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A Comparative Study of the Rheological Properties of Class G Cement Sheath in Niger Delta

J.O Etoh, A. Dosunmu
(Department of Petroleum Engineering - African Centre of Excellence for Oilfield Chemicals Research, University of Port-Harcourt, Nigeria)

ABSTRACT: *Cement sheath is considered a Well barrier because it prevents the unintentional and uncontrollable flow of fluids (either fluids or gases) from a formation into another formation or back to the surface. A lot of research has been conducted with regards to the mechanical durability of the wellbore cement sheath. These researches are classified into two major groups:*

a. Experimental lab techniques
b. Modelling methods (Finite element analysis)

Several factors affect the mechanical integrity of the cement sheath, of these, water/cement ratio is a crucial one which influence the concrete workability. Generally, a water cement ratio of 0.45 to 0.6 is used for good workable concrete without the need of an admixture. A higher water/cement ratio yields a higher water content per volume of concrete hence it will be more workable and easily placed in the well.

This paper describes an experiment in which the rheological properties of Class G cement were analyzed for its performance and workability. Three tail cement systems with varying water-to-cement commonly used in Niger-delta formations were investigated.

KEYWORDS - *Well integrity, Cement Sheath, Workability*

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I. Introduction

Borehole stability became of increasing concern in the early 1980s as the continuous evolvement of long, highly inclined wells was underway to drain larger reservoirs from single offshore platforms. This introduces a basic need for "Well integrity" such that these drilled complex wells achieve and serve its purpose throughout its active (*Drilling, Production and Intervention*) and inactive (*Abandonment*) lifecycle.

NORSOK D-010 defines Well Integrity as "Application of technical, operational and organizational solutions to reduce the risk of uncontrolled release of formation fluids throughout the life cycle of the well". The principle of well integrity is based upon maintaining well control with sufficient barriers. It is therefore necessary that the well barriers put in place are deemed effective and should be always assessed. These well barriers ensure that the well operates optimally throughout its lifecycle with the identified risks being kept as low as reasonably practicable "ALARP".

Table 1: General Principles of Well Barriers, Mahmoud Khalifeh (2020)

S/N	PHASE	PRIMARY BARRIER	SECONDARY BARRIER
1	Drilling	Overbalanced mud with filter cake	Casing cement, casing, wellhead and BOP
2	Production	Casing cement, casing, packer, tubing and Downhole Safety Valve	Casing cement, casing, wellhead, tubing hanger and Christmas tree
3	Intervention	Casing cement, casing, deep-set plug and overbalanced mud	Casing cement, casing, wellhead and BOP
4	Plug & Abandonment	Casing cement, casing and cement plug	Casing cement, casing, and cement plug

From TABLE 1, it is observed that in all four phases of the well, the Casing-Annulus-Cement system serves as both primary and secondary barriers. This highlights how the barriers affects the technical integrity and operability of a well, and as the petroleum industry enters more complex and demanding environments, it is crucial that the barriers serve their purpose throughout the entire lifecycle of the well.

1.1 Cement sheath as a well barrier

In order to prepare a well for further procedures such as drilling, production or abandonment, cement slurry is pumped down the wellbore, through the casing and into the annulus between casing and formation wall or previous set casing. When the cement slurry hardens and sets, it creates a seal such that it isolates the well flow from unwanted formation fluids while permanently positioning the casing in place. The cement sheath is a crucial element in sustaining well integrity.

The cement failure is usually due to the stress on the cement sheath being greater than its yield strength**.** These are various mechanical factors that control the failure of the cement sheath in this system:

- Cement compressive strength
- Young's modulus
- Tensile strength
- Bond strength
- Loading conditions (in-situ stresses)
- Cement history (shrinkage)
- Wellbore architecture: cement sheath eccentricity and diameter, formation properties, wellbore trajectory

The failure of the cement sheath can either be due to shear and compressional stresses. These stress conditions can be due to radial loads, high pressures within the cement sheath and tectonic movement of the formation.When the stress conditions above are present in the wellbore, the set cement can fail either by:

- Radial circumferential cracking of the cement matrix
- Breakdown of bonds in the Casing-Cement Sheath-Formation system

Ghazbeloo et al. 2008 [1] performed lab test on a Class G cement under temperature and pressure. He observed creep effect under isotropic loading at high stresses and permanent strains on the cement during unloading, due to the heterogeneity of the cement. This is characteristic of cement micro cracking. Bois et al. 2012 [2] conducted and experiment to check when the cement-sheath integrity loss occurred. He observed that at the maximum ICP, no integrity loss but upon decrease of ICP loss of integrity occurred

