Foamed Cement Properties for Zonal Isolation in Coalbed Methane (CBM) Wells

Sonny Irawan
Chow Weng Sum
Mazuin Bt Jasamai
Saleem Qadir Tunio*
Arthur Goh Jin Wang
Geosciences and Petroleum Engineering Department
Universiti Teknologi PETRONAS
Tronoh 31750, Perak, Malaysia
E-mail: saleem_tunio@petronas.com.my*, Phone: 0060-53687055*

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Abstract

Wells drilled into coal beds for coalbed methane (CBM) generally encounter weaker structures within the beds and have lower fracture gradient as compared to conventional oil or gas wells. CBM is more vulnerable to downhole problems such as lost circulation and formation fracture as the formation cannot withstand a cement density above 11 ppg. Conventional neat cement without light weight additives with average density of 15.9 ppg is not suitable. Foamed cement with a low density of 7-11ppg, high strength per unit volume offers a versatile and economical cementing job. Primary purpose of using foamed cement is to decrease the density of the slurry but here, other advantages have also been identified with applications of this cement. A better understanding on the properties of foamed cement allows the optimization of cement slurry design during its circulation and placement.

Keywords: Foamed cement, zonal isolation, coalbed methane, compressive strength, cement density, fluid loss.

1. Introduction

The use of foamed cement is still a relatively new technique in the context of oil well cementing to overcome problems such as low formation fractures and lost circulation zones. The foamed cement is primarily a mixture of base cement slurry, foaming agent, and foam stabilizer to produce slurries with ultra light-densities and moderate cement strength at a relatively low cost [David & Hartog, 1981]. When conventional cement is used, problems such as zonal isolation, formation fracture and lost circulation may be encountered and the use of foamed cement may be one of the most effective methods to eradicate such problems which can help in reducing the high cost in cement recovery work over jobs.

Cementing for CBM wells may be comparable to those in conventional wells except for the need to control fluid invasion and lower fracture pressure gradient of the brittle cleat system. The delicate and brittle cleat structures within the CBM reservoirs are relatively weak and highly vulnerable to downhole problems such as lost circulation, fluid/gas intrusion and formation fracture. Neat cement (conventional) used for oil and gas wells has an average density above 15 ppg (1797kg/m^3) which exceeds the fracture gradient of the coal bed formation. Most coalbeds have a fracture gradient of 0.6 - 0.7psi/ft (or equivalent density of 11.53 - 13.5 ppg). Furthermore, neat cement is relatively brittle and may crack due to cyclic stress loads which may require costly and time consuming remedial workovers. These relatively weak formations will benefit from the use of low density foamed cement which also does not segregate due to gravity.

This paper describes the results of investigations on the characteristics of CBM reservoirs, preparation of cement slurry and cubes, laboratory data analysis and comparison of the properties for neat and foamed cement design. The properties of foamed and neat cement are determined utilizing conventional cementing equipment and a portable foaming generator.

2. Objectives of the Study

The objectives of this study are to:

- Determine the densities of foamed and neat cement, compressive strengths, porosities, permeability, fluid losses and thickening time.
- Determine the effect and compatibility of foamed cement against neat cement on the reservoir structures in the Mukah Coalfield.

3. Literature Review

3.1 CBM Reservoir Characteristics

CBM reservoirs have unique cleat structures which are relatively less stable and weaker as compared to gas/oil reservoirs having a higher cleat density essential for better fluid flow. The fracture gradient of coalbed ranges from 0.62-0.69psi/ft as compared to that in a sandstone reservoir which has a range of 0.8-0.9psi/ft. [I.Palmer, & Z.Moschovidis & J.Cameron, 2005]. Conventional cement sheath may not be able to fully withstand the annular deformation and may crack because of cyclic stress loads and may fail at high pressure. [E.Fidan, 2003].

