UNIVERSITI TEKNOLOGI PETRONAS

PROPERTIES OF FOAMED CEMENT WITH ADDITIVES FOR ZONAL ISOLATION IN COAL BED METHANE (CBM) WELLS (A CASE STUDY ON MUKAH COALFIELD, SARAWAK)

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BY

KAMRAN HAIDER TUNIO

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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ABSTRACT

Coal bed methane (CBM) generally has lower fracture gradient as compared to conventional oil or gas wells due to weak structures of coal. Therefore, CBM are more vulnerable to downhole problems faced such as lost circulation and formation fracture as the formation cannot withstand the cement densities of averagely above 11 ppg (1320kg/m³). Foam cement when used together with additives offers a versatile and economical means of cementing with low density (5-13 ppg) and high strength per unit volume. Foamed cement was first introduced in the application of light weight cement for use in constructions and site building, which later, similar theory were applied in the foamed cementing process for the oil and gas industry. The objectives of this project are to determine properties of the foamed cement when used with Microsilica and BJ Ultra additives (density, compressive strength, fluid loss, porosity and permeability) to be compared and analyzed for their compatibility for the Mukah Coalfield, Sarawak. This thesis will discuss the characteristics of CBM reservoirs, foamed cement with additives sample preparation methods and data analysis. The various aspect of slurry design, including their method of determination is discussed. The properties of the conventional Class G cement can be determined directly with existing equipment which includes the curing chamber, compressive strength testers, and HPHT Filter Press. For the foamed cement, since these parameters are determined by the air quality and water to cement ratio and type of additive used, their relationships to density are focused.

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INTRODUCTION

1.1 BACKGROUND OF STUDY:

Foam cement is a mixture of cement slurry, foaming agent, foam stabilizer, and nitrogen gas. When the foam cement is properly generated, stable and lightweight slurry that looks like gray shaving cream is formed. When foam slurries are properly mixed and sheared, they often contain microscopic discrete bubbles that will not coalesce or migrate. The bubbles formed are not interconnected, which results in a low density cement matrix with low permeability and relatively high strength. [E. Fidan, 2003]

Foamed cement technique is still new in context for oil well cementing in overcoming problems with low formation fractures and lost circulation zones. The foamed cement has ultra light-density property and moderate cement strength at a relatively low cost [David & Hartog, 1981]. This is because the foam can increase the volume of slurry based on the quality of foam bubble applied. Foam cement, at present time, may be one of the most effective method to eradicate problems faced in zonal isolation, formation fracture, and lost circulation when conventional cement are used, which can resuscitate the high cost of 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 general requirement for cementing jobs is mainly, the hydrostatic pressure should never exceed the fracture pressure as fractures may form (or further elongation of fracture) and high proportion of cement volume might be lost to the formation. These relatively weak formations necessitate and will benefit from the use of the low density foamed cement which does not segregate due to gravity. [E.Fidan, 2003]

The Mukah Coalfield, located in Sarawak, Malaysia is underlain by two formations, Balingian Formation (Upper Miocene) and Bergrih Formation (Lower Pliocene). The coalfield hosted substantial amount of sub-bituminous coal which is calculated to be approximately 550 Million Tonnes [Sia, *et al*, 1995]. Methane or commonly known as natural gas is richly generated during coalification stage in CBM wells, and is stored within the internal surfaces of coal. Coal can store surprisingly large volume of methane-rich gas, six or seven times as much as conventional natural gas reservoir of equal rock volume [V.Nuccio,2000].

1.2 PROBLEM STATEMENT

In the completion of oil and gas wells, cementing operations are employed to seal the annulus and provide zonal isolation establishing structural integrity for the wellbore. Some of the most critical factors to success in a cementing operation are effectively displacing the drilling fluid, preventing loss of circulation, withstanding formation pressure and temperature. Several formations' like coal bed methane formations have delicate cleat structure systems which are relatively weak and are vulnerable to downhole problems such as lost circulation, fluid/gas intrusion and formation fracture. As the gas storage mechanisms in the coal bed methane reservoirs release methane and other light gases through diffusion, bedding structures can be even more destabilized. Neat cement (conventional) used for oil and gas wells has densities averagely above 15 ppg which exceeds the fracture gradient of the coal bed formation; as most coalbed has fracture gradient of 0.6 - 0.7psi/ft (13.5 ppg). Furthermore, Conventional cement is relatively brittle and may not withstand annular deformation and may crack due to cyclic stress loads.

1.3 OBJECTIVES:

The objectives of this project are given below:

1. To determine Foam Cement with additives compressive strength, fluid loss, porosity and permeability variate with foam cement density and cement composition
2. To determine the compatibility of foamed cement with additives on the Mukah"s coalfield reservoir structure.

1.4 METHODOLOGY

The following equipments will be used to perform tests on foamed cement with additives:

1. Constant speed mixer (4000-12000rpm rating)
2. Foaming generator (2900rpm, 1.5kW rating)
3. Cement Balance
4. Poroperm (300psi confining pressure)
5. Pressurized Curing Chamber (20,000psi/300°F),
6. Compressive Strength Tester (10,000psi rating),
7. Core Drill
8. OFITE HPHT Filteration Press

Tests conducted in the labs are compressive strength test, porosity test, permeability test, and fluid loss test for various cement densities ranging from 9ppg to 12 ppg for foamed cement with additives. Various foam quality based on proper calculations is used to adjust density for foamed cement while keeping the additive content and water to cement ratio constant. Additive content is kept constant at 35% BWOC and water to cement ratio is maintained at 2:1 to give a base slurry density of 15.6 ppg as per API standards.

1.5 SCOPE OF STUDY:

Foamed cement has numerous uses in Oil and Gas industry stretching from mud displacement to prevention of lost circulation in oil and gas Industry. Due to its obvious advantages over conventional cement, it is widely used in Oil and gas Industry. The scope of study firstly involves the literature review on the identification of the reservoir properties analysis of the coalbed in Mukah, Sarawak. From the information obtained, the experiment parameters such as reservoir pressure and temperature and cement properties to be tested will be determined. This is followed by the preparation of the cement slurry for foamed cement with additives. Foam generator will be used to generate foam for the foamed slurry. Curing under reservoir conditions will be conducted using the pressurized curing chamber and cured for 24 hours in water bath. The compressive strength tester is used for the compressive strength determination, poroperm for porosity and permeability, fluid loss filtration tester for fluid loss. A total of 50-80 cubes are required for the experiment for compressive strength test, and sampling. Other tests require the cement in the slurry form. Finally, the detailed analysis of the findings will be discussed in the data analysis section.

1.6 FEASIBILITY OF STUDY WITHIN SCOPE AND TIME:

The first phase (FYP-1) of the project involves the literature review on current utilization and properties of cement for casing integrity and also the coalbed structure (wells drilled, maximum depth, reserves etc) for the Mukah Coalfield. Laboratory works will also be performed to obtain the required cement and slurry density suitable for use in Mukah Coalfield.

The second phase (FYP-II) of project involves analysis and laboratory works for foamed cement with additives. The foamed cement produced will be subjected to vigorous testing, measurement of its physical, chemical and mechanical properties, testing its compressive strength, Permeability and porosity and fluid loss ratio with density, cement composition and additives variations based on API standards. Results obtained will be analyzed and discussed and compared with the results obtained in the first part of studies thoroughly to be utilized for Mukah Coalfield followed by thorough discussion on the utilization of foamed cement with additives to conclude the project.

THEORY AND LITERATURE REVIEW

2.1 THEORY

2.1.1 Neat Cement Volume and Densities

A slurry volume of approximately 600 ml shall be sufficient to perform most laboratory tests while not overfilling the mixing container. Laboratory blend requirements may be calculated by use of the following formulas. Alternative, suitable equations may also be used to calculate laboratory blend requirements.

For the purpose of these calculations, it is assumed that relative density is equal to density expressed in grams per millilitre.

Slurry volume (ml), $Vs = (Vc + Vw)^{\wedge}A + Va$ .... (2.1)

Slurry mass (grams), $ms = mc + mw + ma$ .... (2.2)

Slurry density (grams/ml), $\rho s = ms/Vs$ ....(2.3)

Where

Vc is the cement volume, in millilitres;

Vw is the water volume, in millilitres;

Va is the additive volume, in millilitres;

mc is the cement mass, in grams;

mw is the water mass, in grams;

ma is the additive mass, in grams;.

$Vc = mc / \rho c$

where ρc is the density of cement, in grams per millilitre;

$Vw = mw / \rho w$

where ρw is the density of water, in grams per millilitre;

$Va = ma / \rho a$

where ρa is the density of additive, in grams per millilitre.
[API Recommended Practice 10B-2 / ISO 10426-213]

Coefficient A reduces the slurry volume as cement is reactive towards water. The resultant slurry will have lower volume than the volume of water and cement summed. From experimental methods of approximately 60 sample test, the value of A is determined to be around 0.765.

Conversion Factor:

ppg (lbm/gal) X 1.198264E + 02 = kg/m^3 .... (2.4)
(Kg/$m^{3)}$ X (1000g/1kg) X (1m^3/1000L) X (1L/1000ml) = g/ml .... (2.5)

2.1.2 Foamed Cement Volume and Densities

The Portafoam (Portable Foam Generator) consists mainly of an air compressor, water and foam agent mixer, and also a lance for the outlet. The compressor has rating of 1.5kW power, 2900rpm, and requires 1.08A current, and voltage of 250V. Some specifications of the foam agent and equipment are as follows:

Foam Agent : *Palm Oil (Protein Foam)*

Foam Expansion Factor : *12-15times of premix foam*

Foam: Water Premix Ratio : *1:30*

Foam Density : *0.08 g/ml*

Foam Half Life: *Approximately 6-8 minutes*

Minimum Operating Pressure for Compressor: *4.0 MPa*

Stable slurry Density : *16 ppg (Water 1:2 Cement ratio)*

The formulas used for calculation for foamed cement slurry densities are:

Volume of Foam Agent required, $Vfa = Vwf/30$ .... (2.6)

Volume of Premix Foam, $Vpf = Vwf + Vfa$ ....(2.7)

Volume of Stable Foam, $Vsf = Vpf \times Expansion\ Factor$ ....(2.8)

Mass of foam produced, $mf = Vsf / Foam\ Density$... (2.9)

Total volume of foamed slurry, $Vfs = (Vc + Vw) * 0.765 + Vsf$ ....(2.10)

Total mass of foamed slurry, $mfs = mc + mw + mf$ .... (2.11)

Density of foamed slurry, $\rho fs = mfs / Vfs$.. (2.12)

The factor of 0.765 is used because of the reactive nature of the cement when in contact with water. Calcium microsilicate hydrate will form and interlink between grains, increasing the strength of the cement, while reducing the permeability and volume.

2.1.3 Additive Weight:

Additives are chemicals and materials added to a cement slurry to modify the characteristics of the slurry or set cement. Cement additives may be broadly categorized as accelerators, retarders, fluid-loss additives, dispersants, extenders, weighting agents, lost circulation additives and special additives designed for specific operating conditions. Cement additives are commonly available in powder or liquid form, enabling some flexibility in how the cement slurry is prepared. [http://www.glossary.oilfield.slb.com/search.cfm]

Weight of additive required, $W_A =$ BWOC X % of Additive

2.1.4 Foam Quality

Foam Quality is a term used to define the ratio of gas volume to the total foam volume at specific pressure and temperature. High foam quality indicates there is a relatively high gas ratio in slurry. Higher foam quality cement indicates higher gas bubbles intensity inside the cement slurry. Therefore, cement slurry with higher foam quality will yield weaker and lighter dry cement cubes after curing. In higher pressured reservoir, the cement will be more compressed thus reducing the foam quality of the cement slurry. Neat cement which is compacted have maximum, less than 2% of quality. The optimum foam quality to be used for foam cement is between 18-38%. Above about 35%, the cement is too porous to provide isolation, and below about 18%, it becomes brittle.

Foam Quality (%) = (Base Slurry – Foamed Slurry) / Base Slurry X 100%, ppg .. (2.13)

2.1.5 Compressive strength

Compressive strength is the strength of a set cement sample measured by the force required to crush it. It is expressed as force per unit area. [API Recommended Practice 10B-2 / ISO 10426-2]. Properly designed cement slurry will set after it has been placed in its appropriate location within the well. Cement strength is the strength the set cement has obtained, which is referred as compressive strength or tensile strength. Compressive strength is the force per unit interval cross-sectional area in psi necessary to crush the cement specimen. The average value of the samples are obtained and reported as the compressive strength of the set cement for 4 samples for each density variation. When cement has developed 500psi (3447 kPa), compressive strength in 24 hours, the strength is usually deemed sufficient to hold pipe or casing and continue for operations. For lead slurry operations, minimum strength required is normally around the range of 250-300psi (lower density of cement), while for tail slurry, around 500psi as tail slurry has higher density.

Higher pressure and higher temperature reservoir conditions of the well will exhibit higher compressive strength from the cement compression test. In the compression test, 8 cubes were allowed to cure for a specified period of time in the pressurized curing chamber. The compressive strength of cement is dependent upon the W-C ratio used in the slurry, foam quality, type of additive used, the curing time, temperature and confined pressure during curing.

2.1.6 Permeability and Porosity

Permeability is defined as the measurement of the ability of fluid to channel in the cement. Porosity is defined as measure of pore spaces over the bulk volume. The design of neat cement would not be affected by the permeability or porosity since it is compacted with little or zero air quality. However, with foam cement, high permeability and porosity becomes a concern. At higher temperature and pressure, fluid intrusion may occur more drastically due to higher formation pressure of fluids against the cement. The calculation of permeability and porosity is shown below:

Porosity, $\varphi = (V_{bulk} - V_{particle}) / V_{bulk}$ .... (2.14)

Darcy's Flowrate , $Q = -(k \times A/\mu) \times (dP / dL)$ ....(2.15)

Where

k = permeability of the porous rock, mD

A = cross-sectional area of the cement core plug

μ = viscosity of the fluid, centipoises (cP)

dP / dL = pressure gradient in the direction of the flow,

2.1.7 Fluid Loss

Fluid loss is the measurement of the water loss of the cement expressed in volume per unit time under reservoir temperature and pressure. The fluid loss for neat cement is directly proportional to water cement ratio. API Fluid loss is double the filtration volume obtained if blowout is not obtained. On the contrary, foamed cement with lower density is predicted to have lower fluid loss effect. Dehydration is the loss of water from cement slurries by process of filtration. However, the cement is not completely dehydrated, where sufficient water remains to allow setting of cement. For tests at temperature less than 200°F, testing is performed using a static fluid-loss cell. The fluid loss test in laboratory involves a static condition where slurry will be placed in a standard filter cell. The water loss through filter paper is measured as a function of time. The cement slurry will be in static form and dehydration of slurries will usually result in decreasing fluid loss behavior with time.

$$\textit{Calculated API Fluid Loss: } 2 \times Qt\,(5.477 / t^{1/2}) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2.16)$$

Where, *Qt* is the volume of filtrate collected at the time of blowout, ml

t is the time of blowout, expressed in minutes

**Blowout – The time when nitrogen blows through in less than 30mins of testing*

2.2 LITERATURE REVIEW:

2.2.1 Foamed Cement:

Foamed cement is a homogeneous, ultra light weight cement system consisting of base cement slurry, gas (usually nitrogen) and surfactants. If mixed properly, foamed cement forms stable, lightweight grayish cement slurry. Foamed cements are commonly used to cement wells that penetrate weak rocks or formations with low formation-fracture gradients.

The slurry is first mixed and pumped downhole, then proportional amounts of a foaming agent and stabilizer are injected into the slurry. To shear the slurry and create foam, operators inject the N_2 into the mixture at a high pressure.