Kiu Liu et al, 2018 [3] analyze the stress of cement sheath in horizontal shale gas wells by considering the location of the casing in the wells. He observed that for centered casing the tensile failure of the cement sheath occurred first at the inner wall of the cement sheath and for off-centered casing, the failure of the cement sheath was at a much lower external load. J. De Andrade et al, 2015 [4] assessed the mechanisms by which the cement sheath fails for realistic wellbore curing and operating conditions. He observed that cement hydraulic pressure provided a superior cement job than for previous cemented samples with no hydraulic pressure.

The purpose of primary cementing, when an annular cement sheath is placed around a casing or liner, is to provide mechanical stability to the well and to prevent fluids from flowing from one geological zone to another or up to the surface (zonal isolation). This zonal isolation, which is important with respect to well integrity, should last throughout the well's life cycle including the abandonment phase. The long-term sealing ability of annular cement is, however, difficult to maintain – and this is one of the reasons for why many wells develop annular pressure problems as they age. Goodwin and Crook, 1992 [5], conducted an experimental work to study the effect of pressure tests and high flowing temperature on cement sheath failure. The development of radial cracks as failure mode was part of their main observations.

It is vital that that set cement material behavior and the coupled behavior of casing, cement and formation should be more fully studied and analyzed. This is because there is increasing awareness of problems associated with cement sheath failure and subsequent loss of zonal isolation or sustained casing pressure have demanded that rational engineering decisions be made.

II. Equipment and processes

The cement compositions used for this study was obtained from an operational service company in the Niger Delta. The cement slurry used for production section of the well had their water cement ratio varied, and then rheology and mechanical properties investigated in a fluids lab.

Table 2: Cement slurry composition

Cement System	System 1	System 2	System 3
Density (ppg)	14.19	14.89	15.75
Water-cement ratio	0.6	0.5	0.4
Cement Type	Class G	Class G	Class G
Seawater %bwoc	0.4	0.4	0.4
Antifoam %bwoc	0.0044	0.0044	0.0044
Gasblok %bwoc	0.04	0.04	0.04
Dispersant %bwoc	0.01	0.01	0.01
Retarder %bwoc	0.18	0.18	0.18

The tests carried out on the cement systems include standard cement tests to investigate the workability of the cement, the following tests were carried out:

- Cement slurry density – measured with a pressurized mud balance

- Compressive strength – measured with an Ultrasonic Cement Analyser
- API rheology (Yield point/Plastic viscosity) – measured with a Fann Viscometer
- Free fluid tests
- Thickening time
- API static gel strength
- Shrinkage test

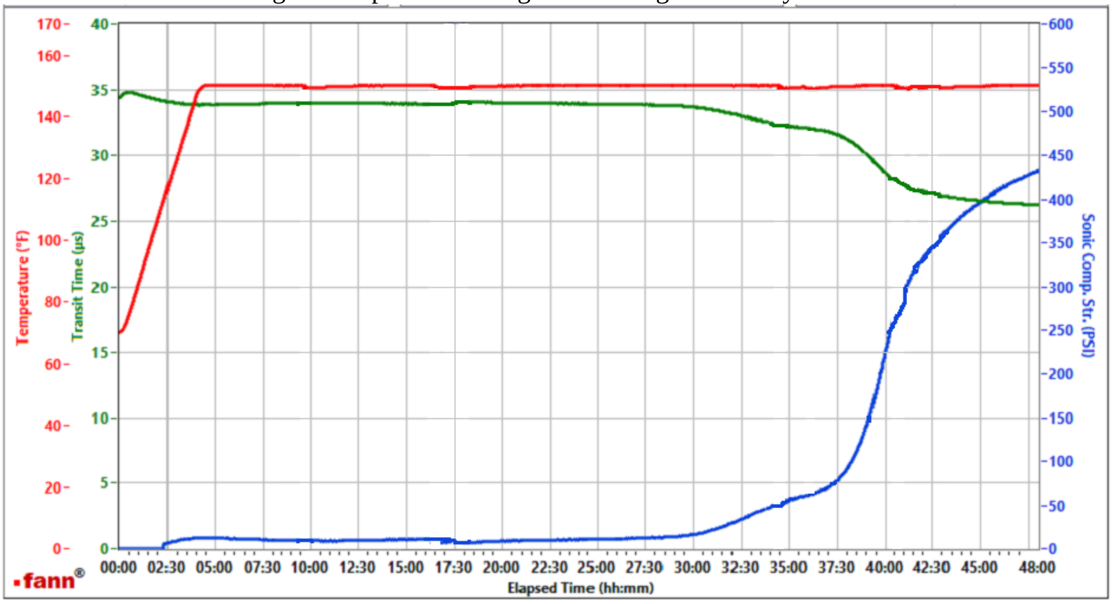
2.1 Slurry with water/cement ratio of 0.6

