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Research on Low Density Cementing Technology of Coalbed Methane Well

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Abstract

The pressure of the coalbed methane (CBM) reservoir is relatively low, there is serious loss circulation, andlow mechanical strength of the coal, which seriously influence the cementing quality. In this paper, according to the characteristics of coal in southern Qinshui basin, an ultra-low density cement slurry system and a foamed cement slurry system are designed and developed to reduce the density of cement slurry by adding lightening admixture and foaming agent through the experimental method. An appropriate bridging type preflush system is also researched and developed. Considering the drilling conditions, the operation technologies are put forward.The ultra-low density cement slurry system has good rheological performance, small API filter loss (≤ 45 mL/ (30 min·6.9 MPa)), excellent sedimentation stability, suitable thickening time and higher early strength. Foamed cement slurry systemhas good rheological performance, excellent sedimentation stability andsuitable thickening time, and can satisfy the compressive strength requirements for the cementing of CBM wells. The fluid loss of the bridging type preflush system is small under the medium or high pressure, withgood rheological performance,andexcellent plugging ability. The ultra-low density cement slurry system and foamed cement slurry system were applied in 14 and 11 CBM wells respectively, and good results have been achieved.

Key words: Coalbed methane well; Low density cementing technology; Ultra-low density cement slurry system; Foamed cement slurry system; Bridging type preflush system

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INTRODUCTION

As a clean and efficient new energy, coalbed methane (CBM) is mainly concentrated in two large coal accumulating areas in north and northwest China. The CBM reserves of the Qinshui basin in southern Shanxi province reaches 6.25×10^{12} m^3, 17% of the total CBM reserves in China. With great prospects for development, a CBM exploration and development demonstration project has been established in Qinshui basin by the state[1]. The altitude of the pilot area is 780 m~1,180 m, generally around 1,000 m, #3 coal and #15 coal are the major target coal seam. The coal is mainly anthracite which is formed by magmatic thermal metamorphism and magmatic thermal metamorphism, which can make good preservation of the coal native structure fracture, and cleats and fractures are well developed. The pressure of the CBM reservoir is relatively lowin the south pilot area, low pressure reserves accounted for over 70%, pore pressure gradient is generally less than 10 kPa/m[2-3]. There is serious loss circulation while drilling CBM wells, a large amount of cement slurry is leaking into the coal while cementing, which seriously influence the top of cement and cementing quality. Meanwhile, there are mutually perpendicular natural cracks in the coal, and the mechanical strength of the coal is small, so that the coal is easy to break. The wall of borehole is not stable after drilling, very easy to collapse, the borehole diameter enlargement is rather serious, and drilling fluid often carries large quantity of pulverized coal, which reduces the rheology of the drilling fluid and lowing the displacement efficiency of the cement slurry[4-5]. Therefore, it is necessary to make research on the appropriate CBM well cementing slurry system and corresponding supporting technologies.

At present, the cementing technologies commonly used for weak formation mainly include low density cement slurry cementing[6-7], foamed cement slurry cementing[8-10], and the multiple stage cementing and plug flow displacement technology. In this paper, according to the characteristics of coal in southern Qinshui basin, an ultra-low density cement slurry system and a foamed cement slurry system are designed and developed to reduce the density of cement slurry by adding lightening admixture and foaming agent. An appropriate bridging type preflush system is also researched and developed.Considering the drilling conditions, the operation technologies are put forward. The ultra-low density cement slurry system and foamed cement slurry system were applied in 14 and 11 CBM wells respectively, and good results have been achieved.

1. BRIDGING TYPE PREFLUSH SYSTEM AND ITS PERFORMANCE

According to the design principle of the bridging type preflush, the water soluble fiber type lost circulation agent DL–X, the performance modifying agent TJ-P which can control the filter loss and adjust the rheological properties, and the aided filler TC-S which is helpful to form filter cake and ensure the stability of slurry are researched and developed. Through a large number of laboratory tests, the formula of the bridging type preflush system is determined (admixture dosage for the mass percentage of the total water quality), as shown in Table 1.