The properties of a coal formation differ from that of a sandstone or carbonate reservoir. Besides, coal properties within a coal seam in a particular area may differ from that in another area. Therefore, it is not appropriate to consider a single cement design for all CBM wells. The cement should instead, be tailored to accomodate the relative composition of the coal as well as the reactivity of the formations. The fractures in CBM beds are usually in the form of vertical cleats and thus wells are more commonly drilled horizontally to intersect all, if not most of the cleats for maximized production. [M.Ali (ONGC), A.Sakar, R.Sagar, 2008]

Figure 1 illustrates the comparison of hydrostatic pressure attained for casing cementation when foamed cement is used against that of API neat cement. The casing shoe is estimated to be set at 500m (1640ft) and the fracture gradient of the formation is 0.66 psi/ft for the Mukah Coalfield. It illustrates that if neat cement is to be utilized in the CBM reservoir, it will exceed the fracture pressure by a big margin. Thus may lead to lost circulation and unstable formation. Lost circulation will in turn, lead to high cement loss into the formation, causing formation damage and increment of skin effect. Besides this, the calculated volume of cement to reach Top of Cement (TOC) will be reduced and there will be zonal isolation for the casing and formation failure, these will reduce significantly, the cement integrity. [David, D.R & Hartog, J.J, 1981]

3.2 Application of Foamed Cement

The utilization of foamed cement in reservoirs has many advantages over neat cement . The advantages are listed below:

3.2.1 Cure for lost circulation in vugular/cavernous zones in reservoirs

Denser slurry tends to slump to the bottom of the cavernous environment due to gravity even before they have time to harden. The thixotropic properties of the foamed cement match the density of the fluid in the vugs to prevent gravity segregation. [O'Rourke, T.J and Crombie, D.L, 1999].

3.2.2 Prevention of fluid intrusion which may result in micro-annulus behind casing

Inclusion of gas bubbles turns the cement into 'expandable cement' and the intrusion fluid travels a further distance across the gas bubbles. [E.Fidan and E.Kuru, 2003]

3.2.3 Prevention of formation fracturing of the delicate cleat system in CBM beds

Cementing operation has to be slightly overbalanced to prevent free-gas migration into cement column. The light weight *(Figure 3)* of the foamed cement places less pressure on the unique cleat structures within the coalbed, reducing the tendency of the cement to exceed the fracture gradient of the coal. [Kopp,K, 2000]

3.2.4 Flexibility and ductility for longer cement sheath life cycle

The foamed cement allows the cement sheath to withstand a higher hoop stress from high casing pressure, stress and temperature. This is achieved as the cement sheath tends to "give" as the well casing expands. In general, depletion of reservoir pressure will result in an increase in effective stress which leads to a large compaction strain and may in turn, deform the casing. [David, D.R & Hartog, J.J, 1981]

3.2.5 Long term economic feasibility

The improved zonal isolation attained through the usage of foamed cement can result in substantial cost saving over the life of the well because its useful life is by-far longer than conventional cement used. Conventional cement tends to crack in two to ten stress-relaxation cycles as compared to foamed cement, which may attain hundreds of cycles. [Kopp,K , 2000]

4. Methodology

4.1 Reservoir Characteristics

For this research Mukah coalfield is considered which is located in Mukhah district, Sibu division of Sarawak, Malaysia. The characteristics of this Coalfield are investigated in terms of the bottomhole pressure, temperature, coal rank, chemistry, gradient and coal strength. Sia *et al*, 1995 reported that the coal in Mukah is Sub-Bituminous B which is hydrophilic and is reactive towards fresh water. The pore gradient is approximated to be 0.43-0.45psi/ft with a relatively low fracture gradient of 0.66-0.69psi/ft.

4.2 Preparation of Cement Specimen

The standard constant speed mixer was used for the mixing of the base slurry. Water to cement ratio was varied from 1:1 to 1:3 to obtain a range of density of the neat slurry. As for the foamed cement, the volume of foam was varied to obtain a range of density of the foamed slurry. The foam was generated using a portable foam generator. The volume of foam to be added to 15.9 ppg base slurry was computed in a spreadsheet file. The foamed and neat slurry was cured in a standard pressurized curing chamber at 150˚F and 750psi.