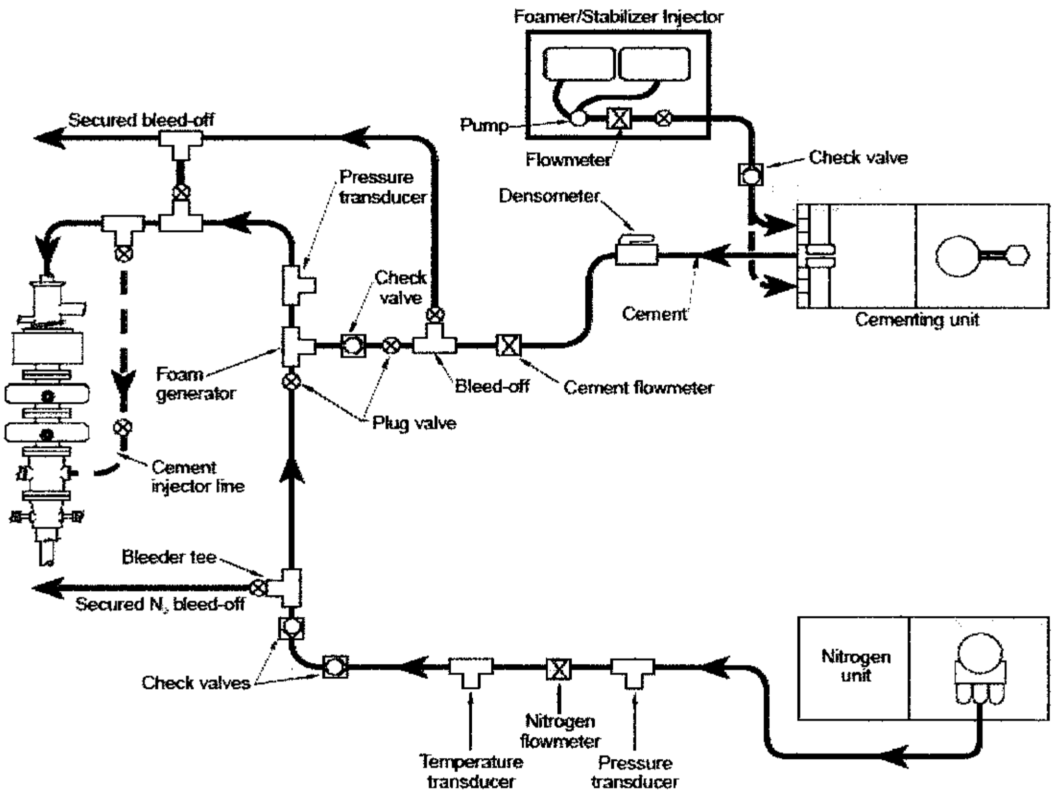


Figure 1: Sample foam-generation set up. The slurry is first mixed and pumped downhole. Then, proportional amounts of a foaming agent and stabilizer are injected into the slurry. To shear the slurry and create foam, operators inject the nitrogen into the mixture at a high pressure.

[Ron Crook, August 1999]

When the N2 is introduced into cement slurry with sufficient energy to create discrete gas cells, physical stabilization results (the gas is stabilized as small cells, or bubbles, within the slurry). The bubbles are not interconnected and do not coalesce resulting in a low density cement matrix with low permeability and relatively high strength

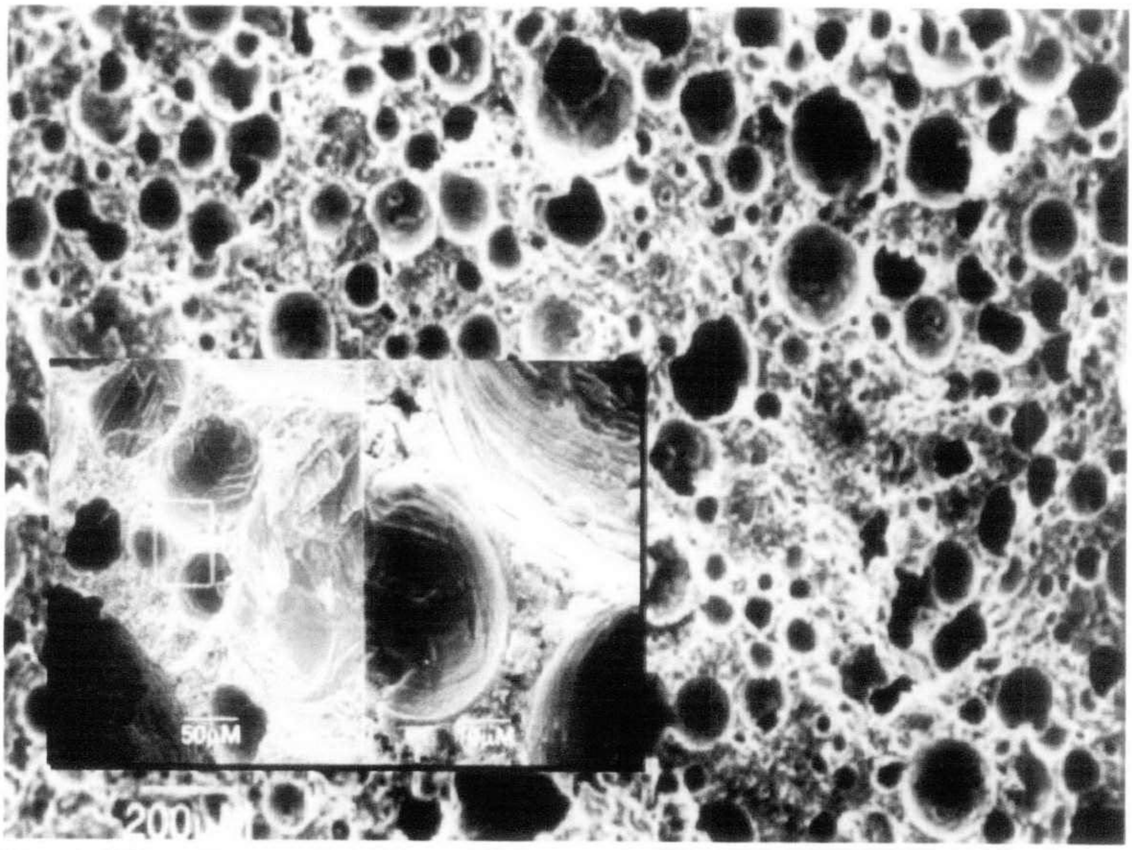


Figure 2: Microphotograph of a foamed cement sample. When N2 is introduced into the cement slurry with sufficient energy to create gas cells, the gas is stabilized as small cells, or bubbles, within the slurry. The bubbles are not interconnected and do not coalesce, resulting in a low-density cement matrix with low permeability and relatively high strength.

[Ron Crook, August 1999]

During pumping operations, foamed cement develops higher dynamic-flow shear stress than conventional cements, increasing its mud-displacement capabilities. In addition, foamed cement, which consists of cement slurry injected with nitrogen gas, can be optimized for individual well conditions. Slurry density, determined by gas content or quality (the porosity in the set cement), depends on the pump rate of the base slurry, foam agent and stabilizer injection rates, and nitrogen rate. Computer programs help optimize slurry design and predict job placement pressures.

The gas used to foam the cement continues to expand while the cement volume reduces, allowing slurry pressure to remain almost constant during the cement's transition period.

Consequently, foamed cement can control gas migration and formation-fluid influx better than any other type of cement, and it resists temperature- and pressure-induced cement-sheath stresses.

Foamed cement is at least one order of magnitude more ductile than other cements. Testing has shown that foamed, 18- to 35-quality cement remains more ductile than other cements, allowing the cement sheath to withstand higher internal casing pressures. This feature allows the cement sheath to "give" as the well's casing expands, helping prevent cement-sheath cracking on a long-term basis. Above about 35%, the cement is too porous to provide isolation, and below about 18%, it becomes brittle.

Brittleness or lack of ductility of conventional cement has always been the factor for primary cement job failures. With the development of efficient liquid nitrogen vaporizing units, uniform disbursement of small nitrogen bubbles nitrogen in the slurry greatly diminishes the mobility of the gas in the slurry [McElfresh, 1981].

2.2.2 PHYSICAL PROPERTIES OF FOAMED CEMENT

Some of the favorable physical properties of foamed cement due to the effect of inclusion of nitrogen as observed by E.Fidan (2003) in his experiments are given below:

- **Fluid Loss:** The nitrogen bubbles in the slurry does not move or coalesce with each other under high pressure. In the system, the only way the water loss can occur is around the bubbles, and thus when the bubble density is increased, there will be more surface area for the bubble membranes, resulting in an increase distance of the fluid to travel to escape the slurry – decrease in fluid loss. [E.Fidan, 2003]

$$\textit{Calculated API Fluid Loss} : 2 \times Qt\ (5.477 / t^{1/2})$$

Where, *Qt is the volume of filtrate collected at the time of blowout, ml*

T is the time of blowout, expressed in minutes

**Blowout – the time when nitrogen blows through in less than 30mins of testing*

- **Volume Enhancement**: The inert nitrogen gas used as filler enables the slurry yield to be very high, increasing the slurry's volume with inclusion of the nitrogen gas bubbles. [E.Fidan, 2003]
- **Compressive Strength:** Foamed-cement contains less water ratio is relatively much stronger than neat cement that carries more water. The inert filler of nitrogen gas enables slurry with low density to have high solid contents leading to high ultimate strength. For conventional cementing job, it is sufficient if the cement can withstand 500psi in 8 hours. [E.Fidan, 2003]
- **Permeability:** At density lesser than 7 ppg, permeability of foamed cement exceed 1md, where the resistance to fluid intrusion would not be effective. Nitrogen bubbles do not coalesce thus, the permeability still remains low although it is higher than conventional. [E.Fidan, 2003]
- **Lightweight:** stable foamed cement can yield 720kg/m3 downhole density at bottom hole conditions. During primary cementing, foam cement can prevent formation breakdown, lost circulation, and post-job cement fallback. The extremely lightweight quality of foam is especially useful for lost circulation plugs where conventional methods of cementing may not be applicable [E.Fidan, 2003]
- **Excellent Strength to Density Ratio:** foam cement has an excellent strength-to-density ratio. Slurries that contain less water are usually stronger than those that carry a lot of water. With inert nitrogen gas as a filler material, slurries of even very low density can still have high solids content, which causes the ultimate strength to be relatively high. [E.Fidan, 2003]
- **Enhanced Mud Removal:** foamed fluids have higher apparent viscosity which can allow foamed cement slurries to yield better energy transfer to low mobility

drilling mud and filter cake. The improved transfer can result in better removal and improved solids-lifting capability. [E.Fidan, 2003]

- **Expansion:** foamed cement can expand to fill washed out hole sections and mega Darcy lost circulation zones without formation breakdown. [E.Fidan, 2003]
- **Preventing Gas Migration:** foam cement produces discrete nitrogen bubbles in the cement matrix that do not coalesce or migrate. As a result the permeability compared to conventional lightweight systems is lower. [E.Fidan, 2003]
- **Insulation:** low thermal conductivity and subsequent low heat transfer during production can help prevent deposition of unwanted deposits by minimizing cooling. [E.Fidan, 2003]
- **Stability at High Temperatures;** foam cement can be stable at up to 600^{o}F. Foam cement helps prevent strength retrogression of cement, and the ductile nature of foam cement can provide high resistance to failure from thermal cycling. [E.Fidan, 2003]

2.2.3 Foamed Cement Advantages

Laboratory test has shown that foam-cemented annulus can elastically absorb stresses from pressure-induced expansion of internal casing to "give" as the casing expands and deform without failure. The ductility and high compressive strength of the foamed cement allows it to withstand higher hoop stress. [McElfresh, 1981]. Foamed cement utilization in reservoirs can have many advantages over neat cement in reservoir with lost circulation, zonal isolation and fluid intrusion problems.

a. Cure for lost circulation in vugular/cavernous zones in reservoirs

Denser slurry tend to slump to the bottom of the cavernous environment even before they have time to harden due to gravity. The thixotropic properties of the foam cement match the density of the fluid in the vugs to prevent gravity segregation. [David, D.R & Hartog, J.J, 1981] *b. 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 at a further distance across the gas bubbles. During pumping operations, foamed cement can develop higher dynamic-flow shear stress than conventional cement, increasing the mud displacement capabilities. This system effectively controls gas migration and formation-fluid flux, which limits migration channels in the set cement sheath. [McElfrech, P.M. and Boncan, V.C, 1981]

c. Prevention of formation fracture for CBM's delicate cleat system

Cementing operation has to be slightly overbalanced to prevent free-gas migration into cement column. The light weight (refer **Figure 3**) of the foam cement places less pressure on the unique cleat structure on coalbed, reducing the tendency of the cement to exceed the fracture gradient of the coal. [Technical Data Sheet HO2656, 2001]. The low compressive strength of foamed cement due to relatively low density maybe a concern for operators who considered compressive strength as a leading indicator of cement sheath integrity in high pressure fracturing conditions. Foamed cement low compressive strength does not increase the risk for fracture initiation and propagation during hydraulic fracturing treatments. The sheath ability to withstand these stresses is predominantly determined by cement"s mechanical properties (Young"s Modulus and Poisson ratio) and tensile and thus, cement"s compressive strength is of minimal importance. [E.Fidan & E.Kuru, 2003]

e. Long term economic feasibility

The initial cost of conventional cement (without any specific additives for lightweight or strength purposes) can be less than that for the foamed cement. However, the improved zonal isolation capabilities of foamed cement can provide substantial cost saving over the life of the well because the useful life is by-far longer than for conventional cement. Conventional cement tend to crack in two to ten relaxation cycles compared to foamed cement, measured in hundreds of stress-relaxation cycles. [Kopp,K , 2000]. The light weight of foam cement makes it useful for lost circulation plugging where conventional method of cementing may not be applicable and ineffective. The slurry that contain less water are generally stronger and has lesser setting time as compared to those with high water percentage. With addition of inert gas as filler, slurry can have low density and high solid content, contributing to the strength of the cement. [Technical Data Sheet HO2656, 2001]

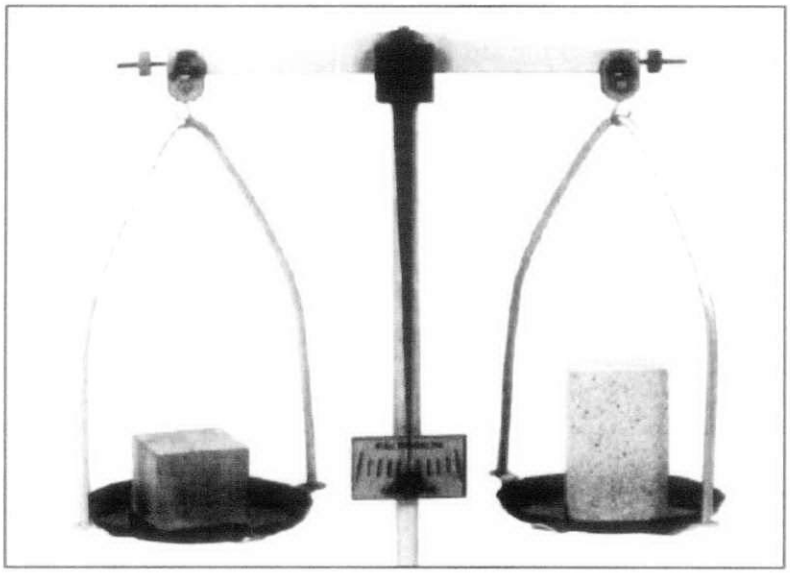


Figure 3 Relative Volume of Equal weighted blocks of neat (left) and foamed (right) cement.

Density of foamed cement is 1030 kg/m3 while for neat cement is 1910kg/m3,

Source: [David, D.R and Hartog, J.J, 1981]

Foamed cement costs approximately 1/3 less than other non-foamed, premium light weight cement slurry system on a cost per cubic foot basis. In addition to that, the useful life of a foamed cement sheath to provide zonal isolation can last up to hundreds of stress-relaxation cycles compared to conventional cement, which crack in two to ten stress relaxation cycles [Kopp, K, 2000]. In CBM wells, pump rate should be kept at maximum rate to displace mud, slurry density as low as possible to remain below the fracture gradient and equivalent circulating density (ECD) should remain below the fracture gradient of the weakest zone in the annulus.

