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Evaluating Foamed Cement Slurry Stability in Laboratory Measurement

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Abstract

Foamed cement is commonly used in well construction situations where low cement slurry density and enough compressive strength development are required in the cement job design, particularly in shallow hazards mitigation. Foamed cement slurry is generated by injecting nitrogen gas into conventional cement slurry containing foam stabilizers. Being chemically inert, the nitrogen does not affect the chemical properties of the cement slurry. The amount of nitrogen required is a function of the desired in-situ foam density and the hydrostatic pressure exerted on the foamed slurry.

Controlling the stability of foamed cement slurries ensures that the nitrogen will not break out of the cement slurry. If the gas bubbles coalesce and their size increases, gas pockets can form and rise in the cement column, resulting in un-cemented sections or channels in the annular space.

This paper will review the results of laboratory tests carried out to quantify the stability of the foamed cement. Free fluid and foam half-life measurements provided a visual method to evaluate the stability of the foamed based fluid. Foamed cement slurry stabilities are determined following procedures defined in API RP 10B-4. Foam quality and base fluid density were varied to better understand their effects on the stability and zonal isolation capability of the foamed cement column.

Introduction

Foamed cement is a mixture of cement slurry, surfactant and stabilizer (liquid continuous phase) and nitrogen (gas continuous phase) that results in a lightweight cement system. Foamed cement slurry can be prepared by injecting nitrogen gas at varying concentration into base cement slurry at any density.

Foamed cement slurries are compressible fluids, as the nitrogen volume factor depends on the pressure and temperature. As the foamed cement slurry pumped downhole, the density will constantly change with varying depths.

The use of foamed cement particularly in deepwater environment requires good understanding of the foamed cement properties and stability. As per current API RP 10B-4, the foam stability is required to be tested at atmospheric conditions only. As industry standardized consistometers are not designed for testing an energized fluid, the foam stability are not tested under pressure.

Evaluation of the laboratory test results, especially foam stability test will assure that the nitrogen gas bubbles will not break out of the cement slurry. If the gas bubbles coalesce and the bubble size increases, gas pockets can form and rise in the cement column, resulting in un-cemented sections or channels in the annular space, which eventually could lead to zonal isolation failure. Unstable foamed cement develops lower compressive strength and higher permeability than designed.

A stable foam cement slurry can be produced with the correct design, foamer/stabilizer and mixing procedure.

Foamed Cement Slurry Characterization

Foamed cement slurries are usually categorized by foam quality (FQ), or the ratio of the volume occupied by the gas (V_{gas}) to the total volume of the foamed slurry ($V_{foam\ slurry}$) (expressed as a percentage). FQ can also be computed from the base slurry density(ρ_{BS}), the designed foamed slurry density (ρ_{FC}) and nitrogen volume factor (BN_2).

$$FQ = \frac{V_{gas}}{V_{foam\ slurry}} \qquad \ldots.\ (1)$$

or

$$FQ = 1 - \left(\frac{\rho_{FC} - 0.00172BN_2}{\rho_{BS} - 0.00172BN_2}\right) \qquad \ldots.\ (2)$$

where

V_{gas}	= volume of gas, bbl
$V_{foam\ slurry}$	= volume of foamed slurry, bbl
ρ_{BS}	= base slurry density, lbm/gal
ρ_{FC}	= foamed slurry density, lbm/gal
BN_2	= nitrogen volume factor, scf/bbl

Because the foamed cement slurry density varies as the pressure and temperature change, the resulting density downhole is not constant. The density at the top of cement column (ρ_{TOC}) will be less than the density at the bottom of the column(ρ_{BOC}). An equivalent density can be calculated by the commonly used assumption below:

$$\rho_{average} = \frac{(\rho_{TOC} + \rho_{BOC})}{2} \qquad \ldots.\ (3)$$

The density of foamed fluids is calculated on the assumption that the foam consists of a gas phase and an incompressible base fluid as given by Eq. 4:

$$\rho_{N_2} = \frac{M_{N_2} P}{Z_{N_2} R T} \quad \ldots. (4)$$

where

ρ_{N_2} = foamed cement slurry density, lbm/gal
M_{N_2} = molecular weight of nitrogen gas, (28.0134 g)
P = absolute pressure, (psi)
Z_{N_2} = compressibility factor of nitrogen gas
R = universal gas constant, (8.3143510 J/mol K)
T = absolute temperature, (K)

As a result, the density of the foamed cement slurry is a function of the foam quality. As *FQ* depends on nitrogen ratio, pressure and temperature, the more nitrogen (higher *FQ*) means lower foamed cement slurry density.