4.3 Laboratory Experiments

The destructive method of compressive strength test was used for testing both the neat and foamed cement cubes. To measure permeability and porosity, cement core plugs were evaluated using the Poroperm which is commonly used to test rock core samples. It is still applicable for the testing of cement cubes, but the confining pressure had to be much lower than the normal rating of 500psi. For the fluid loss test, the OFITE Filtration Loss Tester was preferred over to the Stirr Loss Fluid Tester because the reservoir temperature was lower than 200˚F and besides, no fluid-loss additives were added. The standard Pressurized Consistometer was used for both types of cement slurries. However, it should be noted that a non-destructive method of analysis is recommended for the foamed slurry as the shear is not uniform in the cup, where some portion of the foam remains static during rotation.

4.4 Data Analysis

The properties of neat cement and foamed cement were compared and analyzed for their compatibility to be used in wells in CBM reservoirs.

5. Results and Discussion

5.1 Cement Specimens

It was observed that for neat cement with a density below 14 ppg (water cement ratio of 1:1), the slurry was not stable and was too dilute. The amount of water that gravitationally separated from the cement during the curing stage in the mould was high, resulting in excessive fluid loss. This was because no fluid loss additives or surface-active agents were added to the slurry to prevent the separation of water molecules from the base slurry. For neat cement without additives, the maximum attainable density was 17.1 ppg (water cement ratio 3:1) and the minimum, 14.2 ppg. The maximum density was achieved due in part, to the fact that there was insufficient amount of water for the slurry to mix evenly in the constant speed mixer.

In contrast, the density of foamed cement could be as low as 5.5ppg and still would not encounter fluid loss problem during the curing stage. The foamed cement produced near to perfect cube shapes without distortion in height. When the foam slurries were properly mixed, they often contained microscopic discrete bubbles that would not migrate from one bubble to another. The amount of powdered cement required to produce foamed cement was significantly less than that for neat cement. This was because the foamed cement was bulked by the foam which contained air bubbles that were entrapped in the cement but did not coalesce.

Figure 2 showed that cement having higher foam quality (FQ) would have lower density. As more gas bubbles were injected into the slurry, the volume of slurry expanded. This expansion of slurry affected the physical properties of the cement such as weight, permeability, porosity, compressive strength (strength-to-density ratio), fluid loss and setting time because the particle-particle interactions would be diminished or diluted by the presence of gas throughout the slurry.

5.2 Compressive Strength

Table 1 shows that although the compressive strength of foamed cement was lower than that of neat cement, it had higher strength-to-density ratio. The reason for this is because slurries that contain more water ratio are usually weaker. With inert gas as a filler material, even light weight cement can have high solid content, which gives relatively high strength to the cement. **Figure 3** showed that foamed cement with a density below 6.5 ppg did not have the required strength to hold the casing in the lead slurry. For the tail slurry, the minimum density required was approximately 8.5 ppg, inclusive of a design or safety factor. The difference between the compressive strength of 15ppg neat cement (1247psi) and a 13ppg foamed cement (969psi) was not very significant, and if light weight additives were added to the neat cement, it might exhibit values almost similar to that of the foamed cement.

Another interesting feature observed was the ductility of the foamed cement during the compressibility test. When the foamed cement was crushed, the cube did not break into parts but, exhibited a ductile compression. The label on the top and bottom marker could still be seen clearly. For neat cement, the cube broke into brittle pieces the moment it reached its maximum compressibility strength value.

The foamed cement exhibited ductility over the neat cement, thereby; it allowed the cement sheath to withstand higher hoop stresses from casing pressure and temperature cycling. The ductility of the foamed cement allowed for it to “give” and not crack (as neat cement might) during the expansion of well casing. The lower compressive strength of the foamed cement is not a big concern as the main priority in cementing is to get to the top of cement (TOC) with sufficient pressure exerted by the cement to hold the casing and prevent fluid migration from the rock formation.

