cm), and D is the inner diameter of SWB (3.3 cm).

Experiment results. The results of SSCFI with conventional technology and mud cake solidification technology are shown in Fig. (**2**). Compared to the conventional technology, SSCFI is increased by 629.03% (3 days), 222.37% (7 days), 241.43% (15 days) and 273.33% (30 days). The increasing rate of SSCFI decreases with curing time but it is always above 200%.

Compatibility Experiment of Mud Cake Solidifiers

GJ-II prepad fluid contact with the cement slurry directly, and GJ-I may not. The compatibility among mud cake solidifier, cement slurry, drilling fluid and prepad fluid is extremely important for cementing operation safety (safety standards: thickening time not smaller than construction time plus 1 h).

Compatibility experiment. Compatibility experiments are conducted at bottomhole circulating temperature (80°C) and bottomhole circulating pressure (60MPa). The experiments stop when the torque on the paddle in the slurry cup reaches 70Bc. According to the experimental scheme, nine groups of thickening tests were designed. The experimental results of the compatibility are listed in Table **2**.

Experiment results and analysis. The results show that all mixed cement slurries have good compatibility and can meet the requirement for the cementing operation of well Yuanye HF-1. The thickening property of the cement slurry is stable. When the mixing ratio of GJ-I, GJ-II and cement slurry is 2:1:7, the thickening time gets shorter but it is sufficient to place the slurry safety and to allow for an unexpected job difficulty. Previous work has proved that the GJ-I prepad fluid may accelerate the cement hydration process, however, it should be noted that during the cementing operation, GJ-I and cement slurry is separated by GJ-II, so they have no chance to contact with each other actually.

APPLICATION ANALYSIS

Field Application

The entire construction process went smoothly on March 5, 2012. The records of cementing operation are listed in Table **3**.

Effect Analysis

The cementing quality of Yuanye HF-1 was evaluated using CBL/VDL logging technology after 3 days of cementing. Yuanba 9 well shares the similar geology structure with Yuanye HF-1 [32, 33]. Therefore, their cementing qualities were compared to evaluate the effect of

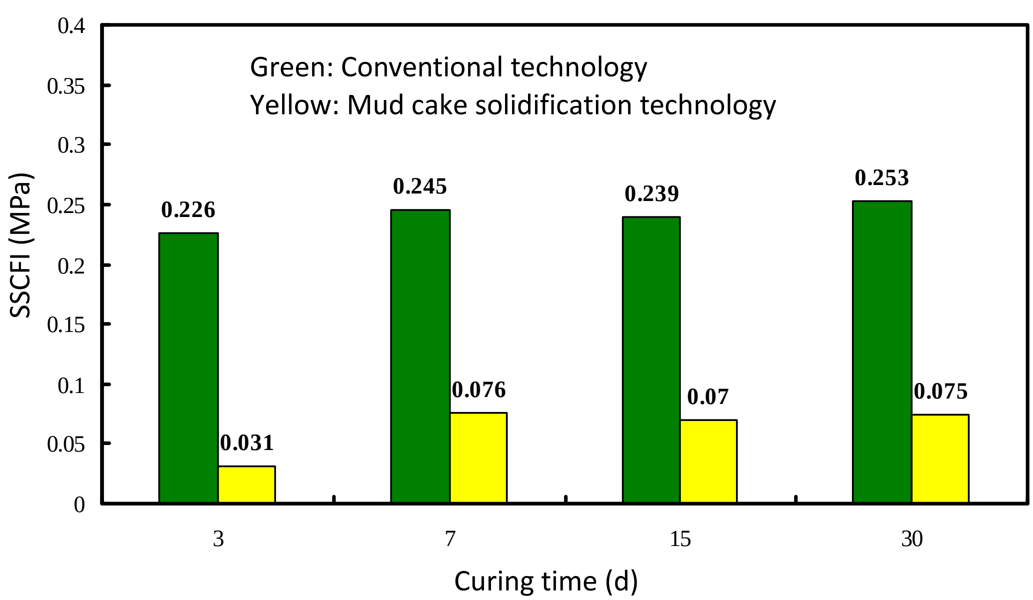

Fig. (2). Comparison of SSCFI in conventional technology and mud cake solidification technology.

Table 2. Experimental scheme of compatibility.