Table 1
Composition of Bridging Type Preflush

Density (g/cm^3)	Dispersion medium	Lost circulation agent DL-X /%	Aided filler TC-S/%	Performance modifying agent TJ-P/%	Defoamer SWX-1/%
1.04	Water	2.6	5.6	1.72	1.0

Tests were conducted under the condition of 0.69 MPa and 6.9 MPa, the filter loss of bridging type preflush in 30 min are 5.5 ml and 19 ml respectively, which indicated that the fluid loss control ability of the bridging type preflush is very strong, the fluid loss is small under the medium or high pressure, it helps to prevent the invasion of liquid or solid particles of the preflush into the coal seam,and reduce the damage to coal and protect the CBM reservoir. The rheology of bridging type preflush, the liquidity index n and the consistency coefficient are tested, the results are 0.819 and 0.0526 $Pa·s^n$ respectively, which shows that the bridging type preflush has good rheological properties, and is conducive to the realization of turbulence displacement. The on-site No.3 coal seam core is selected to conduct the evaluation of actual plugging performance, the effect contrast diagrams are shown in Figures 1 and 2. No solid particles of the cement slurry are found in No. 3 coal seam core, which proves that the bridging type preflush has excellent plugging ability, and is beneficial to prevent the pollution of coal reservoir, and is able to achieve the goal of protecting coal reservoir.

Figure 1
No.3 Coal Seam Core of Qinshui Basin

Figure 2
Shut Off Capacity of Bridging Type Preflush to No.3 Coal Seam Core of Qinshui Basin

2. ULTRA-LOW DENSITY CEMENT SLURRY SYSTEM AND ITS PERFORMANCE

2.1 Ultra-Low Density Cement Slurry System

Based on class G oil well cement, according to the close packing theory, the active filling material RM is selected. To reduce the density of cement slurry, the lightening admixture of middle-empty glass micro-bead S38 is added. To further adjust the cement slurry performance, the fluid loss agent CM-L, dispersant CM-D and early strength stabilizing agent LA-P are used. Through a large number of laboratory tests, the ultimate density of the ultra low density cement slurry system (ULWC) is confirmed to be 0.82-1.20 g/cm^3, the specific composition and components are shown in Table 2.

Table 2
Composition of Ultra-Low Density Cement Slurry System ULWC

Density (g/cm^3)	Oil well cement	Lightening materials S38 (%)	Filler RM (%)	Fluid loss agent CM-L (%)	Dispersant CM-D (%)	Early strength stabilizing agent LA-P (%)	Defoamer SWX-1 (%)	Water cement ratio
1.20	Class G	23	28	4.95	1.6	4.0	0.50	1.16
1.10	Class G	34	30	5.25	1.7	4.2	0.53	1.23
0.95	Class G	60	34	5.50	2.0	4.4	0.55	1.28
0.82	Class G	103	38	5.85	2.5	4.7	0.60	1.37

2.2 Performance of Ultra-Low Density Cement Slurry System

2.2.1 Rheological Properties

In accordance with the oil and gas industry standard SY/T 5480-92 "Rheological Design of Cement Slurry", under the condition of room temperature (20 ℃), the rheological data of the ultra-low density cement slurry system are measured, and the results are shown in Table 3.

Table 3
Rheological Properties of Ultra-Low Density Cement Slurry ULWC System

Density (g/cm^3)	Φ300	Φ200	Φ100	Φ6	Φ3	n	K/(Pa·s^n)
1.20	63	46	27	5	4	0.770	0.264
1.10	106	74	42	7	6	0.841	0.285
0.95	121	87	56	15	13	0.700	0.786
0.83	150	109	77	21	17	0.606	1.751

The results show that the flow index of the ultra-low density cement slurry system is: $n \geq 0.606$, and the consistency coefficient is $K \leq 1.751$, indicating that the cement slurry system has good rheological performance and can help to reduce the friction resistance of cement slurry, so as to reduce the pump injection pressure of cementing, and meet the requirements of cement slurry flow index $n \geq 0.6$ for field cementing.