5.3 Permeability & Porosity

When the density of cement is reduced, the porosity and permeability characteristics will be a concern. **Figure 4** showed that neat cement with densities varying from 14.9-17.9 ppg had zero or near zero permeability. As such, fluid intrusion would not be a concern. For foamed cement, the reverse was true; the permeability increased sharply with a reduction in the density. As the density was reduced from 13ppg to 8ppg, the increase of permeability was gradual. However, from 8ppg to down to 5ppg, the permeability increased exponentially. As the density was reduced, the quality of air in the cement would increase, and with a constant cube being used and measured, more channelling and pores would be created.

An analogy to account for the sharp increase of permeability with the decrease in density of the foamed cement is as follow: Imagine having a 100% compacted cube of cement with zero porosity and if 10 bubble size pores are injected, the possibility of any of that pore to interconnect with each other is very low. Therefore even after 10 pores are injected, the permeability might not be changed. But if 10000 bubble size pores are injected in that same volume of cement cube, most of the pores will interconnect (side by side), and therefore as the number of injected pores are increased, the permeability of that cement cube will start to have a sharp increase as shown in the illustration below.

Figure 5 showed that the porosity of both foamed and neat cement increased correspondingly with the increment of air quality (lower density). The porosity curve displayed a more linear line, because porosity is a function of air quality and not channelling. Neat cement with densities of 14.9-16.9ppg had a low porosity of <5% and this explained for its higher compressive strength. Foamed cement, at a cut-off point of 40%, cement with a density less than 8.7ppg would averagely, have porosities of more than 40% and this might induce further cracks in the cement sheath during the completion stage.

5.4 Fluid Loss

Figures 6 and 7 shows when the density of the neat cement was reduced, the fluid loss would be higher. The reverse is true for the foamed cement whereby, a reduction in its density would result in lower fluid loss. The fluid loss for 16ppg and 15ppg were excessive in 30mins (exceeding 5% in 30minutes of the total volume) at 10.80% and 5.6%. The loss of cement volume would also reduce significantly from what had been initially planned and calculated at the surface (dehydration of cement). For the foamed cements, they had excellent low fluid loss even at density as low as 7 ppg.

The different characteristics of the foamed cement and the neat cement can be explained in terms of foam quality in the cement slurry. When the density of the foamed cement was reduced, the foam quality (gas bubble intensity) would increase. The only mode of water loss in the foamed cement would be around the bubble of gas. As the density of the foamed cement decreased, there would be an increase in the surface of the bubble membranes. When this occurred, the distance that the fluid would have to travel in order to leave the slurry would increase significantly, and this would lead to a reduction of fluid loss.

The stable two-phase nature of foamed cement slurry would resist fluid loss to the formation, as the reduced water loss would help protect the water sensitive zones such as shale, clay and salt formation in the well bore. The calculated API fluid loss doubled that of filtrate (in ml or grams) because the blowout point had not been reached in these experiments. The water loss for this experiment was thus proportional to the water used for the slurry because the powdered cement itself was unable to preserve the fluid in the slurry without fluid loss additives.

5.5 Thickening time

Table 4 indicates that the initial setting time of neat cement increased as the densities of the slurry were lowered. All three experiments were conducted under a pressure of 750psia and a temperature of 150˚F. Lower density cement had higher water content, thus it would take a take a longer time to reach a sufficient consistency level of strength due to fluid loss effect. As the consistency reached 70Bc, it would only take a few extra minutes to reach 100Bc as that was when the slurry was deemed unpumpable during the API thickening time test.

The tests for foamed cement were run in atmospheric temperature and pressure. For the setting time for foamed cement, it could be seen that increasing the foam quality would increase the thickening time of the cement. The shear was not uniform for foamed cement in the cup, and because of the specific rheological properties and behaviour, a large portion of the foam would remain in a static condition whilst a small amount that was sheared was finally destabilized. Therefore, it could be said that the standard pressurized consistometer would not be suitable for measuring the setting time of foamed cement. A non-destructive method (ultrasonic) would be more suitable to run a proper test for this experiment.