Foamed cements can help support both primary and remedial cementing functions for offshore and onshore situations, as indicated in the following list:

1. Foamed cements offer a low density alternative to conventional cements. For example, slurries can be foamed to a density as low as 4lb/gal. low density foamed cements (4 to 15lb/gal) can be placed more easily across weak formations, helping prevent lost circulation and fallback problems [Ron Crook, August 1999]

2. With some cement additives, foaming creates a synergistic effect that enhances the properties of the additives. This effect is evident with some fluid loss additives, lost circulation materials and latex [Ron Crook, August 1999]

3. The density of foamed cement is variable. Its ductility allows for expansion and pressure maintenance during hydration, thus helping provide long term zonal isolation. As the cement expands, it can fill washed out hole sections and megadarcy lost circulation zones without formation breakdown [Ron Crook, August 1999]

4. The improved mud removal capacity of foamed cement also helps enhance zonal isolation. Because of its ductility, foamed cement can provide casing support for the life of the well. [Ron Crook, August 1999]

2.2.4 Additives:

Additives are materials added to cement slurry to modify or enhance some desired property. Some common properties that are modified include: setting time (by use of retarders or accelerators), fluid loss control, viscosity, etc. [API Recommended Practice 10B-2 / ISO 10426-2]. Cement additives are commonly available in powder or liquid form, enabling some flexibility in how the cement slurry is prepared.

Folloing additives are used in this project:

2.2.5 MICROSILICA

Microsilica, also known as silica fume, is a fine-grain, thin, and very high surface area silica. Because of its extreme fineness and high silica content, silica fume is a very effective pozzolanic material. Microsilica is added to Portland cement concrete to improve its properties, in particular its compressive strength, bond strength, and abrasion resistance. These improvements stem from both the mechanical improvements resulting from addition of a very fine powder to the cement paste mix as well as from the pozzolanic reactions between the microsilica and free calcium hydroxide in the paste. Microsilica reduces bleeding significantly because the free water is consumed in wetting of the large surface area of the microsilica and hence the free water left in the mix for bleeding also decreases. It also blocks the pores in the fresh cement so water within the cement is not allowed to come to the surface. [http://en.wikipedia.org/wiki/Microsilica_fume]

Silica fume is used extensively in Oil well grouting In both primary oil well grouting, when the grouting is used as a hydraulic seal in the well bore and secondary grouting such as leak repairs, sealing splits, and closing depleted zones. The addition of silica fume to the oil well grout produces a blocking effect that prevents gas migration. Silica fume's ability to decrease the permeability of the grout, slows or stops gas leakage from the well. Increased strength of the cured slurry provides greater durability of the installation and the addition of silica fume to the slurry, improves its flow, so the installation is more effective. [Gary M. Gapinski, Silica Fume]

Whether used for primary (placement of grout as a hydraulic seal in the wellbore) or secondary applications (remedial operations including leak repairs, splits, closing of depleted zones), the addition of microsilica fume enables a well to achieve full production potential. Besides producing a blocking effect in the oil well grout that prevents gas migration, it provides these advantages:

- Improved flow, for easier, more effective application
- Dramatically decrease permeability, for better control of gas leakage

- Increased durability and compressive strength
- Lightweight

[http://www.norchem.com/applications-oil-well-grouting.html]

2.2.6 Fluid loss additive:

Fluid loss additive is a chemical material used to control the loss of fluid to the formation through filtration. In cementing operations, loss of the aqueous phase can severely affect the performance of the slurry and set cement. In almost any operation, loss of fluid to the reservoir formation carries a high risk of permeability damage.

Following fluid loss additive is used in this project:

BJ ULTRA:

BJ ULTRA is a multipurpose cement additive based on novel, high performance polymers. BJ Ultra has specifically been designed to perform with Portland cement systems. BJ Ultra provides ease of use for mixing and handling. This product offers exceptional fluid loss control across a wide range of temperature conditions for primary and remedial cementing applications.

BJ Ultra alone can control fluid loss, free water and rheology for fresh, seawater and light brine slurries. Thickening time can be easily adjusted with the aid of retarders and accelerators.

Main benefits of BJ Ultra are:

- Eliminates free water and slurry density segregation
- Imparts a high degree of fluid loss control, readily obtaining values of less than 100 ml/30minutes
- Provides acceptable flow properties in low fluid loss slurries to improve displacement efficiencies.

- Combined fluid loss and gas control properties reduce chances for remedial cementing due to gas migration
- Superior slurry stability improves bonding
- A cost effective multifunctional additive.

2.2.7 Coalbed Methane (CBM) Reservoir Characteristics

CBM reservoirs have unique cleat structures which are relatively less stable and weaker as compared to gas/oil reservoirs where higher cleat density is essential for better fluid flow. The fracture gradient of coal bed ranges from 0.62-0.69psi/ft as compared to sandstone reservoir with 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 & E.Kuru, 2003].

Coal formation differs from traditional reservoirs of sandstone or carbonates and coal properties also vary greatly from coal seams in a particular area to another. Therefore, it is not appropriate to consider a single cement design for all CBM wells, whereby the cement should be tailored to the relative composition of the coal as well as the reactivity of the formations. Coal bed methane fractures are usually in the form of vertical cleats (fractures), thus, they are more commonly drilled horizontally across to meet pass all the cleats for maximized production. [M.Ali (ONGC), A.Sakar, R.Sagar, 2008].

From recent studies in coal bed wells in Mukah, Sarawak maximum depths of the wells drilled were approximately 500m below the surface or 450m below the mean sea level because the topography of the area is around 30m. The reserves for the drilled wells were calculated based on seam by seam method, and are classified into 3 categories based on the radius of area of influence which are 400m: *Measured reserve*, 400m-1200m: *Indicated reserve*, and 1200m-4800m: Inferred reserve. A total of 551.9mt of coal has been identified, comprising of 20.0mt (*3.6%*) measured reserve, 80.8mt (*14.6%*) indicated reserve and 451.1mt (*81.7%*) inferred reserve. [Sia *et al*, 1995]

For Mukah's CBM, the coal rank is Sub-bituminous B coal having coal strength of lignite around 5390psi range. The lower the rank coal such as Sub-bituminous B coal from Mukah will be termed hydrophilic, where it tends to be more reactive to water (fresh water). The water risks of blocking the cleat structure as well. Mukah coal contains high percentage of moisture ranging from 16.2% to 30.4% for core samples. Therefore, if neat cement is used without fluid loss additives, the water loss will cause severe shale and clay sloughing. The fluid additives at the same time may cause inherent formation damage where it reacts to create clay precipitates in the formation. Hence, the best possible choice is to use foamed cement together with fluid loss additives.

Figure 3 illustrates the hydrostatic pressure attained when foamed cement are used compared to API neat cement for a casing cementation. The casing shoe is estimated to be set at 500m (1640ft) and the fracture gradient of the formation is 0.66 psi/ft.

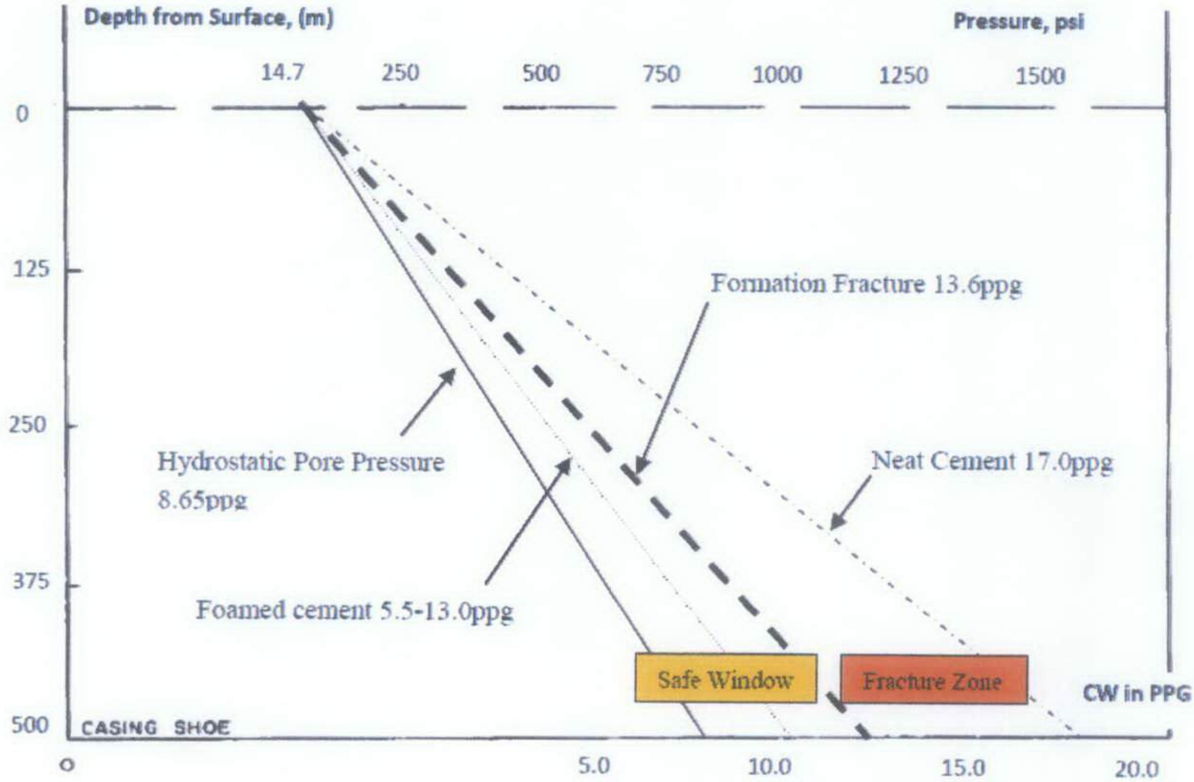


Figure 4 Idealized pressure plot with foamed and neat cement pressure for CBM

It is clearly illustrated that, if the neat cement is to be utilized in the CBM reservoir, it will exceed the fracture pressure by a large margin, thus may cause high possibility of lost circulation and unstable formation. Lost circulation will lead to high volume of cement loss into the formation, causing formation damage in increment of skin effect. Besides that, the calculated volume of cement to reach Top of Cement (TOC) will be lesser and zonal isolation for casing and formation fails, reducing, significantly cement integrity.

The coal specific gravity ranges around 1.3, whereas, sandstone reservoir normally have a specific gravity of approximately 2.65 and higher for carbonates. During drilling stages, the weaker formations are more prone to damage due to the trowelling movement of the bit and drill string and cavernous zones may form. These cavernous zones may originally exist in the formation as well. Cementing with conventional neat cement would pose a problem, as the denser cement will tend to slump, under the influence of gravity when the cement are set as shown in Figure 4. [David, D.R & Hartog, J.J, 1981]

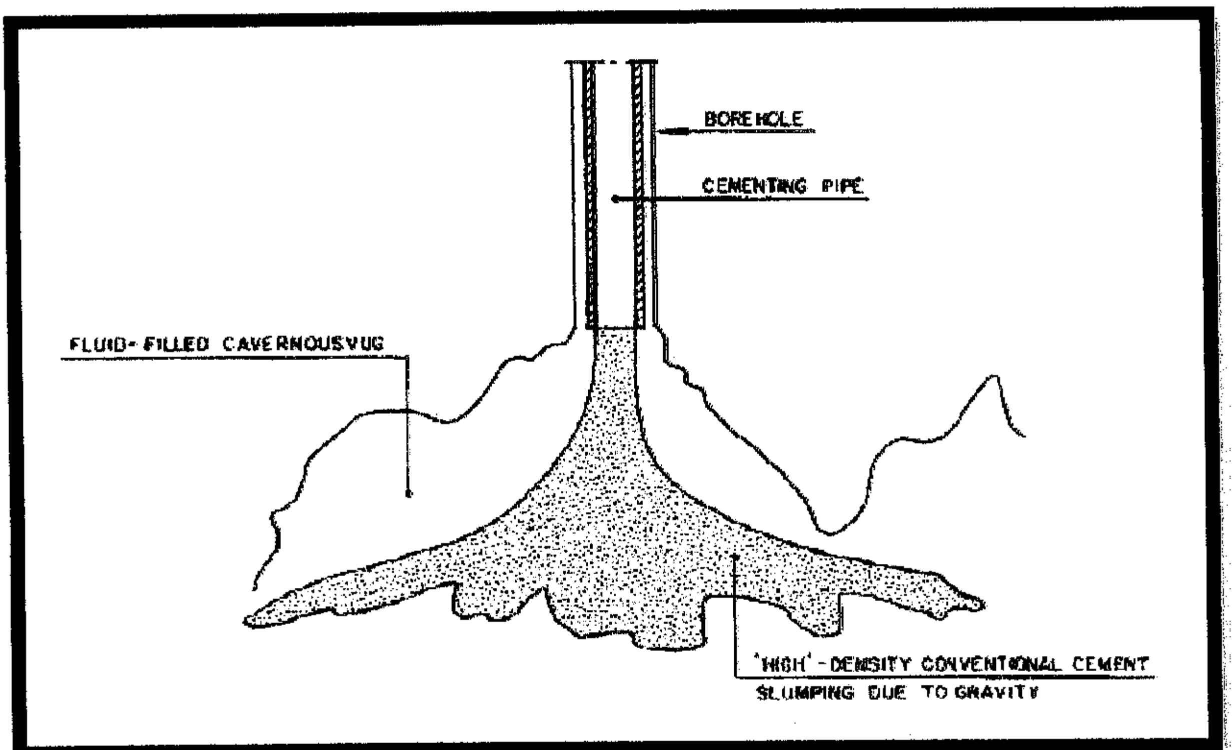


Figure 5 Conventional neat cement gravity segregation prevents proper setting

Therefore, it is understood that, these coal bed reservoirs are very delicate and proper measure of properties control of fluid and cement is required. For instance, if the cement slurry which is set does not reach the expected TOC due to fractures in the coal formations, secondary cementing jobs which adds on to the cost will be necessary. In general, the cement slurry should be adjusted based on the suitable value of the coal bed to minimize the losses of properties while trying to maximize the strength. [Reddy, B.R. *et al,* 2002*]*. This can be achieved for foamed cement by adjusting the air quality percentage for the slurry before it is pumped into the well where it provides not only better thixotropic properties, light weight and cost effective as reviewed in the next section.