2.2.2 API Filter Loss

In the process of slurry pumping, filter loss will occur when the cement slurry flows through the high permeability formation under the pressure. The filter loss of the cement slurry will lead to the following main influence on cement slurry performance: increase the density of the cement slurry, the thickening time and the rheological properties of the cement slurry will seriously deviate from the original design requirements, even can make the cement slurry unpumpable, and may cause the failure of the cementing operation when it is serious. It increases the static shear stress between the cement slurry and the wall of the borehole and the volume shrinkage of cement stone, thus to enhance the cement slurry weightlessness speed, and easy to occur fluid channeling. The formed filter cake is often loose and thick, which is not conducive to the interface cementation between the cement loop and the borehole wall, easy to form microclearance, thus cause the existence of potential channel for fluid channeling. To this end, the filter loss of the ultra-low density cement slurry is strictly controlled. The API filter loss of the cement slurry should be as small as possible, it is better to be controlled within 50 mL/30min. The syneresis rate of cement slurry is related to the sedimentation stability and the volume shrinkage of cement stone. To ensure the stability of cement slurry and reduce the volume shrinkage rate, the syneresis rate is demanded to be zero, namely no free liquid in cement slurry. Table 4 shows the amount of free fluid and API filter loss of the ultra-low density cement slurry system, the results indicated that the system has no free liquid, and the filter loss is very small (API filter loss ≤ 45 mL/30 min).

Table 4
Free Fluid and Water Loss of ULWC System

Item	Number				
Slurry density (g/cm^3)	1.20	1.10	0.95	0.83	Slurry of conventional density
Syneresis rate (%)	0	0	0	0	1.9
API fluid loss (mL/30 min)	37	35	40	45	>1000

2.2.3 Sedimentation Stability

In the process of cementing operation, if the sedimentation stability of the cement slurry is poor, it is bound to cause the dynamic changes in the density of cement column. Similarly, the rheological properties of the cement slurry in corresponding strata also present dynamic changes, which bring certain difficulties to the rheological design and displacement efficiency of cement slurry. In severe cases, it will increase the displacement pressure, causing pump suffocation, formation breaking and other serious accidents. For ultra-low density cement slurry, the water cement ratio in itself is quite big, while the density difference among lightening admixture, cement and other materials is rather big, which are not conducive to the stability of cement slurry. Therefore, it is particularly important to study the sedimentation stability of the ultra-low cement slurry.

In order to reflect the real stability of the ultra-low density cement slurry as far as possible, the measurement of the density change of solidified cement stone is used to reflect the stability of the system. The specific experimental steps are as follows:

(a) Prepare a cylindrical steel cylinder mold, with the diameter of 25 mm and height of 250 mm, to coat with a layer of calcium lubricating oil evenly on the inner wall of the tube and the inner surface of the top and bottom screw caps of the mold, and pour the prepared cement slurry into the mold.

(b) Put the mold with cement slurry into 40 ℃ constant temperature water bath for 24 hours' curing.

(c) Divide the cement pillar into 8 pieces, and number them in sequence, measure their quality by electronic analytical balance, to obtain the volume of the cement stones by using the drainage method, and calculate their corresponding density respectively.

According to the above method, the sedimentation stability of the four kinds of ultra-low density cement slurry with different density is tested, and the results are shown in Table 5.