An interesting finding from the experiment was that, when an API cement of 15.6ppg was tested at atmospheric temperature and pressure, it would exhibit a thickening time of 6-7 hours. This proved that at the same pressure condition, the foaming provided little noticeable effect on the thickening time. The thickening time did not depend on the foam quality or gas content. This was because the hydration process should not be affected by the presence of inert gas in the slurry system. For field use, the thickening time should be determined in a pressurized consistometer for neat cement and an ultrasonic non-destructive consistometer for foamed cement. The thickening time required for field use is based on specific information such as the depth of wells, pressure and temperature and geographical locations.

5.6 Proposed Foamed Cement Design

The proposed foamed cement density should have a minimum density range of 9.5ppg to 12.8ppg with low fluid loss effect and without exceeding the fracture gradient of the coal bed formation. The foamed cement below 9.5ppg would have a permeability exceeding 1mD and a porosity exceeding 35-40%. The thickening would be based on the planned well trajectory and condition. From the experiments, it could be seen that the foamed cement has many advantages over the neat cement. They are:

i. Low density slurry that envelopes within the safe cement window for cementing in weak coal.

ii. High strength to density ratio since the lesser percentage of solid in foamed cement can provide near to similar strength as neat cement.

iii. Low fluid loss compatible for hydrophilic coal which may slough due to presence of water.

iv. Variation of cement density can be carried out in a single pump based on variation of foam quality introduced.

v. Reduction of cement sacks required as foamed cement yield is high

6. Conclusions

i. Foamed cement with a density of 9 ppg to 13 ppg provides sufficient strength to hold the casing, with adequate permeability and porosity and at the same time, very low fluid loss and satisfactory thickening time. For neat cement with a density of 14ppg to 17ppg and without the addition of fluid loss additives, although the strength is significantly higher, and it has low permeability and porosity It experiences severe fluid loss at 14ppg (minimum density) and produces relatively similar thickening time.

ii. The lightweight foamed cement provides a good option for cementing in CBM wells with benefits of high strength per unit volume of cement, low fluid loss and higher cement slurry volume yield. The utilization of neat cement would exceed the fracture gradient of the weak structure of the coal bed and there is a high possibility of cement slump due to gravitational effects. The effect of the foam in the slurry is also beneficial in the case of density control and fluid loss control which minimizes the damage towards the CBM reservoirs.

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Table 1- Comparison of compressive strengths with density

Density of cement				Averaged Compressive Strength	
Neat		Foamed		psi	Mpa
ppg	kg/m³	ppg	kg/m³		
16.9	2025			3508.8	24.19
15.8	1893			1974.5	13.61
14.9	1785			1246.9	8.6
		12.8	1536	969.3	6.68
		12.1	1145	955.9	6.58
		11.8	1416	852.3	5.87
		9.5	1134	824.6	5.68
		8.0	956	329.2	2.27
		6.4	761	258.0	1.78

Table 2- Variation of cement permeability and porosity

Density, ppg		Permeability	Porosity	Diameter	Length	Weight,
Neat	Foamed	mD	%	mm	mm	g
16.9		0.007	1.65	38.11	40.85	97.27
15.8		0.009	1.71	38.09	41.48	90.96
14.9		0.009	2.34	37.86	34.03	68.1
	12.2	0.618	30.25	37.87	49.04	79.44
	11.8	0.996	33.54	38.12	45.89	73.97
	11.1	0.999	35.11	37.91	41.73	62.90
	9.5	1.593	38.28	37.64	49.2	43.64
	7.9	2.122	44.94	37.3	50.23	40.90
	7.1	3.503	46.32	37.58	51.07	34.82
	6.6	4.203	51.70	37.37	50.35	36.79
	5.5	141.870	54.20	37.22	48.38	33.24

