Pergamon

CEMENT AND CONCRETE RESEARCH

Cement and Concrete Research 29 (1999) 523–526

A new rheological approach helps formulation of gas impermeable cement slurries

Giuseppe Calloni [a,*], Paolo D'Antona [a], Nevio Moroni [b]

[a]EniTecnologie S.p.A., Via F. Maritano 26, 20097 S. Donato Milanese, Milano, Italy

[b]Eni-Agip S.p.A., Via F. Maritano 26, 20097 S. Donato Milanese, Milano, Italy

Manuscript received 8 October 1998; accepted manuscript 4 November 1998

Abstract

The prime tasks of cementing an oil well are to keep the casing in place, to prevent corrosion from formation water, and, most importantly, to avoid the flow of fluids on the outside of the casing. Sometimes gas migration in cement slurries occurs when gas present in the formation exerts pressure against the cement slurry column, causing the formation of microfractures in the setting matrix, expecially during the transition time of the slurry. Many studies have been conducted in the last two decades to help in understanding which properties the cement slurry must have to avoid the migration of such fluids. In this paper we propose a new rheological approach to evaluate the capacity of a cement slurry to stop the migration of fluids from the formation in the wells where the risk of gas migration is relatively high, especially during the transition time. Our rheological approach is based on small amplitude oscillatory measurements. We collected information on either kinetics of gelation of cements for oil well usage or the strength of their structures. This fundamental approach has been useful to formulate different cement slurries that have been used with success in several field trials where the risk of gas migration was relatively high.

Keywords: Rheology; Permeability; Oil well cement; Transport properties

As reported in the literature [1–7], poor bonding at the "formation-cement-casing" interfaces initially was considered the main reason for gas invasion in the annular space. Later on, the industry also accepted that gas could flow through the cement matrix. Therefore, it was concluded that, during the setting process, the cement column becomes self-supporting and that, as a consequence, the hydrostatic pressure is only partially transmitted onto the formations. This causes the reaching of pressures, at times, well below the pore formation pressure and the onset of underbalanced conditions, which favor gas migration in the annulus. Some years ago, Sutton and Ravi [8] demonstrated that channels in a cement column are the combined results of static gel strength development and downhole volume losses, because of filtration and shrinkage.

With time, many specialized cementing techniques and cement systems were designed to combat early gas migration. To reach this goal, most slurries are added with particles at least one order of magnitude smaller than those of the cement; these additives impart to the cement column better performance in terms of elastic behavior against the back-pressure exerted by the gas, which tries to leave the formation. The additives, most widely used nowadays to control gas migration occurrences, are silica fume and synthetic latices [9,10]. These products are efficient, but also chemically reactive and expensive. To understand better the structural properties of cement slurries in terms of gas block systems, we performed standard tests and oscillatory rheological measurements on different types of slurries at two suitable temperatures. The comparison was done between a fresh cement and slurries containing three different gas block additives (silica fume, carbon black, and a thixotropic agent).

1. Experimental methods and discussion

The compositions of cement slurries, prepared with carbon black (slurries A, B, C), are shown in Table 1 and compared with traditional (silica fume and thixotropic agents) formulations (slurries D, E, F).

In the slurry formulations listed in Table 1, all the analyses and the standard tests, recommended by the API SPEC-10 [1], were carried out. In particular, the following tests and apparatus were used:

* Corresponding author. Tel.: 39-2-52046737; Fax: 39-2-52056364; E-mail: gcalloni@enitecnologie.eni.it.

PII: S0008-8846(98)00206-3

Table 1
Slurry compositions

Components	Slurry A	Slurry B	Slurry C	Slurry D	Slurry E	Slurry F
Cement (%)	G-HSR	G-HSR	G-HSR	G-HSR	G-HSR	G-HSR
Carbon black (%)	10	10	10			
Microsilica (%)					12.0	
Dispersant (%)	0.75	0.75	1.0		0.4	
Fluid loss (%)	0.4	0.7	1.2	0.4	0.4	
Extender (%)	3	0.5	1			
Thixo agent (%)						4.0
Density (kg/L)	1.91	1.91	1.88	1.91	1.91	1.91

Slurries A, B, and C refer to formulations containing carbon black.

- For the thickening time evaluation: standard Chandler Engineering consistometers in the temperature range between 25 and 65°C;
- For the fluid loss determination: an HP-HT vertical filter press in the same range of temperatures;
- For the compressive strength measurement: the Ultrasonic Cement Analyzer (UCA);
- For viscosity evaluations: a Fann-35 viscometer with measurements performed at room and bottomhole temperatures;
- For the gas-blocking properties estimation: a gas flow apparatus following a scale-down procedure [11]. A sketch of the gas flow apparatus as well as a typical curve obtained with it are illustrated in Fig. 1.

