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Gas migration through cement slurries analysis: A comparative laboratory study

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Abstract
Cementing is an essential part of every drilling operation. Protection of the wellbore from formation fluid invasion is one of the primary tasks of a cement job. Failure in this task results in catastrophic events, such as blow outs. Hence, in order to save the well and avoid risky and operationally difficult remedial cementing, slurry must be optimized to be resistant against gas migration phenomenon. In this paper, performances of the conventional slurries facing gas invasion were reviewed and compared with modified slurry containing special gas migration additive by using fluid migration analyzer device. The results of this study reveal the importance of proper additive utilization in slurry formulations. The rate of gas flow through the slurry in neat cement is very high; by using different types of additives, we observe obvious changes in the performance of the cement system. The rate of gas flow in neat class H cement was reported as 36000 ml/hr while the optimized cement formulation with anti-gas migration and thixotropic agents showed a gas flow rate of 13.8 ml/hr.

Keywords: *Compressive strength, Fluid loss, Gas migration, Gel strength, Hydrostatic pressure.*

1. Introduction
The oil industry has been wrestling with the issue of gas migration after cementing since the early 1960s [1]. Approximately 80% of wells in the Gulf of Mexico have gas transmitted to surface through cemented casings [2]. A 1955 study by Westport technology revealed that 15% of primary cement jobs in the U.S. fail, costing at that time, $470 million annually. Approximately one-third of those failures were due to gas or fluid migration into the cement [3].

Gas migration through cement slurry is a worldwide problem, especially in the completion of gas bearing zones. There are ways of addressing this problem; these solutions are presented in different phases and categories. Optimization of the slurry plays a key role in fighting gas invasion, however, a mere formula modification will not guarantee success of the cement job in fulfilling its tasks. Operational procedures and techniques, mud removal from the borehole and other factors affect the final result. In fact, slurry design should be accompanied with cement pre and post placement proceedings to ensure success of the cement column in facing gas flow.

Many researchers have investigated different aspects of this problem. Nowadays and the root causes of gas migration are known and suitable responses have been introduced [4]. Operational techniques [3,5], mechanical devices, optimization of cement slurry characteristics like fluid loss and gel strength [6,7,8], special enhanced slurries like impermeable, expanding RAS cements [9, 10] and several other methods have been presented in order to mitigate the problem of fluid migration through cement.

Cheung and Beirute investigated the performance of slurries against gas invasion using a special designed gas flow cell device [1]. Fluid migration analyzer (FMA) evolved from this design. FMA has the capability of simulating well bore and cement job conditions. Parameters such as formation pressure and temperature, hydrostatic and confinement pressure can be applied and considerable outputs of this test consist of Filtration and Gas migration volume.

In this paper, previous test results are reviewed and compared with the slurry particularly designed herein using special additives. The gas migration additive used controls free water and fluid loss of the slurry. Improved gel strength, compressive strength and consistency profile of the cement slurry are other effects of this additive. These modifications result in the formation of a slurry more resistant against gas migration. In fact, the performance of the designed slurry was put into test using FMA device and the results compared with other cement formulations.

2. Methodology

2.1. Theory

The results of more than five decades of investigation on the gas migration phenomenon were summarized and categorized. Various parameters play different roles in this issue. Table 1 defines these factors and describes how they affect cement integrity.

Table 1. Gas migration through cement effective parameters

Parameter	Effect
-Incorrect slurry density	-Hydrostatic imbalance
-Poor mud removal	-Establishment of channels for gas flow
-Premature gel	-Loss of hydrostatic pressure control
-High fluid loss and free water	-Development of spaces for gas entrance
-Permeable slurries	-Weak zonal isolation and low resistance against gas invasion
-High shrinkage	-Porosity and stress increment which leads to creation of micro annulus in cement
-Cement failure due to regional stress regime	-Helps the gas to fracture cement sheaths
-Poor bonding	-Weak bonding in cement and formation/casing interface

It is essential to identify all the factors involved. Some of these parameters cannot be controlled in slurry optimization phase. For instance, in the case of mud removal, a suitable flushing operation and use of well sidewall cleaning tools is the only solution. There are also cement post placement operation techniques which have proved to be useful.