- Cement Slurry Density – 14.19 ppg
- UCA Compressive strength: At a temperature of 150°F and a pressure of 3000 psi (wellbore conditions

Table 3: Table of compressive strength at different curing time for system 1

Time (hr)	8	12	16	24	48
CS (psi)	7	9	11	11	432

Fig 3: Compressive strength vs. Curing time for System 1



- API rheology (Yield point/Plastic viscosity)

Table 4: Table of Yield point and Plastic viscosity for System

	Ramp	600rpm	300rpm	200rpm	100rpm	6rpm	3rpm	PV	YP
Surface @80 °F	Up		12	10	6	4	4	9	3
	Down	22		10	6	4	4		
Downhole @ 150 °F	Up		10	8	6	4	4	6	4
	Down	14		8	6	4	4		

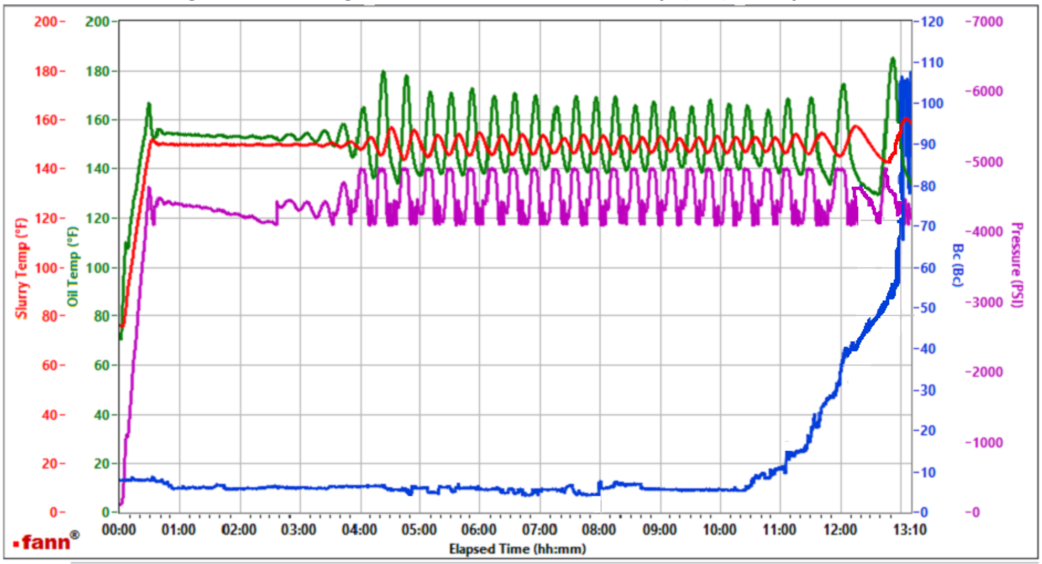
- Free fluid test: There was no free fluid observed

- Thickening time: At a pressure of 4500psi, temperature of 150°F and heating time of 28 mins

Table 5: Table of thickening time at surface and downhole conditions for System 1