Table 3- API Fluid loss over 30 min within 5 min interval

Density, ppg	API Fluid Loss (double of filtrate volume)										
Neat cement	Time (min)	1	2	3	4	5	10	15	20	25	30
17.0		3.6	5.0	5.6	6.8	7.2	10.8	12.6	13.6	14.2	14.4
16.0		5.8	9.0	12.6	15.8	18.2	29.0	36.2	42.6	47.0	51.0
15.0		8.0	16.8	23.0	29.6	35.6	58.0	63.4	76.6	87.8	97.6
Foamed Cement	**Time (min)**	**1**	**2**	**3**	**4**	**5**	**10**	**15**	**20**	**25**	**30**
13.0		4.2	6.6	8.4	9.0	10.8	16.2	18.6	20.0	21.2	22.6
12.0		2.8	4.1	5.3	7.4	8.0	10.2	11.8	13.2	14.6	15.2
11.0		3.2	4.2	5.6	7.6	8.1	9.7	11.0	13.2	13.8	14.6
9.0		1.3	2.2	2.8	3.2	3.8	5.3	6.2	7.0	7.7	8.3
7.0		1.4	1.8	2.0	2.4	2.6	3.6	3.8	4.2	4.3	4.4

Table 4- Thickening time for neat and foamed cement

Density (ppg) of slurry	Pressure , psia	Stabilized Min Initial	Elapsed Time (hr:min) to reach Bearden consistency (Bc)		
		Consistency Bc	30	70	100
Neat Cement					
17.0	750.0	54.0	-	1:35	1:44
16.0	750.0	9.8	1:07	1:22	1:31
15.0	750.0	9.6	1:48	2:29	2:36
15.6 (API Cement)	14.7 (atm)	9.8	5:56	6:21	6:32
Foamed Cement					
13.0	14.7 (atm)	25.4	4:55	5:24	5:33
11.0	14.7 (atm)	11.3	5:26	5:59	6:14
7.0	14.7 (atm)	15.7	7:16	8:01	8:12