Understanding the mechanism of gas migration is vital, offering a solution is only possible if the concept is well understood. Before slurry design, formation data should be collected. Based on formation pressure, temperature, permeability and thickness the situation is analyzed and the cement slurry is designed.

The gas migration issue is a struggle of pressures; pressure of the gas bearing formation and the well. In order to avoid fluid invasion, pressure inside the well should be kept above formation pressure, hence an overbalanced condition is desired. By weighting slurry, it is possible to create this condition. Cement slurry hydrostatic pressure is calculated by Equation (1) [1].

$$P_c = S_w \times L_c \times (0.052) \tag{1}$$

where:

P_c: cement column hydrostatic pressure (psi)

S_w: slurry density (ppg)

L_c: cement column length (ft)

It is important to note that even though the wellbore pressure is higher than the formation pressure, it must not exceed the formation fracture pressure. Therefore, well pressure should always be between formation pore pressure and fracture pressure as this is a safe pressure window.

Maintenance of this overbalanced condition is not easy. As the cement hydration begins, water is consumed. Filtration and shrinkage are other reasons for cement system water loss. This water volume reduction results in hydrostatic pressure decrement [11]

In the cement setting process, 3 total phases are recognized: fluid, gel and solid phases. The initial state of slurry is liquid. In this stage, hydrostatic pressure is easily transmitted through the cement column. Once the cement sets, it’s a completely solid state and no gas can invade it. The most critical phase, then, is the gel form. In this stage, cement is something between liquid and solid phase. This transition time should be ideally short since in this phase, the cement system pressure decay is observed. This decrease in pressure is shown in Equation (2) [12] thus:

$$P_r = \frac{GS \times L}{300 \times (D - d)} \tag{2}$$

where:

P_r: pressure reduction due to gel strength (psi)

GS: gel strength of the cement at the point in time (lb/100 ft^2)

L: measured length of the cement column above the given location (ft)

D: diameter of the hole (in)

d: diameter of the pipe (in)

Gel development of the slurry results in pressure reduction in the cement column. This pressure is calculated using Equation (3) thus:

$$P_G = P_i - P_r \tag{3}$$

where:

P_G: pressure of the coment column at a point in time with a certain gel strength (psi)

P_i: initial hydrostatic pressure of the coment column (and mud column above)(psi)

P_r: pressure reduction due to gel strength (psi)

At a certain point in time slurry system pressure drops below formation pressure and gas migration occurs. It is important to keep the gas flow rate as low as possible to save the well from a difficult and risky remedial work over. It is most preferable to avoid than treat.

2.2. FMA Test

Fluid migration analyzer (FMA) is a specially designed device used to measure gas flow through cement systems. Actual well and job conditions are simulated using FMA in a laboratory scale. Gas migration volume is a worthy output of this test.

This apparatus consists of a 10 in long and 3 in ID high pressure test cell. A hydraulic piston with a 325-mesh screen is inserted into the cell through the top thus simulating a very permeable formation at the top of the cell. A simulated hydrostatic head is applied by pressurizing the piston with water, which in turn is pressurized with nitrogen gas. The hollow piston shaft is connected to a back pressure receiver where filtrate from the top of the cell can be collected. Another 325 mesh screen is placed at the bottom of the cell. A nitrogen gas source is connected to a very sensitive device for measuring gas entry. This, in turn, is connected to the bottom of the cell, which simulates a high pressure gas zone. The pore pressure of the cement slurry is recorded continuously by using a pressure transducer located in the middle of the cell. Temperature is monitored by a thermocouple inserted into the side of the cell. The general procedure for running tests using this gas flow apparatus is as follows [13]:

- The slurry is mixed in a blender according to API procedures and then stirred for 20 minutes in an atmospheric consistometer
- Simultaneously, the test cell is preheated to the test temperature
- The cement slurry then is poured into the cell from the top and a simulated

hydraulic pressure is applied by using the piston

- A simulated gas formation pressure then is exerted at the bottom of the test cell
- Next, the valves on the piston shaft and at the bottom of the cell are opened. The filtrates from both ends of the test cell are measured and recorded periodically. Periodically, the downward movement of the piston also is measured carefully to determine when the cement becomes load-bearing (no more piston movement) at the given constant hydraulic pressure applied to the piston.
- The gas flow rate, measured by the highly sensitive gas flow measuring device at the bottom of the test cell, is recorded periodically throughout the test period.