Table 5
Changes of Cement Stone Density

	Density of cement slurry system (g/cm^3)			
	System 10.83	**System 20.95**	**System 31.1**	**System 41.2**
Density of cement stone (g/cm^3)	0.818	0.940	1.090	1.192
	0.822	0.941	1.093	1.193
	0.826	0.943	1.095	1.196
	0.829	0.947	1.098	1.198
	0.832	0.950	1.098	1.199
	0.836	0.953	1.100	1.201
	0.840	0.957	1.102	1. 202
	0.843	0.959	1.106	1. 205

It can be seen from Table 5, for the aforesaid four kinds of ultra-low density cement slurry system with different density. From top to bottom, the density difference of the cement stone after solidification are 0.025 g/cm^3, 0.019 g/cm^3, 0.016 g/cm^3, 0.013 g/cm^3 respectively, all are less than 0.025 g/cm^3. It is generally believed that the requirements for the stability of the conventional cement slurry, the density difference of the cement stone from top to bottom should be less than 0.08 g/cm^3, which fully shows that the ultra-low density cement slurry system has excellent sedimentation stability.

2.2.4 Thickening Time

Thickening time refers to the time that the consistency of cement slurry reaches 100 Bc under the conditions of simulated downhole temperature and pressure. It is one of the most important performance indexes of the cement slurry, which directly reflects the duration of keeping the state of pumping, to provide a reliable pump injection time for the cementing operation. Table 6 lists the thickening time of the ultra-low density cement slurry system under the condition of 40 ℃/15 MPa.

Table 6
Thickening Time of Ultra-Low Density Cement Slurry System

Item	Number			
Cement slurry density (g/cm^3)	1.20	1.10	0.95	0.83
Thickening time (minute) (at 40 ℃×15 MPa)	176	183	210	302

Figure 3 is the thickening curves of the cement slurry system with the density of 0.95 g/cm^3 under the condition of 40 ℃/15 MPa.

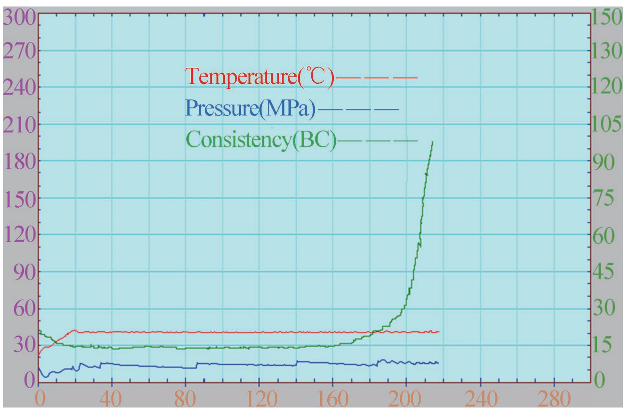

Figure 3
Thickening Curve of the Cement Slurry System With the Density of 0.95 g/cm^3

Test results showed that the ultra-low density cement slurry system with the density of 0.95 g/cm^3 has a suitable thickening time, and the thickening curve also shows a good "right angle thickening" characteristics, which helps to improve the anti-channeling ability of the cement slurry.

2.2.5 Compressive Strength

For CBM well, the downhole temperature is low, cement slurry with a relatively high early compressive strength can shorten the time waiting on cement. By using the ultrasonic technology, the continuous development rule of the compressive strength for the ultra-low density cement slurry system with the density of 0.95 g/cm^3 and 0.83 g/cm^3 under the condition of 40 ℃/15 MPa is tested out (see Figures 4 and 5).