2.2.8 General Properties Requirement for Slurry

[ANSI/API Recommended Practice 10B-2]

a. Minimum & Maximum Density

For conventional onsite requirement, the density of the cement slurry has to be a least:

- +0.5 – 1.0 ppg > drilling Fluid Density
- +0.5 ppg > spacer density
- Lower than Equivalent circulating Density (ECD) to the formation fracture

b. Maximum Permeability and Porosity

According to [McElfresh, 1981], the porosity exceeding 35-40% induce cement elongated cracks during perforation stages. For the permeability, it should not exceed 1mD to provide a barrier for fluid intrusion to contact with the casing from formation.

c. Maximum fluid loss of the slurry *(classified based on the different casing sections)*

Surface Casing ≤ 500cc/30min

Intermediate Casing ≤ 250cc/30min

Production Casing ≤ 100cc/30min

d. Minimum Thickening time

The minimum thickening time is the job time plus safety factor (normally 30 minutes to 60 hours). Based on Equation 2.7, the thickening time consists of mixing time, pumping displacement time, time for plug to rupture and safety factor.

e. Rheology

Conductor/ Surface – mixable and pumpable, thixotropic for lost circulation zone

- Intermediate – PV $\leq$ 150, YP $\leq$ 40
- Production – PV $\leq$ 100, YP$\leq$ 20

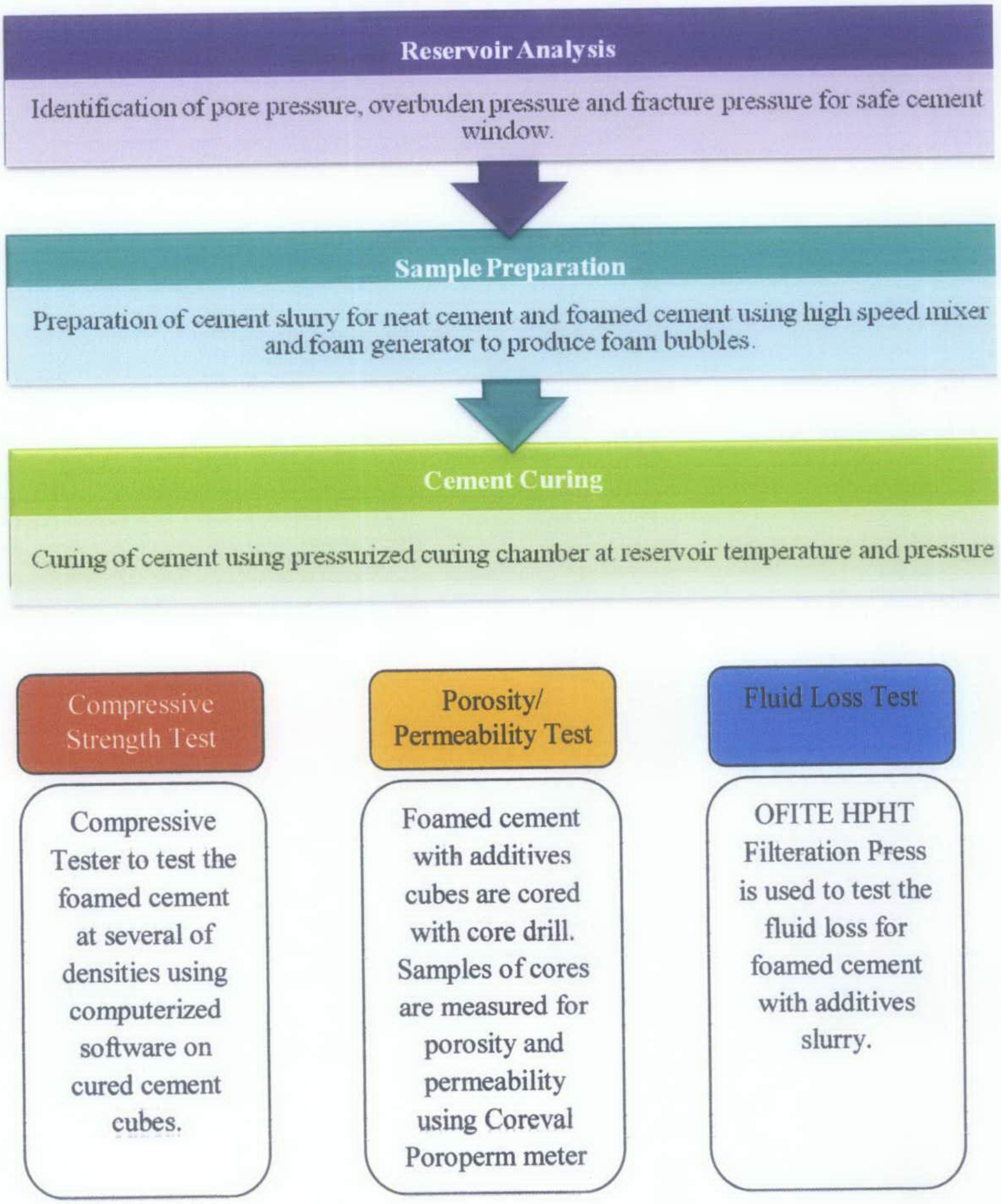
f. Cement Evaluation Method

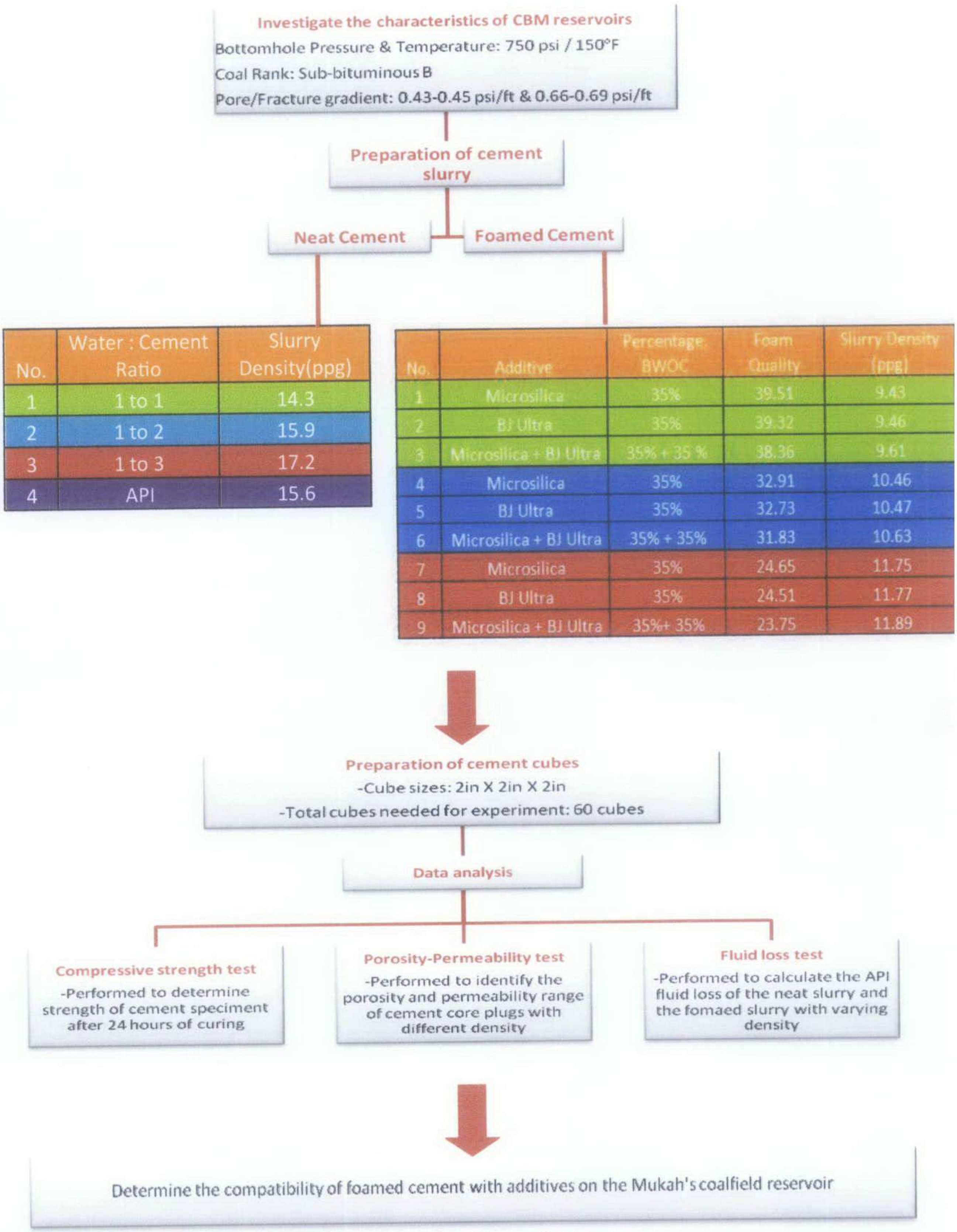
Assessment of cement effectiveness by detecting TOC and quality of cement bond by Cement Bond Logs, Variable Density Log and Temperature/Radioactive Surveys.

METHODOLOGY

3.1 General Project Flow Chart

The flow chart below shows the activity sequence of the project and progression.





No.	Water : Cement Ratio	Slurry Density(ppg)
1	1 to 1	14.3
2	1 to 2	15.9
3	1 to 3	17.2
4	API	15.6

No.	Additive	Percentage, BWOC	Foam Quality	Slurry Density (ppg)
1	Microsilica	35%	39.51	9.43
2	BJ Ultra	35%	39.32	9.46
3	Microsilica + BJ Ultra	35% + 35 %	38.36	9.61
4	Microsilica	35%	32.91	10.46
5	BJ Ultra	35%	32.73	10.47
6	Microsilica + BJ Ultra	35% + 35%	31.83	10.63
7	Microsilica	35%	24.65	11.75
8	BJ Ultra	35%	24.51	11.77
9	Microsilica + BJ Ultra	35%+ 35%	23.75	11.89

Figure 6 Project Flow Chart

3.2 Consumables and Equipments

The consumable materials which are required for this project are Class G Oil well cement, fresh water, light grease, black oil grease and palm oil foam agent. The consumables are used only in the cement slurry and specimen preparation. Below are the quantities that were required:

Consumable	Quantity
Class G Oil Well Cement	40-45 kg
Fluid loss additive, ULTRABJ	1 Liter
Microsilica	5-15 kg
Fresh Water*	30-40 liters
Light Grease	5-10 usages for Compartments
Black Oil	10-15 usages for Compartments
Palm Oil Foam Agent (Protein Based)	50 ml

Table 1 Type of Consumables and Quantities

**Only used for purpose of cementing not including flush/wash*

The laboratory equipments listed below are used for cement slurry preparation, cement curing stages and also for laboratory testing methods. Below are the equipment and the primary functions:

Equipment	function
Model 7000 Constant Speed Mixer	Mixing of Base slurry
LIDA Portable Foam Generator (Portafoam)	Generating foam for foamed slurry mix
Sieve Shaker	Distributing slurry evenly in mold
Cement Balance	Determining Cement Density
SOLTEQ® Curing Chamber	Curing of cement slurry under HPHT
SOLTEQ® Compressive Strength Tester	Determination of compressive strength

Core Drill	Drilling of cement cubes into core plug
FANN Roller Oven	Drying of cement core plugs
COREVAL Poroperm Meter	Determination of permeability/porosity
OFITE HPHT Filtration Press	Determination of fluid loss volume

Table 2 Main Equipments for Laboratory Preparation and Testing

3.3 Mixing and preparation of cement slurry base:

1. The Class G cement and fresh water is weighted using the electronic balance.

2. Cement density is adjusted by varying foam quantity introduced in cement while keeping water cement ratio constant at 1:2 for both additives i.e. microsilica or BJ Ultra whether used separately or used together with each other. The content of both additives is kept constant at 35% of weight of cement (WOC)

3. The appropriate amount of water and additive (liquid form i.e. ULTRABJ) is poured into the mixer container.

4. The power is turn to ON in FIXED position. The START button is pushed to start the motor and begin timer from 50 seconds. Cement and additive (powder form i.e. MICROSILICA) is slowly added to the water during the first 15 seconds at low speed at MIX 1. (4000rpm)

5. The cover is placed on the container after cement has been added. When timer reaches 35 seconds, MIX 2 button is pressed to mix at high speed. (12000rpm)

6. Water and foam agent of ratio 30:1 is added into the Portafoam.

7. Pressure is allowed to reach 4MPa before white foam is allowed to be generated through the outlet lance. The foam is mixed with the base slurry thoroughly and ready to be tested.

Figure 7. LIDA Portable Foam Generator (Portafoam)

Figure 8. Foam ready to be mixed with Base cement slurry.

Figure 9. Foamed Cement with Additives

Figure 10. Model 7000 Constant Speed Mixer

3.4 Determining Cement Density

1. Fill the sample cup with the fluid, the density of which is to be determined. The cup should be filled slightly below the upper edge of the cup (approximately ¼ in)

2. place the lid on the cup with attached check valve in the down (open) position

3. push the lid downward into the top opening of the cup until the surface contact is made between the outer skirt of the lid and the upper edge of the cup

NOTE: if the O-ring on the lid makes it difficult to push the lid onto the cup, do not force it. Forcing the lid can cause the fluid to exit from the check valve opening and possibly spray the person in the face

4. place the threded cap over the lid and screw it into the place. This placement forces the lid against the cup and allows excess fluid to slowly exit from the check valve opening.

5. with the outer ledge of the lid contacting the cap and the check valve open, some fluid shall be expelled from the check valve. If fluid doesnot come out of the check valve, remove the lid and pour more liquid into the cup.

6. the pressurizing plunger is similar in operation to a syringe. Fill the plunger by submering the nose of the plunger assembly in the fluid with the piston rod in completely inward position. Then, pull the piston rod upward to fill the plunger cylinder with the fluid.

7. push the nose of the plunger into mating O-ring surface of the check valve. To pressurize the sample cup, maintain a downward force on plunger cylinder housing to hold the check valve down (open) position. At the same time apply and maintain a downward force of approximately 50 lb on the piston rod.

8. the check valve in the lid is pressure actuated. When pressure is applied within the cup, this same pressure tends to push the valve upward into the closed position. The valve is therefore closed gradually.

9. While maintaining the same force on the plunger, decrease the force applied by the hand holding the cylinder. This process allows the check valve to move upwards slowly.

10. When the check valve closes pressure can be released from the plunger and the cylinder disconnected from the check valve.

11. The pressurized fluid is now ready for weighing. Rinse the exterior of the cup and wipe it dry

12. Place the instrument on the edge knife.

13. Move the sliding weight left or right until the beam is balanced. The beam is balanced when the attached bubble is centered between two black marks.

14. obtain the density by reading one of the calibrated scales on the arrow side of the sliding weight.

15. once the density reading is obtained the pressure is released by pushing the valve downward. Push the valve downward by reconnecting the empty plunger assembly and pushing it downward on the cylinder housing.

16. Empty the cup and thoroughly rinse and clean all components with water.

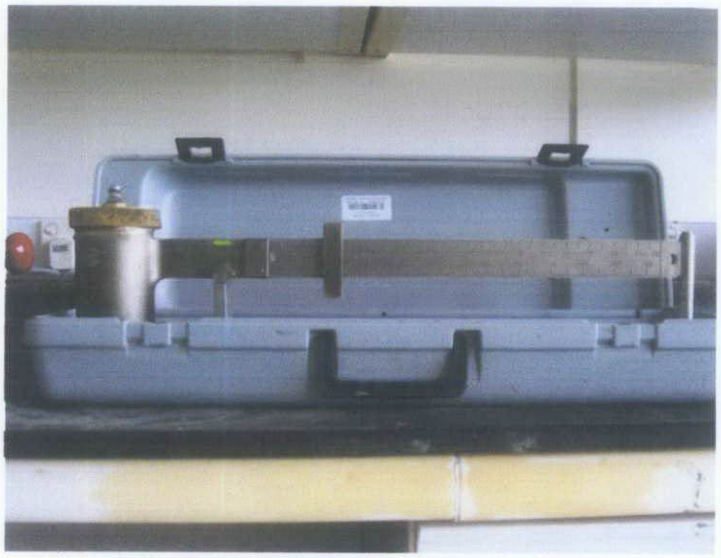


Figure 11. Cement Balance

3.5 Cement curing at reservoir temperature

1. The temperature ramp and soak parameters are programmed at the curing chamber to be 100˚F for first 60 minutes, and the soaked to 150˚F for another 30minutes and soaked for the 8 hours.

2. Each pair of the mold bodies (2"x2"x2" dimension) are assembled. The inside on mold should be lightly greased, and to be repeated for 4 stacks of molds and clamped once done. Cement slurry is to be filled into each mold and are stacked.

3. The filled molds are lowered into the stainless steel mold bucket and into the pressure vessel of the pressurized curing chamber.

4. The cylinder plugs threads are lubricated. The plugs are treaded into the cylinder and tighten securely by hand. The thermocouple is inserted in the center of the cylinder plug but not tighten completely.

5. The AIR SUPPLY valve is open to allow the air pressure to be forced from the oil vessel into the pressure vessel consisting of the cement slurry in molds. As soon as hissing sound stops and oil appears around the thermocouple, the thermocouple is tightened with a spanner.

6. The PUMP is switch ON gradually to allow the pressure to build up to 750psi and maintained. The pressure needs to be released as it increased gradually with time.

7. HEATER and TIMER switch is turned on, and the test will be run until the timer from the soaking is completed.

8. After complete, HEATER is turned off, and CYLINDER COOLING valve is opened to allow flow of cooling water to cool the pressure vessel.