The slurry performances and the physical-chemical properties obtained from the above tests are shown in Table 2. From analysis of Table 2, it appears that the slurries containing carbon black have better performances in terms of gas migration control, standard rheology, and fluid loss.

Table 2
Main physical–chemical characteristics of the slurries prepared for field use

	Formulation type					
	A	B	C	D	E	F
Fluid loss (mL/30) at 25°C/65°C	35/—	42/—	—/50	140/184	70/66	460/500
Viscosity readings						
300 rpm	90	55	65	90	104	230
200 rpm	70	39	48	77	85	221
100 rpm	48	21	28	59	63	210
60 rpm	38	14	20	53	52	204
30 rpm	30	8	13	50	43	190
Gels 10′′–10′ ($lb/100\ ft^2$)	16–70	3–22	14–58			
Thickening time (min)	250	187	264	280	210	—
Strength (MPa) 8/24 h	0.4–12	10.3–20.2	3.4–20	—	—	—
Temperature (°C)	25	41	56	25	25	25
Gas flow test	No gas	No gas	No gas	Gas	No gas	Gas
Density (kg/L)	1.91	1.91	1.88	1.91	1.91	1.91

Slurries A, B, and C refer to formulations containing carbon black.

With the aim of obtaining more fundamental information about the kinetics of gelation and the gel strength development, an innovative rheological approach was applied, based on small-amplitude oscillatory measurements. Rheological measurements were performed with a controlled strain rheometer (RMS800, Rheometric Scientific Ltd, Leatherhead, UK), equipped with a serrated plate geometry, to avoid slepping phenomena. All the cement slurries were studied through the following rheological test, that is, "time sweep" measurements, where the storage modulus G′ was derived as a function of time at a fixed angular frequency (equal to 6.28 rad/s and a low amplitude <1%).

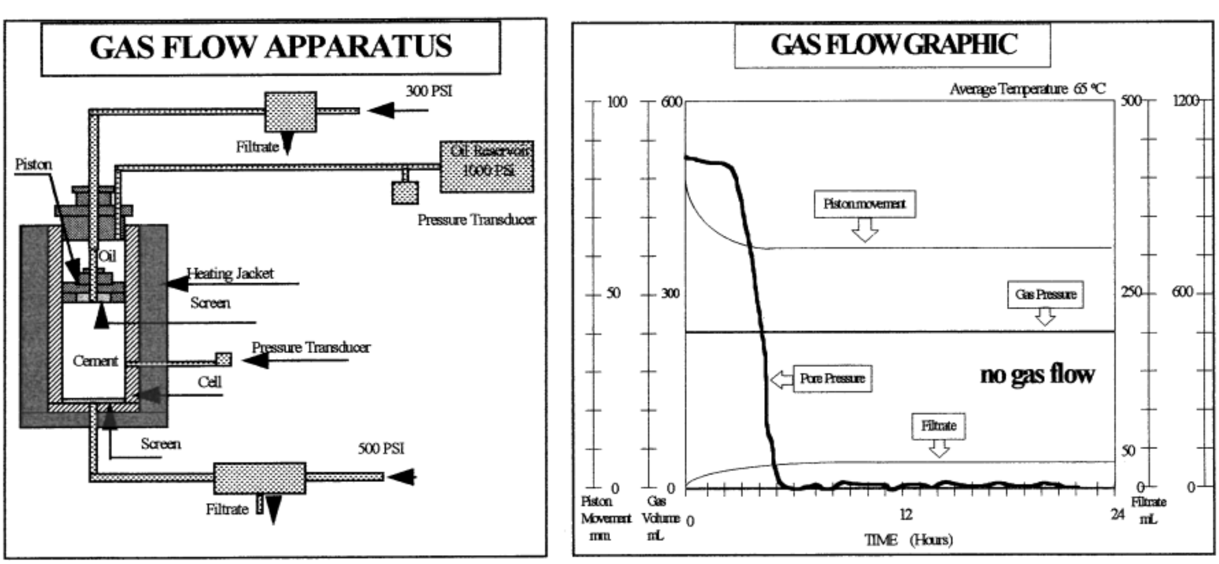

Fig. 1. *(Left)* Schematic diagram of the gas flow apparatus used during the tests. *(Right)* A typical test output is proposed.