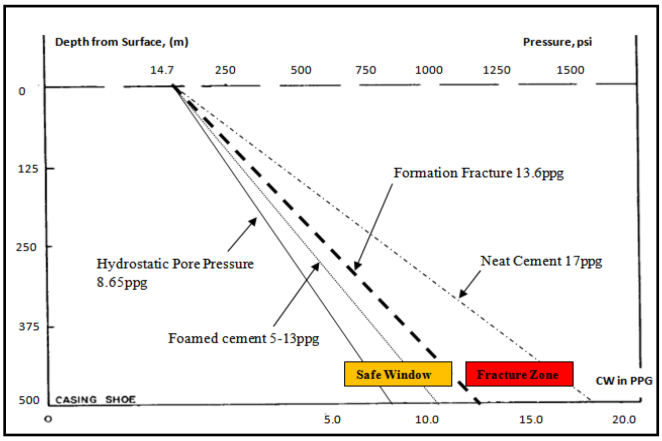

Figure 1- Idealized pressure plot with foamed and neat cement pressure for CBM

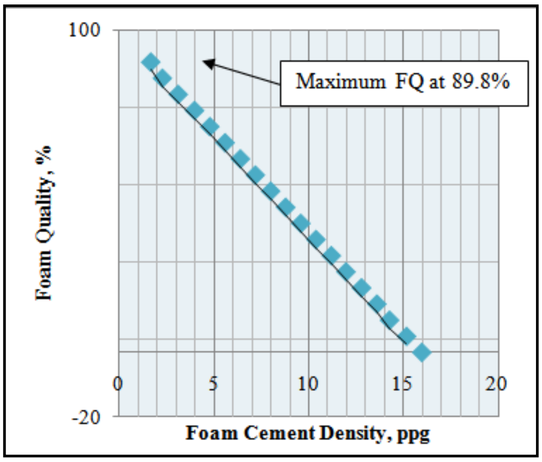

Figure 2- Plot of FQ vs Foam Density

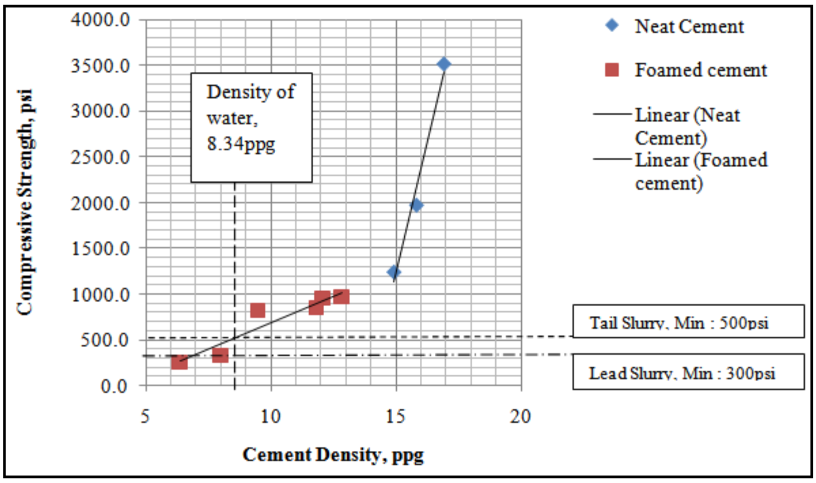

Figure 3- Comparison of compressive strengths at different densities

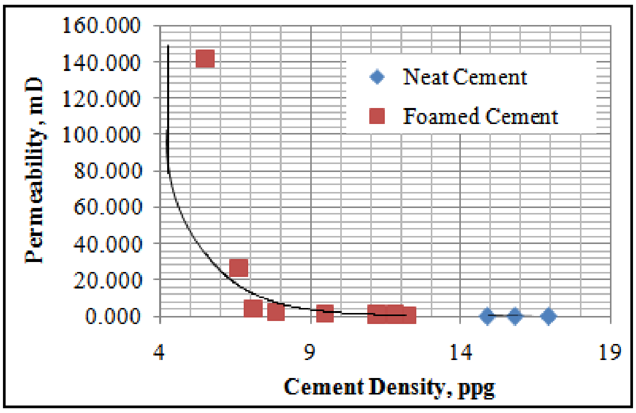

Figure 4 - Permeability distribution of neat and foamed cement with density

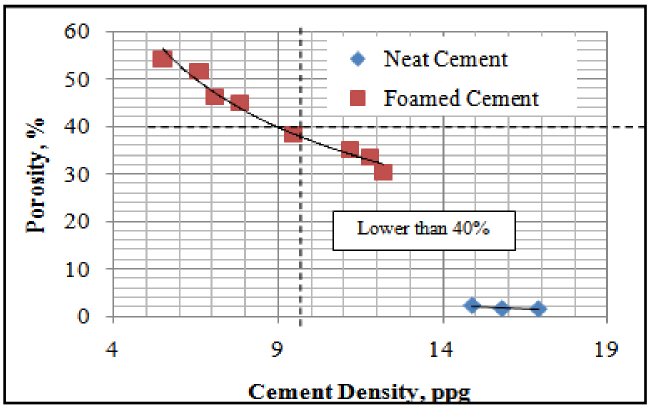