Before using FMA, it is essential to run a gel strength test on cement slurry. SGSA (static gel strength analyzer) measures gel strength of the cement at desired time intervals. Once a complete gel strength profile is achieved, it is possible to use the gas flow cell to measure other important parameters such as gas flow rate, filtration and load bearing capacity of the cement system. By plotting the pressure profile of cement versus time, as was earlier discussed at a point in time, slurry pressure drops below formation pressure, critical times at which migration occurs is recorded and this time table instructs the research team on FMA test procedure.

In the FMA test in the gas flow cell, flow rate of 30 ml/min corresponds to a specimen calculated bulk permeability of approximately 0.075 md[1], hence this test measures permeability of the cement indirectly.

Figure 1 shows FMA used for running the tests.

3. Tests

In this paper, a slurry formula was modified according to an optimization plan. The purpose of this modification was to enhance cement performance against gas migration. Filtration, free water, settling condition, consistency, rheology, compressive strength and gel strength were the main parameters considered for which cement formulation was modified.

Fig. 1. Fluid migration analyzer

The cement formulations are shown in Table 2 The anti gas migration additive used is a domestic agent, D65 was used as the dispersant, CR450 as the retarder and thixotropic agent as the gel strength modifying additive. One of the research purposes of this test was to examine the performance of the gas migration additive used in cement formulation.

It is well known in the industry that neat cements are completely defenseless against fluid invasion. This is because of the disability of filtration control in these types of cement slurries. This issue is explained in the discussion section with reference to other experiments. The cement slurry formulations were designed in accordance with the cement job and operating conditions which are specified in details.

Table 3 shows the test results for the designed and optimized slurries. Slurry 1 was prepared initially and was optimized into slurries 2 and 3, respectively. The test results are the basis for the optimization method used. The final slurry prepared met all the requirements of a gas resistive cement slurry.

Table 2. Slurry formulations

Slurry	Class G cement (g)	Gas migration additive (g)	Dispersant (g)	Fresh water (ml)	Gel strength additive (g)	Retarder (g)
1	1000	117	-	377		-
2	1000	105	-	377	12	-
3	1000	115.8	4	377	0.6	4

Table 3. test results for modified slurries

Slurry	API Filtration	Thickening Time (minutes)	Weight of slurry (pcf)	Mix time (seconds)
1	44	230	115	30
2	-	60	115	30
3	10	138	115	30

Test results for slurry 1 are acceptable at a glance, but the weakness of this formulation design is in gel strength. SGSA test for slurry 1 shows 300 min of time necessary for gel strength development of 500 lb/100ft^2. Therefore critical transition time for slurry 1 is too long and unacceptable. The thixotropic agent was then added to the cement composition (Table 2) resulting in slurry 2. The problem with the design of slurry 2 was very short thickening time, which is unacceptable with regards to the job requirements. Hence the thixotropic agent was used in lesser concentration in slurry 3.

Figure 2 shows the gel strength profile of slurry 3. The results were ideal. A profile with less than 10 min of critical transition time was achieved. In this paper, critical transition time is considered as the time window between gel strength range of 250 and 500 lb/100ft^2. The last measured gel strength almost equals the initial compressive strength of the cement. As slurry reaches 500 lb/100 ft^2, cement is so hard that gas invasion in this state is less likely. Before the gel strength of 250 lb/100 ft^2, the slurry is somewhat still in the liquid form therefore, hydrostatic pressure is transmitted through the cement column. Hence, it is important for this time window to be as short as possible.