Foamed Cement Laboratory Test

Test Procedure

The foamed cement slurry was investigated using industry standard methods in the laboratory. A base cement slurry was generated and the performance was measured in the unfoamed state. Then this base cement slurry was foamed and stability was measured and analyzed across multiple foam qualities.

Typical base cement slurry that is used in deepwater operations was selected for this study. The base cement slurry was a Class H cement system mixed at 16.2 lb/gal density using seawater as the mix fluid. A typical additive package including fluid loss control additive, dispersant, accelerator, foaming agent and foam stabilizer was also incorporated in the slurry formulation. Performance of the base cement slurry was measured using techniques described in "API RP 10B-2: Recommended Practice for Testing Well Cements". The performance of this base slurry is shown in Fig.1 - Base Slurry Properties. Rheology, thickening time, free fluid and fluid loss control performance are all typical for application in the Gulf of Mexico operations.

Job Type	Primary	Depth	7650.0 ft	TVD	7650.0 ft
BHST	64 degF	BHCT	51 degF	BHP	3850 psi
Starting Temp.	80 degF	Time to Temp.	01:31 hr:mn	Heating Rate	-0.32 degF/min
Starting Pressure	525 psi	Time to Pressure	04:40 hr:mn		

Rheology (Average readings)

(rpm)	(deg)	(deg)
300	88.0	111.0
200	65.0	79.5
100	41.0	47.0
60	31.0	33.5
30	22.0	23.0
6	16.0	13.0
3	14.0	12.0
	Surface Rheology without foaming agents	Rheology at 51F with foaming agents
10 sec Gel	14	13
10 min Gel	70	19
Temperature	80 degF	51degF
	P_v : 73.679 cP T_y : 15.48 lbf/100ft2	P_v : 97.272 cP T_y : 14.07 lbf/100ft2

Thickening Time

Consistency	Time
30 Bc	04:32 hr:mn
70 Bc	06:24 hr:mn
100 Bc	07:34 hr:mn

API Free Fluid

0.0 mL/250mL	in 2 hrs
At 51 degF **and** 0 deg **incl.**	
Sedimentation	None

Fluid Loss

API Fluid Loss	44 mL
22 mL in 30 min at 51 degF and 1000 psi	

Fig.1 - Foamed slurry (base density) properties

The stability of the foamed cement was investigated after the performance of the base slurry was determined. Foam cement was generated using the methods described in "API RP 10B-4: Recommended Practice on Preparation and Testing of Foamed Cement Slurries at Atmospheric Pressure". For each quality of foam that was generated the following steps were taken:

- Foam the cement slurry in the waring blender cup (using a 5-blade assembly), and report whether or not the foamed slurry filled the cup after shear (API RP 10B-4, Section 7.2)
- Transfer the foamed cement slurry to a 250 mL graduated cylinder, cover, and let stand for a 10 min period at ambient conditions.
- Record the foamed cement slurry density of the total volume in the graduated cylinder.
- Transfer additional foamed cement slurry from the blender to another 250 mL graduated cylinder, cover, and let stand for 2 hour period at ambient conditions.
- Record the foamed cement slurry density of the total volume in the graduated cylinder.
- Transfer additional slurry to a curing mold that can be sealed (API RP 10B-4 section 9.4) and cure in the water bath at 60 degF temperature.
- Record the density of a set foamed cement sample that has been cured until set at 60 degF in the water bath. Sample should be cut into three pieces, and measured the density of each piece (top, middle, and bottom) according to API RP 10B-4, Section 9.3.3.
- Record the density of each sample piece.

As explained in the previous section, the determination of foam stability is based on two variables, foam quality and base slurry density. Following the testing procedures outlined above, the stability of the foamed based fluid was analyzed at various foam qualities (10% - 80%) and varying the density of the base cement slurry (+ 0.2 lb/gal, base slurry density, - 0.2 lb/gal, - 0.4 lb/gal). From 40% to 80% the stability was test for 10 min only to mimic field mixing conditions.

Test Results

Test results are summarized in tables below for foamed cement slurry mixed at varying density.