9. When the plug and cylinder temperature has reduce below 120F°, thermocouple can be removed and PRESSURE RELEASE valve to be opened and AIR SUPPLY valve closed, and AIR EXHAUST valve open to allow the oil to be pumped back into the oil vessel. The plug can now be opened, and the mold is removed from the pressure vessel. The mold is tapped lightly to release the cement cubes.

10. The cement cubes are left to be cure in water bath for 24 hours prior to testing.

Figure 12. SOLTEQ® Curing Chamber

Figure 13. Curing Chamber Molds after being greased

Figure 14. Molds filled with Cement Slurry

Figure 15. Some of the molds produced.

3.6 Laboratory Testing Method

The data analysis section consists of 3 main testing methods to evaluate the variation in properties of foamed cement depending on type of additives used. The Compressive Strength Tester will be used to determine the compressive strength, the OFITE HPHT Filtration Press to determine fluid loss and finally the Poroperm to determine Permeability and porosity.

3.6.1 Compressive strength test

1. The OFITE Compressive Strength Tester is turned on.

2. The cement cube specimen is placed in the lower platen of the hydraulic cylinder. The upper platen is adjusted to ensure that it touches the specimen. The upper platen is adjusted by loosening the locking nuts above the platen, and then the two lower nuts are turned to fit the cement specimen. The surfaces of the two platens are ensured to be parallel.

3. Safety shield is closed before beginning the test. The Compressive Strength Tester Software in the PC is opened. The "Options" from the "Edit" menu is selected. In "Data File Directory", the folder for the data to be saved is chosen.

4. The height (in inches) is input into the main screen in the "Cube Height" field. The file data is selected from the "Edit File". Relevant information are filled in and "OK" is clicked. The loading rate of "4000PSI/min" is selected for this experiment.

5. "Pump On" button is clicked to start test. Then, "Run Test" is clicked and is hold to begin test while observing the specimen.

6. When the specimen fails (crushed), the "Run Test" button is released to stop the test and pump. The maximum load (compressive strength) is shown in the "Max Load (PSI)" field. Step 1-7 is repeated for 2 more specimens for each density.

7. The results obtained for every 3 samples are taken as average and recorded.

Figure 16. SOLTEQ® Compressive Strength Tester

3.6.2 Fluid loss test

1. Connect the heating well power cord to an appropriate power source. Place a dial-type metal thermometer into the well in the heating jacket and preheat to 10°F (6°C) above the desired test temperature. A pilot light will come on when the heating jacket is at the desired temperature as selected by the thermostat control knob.

2. Be sure all of the o-rings on the valve stems are in good working condition (pliable with no nicks or cuts, etc.), and are not damaged during the assembly procedures. Place a thin film of silicone grease on all O-rings. Screw a valve stem into the test cell on the side opposite the cell cap. Tighten the valve stem completely.

3. Stir the sample for 10 minutes with a high-speed mixer. Carefully pour the sample into the cell. Do not fill the cell closer than 0.5" (13 mm) from the o-ring groove to allow for heat expansion of the fluid. Be careful not to spill fluid on the o-ring inside the cell.

4. Place an o-ring in the cell and another in the cell cap recess. Place a circle of filter paper on top of the cell o-ring and slowly push the cell cap into the cell. Make sure the arrow on the cell cap lines up with the arrow on the cell body. If the cap locking screw seats are oval shaped and no longer round, there is a possibility of stress failure and the cap should be replaced.

5. Tighten the cap locking screws and tighten both valve stems. Place the cell in the heating jacket with the outlet or filter side of the cell pointed down. Rotate the cell in the heating jacket so that the pin in the bottom of the heating well seats into the hole in the bottom of the cell. This will anchor the cell inside the well and prevent the cell from rotating as the valve stems are opened and closed. Transfer the thermometer from the heating jacket to the thermometer well within the cell.

6. Connect the pressuring assembly to the top valve stem and lock it in place with the retaining pin. Place the back pressure receiver on the bottom valve assembly and also lock it in place with the retaining pin.

7. Keeping the valves closed, adjust the top and bottom regulators to the recommended back pressure for your test. Open (loosen) the top valve stem ½ turn to pressurize the sample. Maintain this pressure on the fluid until the desired temperature is stabilized, as indicated by the thermometer. The heating time of the sample should never exceed one hour

8. Open (loosen) the bottom valve stem ½ turn to initiate filtration.

9. Collect the filtrate for 30 minutes maintaining the selected test temperature within ± 5°F (± 3°C) and take readings for every five minutes.

10. API Fluid Loss is calculated based on Equation 2.16 and recorded.

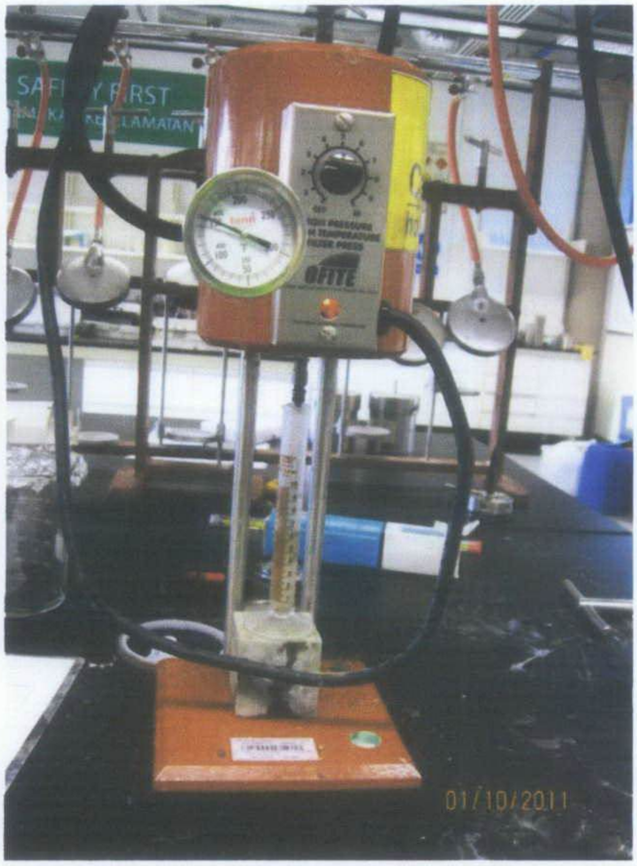


Figure 17. OFITE HPHT Filtration Press

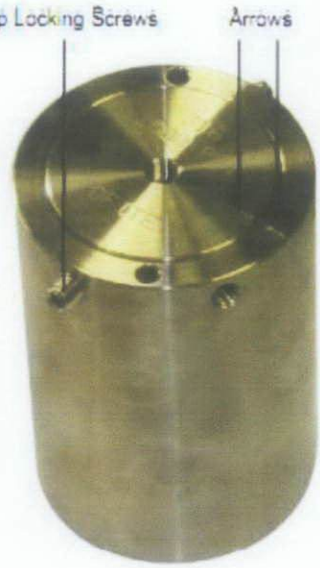


Figure 18. Slurry Containing cup for Fluid Loss Test

3.6.3 Permeability and Porosity Measurement

1. The cement cubes are placed on a 2"x2"x2" mold to sit. The core drill is placed approximately on top of the cubes to produce a 1.5"x2" core plug samples. Core plugs are drilled for 2 specimens for each density.

2. Drilled core plugs are then collected and labeled. The plugs are then dried in the roller oven at 60°C for 1 day before testing.

3. The diameter (mm), length (mm) and weight (g) of the core plugs are filled in the measure Tab Panel in COREVAL POROPERM. Confining pressure is set to 300psi.

4. The core plug is installed inside the core holder and ensure is locked from the bottom. The upper plug is adjusted to ensure that it touches the top of the core plug.

5. The "Start" button is clicked and measurement will show appear when done.

6. Repeat Step 3-6 for 2 samples for every core plugs with different densities.

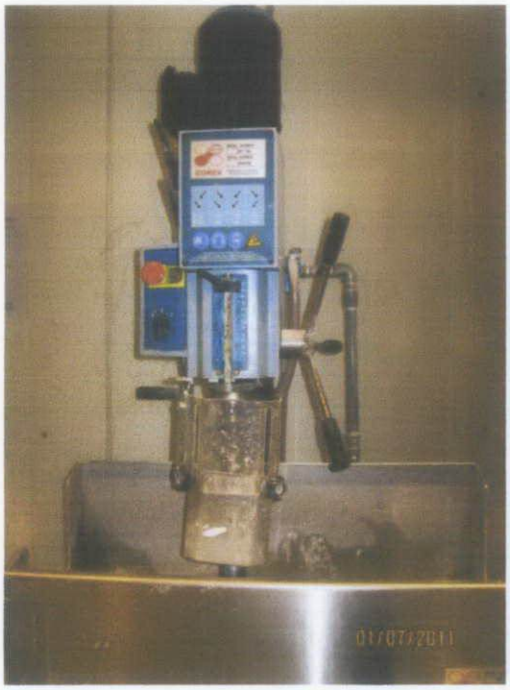


Figure 19. Core Drill

Figure 20. Cubes being cored using Core Drill.

Figure 21. Drilled cores being trimmed

Figure 22. Drilled cores ready to be tested in Poroperm

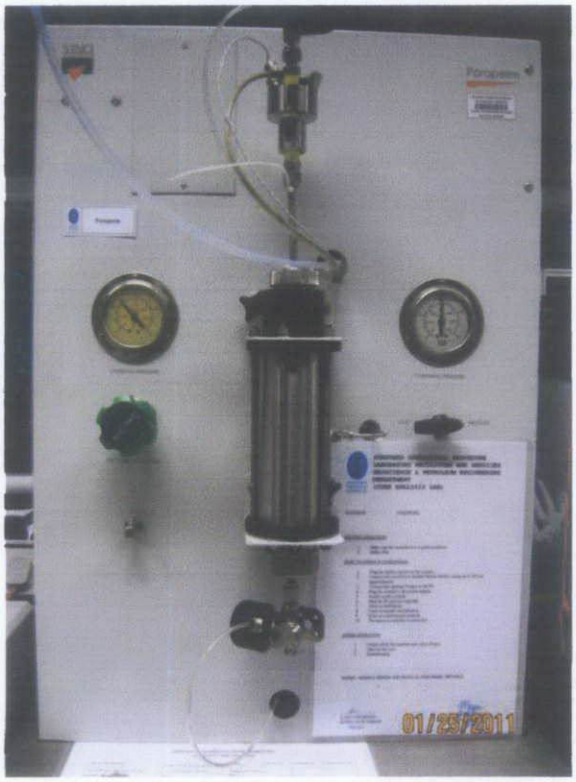


Figure 23. COREVAL Poroperm Meter

RESULTS AND DISCUSSIONS

4.1 Data Gathering and Analysis

Several foamed cement cubes were produced with densities ranging from 9 ppg to 12 ppg. A base slurry of density 15.6 ppg as per API standards were produced first and then density was altered by introducing foam into cement slurry. The foam quality introduced in the cement ranged from 18% to 38% which is optimum foam quality. For each density, first; microsilica and BJ Ultra additives were used separately to examine individual effect of these additives on cement properties and then, both additives i.e. microsilica and BJ Ultra were used together to examine the collective effective on cement properties. The additive percentage introduced in cement was kept constant at 35% BWOC for each additive.

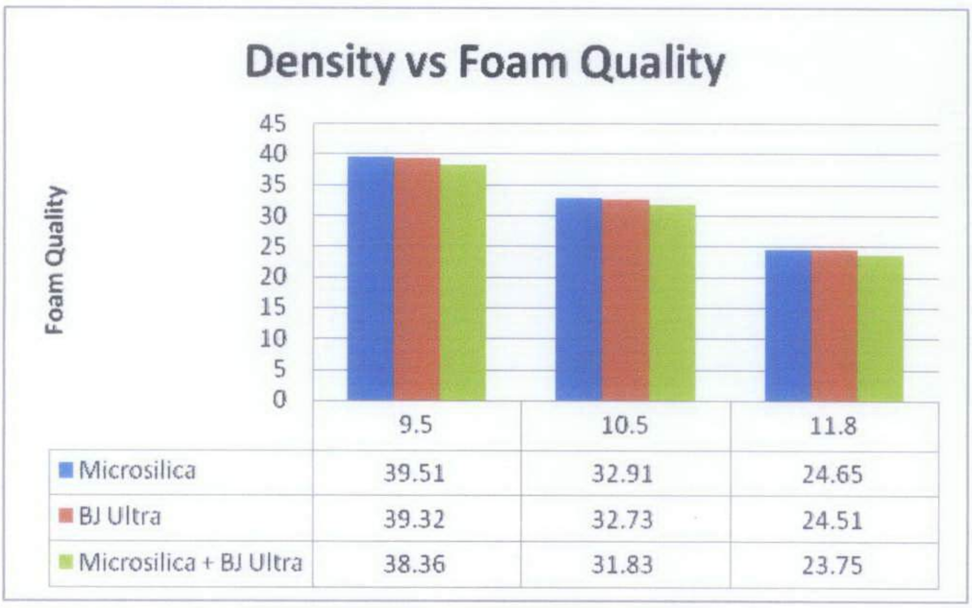


Figure 24. Effect of Foam Quality on Base Slurry

The final density of the cement is dependent on the amount of the foam introduced in the neat slurry. As can be seen from Figure 24, the density of cement reduces as higher foam quality is introduced in the slurry. A foam quality of around 24 reduces the density of cement from 15.6 ppg to 11.8 ppg and when foam quality is increased to 38, the cement density is reduced from 15.6 ppg to 9.5 ppg. As more gas bubbles are injected into the slurry, the volume of slurry expands. This expansion of slurry affects 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 will be diminished or diluted by the presence of gas throughout the slurry.

The preparation of cement slurries varies from that of solid/liquid mixtures due to the reactive nature of cement. This explains why the cement slurry produced will have lesser volume compared to the volume of water and cement used. Formulas for calculating density are shown in **Equation 2.1-Equation 2.12**. Standard API RP 10B-2 suggests that a mass of cement at 792g should be mixed with 358g of water. However, in this project these are altered based on properties exhibited by different densities.

With the use of foamed cement and fluid loss additives, it was possible to get stable slurry of density as low as 9 ppg and hence problem of high fluid loss associated with neat cement slurry was eliminated. For neat cement, usually cement slurry below 14 ppg (water cement ratio of 1:1), is not stable and is too diluted. The high water content becomes separated from the cement during the curing stages. Therefore, the fluid loss during curing stages is excessive where; the cement and water will become gravitationally separated in the mold unless high performance fluid loss additives are used.

Several foamed cement cubes with different densities and different additives were produced for Compressibility Test and Porosity/Permeability Test. Details of the produced cubes are given in Appendix - I.

4.1.1 Compressive Strength Test

For lead slurry operation, the minimum compressive strength required to hold the casing is usually around 250psi-300psi, while for tail slurry which generally has higher density than lead slurry, requires minimum compressive strength of 500psi in 24 hours

Foamed cement generally has lower compressive strength than neat slurry due to the fact that neat cement is a compacted unit of cement with less than 2% of gas bubbles where as foamed cement has high content of nitrogen gas. For foamed cement, the higher the foam quality the lower is the density achieved which results in lower compressive strength as the cement contains more water and gas bubbles per unit volume of cubes.

Lower compressive strength when dealing with foamed cement can be overcome with the use of additives. For this project, microsilica is used to increase the compressive strength of the cement. Microsilica is usually used to increase compressive strength almost immediately compared to silica which takes longer time to achieve maximum compressive strength. BJ Ultra - a high performance polymer additive which is a multipurpose product is also used to determine its effect on compressive strength as compared to microsilica. Both additives are used individually and then collectively to determine their individual and collective effect on compressive strength. Results of Compressive Strength Test for each cube are shown below in Table 3 and interpreted in Figure 25 below.