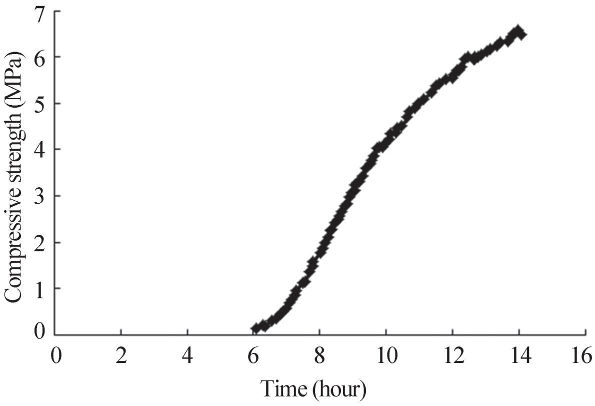

Figure 4
Compressive Strength Continuous Development Rule of the Cement Slurry System With the Density of 0.95 g/cm^3

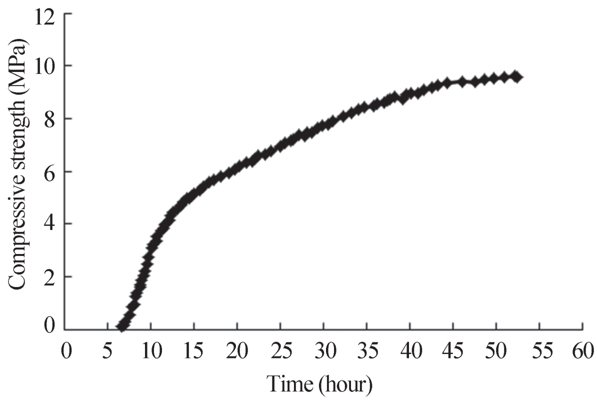

Figure 5
Compressive Strength Continuous Development Rule of the Cement Slurry System With the Density of 0.83 g/cm^3

The Figure 4 shows that the density of 0.95 g/cm^3 system began to have the value of compressive strength in 5 hours and 44 minutes, the compressive strength reached 3.5 MPa in 9 hours and 20 minutes, and reached 5.61 MPa in 12 hours, which can confirm that the ultra-low density cement slurry system has higher early strength, reflects the early strength properties of the system. It is shown in Figure 5 that the density of 0.83 g/cm^3 system began to have the value of compressive strength in 6 hours and 10 minutes, the compressive strength reached 3.5 MPa in 10 hours and 40 minutes, and reached 9.39 MPa in 48 hours, and the compressive strength of the cement stone was continuously growed.

The compressive strength of different ultra-low density cement slurry ULWC system was tested at room temperature (23 ℃), and at the temperature of 40 ℃ and 50 ℃, the experimental results are shown in Table 7. For the ULWC system with different density, the cement stone has higher strength, even at room temperature (23 ℃), the strength of cement stone in 24 hours is greater than 3.5 MPa. When the cement slurry density is ≧ 0.95 g/cm^3, for the compressive strength of the ULWC system, if the lightening admixture is LW-P, the compressive strength is very low, while if the lightening admixture is HGS4000, the compressive strength of the cement slurry system is very high. Under the condition of room temperature (23 ℃), the strength of cement stone in 24 hours is greater than 4.0 MPa, both at 40 ℃ and 50 ℃, the strength of cement stone in 24 hours was greater than 7.0 MPa.

Table 7
Compressive Strength of Cement Stone

Density (g/cm^3)	Strength at 23℃ (MPa)		Strength at 40℃ (MPa)		Strength at 50℃ (MPa)	
	24h	48h	24h	48h	24h	48h
1.20	5.16	9.53	9.31	16.22	12.10	18.02
1.10	4.57	8.10	9.12	14.59	11.35	16.84
0.95	4.12	8.35	8.04	12.73	10.22	14.36
0.83	3.51	6.10	6.37	8.94	7.39	9.25

3. FOAMED CEMENT SLURRY SYSTEM AND ITS PERFORMANCE

3.1 Foamed Cement Slurry System

Based on class G oil well cement, the water cement ratio is 0.50, the foaming agent PN is added to produce nitrogen in the cement slurry which helps to achieve the purpose of "chemical nitrogen filled", foam stabilizer SC-1 and stability enhancer NS-2 are added to form a stable foam system. To further adjust the rheological properties, filter loss and thickening time etc., sulfonated aldehyde ketone dispersant CM-D, non-ionic polyethylenes fluid loss agent CM-L and early strength agent FC-A are used. Through a large number of laboratory tests, the ultimate density of the high performance foam and low density cement slurry system (HPFC) is confirmed to be 1.10-1.20 g/cm^3, the specific composition and components are shown in Table 8.