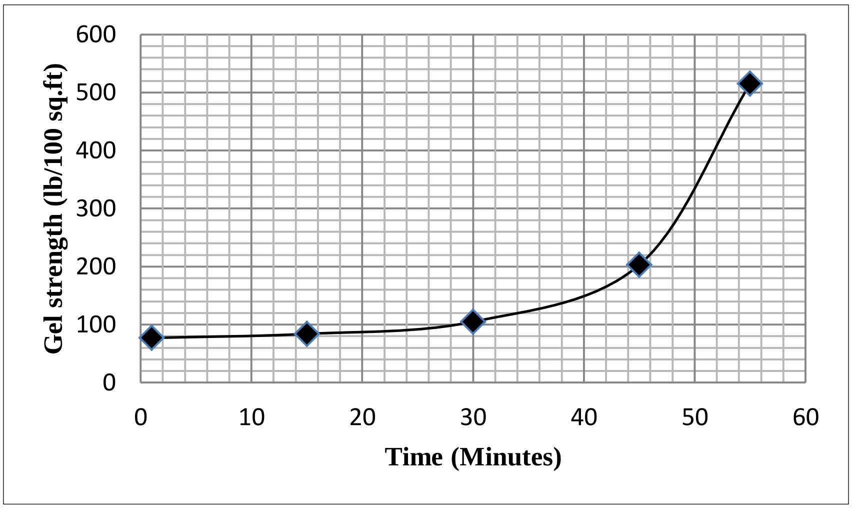

Fig. 2. gel strength profile for slurry 3, critical transition time is less than 10 minutes

According to the gel strength recorded from SGSA; initial hydrostatic pressure, pressure reduction due to gel strength development and gas migration initiation estimated times were calculated using Equations 1-3 for slurry 3. These are the essential data for running FMA test.

In this test, the real condition of the job is simulated using an imaginary. Well data are summarized below:

High pressure gas zone: 7000 psi, 10000 ft
Lower pressure zone: 6500 psi, 9900 ft
Annulus diameter: 1.5 in
Top of cement column: 8000 ft
Density of the mud in the hole: 14.5 ppg
Bottom hole circulating temperature: 180°F

Based on this data and by using Equations 1-3 necessary Table 4 parameters were calculated, containing these parameters and their values. According to this table it is possible to estimate the time, which gas migration occurs. Knowing this critical time, gas injection stage in FMA test is planned.

According to Table 4, highlighted cells indicate gas migration stage in the cement setting process. At these times, slurry hydrostatic pressure drops below the formation pore pressure.

4. Results

We ran FMA test on our modified cement slurry. Table 2 shows components of this formulation. A gas migration additive was used which controls fluid loss and free water significantly and improves the consistency profile of the cement (cement RAS property). Another additive which reduces thickening time and enhances the gel strength profile was also used in the formulation. Tests were run according to the plan. Figure 3 displays results of FMA test.

Table 4. calculated values for required parameters

Time (minutes)	Gel-strength (lb/100sq.ft)	P_G across high pressure zone (psi)	P_G across low pressure zone (psi)
1	77	7288	7225
10	82	7266	7204
15	84	7257	7195
25	95	7208	7149
35	110	7142	7088
45	203	6728	6593
55	515	5342	6376