Mixing Ratio (%)					Thickening Time
Drilling Fluid	Prepad Fluid	GJ-I	GJ-II	Cement Slurry	
			50	50	Not thickening in 420min
			10	90	Not thickening in 420min
		5	5	90	Not thickening in 420min
		10	10	80	Not thickening in 480min
		20	10	70	Reach to 70Bc after 240min
		10	20	70	Not thickening in 420min
	10	10	10	70	Not thickening in 420min
10	10	10	10	60	Not thickening in 420min
20	20	20	20	20	Reach to 70Bc after 324min

Note: The mixing ratio is the volume fraction ratio.

Table 3. Records of cementing operation.

Construction Time	Injection Liquid		Density ($g \cdot cm^{-3}$)	Displacement ($m^3 \cdot min^{-1}$)	Pump Pressure (MPa)	Note
	Type	Amount (m^3)				
14:07-14:20	Flushing fluid	8	1.02	1.2	5	
14:20-14:35	Spacer fluid	8	1.70	1.4	6	
14:35-14:54	Flushing fluid	8	1.02	1.2	5	
14:54-15:04	GJ-I	2	1.11	0.6	5	
15:04-15:15	GJ-II	2	1.05	0.6	5	
15:15-17:15	Pilot slurry[1]	130	1.89	2.0-2.4	15	Cement slurry returns to surface
	Tail slurry[2]	40				
17:15-17:20	Prepad fluid	4		0.8-1.0	4	
17:20-18:31	Drilling fluid	136.64		2.4	8-11	Pumping pressure is 13MPa

Note: 1) Formula of pilot slurry: Class G cement + 3.0% SYJ-3 + 0.175% SYH-1 + 0.5% SYLG-1 + 0.175% SWX-1 + 42.5% well site water; 2) Formula of tail slurry: Class G cement + 3.0% SYJ-3 + 0.125% SYH-1 + 0.5% SYLG-1 + 0.125% SWX-1 + 42.5% locale water.

mud cake solidification method. The total length of isolation section of Yuanye HF-1 and Yuanba 9 is 3663m and 3053 m respectively. The data of their cementing quality are listed in Table **4**.

The CBL/VDL logging curve shows the cementing quality of Yuanye HF-1 (Mud cake solidification technology) is high. The high quality (acoustic amplitude is less than 15%) is 93.49%. Weak casing wave and strong formation wave in the logging curve indicate both casing-cement interface and cement-interlayer interface are of high cementing quality. While the qualified rate of Yuanba 9 (conventional technology) is only 15.54%. In the logging curve, casing wave is very strong from 1998 to 2700 m, indicating a pretty bad cementation between casing and formation. The great differences between these two wells prove that the mud cake solidification technology can improve the cementing quality remarkably.

Logging Interpretation of Gas Reservoir Isolation

The mud logging data of Yuanye HF-1 indicate good hydrocarbon show in the sections from 3131 to 3133 m, 3136 to 3151 m, 3234 to 3241 m, 3378 to 3379 m, 3569 to 3570 m and 3608 to 3611m. These sections should be

Table 4. Comparison of cementing quality of two wells.

Cementing Quality	High Quality		Qualified		Unqualified		Comprehensive Evaluation
	Rate (%)	Length (m)	Rate (%)	Length (m)	Rate (%)	Length (m)	
HF-1	93.49	3424.3	5.91	216.4	0.6	22.3	High quality
Yuanba 9	7.29	222.5	8.25	251.8	84.46	2801.2	Unqualified

Table 5. Cementing quality of gas reservoir in well Yuanye HF-1.

No.	Well Section (m)	Thickness (m)	Interpretation	Cementing Quality
1	3131-3133	2	Micro gas-bearing reservoir	High
2	3136-3151	15	Gas-bearing reservoir	High
3	3234-3241	7	Micro gas-bearing reservoir	High
4	3378-3379	1	Micro gas-bearing reservoir	High
5	3569-3570	1	Micro gas-bearing reservoir	High
6	3608-3611	3	Gas-bearing mudstone fracture reservoir	High

extremely well cemented, or else the gas would channel into the annulus space and leave a channeling path during setting process of cement slurry.

Table **5** presents the results of logging interpretation for the gas reservoir sections. All gas reservoir sections are of high cementing quality, especially the sections form 3136 to 3151 m (gas-bearing reservoir) and 3608 to 3611 m (gas-bearing mudstone fracture reservoir). The results prove that the mud cake solidification technology also plays a significant role in improving the cementing quality of gas well and avoiding gas channeling.