TIME	11h:55m	12h:04m	12h:20m	13h:01m	13h:05m
BC	30	40	50	70	100

Fig 4: Thickening time vs. Bearden consistency (BC) for System 1



- API static gel strength

Table 6: Table of gel strengths for System 1

10 sec gel strength	4
10 mins gel strength	4

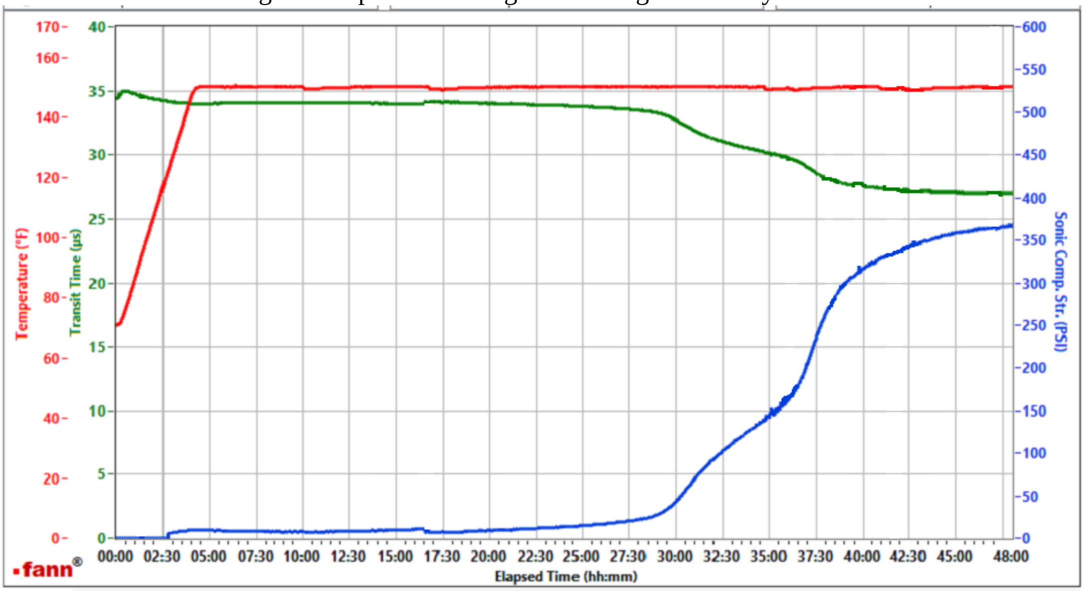
2.2 Slurry with water/cement ratio of 0.5

- Cement Slurry Density – **14.89 ppg**
- UCA Compressive strength: At a temperature of 150°F and a pressure of 3000 psi

Table 7: Table of compressive strength at different curing time for System 2

Time (hr)	8	12	16	24	48
CS (psi)	8	8	10	13	367

Fig 5: Compressive strength vs Curing time for System 2



- API rheology (Yield point/Plastic viscosity)

Table 8: Table of Yield point and Plastic viscosity at surface and down-hole conditions for System 2

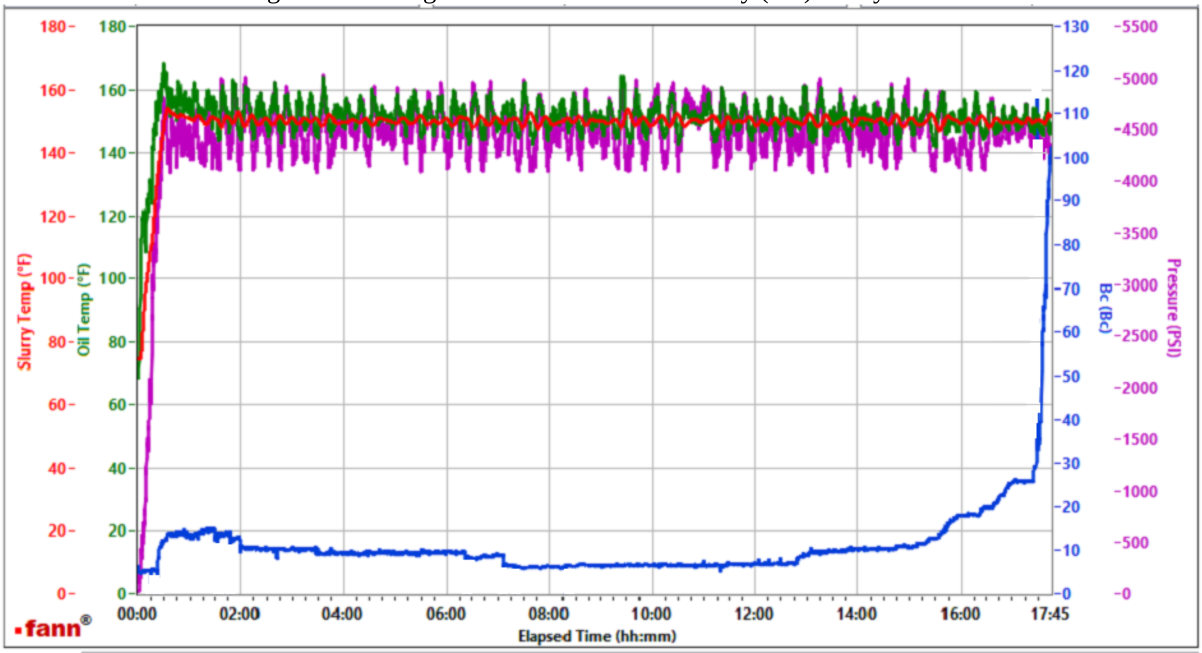
	Ramp	600rpm	300rpm	200rpm	100rpm	6rpm	3rpm	PV	YP
Surface @80 ^{o}F	Up		20	12	6	4	2	19.5	0.5
	Down	32		12	8	4	2		
Downhole @ 150 ^{o}F	Up		8	6	4	2	2	6	2
	Down	20		6	4	2	2		