Sample	Additive	Percentage, BWOC	Density, ppg	Foam Quality	Average Compressive strength, psi
S.1	Microsilica	35%	9.43	39.515	925
BJ1	BJ Ultra	35%	9.46	39.322	1005
BJ.S1	Microsilica + BJ Ultra	35% + 35 %	9.61	38.356	1011
S.2	Microsilica	35%	10.46	32.91033	1015
BJ.2	BJ Ultra	35%	10.49	32.73	1225
BJ.S2	Microsilica + BJ Ultra	35% + 35%	10.63	31.83	1592
S.3	Microsilica	35%	11.75	24.65	1150
BJ.3	BJ Ultra	35%	11.77	24.506	1540
BJ.S3	Microsilica + BJ Ultra	35%+ 35%	11.89	23.75	1920

Table 3. Effect of additives and density on the compressive strength of foamed cement

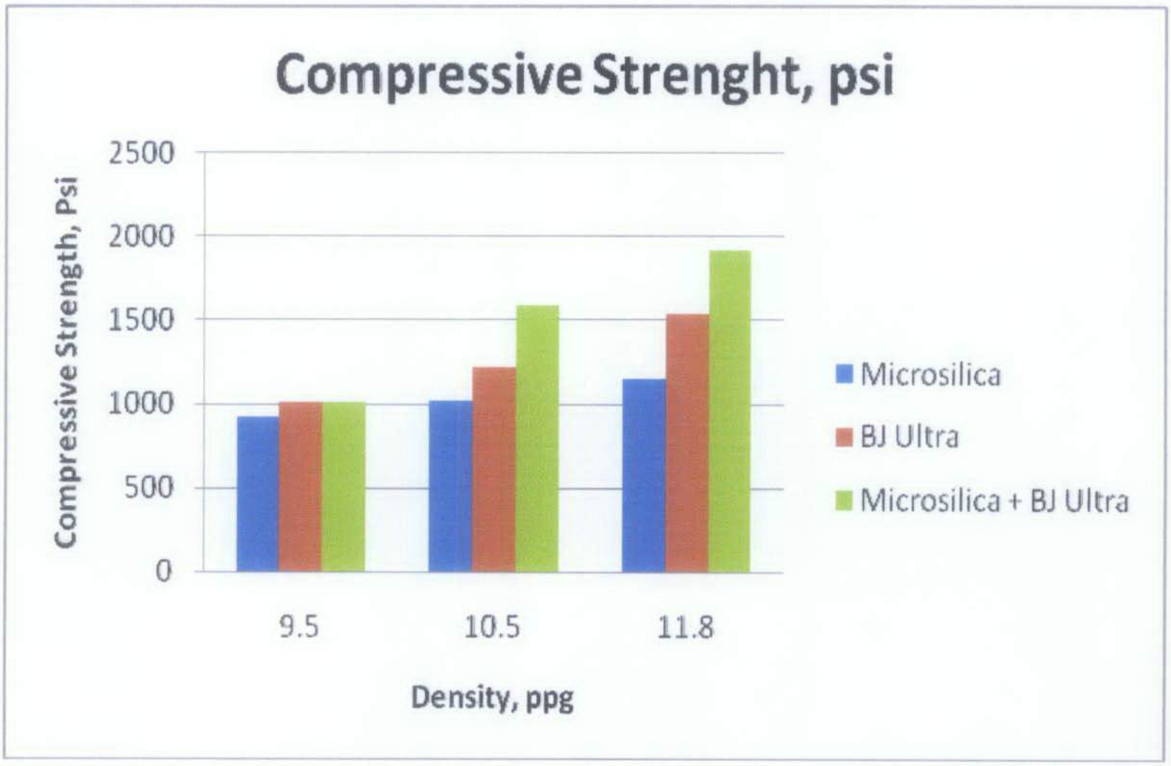


Figure 25. Effect of Additives on Compressive Strength of Foamed Cement

From Figure 25, it is observed that microsilica yields the minimum compressive strength when used alone as additive in foamed cement for all the three (3) different densities. On the other hand, BJ Ultra which is a multipurpose product but commonly used for controlling fluid loss acts more efficiently than microsilica when used as additive in foamed cement for increasing the compressive strength. It is observed that difference between compressive strength yielded by microsilica and BJ Ultra when used separately increases as the density of foamed cement is increased with BJ Ultra becoming more effective compared to the microsilica.

The maximum compressive strength is obtained when both microsilica and BJ Ultra are used together. The combination of both additives for density of 11.8 ppg gives a compressive strength of 1920 Psi which is approximately 55% more than the compressive strength given by foamed cement without additives for the same density and slightly lower than compressive strength of neat cement without additives for a density of 15.8 ppg as shown in Table 4 below:

Density, ppg		Average Compressive Strength
Neat	Foamed	
16.9		3508
15.8		1974
14.9		1246
	11.8	852
	9.5	824

Table 4. Compressive Strength of Neat Cement Slurry and Foamed Cement without Additives [J.W. Goh, July 2010]

The increase in compressive strength of foamed cement when used together with microsilica can be explained by the fact that microsilica interlinks the grains, increasing the strength of the cement, while reducing the permeability and volume.

When the foamed cement was subjected to compressive strength test it was observed that the foamed cement did not break into parts but just compressed where as a neat cement cube will shatter into brittle pieces. The foamed cement exhibits improved ductility over neat cement, therefore it allows the cement sheath to withstand higher hoop stresses from casing pressure and temperature cycling. This property of foamed cement allows for it to "give" and not cracked (as neat cement might) during expansion of well casing as shown below. Lower compressive strength might not be the concern for most job 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 formation.

4.1.2 Porosity-Permeability Test

The values of porosity and permeability are of utmost importance when dealing with cement as a high permeability value will lead to fluid intrusion from the formation during setting time and a high porosity value will crack and shatter the cement sheath during perforations. For conventional operations, the cement that are used normally have a rule of thumb to not to let permeability exceed 1mD (miliDarcy) and to keep porosity value less than 40%. Several cubes with varying densities and additive composition were prepared to be subjected to Porosity/Permeability Test to determine the effect of additives used. The results obtained from the Porosity/Permeability Test are given below in Table 5 and interpreted in Figure 26 and Figure 27.

Sample ID	Additive	Percentage, BWOC	Density, lb/gal	Foam Quality	Dia, mm	Length, mm	Weight, grams	Permeability, md	Porosity, %
A	Microsilica	35%	9.43	39.51	38.45	50.32	53.82	1.02	55.367
D	BJ Ultra	35%	9.46	39.32	37.67	48.71	47.36	1.43	40.268
G	Microsilica + BJ Ultra	35% + 35 %	9.61	38.356	38.19	48.33	52.27	0.89	27.567
B	Microsilica	35%	10.46	32.91	38.8	51.82	75.94	0.97	33.61
E	BJ Ultra	35%	10.47	32.73	38.21	50.31	59.64	1.203	27.09
H	Microsilica + BJ Ultra	35% + 35%	10.63	31.83	38.25	51.76	61.894	0.62	21.949
C	Microsilica	35%	11.75	24.65	38.05	51.17	82.02	0.42	25.06
F	BJ Ultra	35%	11.77	24.51	38.14	49.6	76.139	1.033	22.58
I	Microsilica + BJ Ultra	35%+ 35%	11.89	23.75	38.33	50.69	68.044	0.365	20.603

Table 5. Effect of Additives on Porosity and Permeability of Foamed Cement Cubes

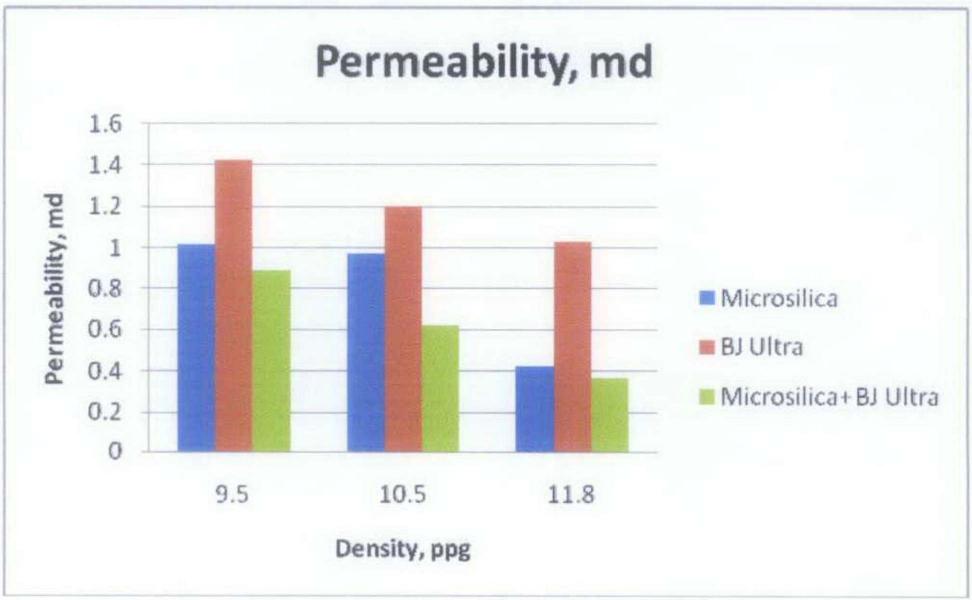


Figure 26. Decrease in Permeability of Foamed Cement Cubes with Increasing Density

From Figure 26, it is observed that permeability reduces with increasing density. This phenomenon is associated with the fact that higher densities required lesser foam quality and hence the amount of nitrogen gas inside the cube is reduced resulting into reduction of pores in cement cube.

The explanation for the sharp increase of permeability with the decrease of foamed cement density can be seen in this manner. Imagine having a 100% compacted cube of cement with zero porosity, if we are to inject only 10 bubble size pores, 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 we are to inject 10,000 bubble size pores 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 start to have a sharp increase.

Furthermore it is observed that microsilica proves to be effective in reducing the permeability of the cement cube to less than 1 md. This reduction in permeability values increases with increasing density. BJ Ultra proves to be least effective in reducing the permeability when used alone and permeability value given by it exceeds 1 md for all the densities under observation making it inappropriate to be used separately in the foamed cement. The combination of both additives i.e. Microsilica and BJ Ultra proves to be the most efficient way of reducing the permeability value giving permeability values as low as 0.365 md for a density of 11.8 ppg.

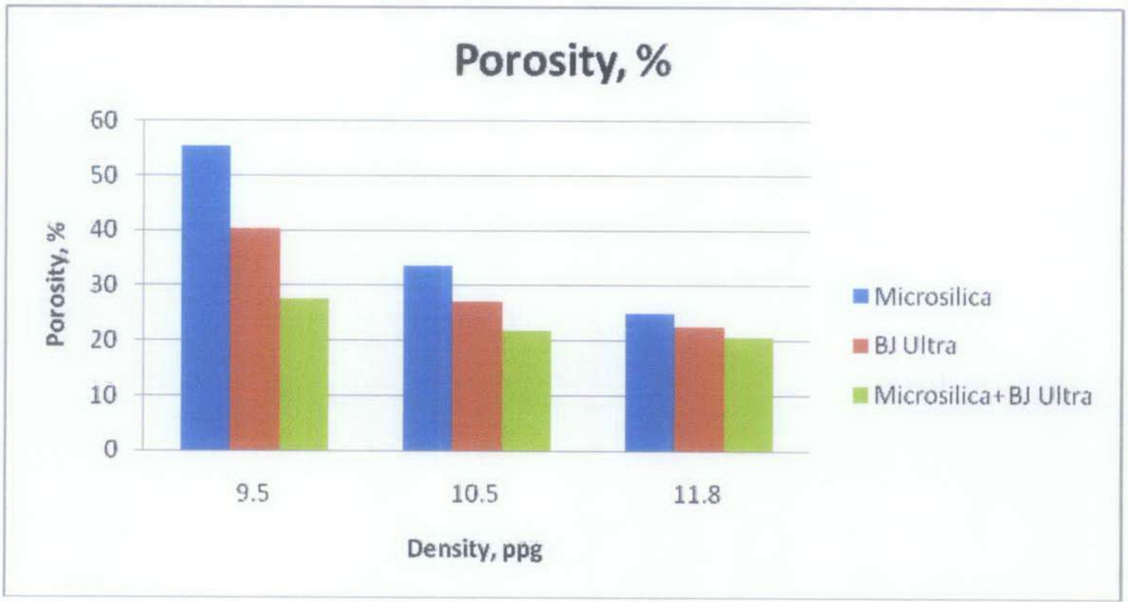


Figure 27. Decrease in Porosity of Foamed Cement Cubes with Increasing Density

Porosity is observed to increase as the foam quality introduced in neat cement slurry is increased i.e. increase in porosity value with decrease in density value. This occurrence can be explained by the fact that lower densities of foamed cement contains higher amount of nitrogen gas which results into more pores and channels being formed inside the cement cube.

In case of porosity, it is obvious that BJ Ultra gives lesser value of porosity than microsilica and as the density increases the prosity continues to decrease. Microsilica gives a relatively higher porosity value and for cement density of 9.5 ppg porosity value given by microsilica exceeds the limit of 40% making it unsuitable to be used alone.

As in the previous cases the best results are given by the combination of Microsilica + BJ Ultra which brings down porosity value to 20% at 11.8 ppg cement density

4.1.3 Fluid Loss Test

Fluid Loss can measured by using any one of the following equipment:

1. OFITE HPHT Filtration Press
2. OFITE LPLT Filtration Press

3. Stirred Fluid Loss Tester

OFITE HPHT Filtration Press was used to measure the fluid loss. OFITE HPHT Filtration press was preferred over Stirred Fluid Loss Tester due to the concern that foam bubbles may break down when stirred and hence may not give desired effect. Another reason for not using Stirred Fluid Loss Tester is that it is generally used for reservoir temperatures above 200 °F. OFITE LPLT could not be used in this case as foamed cement contained additives and hence it was necessary to subject the cement slurry to reservoir pressure and temperature to understand the efficiency of fluid loss additive. The test was performed at reservoir pressure of 750 psi and reservoir temperature of 150 °F. The results obtained from fluid loss test can be found in Appendix – II, Appendix – III and Figure 28, Figure 29 and Figure 30 illustrate the comparison of fluid loss for each of the slurry with different densities.