MECHANISM OF MUD CAKE SOLIDIFICATION

Hydrolysis of Sodium Silicate

GJ-I and GJ-II solution contain abundant sodium silicates, a kind chemical reagent that is very easy to hydrolyze to silicate colloidal particles and hydroxyl. There appear to be two distinct reactions when sodium silicate hydrolyzes in the solution.

$SiO_3^{2-}+3H_2O=Si\ (OH)_4+2OH^-$

$Si(OH)_4+OH^-= H_3SiO_4^- +H_2O$

Formation of Adhesive Bridge

Sodium silicate has good properties, such as dehydration hardening and good bonding performance, etc. The silicates in mud cake solidifier diffuse into mud cake and they are adsorbed on the surface of clay particles. Then, silicates form a long chain of -Si-O-Si- by condensation reaction. As condensation reaction continues, the long chain can form a network structure eventually, connecting the adjacent clay mineral particles together. The condensation reaction of silicates is as follows.

$$
nSi(OH)_4 \rightarrow \left[Si(OH)_4\right]_n \xrightarrow{-2nH_2O}
\begin{array}{ccccccc}
 & | & & & | & \\
- & Si & - & O & - & Si & - \\
 & | & & & | & \\
 & O & & & O & \\
 & | & & & | & \\
- & Si & - & O & - & Si & - \\
 & | & & & | &
\end{array}
$$

Alkali-Activated Reaction

Clay minerals have a potential activity in strong alkali environment. Si-O bond and Al-O bond in some clay minerals will be broken by the alkali-activated reactions. As a result, the silicate tetrahedron deforms and alumina octahedron even transform to alumina tetrahedron. As the alkali reactions continue, these deformed structures will finally be destroyed and release $H_3SiO_4^-$, AlO_2^-, $H_3AlO_4^{2-}$. Condesation reactions also happen when these silicates are released, which reinforce -Si-O- network structure and help bond the particles together.

Formation of Gels

Ions ($H_3AlO_4^{2-}$, $H_3SiO_4^-$, etc) from the alkali-activated reactions and ions (Na^+, $H_3SiO_4^-$, etc) in the mud cake solidifier reorganize with Ca^{2+} and OH^- from cement slurry. In this process, some gels like calcium silicate hydrate (C-S-H) with different silicate-calcium ratio and natrolite form. These gels fill the pores and micro-fractures in the mud cake and bond the particles together, leading to the integrated solidification and cementation of the cement- interlayer interface. The chemical reactions are as follows.

$xCa^{2+}+ yH_3SiO4^- + zOH^- \rightarrow$ C-S-H Hydrated calcium silicate

$5Ca^{2+}+ 2H3SiO4^-+ 8OH^- \rightarrow Ca_5(SiO4)_2(OH)_2+ 6H_2O$ Heavy okenite

$3Ca^{2+}+ 2H_3SiO4^-+ 4OH^- \rightarrow Ca_3Si_2O_7\cdot H_2O +4H_2O$ Killalaite

$Ca^{2+}+ 2H_3AlO_4^{2-} + 6OH^-+4H_2O \rightarrow CaAl_2O_4\cdot 10H_2O$ Hydrated Calcium Aluminates

$1.74Na^++ 2H_3AlO_4^{2-} +3H_3SiO_4^- \rightarrow Na_{1.74}(Al_2Si_3O_{10})(H_2O)_{1.5} + 6H_2O$ Natrolite

CONCLUSION

1. The mud cake solidification technology greatly improves SSCFI of SWBs and increasing rates are above 200%.
2. The compatibility among the mud cake solidifier, cement slurry, drilling fluid and prepad fluid meets the requirements of cementing operation.
3. Logging data show the mud cake solidification technology is very effective in improving the cementing quality of shale well. The high-quality rate of cement-interlayer interface of well Yuanye HF-1 is

93.49% while the unqualified rate of Yuanba 9 (an adjacent well) is up to 84.46%.

4. The mechanism of integrated solidification and cementation of the cement- interlayer interface can be divided into five steps: hydrolysis of sodium silicate, formation of adhesive bridge, alkali-dissolved reaction and formation of gelling materials. It explains why the mud cake solidification technology greatly improves SSCFI and cementing quality of shale well.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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