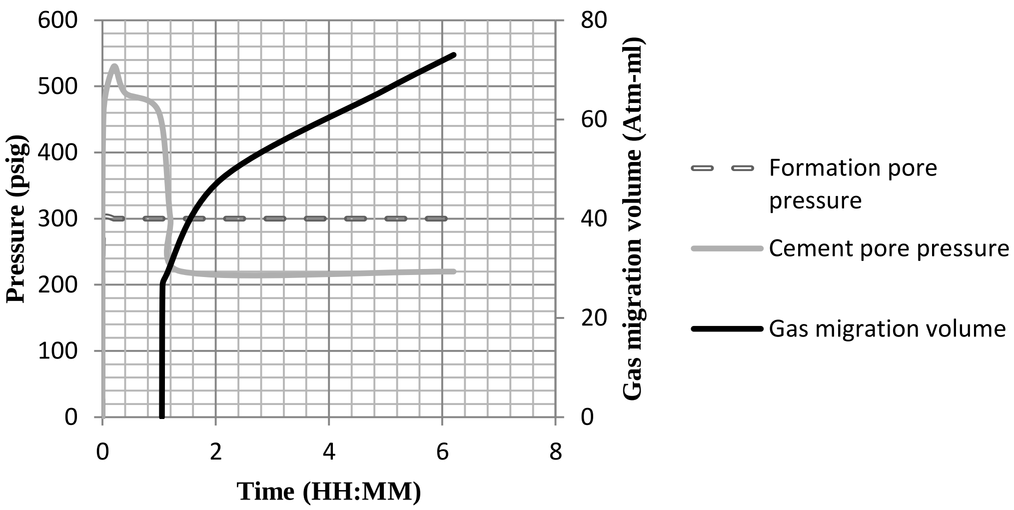

Fig. 3. Recorded parameters in FMA test

According to Figure 3, gas migration starts when the cement pore pressure drops below formation pore pressure in about 80 minutes after cement placement. Nitrogen gas was used in this test. Final gas migration flow rate of 0.23 ml/min was reported. This amount of gas migration volume is desirable and low.

5. Discussion

Chung and Beirute investigated gas invasion through cement phenomenon [13]. They tested several slurries with different formulations results of which are summarized in Table 5.

Table 5. Chung and Beirute's tests on different slurry formulations

Temperature (F)	Formation gas pressure (psi)	Slurry formulation	Top hydrostatic pressure (psi)	Final gas flow rate (cell discharge rate ml/hr)
165	500	Class-H+FLC A+H2O	1000	212
80	100	Neat class-H+H2O	1000	36000
165	500	Class-H+FLC B+H2O	1000	45.5
220	500	Class-H+FLC C+H2O+Retarder	1000	134
165	500	Class-H+FLC B+H2O+Gas generating powder	1000	1704
165	500	Impermeable cement+H2O	1000	0.004

Table 5 shows Chung and Beirute proposition that slurry fluid loss must be controlled as well as particles settling condition in order to address formation gas invasion. They used fluid loss controller additives to minimize slurry filtration and compared the results with neat cement which has no control over water loss. Clearly, they were able to reduce gas invasion rate. Neat cement is completely defenseless against gas migration. They have also proved that usage of special type cements (impermeable cements) which immobilize fluids inside its pore spaces with bridging agents or polymeric materials can prevent formation fluids invasion into cement slurry.

Comparing the results of this study's slurry and Chung and Beirute tests, several noteworthy conclusions are mentioned.

API Classes G and H are base cements. It is common to apply these two classes of cement with other additives in well bores.

In neat cements, gas charge occurs almost instantly. Neat cements are completely defenseless against gas invasion. The use of fluid loss controller additives improves performance of slurry against gas migration significantly. Special type of cements such as expanded and impermeable cements are very useful, but their price and accessibility makes them unpopular for some jobs.

Gas migration controller additives affect consistency profile and fluid loss rate of slurries. In fact, anti-gas migration additives are very strong fluid loss controllers with other properties as well. Combination of additives, if compatible, could largely enhance cement attributes. The advantage of using effective, compatible and strong additives over using special cement types is that in most cases, these formulations are cheaper and more accessible. Proper engineering and slurry design phases play a major role in fighting gas invasion.

6. Conclusions

According to the test results, neat cements are vulnerable to gas invasion. Fluid loss controller additives can reduce filtration and cement system water loss which leads to the hydrostatic pressure maintenance of the cement column. Special type slurries such as impermeable cements have the same effect but their accessibility and price makes them less popular in some places like Iran.

Properly designed slurry with compatible and effective additives (retarder, anti-gas migration, gel strength and compressive strength enhancers e.t.c.) could be absolutely resistant against gas invasion and much cheaper and more accessible than special type cements. We have proven this hypothesis in our case. Although gas migration additives are relatively more expensive than conventional fluid loss controller additives, their performance is definitely better. Therefore to decide between FLC and Gas migration additives, the authors propose formation analysis. In an aggressive gas bearing zone, anti-gas migration additives should be used. Workover operations and remedial cementing are costly and difficult, not to mention the risks of gas invasion that can lead to disasters, Hence, using anti-gas migration additives could be even more economical on the long run.

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