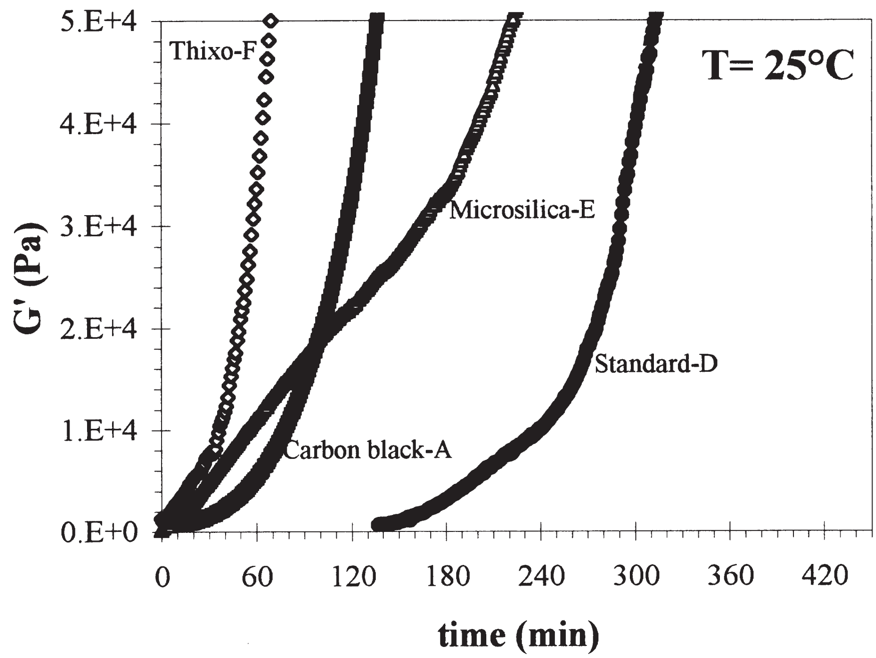

Fig. 2. Kinetic curves of G′ for various slurries at 25°C.

From analysis of the "G′ vs. time" curves (Figs. 2 and 3 at 25°C and 65°C, respectively), it has been possible to derive, for each slurry, the value of the maximum gelation time (t), defined as the time at which $G' = 10^4$ Pa. From the same kinetic curves and precisely in that part where G′ assumes values between 10^3 and 10^4 Pa, it also has been possible to calculate the term "m," their angular coefficient, a parameter that allows prediction of the velocity at which gelation develops.

As previously noted, the work of Sutton and Ravi [8] links the gas migration risks for a slurry to its gel strength development and its downhole volume losses. This risk is

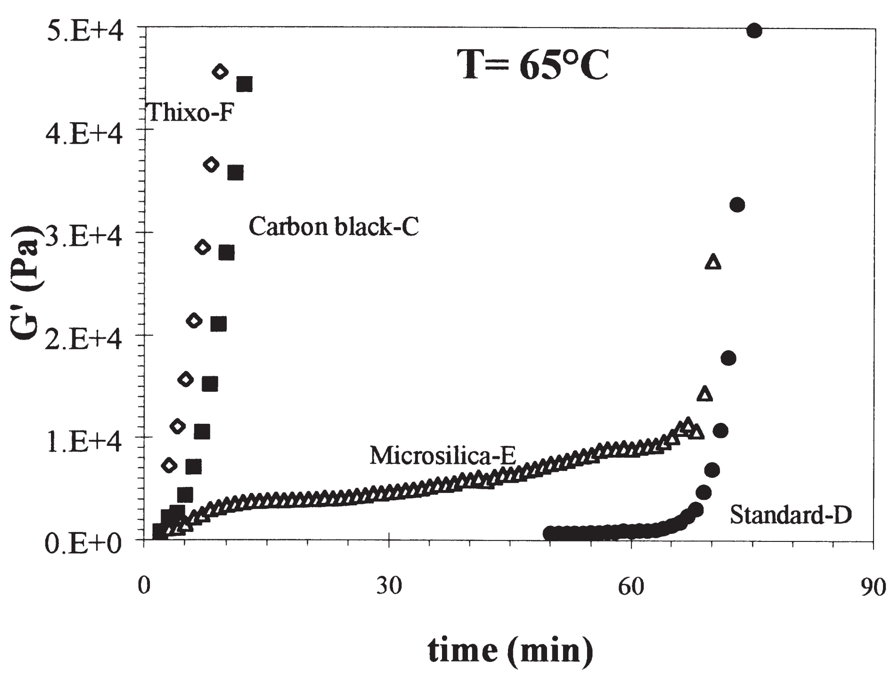

Fig. 3. Kinetic curves of G′ for various slurries at 65°C.