Table 8
Composition of New High Performance Foam and Low Density Cement Slurry System HPFC

Oil well cement	PN /%	SC-1/%	NS-2/%	CM-D/%	CM-L/%	FC-A/%	Water/%	Density/g·cm^{-3}
Class G	1.80	1.2	3	0.20	1.0	2.5	50	1.10
Class G	1.60	1.1	3	0.15	1.0	2.0	50	1.20

3.2 Performance of Foamed Cement Slurry

3.2.1 Fluidity and Free Fluid of HPFC System

Under the condition of room temperature (25 ℃), the fluidity and syneresis rate of the new foamed cement slurry HPFC system were measured, the fluidity was 24.5 cm and 25 cm with the density of 1.10 g/cm^3 and 1.20 g/cm^3, respectively, the syneresis rate for both was 0. It indicates that the HPFC system has good rheological performance and is beneficial to reduce the friction resistance of cement slurry, so as to reduce the pumping pressure while cementing; HPFC system has no free liquid and the zero syneresis rates, indicated that the cement slurry has good sedimentation stability properties.

3.2.2 Filter Loss of HPFC System

Pour the prepared foamed cement slurry into the Model GGS71-A high temperature and high pressure filter press, increase the pressure to 6.9 MPa and set the temperature at 40 ℃, then test the filter loss of cement slurry. The results showed that for the foamed cement slurry with the density of 1.10 g/cm^3 and 1.20 g/cm^3, the API filter losses are 26 mL/30 min and 34 mL/30 min, respectively, and can be controlled within 50 mL/30 min.

3.2.3 Thickening Time of HPFC System

Refer to the method for the determination of foamed cement slurry thickening time provided in API standard 10B-4-2004, to test the thickening time of the new foam low density cement slurry HPFC system under the condition of 40 ℃ and 10 MPa, the test results showed that for the foamed cement slurry with the density of 1.10 g/cm^3 and 1.20 g/cm^3, the thickening time is 201 min and 175 min, respectively. The results show that the thickening time of the HPFC system is about 200 minutes which is a reasonable thickening time.

3.2.4 Development Rules of the Compressive Strength of HPFC System Cement Stone

Make high performance foam low density cement slurry HPFC system according to API standard, cure it for 12 hours till final setting at room temperature (20 ℃), then put the foamed cement stone into water at a certain temperature for curing, and test the compressive strength of cement stone cured for 24 hrs and 48 hrs, respectively. The compressive strength values of HPFC system at different temperature are shown in Table 9.

The test results showed that the foamed cement slurry system has relatively high compressive strength at early time, the compressive strength value in 24 hrs ≥ 8.70 MPa, and ≥ 12.32 MPa in 48 hrs. And the compressive strength of cement stone will continue to increase with the extension of curing time and the increase of curing temperature, and can satisfy the compressive strength requirements for the cementing of CBM wells.

Table 9
The Compressive Strength of HPFC System Cement Stone at Different Temperatures

Performance test		Foamed cement slurry system with different density	
Density (g/cm^3)		1.20	1.10
Compressive strength at 40 ℃ (MPa)	24 h	9.47	8.70
	48 h	13.00	12.32
Compressive strength at 60 ℃ (MPa)	24 h	11.57	10.08
	48 h	15.09	14.56

4. FIELD APPLICATION

On the basis of indoor theoretical and experimental research, considering the abnormal conditions in the process of drilling and cementing of CBM wells in southern Qinshui basin, a complete set of ultra-low density cement slurry and foamed cement slurry cementing technology is formed, and the cementing test with the ultra low density cement slurry for 14 wells and the foamed cement slurry for 11 wells have been conducted.