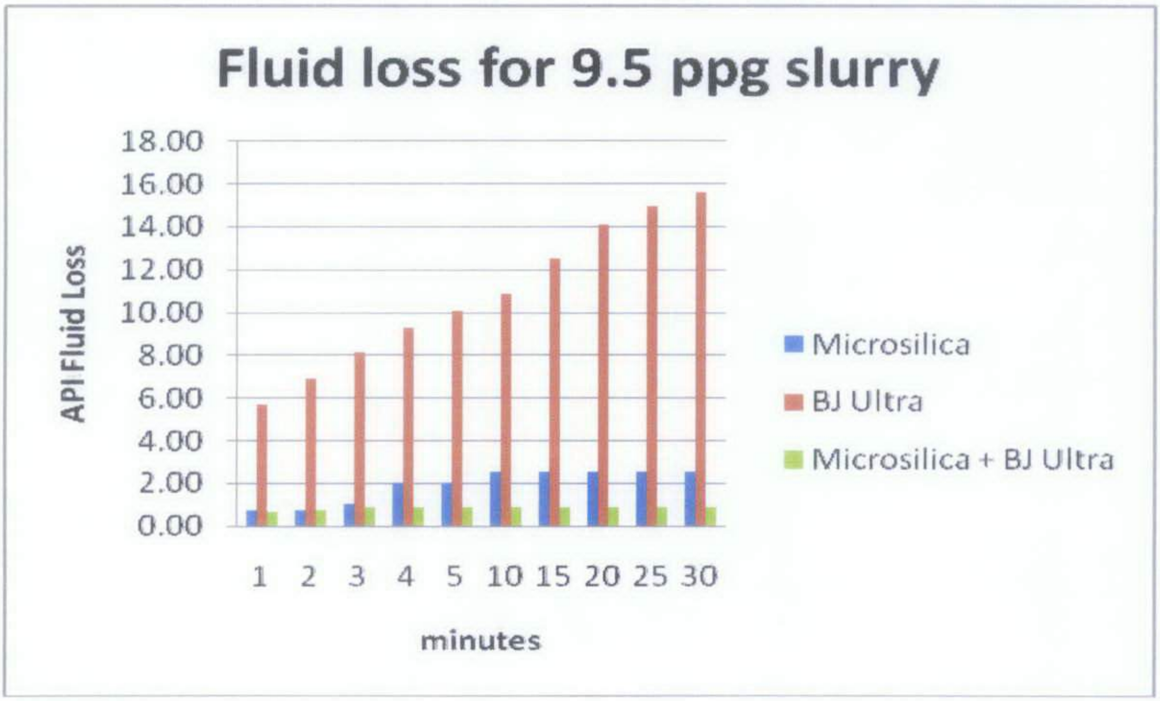


Figure 28. Fluid loss for 9.5 ppg Foamed Cement Slurry

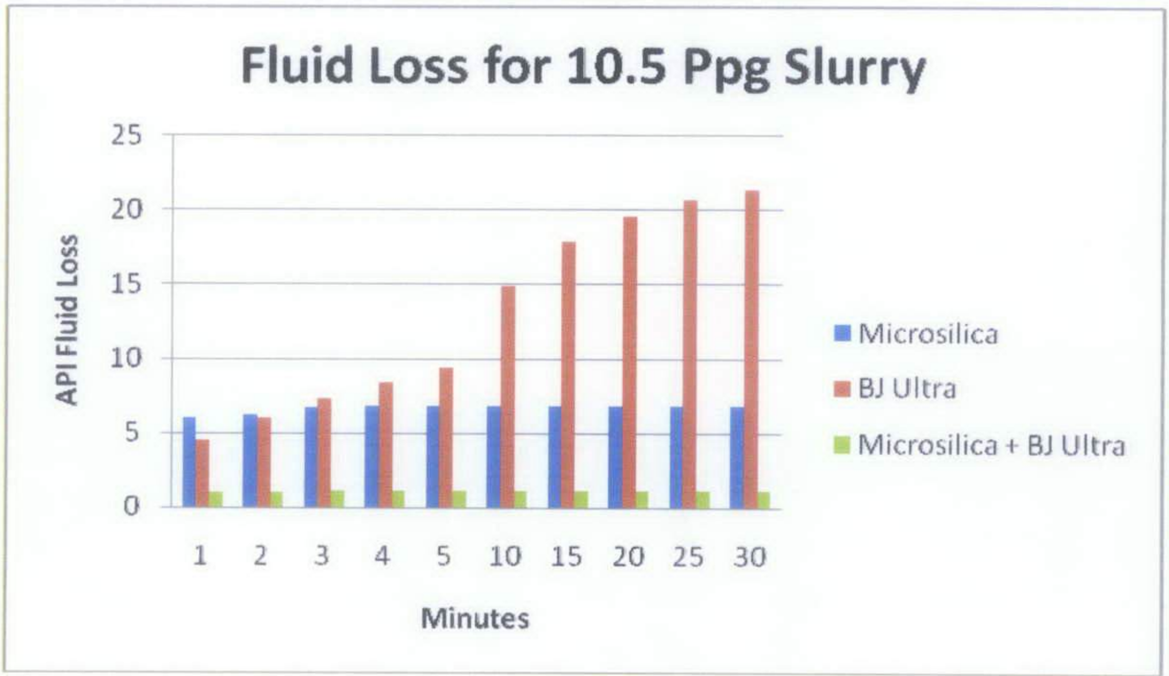


Figure 29. Fluid loss for 10.5 ppg Foamed Cement Slurry

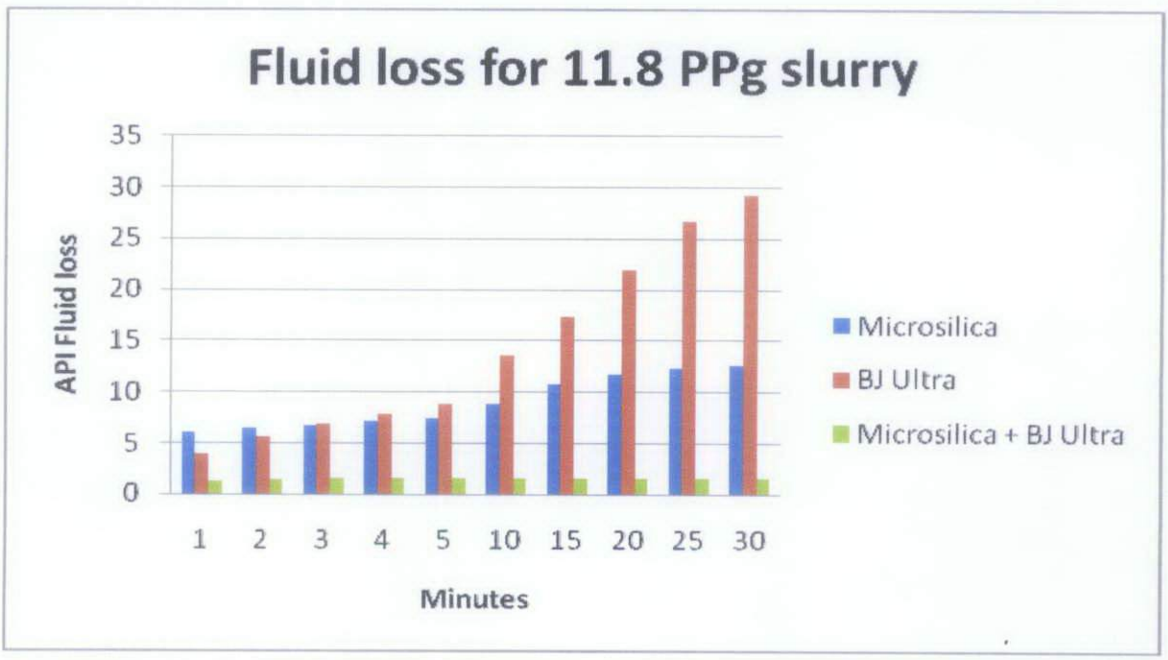


Figure 30. Fluid loss for 11.8 ppg Foamed Cement Slurry

The first observation that can be made from Figure 28, Figure 29, and Figure 30 is that fluid loss reduces with reduction in density. This behavior is opposite to neat slurry where fluid loss increases with reduction in density. This change in property of the foamed cement can be explained in terms of the foam quality in the cement slurry since in foamed cement, when the density is reduced, the foam quality (gas bubble intensity) will be increased.

In the foamed cement, the only mode of water loss would be around the bubble of gas. As the density of the foamed cement is decreased, there will be an increase towards the surface of the bubble membranes. When this happens, the distance the fluid must travel in order to leave the slurry will increase significantly, and this will lead to reduction of fluid loss. This is illustrated in the Figure 31 below:

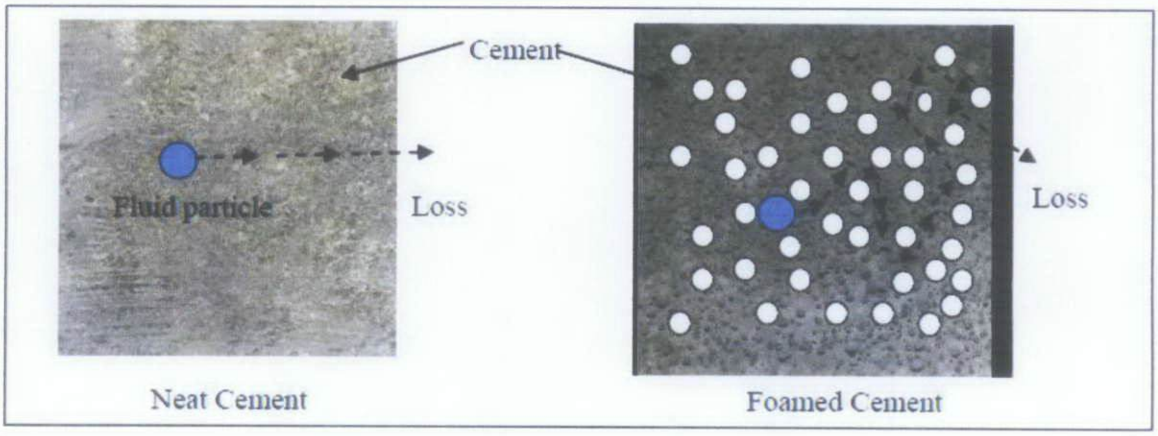


Figure 31. Travel Distance of Fluid in Neat and Foamed Cement

In Figure 31, it can be seen that significant decrease of fluid loss in the slurry is noticed as foamed quality is increased i.e an increase in gas volume. The fluid flowing through the filter is found to be thicker, with dense concentration of foaming agent and fluid loss additives. The stable two phase nature of foamed cement slurry will resist fluid loss to formation, as the reduced water loss will help protect the water sensitive zones such as shale, clay and salt formation in the wellbore.

The water loss for this experiment is thus proportional to the water used for the slurry because the cement powder itself is unable to preserve the fluid in the slurry.

Furthermore, It can be observed from Figure 28, Figure 29 and Figure 30, that BJ Ultra proves to be least effective additive when used alone to control Fluid loss. Micro microsilica gives a better fluid loss control when used alone for all the three (3) densities. Microsilica controls fluid loss several times better than BJ Ultra giving only 2.50 ml of fluid loss for cement slurry density of 9.5 ppg at the end of 30 mins test compared to BJ Ultra which gives 14.1 ml for the same density at the end of 30 mins test. In case of microsilica blow out occurs relative early in the test for almost all densities with the exception of 11.8 ppg density where blowout occurs when nearing the end of the test after which there is no more increase in the filtrate volume collected. Where as for BJ Ultra the the fluid loss continues to increase with time until 30 mins are elapsed for all the three (3) densities under discussion.

As in previous cases the best results are given by the combination of both additives i.e Microsilica + BJ Ultra which reduces the fluid loss to to less than 1ml for cement density of 9.5 ppg compared to 2.50 ppg and 14.1 ppg given by microsilica and BJ Ultra when used alone. For the microsilica + BJ Ultra blowout happens during the first 3 minutes after which there is no more increase in the filtrate collected for all the three densities under discussion.

These phenomenon can be explained by the fact that microsilica has been known to decrease fluid loss and hence it gives smaller fluid loss values. Even though BJ Ultra is a fluid loss additive but it is usually used for densities between 13.5ppg to 16.2 ppg and hence proves to be less effective when used for densities between 9.5 ppg and 11.8 ppg. The combination of microsilica and BJ Ultra gives the best fluid loss control due to the fact that normally these both additives are meant to be used together in the field for optimum fluid loss control.

4.2 Proposed Foamed Slurry Design for Mukah Coalfield

It is proposed that both additives i.e. microsilica and BJ Ultra should be used collectively to obtain the best results. Summary of reservoir properties of Mukah coalfield and results of the experiments are given below in Table 6

Slurry Properties	Design Concept	Conductor and Surface Casing	Intermediate Casing	Production Casing
Density	Min Requirement	Drilling fluid density +0.5 ppg, lesser than ECD to formation fracture		
	Proposed Lead	9.5 ppg	9.5 ppg	10.5 ppg
	Proposed Tail	10.5 ppg	10.5 ppg	11.8 ppg
Fluid Loss	Min Requirement	NA	$\leq$ 200 cc/ 30mins	$\leq$ 100cc / 30mins
	Proposed	5.37 - 6.95 cc /30mins	5.37 - 6.95 cc /30mins	6.95 - 9.486 cc / 30 mins
Rheology	Plastic Viscosity	$\leq$ 150	$\leq$ 150	$\leq$ 100
	Yield Point	$\leq$ 50	$\leq$ 40	$\leq$ 25
Compressive Strength	Min Requirement	Minimum of 500 psi after 24 hours of setting time		
	Proposed	1011 - 1592 psi	1011 - 1592 psi	1600 - 1920 psi
Porosity	Min Requirement	$\leq$ 0.40	$\leq$ 0.40	$\leq$ 0.40
	Proposed	0.21 - 0.27	0.21 - 0.27	0.20 - 0.22
Permeability	Min Requirement	Permeability lower than 3-5 mD to prevent fluid intrusion to contact casing		
	Proposed	0.62 - 0.89 mD	0.62 - 0.89 mD	0.36- 0.62 mD

Table 6. Proposed Foamed Slurry Design for Mukah Coal Bed

It is proposed that both additives i.e. microsilica and BJ Ultra should be used collectively to obtain the best results. The minimum requirement for the design is based on the general requirement for field cementing jobs previously stated in literature review. The different type of casing basically indicates different depth level for below 500m TVD. However this is just a basic overview of cementing design without considering the detailed job design (exact well trajectory and expected production rate).

4.3 Advantages of Foamed Cement Properties on Coalbed

i. Low Fluid Loss

The 2 phase slurry of foamed slurry has decreasing fluid loss with increase of foam quality. This would be compatible for Sub-bituminous coal that is hydrophilic which is reactive to water and slough and protects water sensitive zones such as clays, shale and salt. This will prevent error in TOC calculation as well, as water loss from the slurry will be minimum as a result of use of microsilica and BJ Ultra additives.

ii. Low Density

The low density of wet and dry foam cement has lower density which is beneficial in formation with low fracture gradient such as coal bed and zones facing lost circulation zones. Density reduction additives will not be required if the cementing process involves full foamed cementing job.

iii. Alteration of cement density in a single pump

The foamed cement density to be pumped into the wellbore can be adjusted with the variation of foam introduced to the base slurry. Unlike for neat cement, where for different densities for tail and lead slurry, 2 different pumping units are required in a 2 stages pump. There are basically 2 types of pumping method for foamed cement:

a. Constant Foam Density Method

N_2 injection rate varies to ensure that the slurry density is uniform from the top to the bottom. Rate is initially low and increase as job progress. In order to have a constant density for the whole annular column, pump in N_2 for tail slurry has to be higher, as the cement pressure in lower section will be higher. Higher cement pressure will compress the gas in the slurry, and increase the compaction of slurry of cement. The advantage is an equally competent is placed over the entire cemented interval, but it involves very complicated operation procedure.

b. Constant Nitrogen (N_2) Rate Method

The slurry pumped in constant N_2 rate from surface and the slurry will be denser at the bottom than top when it reaches the annular cemented section. This method is generally easier to perform and design on the surface and the denser cement at bottom yields better compressive strength development so that the shoe joint can be drilled out sooner.

iv. Reduction of cement volume required

Utilizing foamed cement which is light weight indicates reduction of the need of costly light weight additives to be added into the slurry consideration. Foamed cement costs approximately 1/3 less than other non-foamed, premium light weight cement slurry system on a cost per cubic foot basis. Besides, the yield volume for foamed cement is approximately 3-5 times higher than neat cement given the same volume of cement powder. This reduces the volume of the Class G cement powder and, indirectly, the logistic requirement and transportation cost. In addition to that, the useful life of a foamed cement sheath to provide zonal isolation can last up to hundreds of stress-relaxation cycles compared to conventional cement, which crack in two to ten stress relaxation cycles due to its ductile properties.

v. High strength to density ratio

As from the experiment above, foamed cement with additives will have lesser content of cement powder percentage for the same volume when compared to neat cement. The maximum compressive strength is obtained when both additives microsilica and BJ Ultra are used together. The combination of both additives for Density of 11.8ppg (Foam Quality of 23.75) gives a compressive strength of 1922 Psi which is approximately 55%

more than the compressive strength given by foamed cement without additives (852) for the same density and slightly lower than compressive strength of neat cement without additives for a density of 15.8 ppg (1974 Psi). Therefore, even at lower cement powder percentage, the strength would still be higher than neat cement at the same density.