- Free fluid test: There was no free fluid observed
- Thickening time: At a pressure of 4500psi, temperature of 150^{o}F and heating time of 28 mins

Table 9: Table of thickening time at surface and downhole conditions for System 2

TIME	17h:27m	17h:32m	17h:33m	17h:38m	17h:43m
BC	30	40	50	70	100

Fig 6: Thickening time vs. Bearden consistency (BC) for System 2



- **API static gel strength**

Table 10: Table of gel strengths for System 2

10 sec gel strength	4
10 mins gel strength	12

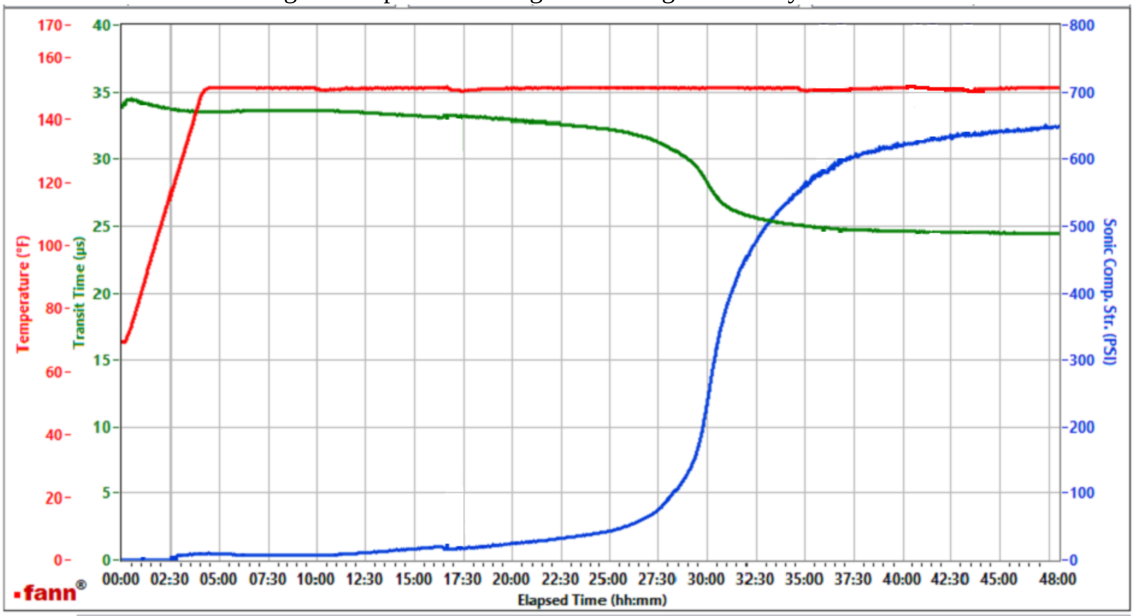
2.3 Slurry with water/cement ratio of 0.4

- Cement Slurry Density – **15.75 ppg**
- UCA Compressive strength: At a temperature of 150^{o}F and a pressure of 3000 psi

Table 11: Table of compressive strength at different curing time for system 3

Time (hr)	8	12	16	24	48
CS (psi)	7	10	19	39	649

Fig 7: Compressive strength vs Curing time for System 3



- API rheology (Yield point/Plastic viscosity)