4.1 Case 1: Borehole Diameter Enlargement Ratio of CBM Well Is Comparatively Big

The wellbore of well TS02-X is instable with serious coal collapse. According to the well logging data of TS02-X l, the average well diameter enlargement rate is 15.86%, it is difficult to achieve the pumping rate for turbulence replacement. Therefore, the turbulent displacement is adopted for preflush, and plug flow displacement is for cement slurry. The formulas for calculating critical flow velocity and critical pumping rate in Reference [13] are as shown in Equations (1) and (2)[11].

$$V_c = \left(\frac{k\,\mathrm{Re}_c}{9800\rho}\right)^{[1/(2-n)]}\left[\frac{4000(2n+1)}{(D_h - D_o)n}\right]^{n/(2-n)}, \tag{1}$$

$$Q_c = V_c \times \frac{\pi(D_h^{\,2} - D_o^{\,2})}{4}. \tag{2}$$

For turbulent flow, Re_c = 3,470-1,370, for plug flow, Re_c = 100.

In the equation, V_c stands for the critical flow velocity (m/s); Q_c stands for the critical pumping rate (l/min); n for flow index; k for consistency coefficient (Pa·s^n); Re_c for critical Reynolds number; ρ is fluid density (g/cm^3); D_h for borehole diameter (mm); *Do* as the external casing diameter (mm).

According to the field data, the critical flow velocity of the bridging type preflush and the foamed cement slurry is calculated by the Equations (1) and (2), as shown in Table 10.

Table 10
Critical Pumping Rate of Turbulent Flow and Plug Flow

	Critical pumping rate of turbulent flow	Critical pumping rate of plug flow
Bridging type preflush	454.6	31.4
Foamed cement slurry	5,608	643.1

It can be seen from the calculation results in Table 10, the critical pumping rate of turbulent flow for the foamed cement slurry is up to 5.61 m^3/min, it is difficult for the field cement truck to meet the requirements. Moreover, under this pumping rate, the friction in the casing and the annulus increases, and is easy to break the formation, resulting in a failure of cementing. Therefore, in the field operations, the turbulent flow displacement for preflush and the plug flow displacement for cement slurry are adopted, and the reasonable pumping rate is 500 l/min~600 l/min, the real pumping rate for TS02-X well is 550 l/min. The CBL log after cementing is shown in Figure 6.