Table 3
Slurries containing carbon black show higher mSRN values than other slurries at 25°C and 65°C

	m (Pa/min)	G′ (Pa)	Fluid loss/API area (cm/min)	mSRN
T = 25°C				
Slurry A	250	8000	0.00823	6.6
Slurry D	80	8000	0.0188	0.93
Slurry E	166	8000	0.0205	1.76
Slurry F	400	8000	0.1584	0.55
T = 65°C				
Slurry C	1500	7000	0.0383	9.72
Slurry D	185	4000	0.0455	1.77
Slurry E	200	6000	0.019	3.04
Slurry F	1866	7200	0.5094	0.88

expressed by the slurry response number (SRN), represented by Eq. (1):

$$SRN = [(dSGS/dt)/SGS_x]/[(dp/dt)/(V/A)] \qquad (1)$$

where dSGS/dt = maximum rate change of the static gel strength, SGS_x = static gel strength at the time of the maximum rate of change, dp/dt = rate of fluid loss velocity at the time of SGS_x occurrence, V = volume of annular space, and A = borehole area.

Entering into Eq. (1) the values of G′ and m as obtained by the rheological studies performed in the oscillatory regime, which better express the gel strength characteristics of a slurry and the rate of fluid loss than other parameters, the authors introduced and used a modified SRN, as indicated in Eq. (2):

$$mSRN = [(m)/(G')]/[(dv/dt)/(V/A)] \qquad (2)$$

where m = maximum rate of change of gelation during the slurry transition period (Pa/min), G′ = storage modulus at time of maximum rate of gelation change (Pa), dv/dt = rate of velocity of fluid loss during transition period/API area (cm/min), V = volume of annular space per unit length (L/m), and A = borehole area per unit length (cm^2/cm).

The mSRN values can provide an empirical mean to rank cement slurries with respect to their capability to stop gas channeling. As defined in the literature [12], slurries characterized by high mSRNs values are more effective in combatting gas migration than slurries with low mSRN values. However, it has been pointed out that Eq. (2) is not claimed to provide an absolute value of the performances of a slurry in facing gas movements, particularly at downhole conditions, but it simply provides a means to compare, on relative terms, different slurries with reference to their gas migration control properties.

As shown in Table 3, slurries containing carbon black (slurries A and C) exhibit higher mSRN values for all the tested compositions and in the entire range of temperatures evaluated than the other formulations (slurries D, E, and F). The reason is that carbon black influences more prominently the kinetics of gel structure in comparison, for instance, to silica fume; in other words, in the presence of carbon black, the gel develops very quickly, thus limiting the transition time and, consequently, reducing the probability of early gas migration by percolation through the cement matrix during the transition period, when the gas flow risk is particularly high.

2. Conclusions

A rheological method to characterize different gas block performance of cement slurries has been proposed. Both kinetics and structural properties can be obtained by the measured parameters t, m, and G′. These parameters were used in the mSRN equation to distinguish different cement slurries with respect to their capability to stop gas channeling during transition time.

The comparison between these parameters obtained for different systems permits better understanding of the mechanisms of action of the gas block additives and can be used to better select gas block cement slurries. Use of the new mSRN has permitted formulation of several impermeable cement slurries for many different field applications where the risk of gas migration was relatively high, saving up to $100,000US for each cementing operation.

References

[1] API Specification 10, fifth edition. July, 1, 1980.
[2] C.E Bannister, Paper SPE 11982 presented at th 58th Annual Technical Conference and Exhibition, San Francisco, California, October 5–8, 1983.
[3] L. Bohlin, J Colloids Interface Sci 72(2) (1980) 423–432.
[4] G. Calloni, N. Moroni, F. Miano, Paper SPE 28959 presented at SPE International Symposium on Oilfield Chemistry, San Antonio, Texas, February 14–17, 1995.
[5] P.R. Cheung, R.M. Beirute, Paper SPE 11207, J Petrol Technol (June 1985) 1041–1047.
[6] M. Grinrod, B. Vassoy, E.O. Dingsoyr, Paper IADC/SPE 17258 presented at IADC/SPE Drilling Conference, Dallas, Texas, February 28–March 2, 1988.
[7] A.A. Guyvoronsky, L.K. Farukshin, Neftjanic 10 (1963) 30–32 (translated from Russian).
[8] D.L. Sutton, R.M. Ravi, Paper SPE 19520 presented at 64th Annual Technical Conference and Exibition, San Antonio, Texas, October 8–11, 1989.
[9] R.B. Stewart, F.C. Schouten, Paper SPE/IADC.14779 presented at IADC/SPE Drilling Conference, Dallas, Texas, February 10–12, 1986.
[10] W.H. Stone, W.W Christian, Paper SPE 4783 presented at SPE/AIME Symposium on Formation Damage Control, New Orleans, Louisiana, February 7–8, 1974.
[11] R.M. Beirute, P.R. Cheung, Paper SPE 19522 presented at 64th Annual Technical Conference and Exibition, San Antonio, Texas, October 8–11, 1989.
[12] K.L. Harris, K.M. Ravi, D.S. King, J.G. Wilkinson, R.R. Faul, Paper SPE 20450 presented at 65th Annual Technical Conference and Exibition, New Orleans, Louisiana, September 23–26, 1990.