Table 1 – Foam stability evaluation for slurry mixed at base density

Foam Quality	10%	20%	30%	40%	50%	60%	70%	80%
Blender Filled?	Yes	Yes	Yes	Yes	Yes	No	No	No
Stability after 10 min	N/A	N/A	N/A	9.40 lb/gal	7.94 lb/gal	6.72 lb/gal	5.97 lb/gal	5.02 lb/gal
Stability after 2 hrs	14.2 lb/gal	12.49 lb/gal	10.87 lb/gal	N/A	N/A	N/A	N/A	N/A
Density after set	Top: 14.75 ppg Middle: 14.67 ppg Bottom: 14.66 ppg	Top: 13.00 ppg Middle: 12.91 ppg Bottom: 12.89 ppg	Top: 11.34 ppg Middle: 11.28 ppg Bottom: 11.30 ppg	N/A	N/A	N/A	N/A	N/A
Calc. Density:	14.58 ppg	12.92 ppg	11.34 ppg	9.72 ppg	8.10 ppg	6.48 ppg	4.86 ppg	3.24 ppg

Table 2 – Foam stability evaluation for slurry mixed at -0.4 ppg base slurry density

Foam Quality	10%	20%	30%	40%	50%	60%	70%	80%
Blender Filled?	Yes	Yes	Yes	Yes	Yes	No	No	No
Stability after 10 min	N/A	N/A	N/A	9.30 lb/gal	7.68 lb/gal	6.32 lb/gal	5.50 lb/gal	4.81 lb/gal
Stability after 2 hrs	13.99 lb/gal	12.26 lb/gal	10.59 lb/gal	N/A	N/A	N/A	N/A	N/A
Density after set	Top: 14.39 ppg Middle: 14.25 ppg Bottom: 14.26 ppg	Top: 12.81 ppg Middle: 12.81 ppg Bottom: 12.99 ppg	Top: 11.10 ppg Middle: 10.97 ppg Bottom: 10.94 ppg	N/A	N/A	N/A	N/A	N/A
Calc. Density:	14.22 ppg	12.64 ppg	11.06 ppg	9.48 ppg	7.90 ppg	6.32 ppg	4.74 ppg	3.16 ppg

Table 3 – Foam stability evaluation for slurry mixed at -0.2 ppg base slurry density

Foam Quality	10%	20%	30%	40%	50%	60%	70%	80%
Blender Filled?	Yes	Yes	Yes	Yes	Yes	No	No	No
Stability after 10 min	N/A	N/A	N/A	9.19 lb/gal	7.73 lb/gal	6.58 lb/gal	5.61 lb/gal	5.02 lb/gal
Stability after 2 hrs	13.76 lb/gal	12.34 lb/gal	10.63 lb/gal	N/A	N/A	N/A	N/A	N/A
Density after set	Top: 14.38 ppg Middle: 14.28 ppg Bottom: 14.26 ppg	Top: 12.92 ppg Middle: 12.82 ppg Bottom: 12.77 ppg	Top: 11.10 ppg Middle: 11.02 ppg Bottom: 11.04 ppg	N/A	N/A	N/A	N/A	N/A
Calc. Density:	14.40 ppg	12.80 ppg	11.20 ppg	9.60 ppg	8.00 ppg	6.40 ppg	4.8 ppg	3.20 ppg

Table 4 – Foam stability evaluation for slurry mixed at +0.2 ppg base slurry density

Foam Quality	10%	20%	30%	40%	50%	60%	70%	80%
Blender Filled?	Filled Blender	Filled Blender	Filled Blender	Filled Blender	Filled Blender	Did not Fill Blender	Did not Fill Blender	Did not Fill Blender
Stability after 10 min	N/A	N/A	N/A	9.52 lb/gal	7.86 lb/gal	6.89 lb/gal	6.29 lb/gal	5.86 lb/gal
Stability after 2 hrs	14.40 lb/gal	12.74 lb/gal	11.19 lb/gal	N/A	N/A	N/A	N/A	N/A
Density after set	Top: 14.84 ppg Middle: 14.77 ppg Bottom: 14.77 ppg	Top: 13.22 ppg Middle: 13.17 ppg Bottom: 13.17 ppg	Top: 11.48 ppg Middle: 11.48 ppg Bottom: 11.47 ppg	N/A	N/A	N/A	N/A	N/A
Calc. Density:	14.76 ppg	13.20 ppg	11.48 ppg	9.84 ppg	8.20 ppg	6.56 ppg	4.92 ppg	3.28 ppg

Discussion

The free fluid/foam half-life results showed minimal change between the initial and final density and volume of the foamed slurry. Also, no indications of large bubbles, striations, channeling, and color changes were observed which are known indications of foam instability.

Generated *FQ* between 10% - 50% were able to fill the waring blender after shearing for all base slurry densities tested. However, the slurries with *FQ* at 60% and greater did not fill the waring blender after shearing (Fig. 2). The results demonstrate a consistent pattern for all four base fluids (*BF*) where the *FQ*, which the lab was able to generate, begins to deviate from the target *FQ* from 60% and above but still increases as the target *FQ* is increased. The maximum attempted *FQ* of 80% still yielded stable foam slurry of 70% for densities ranging from 15.8 ppg to designed base slurry at 16.2 ppg.