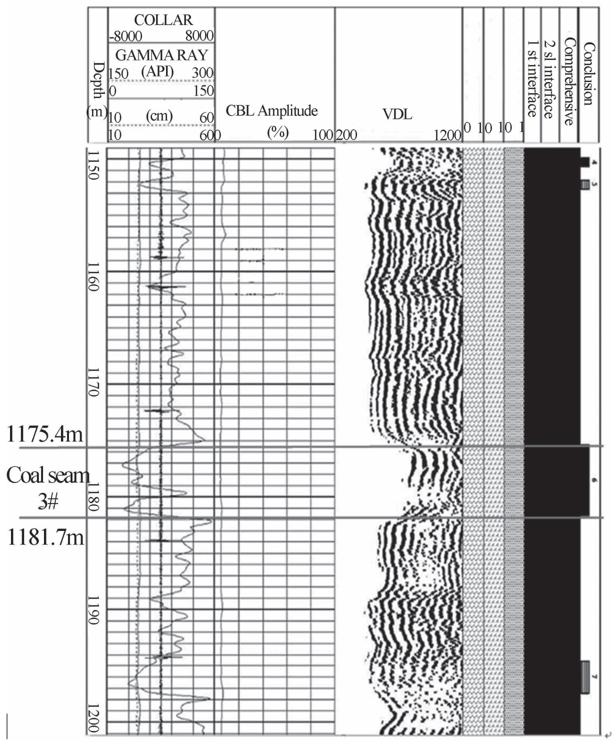

Figure 6
TS02-X Well CBL Logging Curve

4.2 Case 2: Serious Loss Circulation in CBM Wells

The returned drilling fluid in TS53-X well was relatively thick, meanwhile, loss circulation occured at many depths of this well. Although temporary plugging was made to the loss sections before cementing, it was not suitable to wash the wall of the borehole by clean water. Therefore, 5 m^3 bridging type preflush was pumped into the well. It extended the turbulent contact time while protecting the target coal seam, and guaranteed the displacement efficiency of cementing. Figure 7 (see above) is the CBL curve of TS53-X.

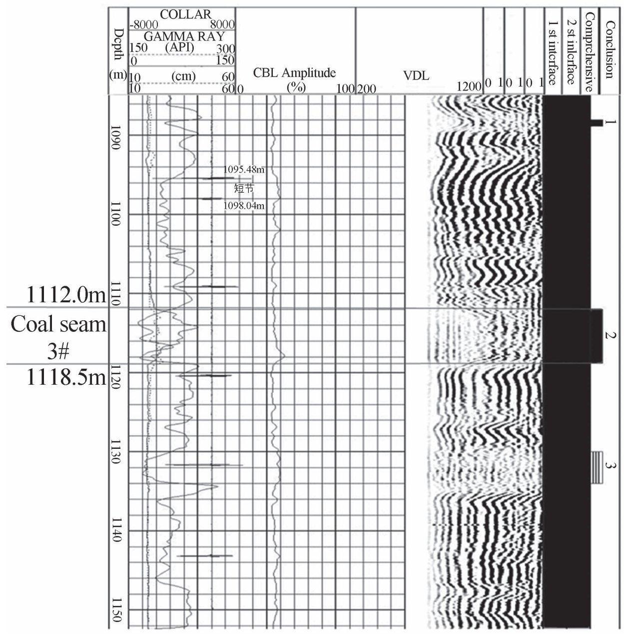

Figure 7
CBL Logging Curve of TS53-X Well

CONCLUSION

(a) An appropriate bridging type preflush system is researched and developed. The fluid loss is small under the medium (5.5 ml/[30 min·0.69 MPa]) or high pressure (19 ml/[30 min·6.9 MPa]), which helps to prevent the invasion of liquid or solid particles of the preflush into the coal seam. It has good rheological properties, and is conducive to the realization of turbulence displacement. Besides, it has excellent plugging ability, and is beneficial to prevent the pollution of coal reservoir.

(b) Based on class G oil well cement, according to the close packing theory, the active filling material RM is selected. To reduce the density of cement slurry, the lightening admixture of middle-empty glass micro-bead S38 is added. To further adjust the cement slurry performance, the fluid loss agent CM-L, dispersant CM-D and early strength stabilizing agent LA-P are used. The ultimate density of the ultra-low density cement slurry system is confirmed to be 0.82~1.20 g/cm^3. The rheological performance, API filter loss, sedimentation stability, thickening time and higher early strength are suitable for the cementing of CBM wells.

(c) Based on class G oil well cement, the foaming agent PN is added to produce nitrogen in the cement slurry which helps to achieve the purpose of "chemical nitrogen filled", foam stabilizer SC-1 and stability enhancer NS-2 are added to form a stable foam system. To further adjust the rheological properties, filter loss and thickening time etc., sulfonated aldehyde ketone dispersant CM-D, non-ionic polyethylenes fluid loss agent CM-L and early strength agent FC-A are used. The ultimate density of the high performance foam and low density cement slurry system (HPFC) is confirmed to be 1.10~1.20 g/cm^3. The rheological performance, sedimentation stability, thickening time and the compressive strength are suitable for the cementing of CBM wells.

(d) The ultra-low density cement slurry system and foamed cement slurry system were applied in 14 and 11 CBM wells respectively, and good results have been achieved.

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