Figure 5 – Porosity of neat and foamed cement with density

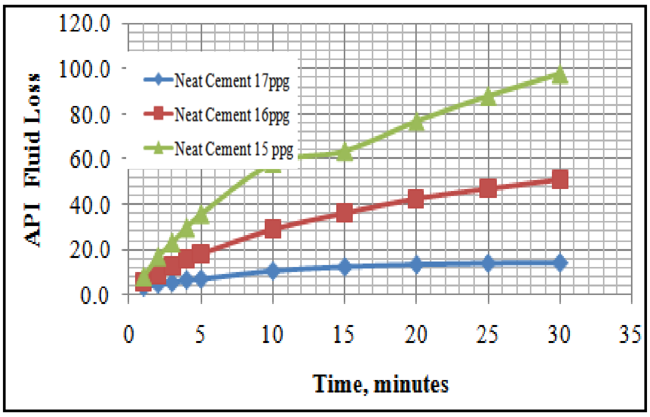

Figure 6 - API Fluid Loss for neat cement in 30mins

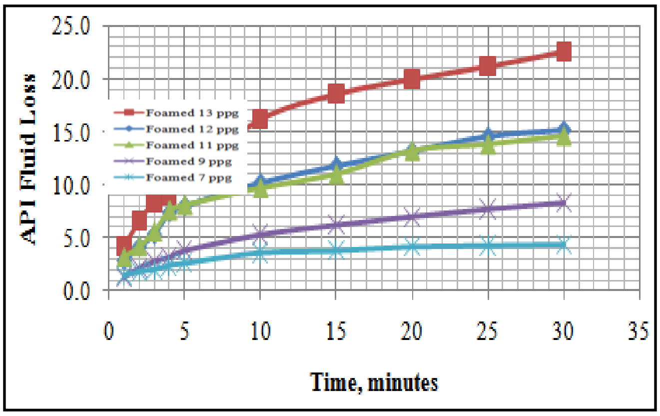

Figure 7 - API Fluid Loss for foamed cement in 30mins

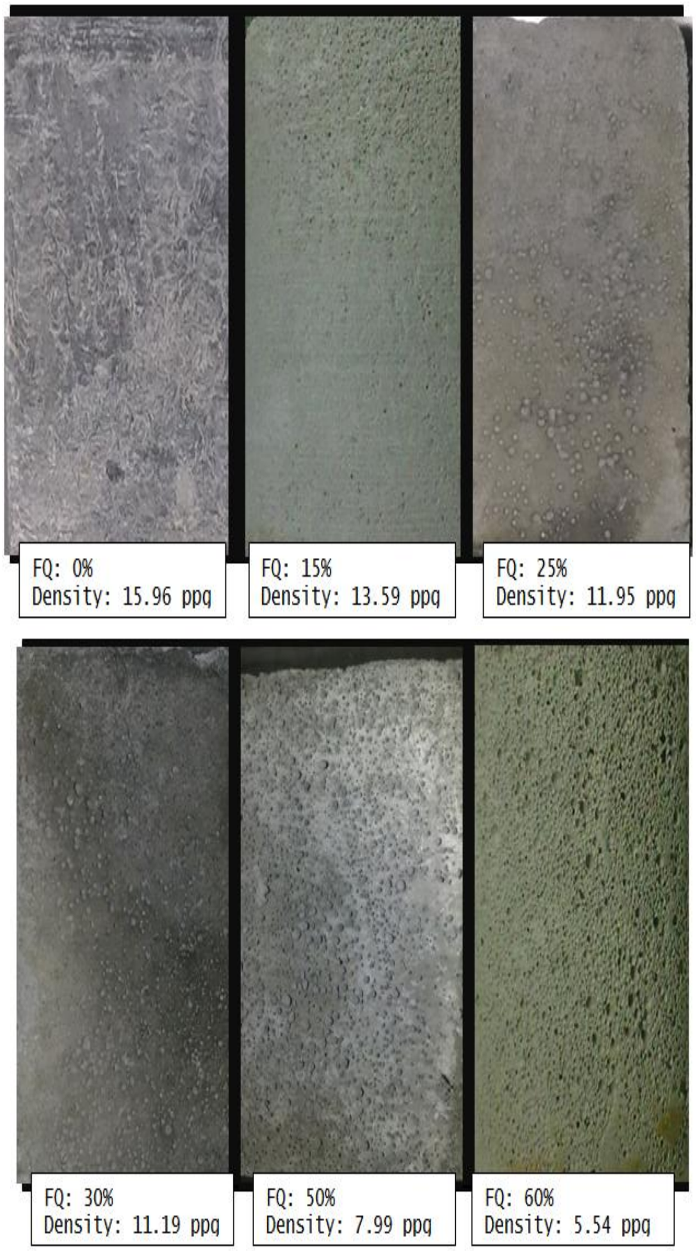

Figure 8 - Cross Sectional of foamed cement of 0% to 60% Foam Quality (FQ). The bubble size distribution (BSD) of 10% to 70% FQ ranges from 0-500μm.