CONCLUSIONS & RECOMMENDATIONS

5.1 CONCLUSION

After thorough experimentation and research it can be concluded that:

1. In order to optimize the cement properties i.e. maximize compressive strength, reduce fluid loss and reduce permeability and porosity, it is best to use microsilica and BJ Ultra together for the use in field. For all the experiments performed the most desirable results were obtained when both of these additives were used in combination. Although for some experiments when these additives were used separately they gave values exceeding the minimum requirements but they failed to give the satisfactory values for other tests. For example BJ Ultra gave better compressive strength and lesser porosity values than microsilica when used alone but for permeability and fluid loss control microsilica gave better performance than BJ Ultra when used alone. Hence, it is concluded that in order to optimize all the essential properties both of these additives should be used together.

2. Foamed cement when used with both additives together i.e microsilica and BJ Ultra with density of 9.5 ppg to 12 ppg gave sufficient strength to hold the casing, very low fluid loss and satisfactory permeability and porosity.

3. Foamed Cement's lightweight 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 which is cost effective (70-80% of conventional cementing cost). Foam in slurry together with additives provides density control and fluid loss control, minimizing damage without exceeding fracture gradient of weak coal formation.

4. The proposed cement design for Mukah coalfield should have density in the range of 8.5 to 12.5 ppg, compressive strength above 500 psi after 24 hours of curing, porosity below 40%, permeability lesser than 3-5mD, and fluid loss lesser than

100cc/30mins. The thickening time shall be based on the depth of the well, with a safety factor of 30-60 minutes.

5.2 Recommendations

The Arthur wishes to make the following recommendations:

1. Further research shall be carried on the feasibility of use of foamed cement with/without additives for HPHT wells.

2. Inert Nitrogen gas (N2) should be used in the generation of foamed cement instead of air in order to enhance the fluid loss characteristics and compressive strength.

3. Silica shall be used as an additive to examine its effect on cement properties and results shall be compared with the results obtained by the use of microsilica.

4. Foaming stabilizers (surfactant) to be used when creating the bubble to increase the half-life of the foam. Without stabilizer, the half-life is approximately 6 minutes, where it may not be sufficient if the laboratories are far apart. As the base slurry needs to be either cured or tested after 5 minutes of mixing in the constant speed mixer.

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APPENDICES

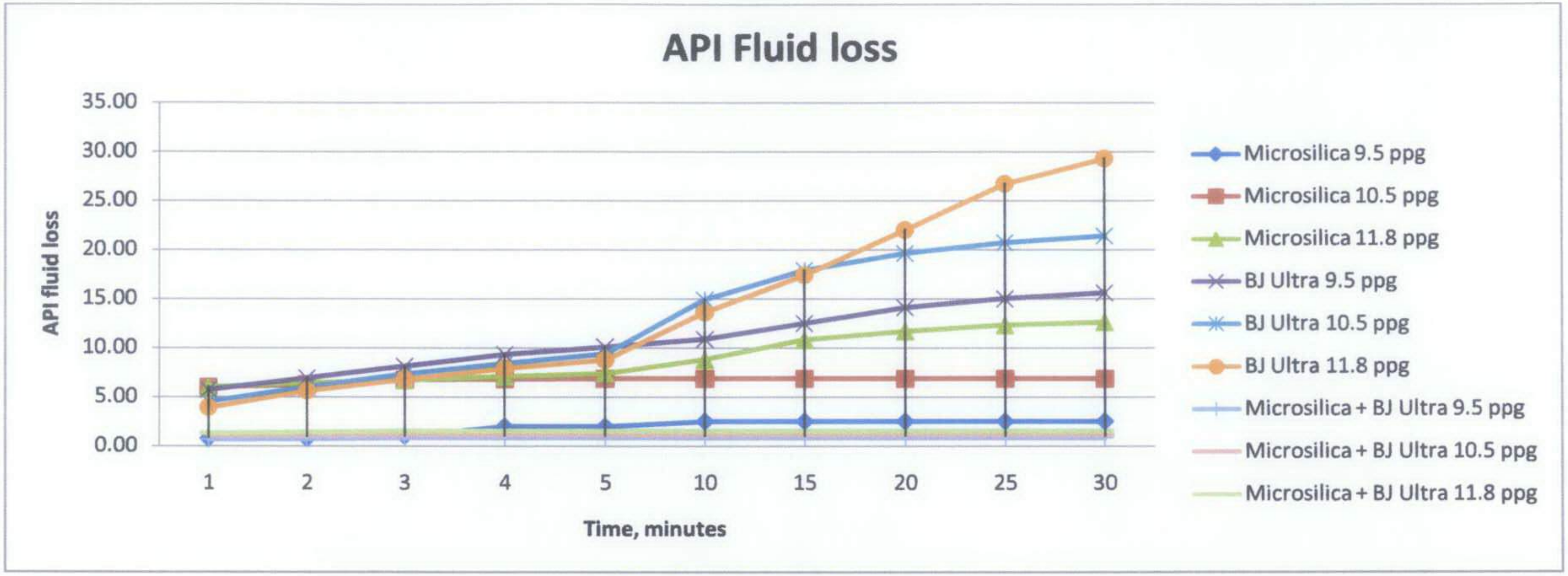
Sample	Additive	Percentage, BWOC	Foam Quality	Density, ppg
S.1.1	Microsilica	35%	39.515	9.43
S.1.2	Microsilica	35%	39.515	9.25
S.1.3	Microsilica	35%	39.515	9.61
S.1.4	Microsilica	35%	39.515	9.52
S.1.5	Microsilica	35%	39.515	9.56
S.1.6	Microsilica	35%	39.515	9.59
BJ.1.1	Bj Ultra	35%	39.322	9.46
BJ.1.2	Bj Ultra	35%	39.322	9.73
BJ.1.3	Bj Ultra	35%	39.322	9.35
BJ.1.4	Bj Ultra	35%	39.322	9.37
BJ.1.5	Bj Ultra	35%	39.322	9.54
BJ.1.6	Bj Ultra	35%	39.322	9.62
BJ.S1.1	Microsilica + BJ Ultra	35% + 35 %	38.356	9.61
BJ.S1.2	Microsilica + BJ Ultra	35% + 35 %	38.356	9.22
BJ.S1.3	Microsilica + BJ Ultra	35% + 35 %	38.356	9.73
BJ.S1.4	Microsilica + BJ Ultra	35% + 35 %	38.356	9.65
BJ.S1.5	Microsilica + BJ Ultra	35% + 35 %	38.356	9.46
BJ.S1.6	Microsilica + BJ Ultra	35% + 35 %	38.356	9.62
S.2.1	Microsilica	35%	32.91033	10.46
S.2.2	Microsilica	35%	32.91033	10.42
S.2.3	Microsilica	35%	32.91033	10.51
S.2.4	Microsilica	35%	32.91033	10.54
S.2.5	Microsilica	35%	32.91033	10.6
S.2.6	Microsilica	35%	32.91033	10.31
BJ.2.1	Bj Ultra	35%	32.73	10.49
BJ.2.2	Bj Ultra	35%	32.73	10.5
BJ.2.3	Bj Ultra	35%	32.73	10.47
BJ.2.4	Bj Ultra	35%	32.73	10.51
BJ.2.5	Bj Ultra	35%	32.73	10.49
BJ.2.6	Bj Ultra	35%	32.73	10.55
BJ.S 2.1	Microsilica + BJ Ultra	35% + 35%	31.83	10.63
BJ.S 2.2	Microsilica + BJ Ultra	35% + 35%	31.83	10.53
BJ.S 2.3	Microsilica + BJ Ultra	35% + 35%	31.83	10.64
BJ.S 2.5	Microsilica + BJ Ultra	35% + 35%	31.83	10.51
BJ.S 2.6	Microsilica + BJ Ultra	35% + 35%	31.83	10.58

S.3.1	Microsilica	35%	24.65	11.75
S.3.2	Microsilica	35%	24.65	11.81
S.3.3	Microsilica	35%	24.65	11.77
S.3.4	Microsilica	35%	24.65	11.77
S.3.5	Microsilica	35%	24.65	11.79
S.3.6	Microsilica	35%	24.65	11.85
BJ.3.1	Bj Ultra	35%	24.506	11.77
BJ.3.2	Bj Ultra	35%	24.506	11.69
BJ.3.3	Bj Ultra	35%	24.506	11.8
BJ.3.4	Bj Ultra	35%	24.506	11.73
BJ.3.5	Bj Ultra	35%	24.506	11.72
BJ.3.6	Bj Ultra	35%	24.506	11.75
BJ.S3.1	Microsilica + BJ Ultra	35%+ 35%	23.75	11.89
BJ.S3.2	Microsilica + BJ Ultra	35%+ 35%	23.75	11.91
BJ.S3.3	Microsilica + BJ Ultra	35%+ 35%	23.75	11.97
BJ.S3.4	Microsilica + BJ Ultra	35%+ 35%	23.75	11.81
BJ.S3.5	Microsilica + BJ Ultra	35%+ 35%	23.75	11.88
BJ.S3.6	Microsilica + BJ Ultra	35%+ 35%	23.75	11.84

Appendix - I Foamed Cement with Additives Cubes Produced for Experimentation

				Minutes	1	2	3	4	5	10	15	20	25	30
Sample ID	Additive	Percentage, BWOC	Density (lb/gal)	Foam Quality	Vol, cc	Vol, cc	Vol, cc	Vol, cc	Vol, cc	Vol, cc	Vol, cc	Vol, cc	Vol, cc	Vol, cc
S.1	Microsilica	35%	9.43	39.51	0.75	0.75	1.00	2.00	2.00	2.50	2.50	2.50	2.50	2.50
BJ1	BJ Ultra	35%	9.46	39.32	5.7	6.9	8.1	9.3	10.1	10.9	12.5	14.1	15	15.6
BJ.S1	Microsilica + BJ Ultra	35% + 35 %	9.61	38.36	0.65	0.75	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
S.2	Microsilica	35%	10.46	32.91	6	6.25	6.75	6.80	6.85	6.85	6.85	6.85	6.85	6.85
BJ 2	BJ Ultra	35%	10.47	32.73	4.50	6.00	7.30	8.40	9.40	14.90	17.90	19.60	20.70	21.40
BJ.S 2	Microsilica + BJ Ultra	35% + 35%	10.63	31.83	1.00	1.05	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
S.3	Microsilicailica	35%	11.75	24.65	6	6.40	6.70	7.10	7.40	8.80	10.80	11.70	12.30	12.60
BJ 3	BJ Ultra	35%	11.77	24.51	3.90	5.60	6.80	7.90	8.80	13.60	17.40	22.00	26.70	29.30
BJ.S 3	Microsilica + BJ Ultra	35%+ 35%	11.89	23.75	1.30	1.40	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50

Appendix - II Fluid Loss Test Results



Appendix - III API Fluid Loss

CEMENT CALCULATION TEST NO.: 8973

COMPANY:	PCSB	DATE:	18-Mar-11	
WELL NAME:	SE-PIATU-1	TVD:	2171.0 m	7123.1 ft
JOB TYPE:	7" LINER	MD:	2171.0 m	7123.1 ft
MUD WEIGHT:	10.00 PPG	BHST:	158.0 F	70.0 C
SLURRY TYPE:	SINGLE	BHCT:	139.0 F	59.4 C
		TEMP. GRAD:	1.10 F/100 ft	
		ROOM TEMP:	80.0 F	

SLURRY DENSITY:	15.80 PPG	**LAB MIX**
MIXWATER DENSITY:	8.55 PPG	600 **ML**
WATER DENSITY:	8.34 PPG	

MATERIALS	**% OF MAT. OR GPS**	**S.G**	**WT. OF MAT. (LBS)**	**ABS. VOL. (GAL)**	**WEIGHT (GM)**	**VOLUME (CC)**	**BATCH NO.**
CEMENT 'G'	100.00	3.20	94	3.522	580.76	184.79	784.02 This weight to be used if you use blended cement
OPC		3.10					
W-5 (HEMATITE)		5.02					
SB-100 (%)		2.93					
LW-7 (%BWOC)		0.38					
S-8 (%BWOC)	35.00	2.65	32.900	1.489	203.27	76.70	04/10/07
BARITE (%BWOC)		4.23					
FP-9LS		0.90					230908
A-300L		1.22					17/10/2001
A-3L		1.40					070512
A-7 (CaCl2)		1.96					
BJ ULTRA / BJ-XL	0.35	1.15	3.357	0.350	20.74	18.03	220908 / 311208
R-8L		1.26					230708
BA-58L		1.36					30304 2
R-21LS		1.08					041103
LSR-1(%BWOC)		1.25					
LSR-1(GHS)		1.25					03/02/00
CD-33L		1.18					301208A
BJ-2000		1.16					27/08/03
BA-100LS		1.10					09/04/03
BJ ULTRAMAX		1.15					160209
T-40L		1.24					200701A
FL-66L		1.06					060308
FA-12L (% v/v)		1.02					03/02/00
GEL		2.65					
W-10 (BWOC)		4.80					200307
FLAG-56		1.32					
BA-86L		1.02					03/02/00
FA-12L (% v/v)							
					352.67	341.81	
			130.257	5.361			
MIXWATER		1.03	53.725	6.284	331.93	323.77	
			183.982	11.644			

TOTAL FLUID :	**6.634 GAL/SK**	**DISP.TIME:**	**29 MIN**
YIELD :	**1.557 CUFT/SK**	**H/RATE :**	**2.05 F/MIN**
MIXWATER :	**6.284 GAL/SK**		
		PRESS :	**660 INITIAL**
		(PSI)	**4364 FINAL**

Appendix - IV Base Slurry and additive Calculations

Wet Density of Foamed Cement 35% BJ ULTRA and 35% silica

Insert Cement mass :	**573.91**	g
Insert Cement density :	3.2	g/cm3
Volume of Cement :	179.346875	cm3
Insert Water mass :	**327.03**	g
Insert Water density :	1	g/ml
Volume of Water:	327.03	ml
Insert Silica Mass	**200.87**	g
Insert microsilica density :	2.65	g/cm3
volume of silica	75.8	cm3
Insert bjultra Mass	**20.49**	g
Insert bj Ultra density :	1.15	g/ml
volume of bjultra	17.8173913	ml
Density of foam agent :	0.08	g/ml
Foam Expansion Rate / Factor:	15	
Mass of foam :	32.441376	g
Volume of Foam agent	0.87203	ml
Volume of Premix foam :	27.03448	ml
Volume of Stable Foam :	405.5172	
Volume of Mix Foam :	405.5172	cm3
Total volume of foamed cement:		979.349
Total mass of foamed cement :		1128.58
Wet density of foamed slurry :		1.15238

(0.04 if for synthetic foam)
(range 12-15 for protein foam)

(before generated)

(after generated)

cm3
g
g/cm3

	Cement	bjultra	Water
Foamed Cement	2	5% of cement	1

for mixing	For agent	Additive
500.8676	26.1624	20.49
1	1	1.15
500.8676	26.1624	17.8173913

(Dry density to be lower)	9.61735 **lb/gal**	
Density range:	4 to 12	lb/gal
Foam Quality	38.3502	
Optimum foam Quality	18-38%	

W:C	
Base Slurry	15.6 ppg
Foam Quality	
BJ ULTRA	35%
silica	35%

Appendix – V Foam Calculations

Reservoir Parameters	
Coal Rank	Sub-bituminous B coal
Crucible Swelling Index	Samples coal did not show any swelling properties
Sulphur content	Low, 0.24% to 2.65% for drill core samples
Likely min UCS	5390 psi
Calorific Value	22.21 MJ/kg (9547Btu/lb)
Maximum Depth	500m (1640ft)
Maximum Pressure at 500m	740 - 940 psia
Estimated Temperature at 500m	150°F (66°C)
Specific Gravity of coal	1.3 (0.563psi/ft)
Assumed Pore Pressure	0.45 psi/ft
Average Fracture Gradient	0.66 - 0.69 psi/ft
Lithologies Present	Clean lustrous coal, shaly coal, coaly shale, and shale/siltstone/sandstone.
**Porosity Range, fraction	0.0158 – 0.0512
**Permeability Range , mD	0.15 – 46.15

*Reservoir Parameters extracted from [14. Sia *et al*, 1995]

** Permeability and Porosity value from laboratory test on coal samples from Mukah.

Appendix – VI Mukah Coalfield's Properties