At 16.4 ppg the maximum achievable *FQ* was 64%. Furthermore, the densities of these higher *FQ* foamed slurries did not change during the 10 minutes static period. These findings suggest that the lab equipment or procedure used for generating the foam is the limiting factors rather than the foam stability of the slurry itself.

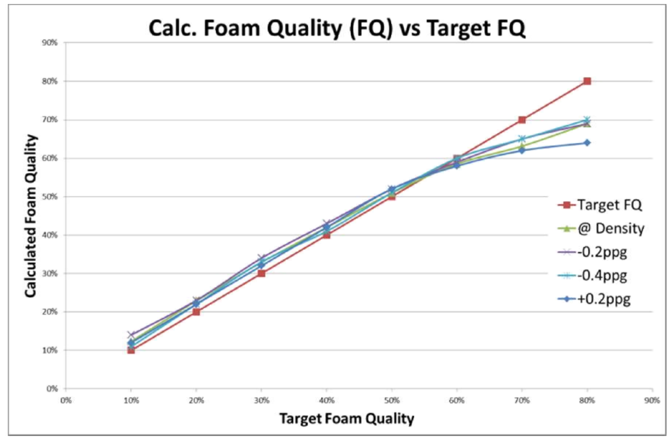

Fig.2 – Target FQ vs. Measured FQ comparison

As observed by the high degree of overlapping data points, it is evident that a deviation from planned base slurry density between - 0.4 ppg to + 0.2 ppg does not appear to negatively affect the foam stability. Between 10 and 50% FQ the measured foam densities are consistently higher than the theoretical foam density. This can be explained by small pressure buildup in the waring blender which causes the slight overflow of foam fluid when the pressure is released. For a Varying blender capacity of ~1300 mL a spill of 15 mL base fluid would cause a foam density increase of 0.1ppg.

After curing the foamed BF (for *FQ* 10%-30%) at design temperature and at atmospheric pressure, the volume which the foamed slurry occupied in the pipe did not change from the initial measurement. Also, the measured density of the segmented samples from top, middle and bottom of the set cement showed no significant signs of settling or instability even for the lowest base slurry density at 30% *FQ*. In fact, all density measurement was within 1% of the average density for the particular sample.

Another factor which could potentially affect the foam stability is dissolution of formation salt. Although the Halite salt as found in the Gulf of Mexico is considered one of the more "benign" salts, the risk is still present and does warrant for an evaluation of the impact on the foam stability.

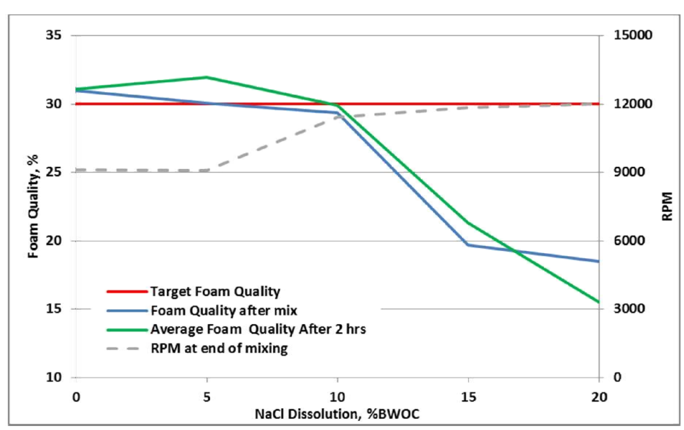

Fig. 3 – Effect of NaCl dissolution on foam quality

Out of the five slurries prepared, ranging from 0% to 20% BWOC NaCl added to the base slurry, the foam stability was tested over a period of 2 hour using 30% quality. At 0% to 10% salt the foam stability seemed to be little impacted. At 15% and 20% salt, the target foam quality could not be reached and dropped to 18% and 16% respectively after mixing. All slurries from 0% to 15% maintained a constant fluid level of the occupied test cylinders over the 2 hours test period with no signs of instability and a maximum density deviation of 2% from average. At 20% salt the fluid level also remained constant over the 2 hours test period. However, a 40% deviation from average density was observed.

Another qualitative method of evaluating the foam generation is to compare the RPM at the end of the foaming process in the blender. At 15% and 20%, the final RPM was markedly higher which indicates that the cup did not fill. This trend is observed at salt concentration above 5%.

Conclusion

1. The foam cement slurries discussed in this paper are stable across a wide range of foam qualities.
2. Foam stability was demonstrated in the liquid slurry as well as the set cement slurry.
3. The single blade blender is not able to generate foam qualities above 60% at atmospheric conditions.
4. Salt dissolution is proven to affect the foam stability. Further investigation is recommended.

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