Table 12: Table of Yield point and Plastic viscosity for System 3

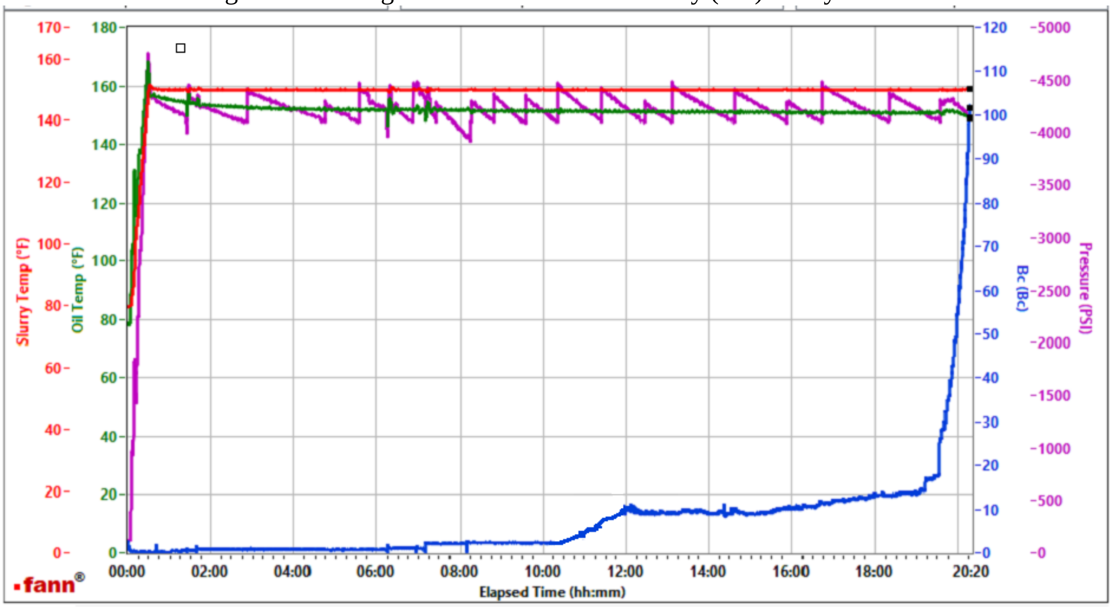
	Ramp	600rpm	300rpm	200rpm	100rpm	6rpm	3rpm	PV	YP
Surface @80 °F	Up		28	20	12	4	2	24	4
	Down	56		20	12	4	2		
Downhole @ 150 °F	Up		19	14	8	2	2	15	3
	Down	36		14	8	2	2		

- Free fluid test: There was no free fluid observed
- Thickening time: At a pressure of 4500psi, temperature of 150°F and heating time of 28 mins

Table 13: Table of thickening time at surface and downhole conditions for System 3

TIME	19h:40m	19h:49m	19h:57m	20h:06m	20h:16m
BC	30	40	50	70	100

Fig 8: Thickening time vs Bearden consistency (BC) for System 3



- API static gel strength

Table 14: Table of gel strengths for System 3

10 sec gel strength	4
10 mins gel strength	16

- Shrinkage Test (24 hrs) – ASTM C157

Table 15: Table showing shrinkage results for system 1, 2 and 3

IDENTIFICATION	WATER-CEMENT RATIO	SHRINKAGE **(με)**
0.4 WC-01	0.4	-234
0.4 WC-01		-244
0.5 WC-01	0.5	-256
0.5 WC-01		-252
0.6 WC-01	0.6	-269
0.6 WC-01		-273

III. Conclusion

Performing a comparative analysis:

- As seen in table 4.1, the cement system with lowest cement ratio had the highest density; this is desired to balance high pressure formations. However low density cement is used in formations with low fracture gradient.

Table 16: summary of density values for the 3 different cement systems

Water-cement ratio	**0.4**	**0.5**	**0.6**
Density (SG)	1.887	1.784	1.704
Density (ppg)	15.7	14.9	14.2

- According to Abram's water cement ratio law, the strength of a concrete mix is inversely related to the mass ratio of water to cement. From the Table 17, it is observed that the cement system with the lowest water-cement ratio had the highest 24hr and 48hr compressive strength. The system with higher cement water ratio had the least strength, this is because after hydration has occurred, the excess water will result in more water filled pores between the grains which in turn decreases the strength of the cement sample.

Table 17: summary of compressive strength values for the 3 different cement system

Water-cement ratio	**0.4**	**0.5**	**0.6**
CS (8 hr)	7	8	7
CS (12 hr)	10	8	9
CS (16 hr)	19	10	11
CS (24 hr)	39	13	11
CS (48 hr)	649	367	432

The Bingham parameters, namely plastic viscosity and yield stress are used to characterize the workability of cement. Cement slurry is a yield stress fluid because its material flow starts as soon as the applied stress becomes greater than the yield stress. From table 18, it is seen that the cement sample with a water-cement ratio of 0.6, exhibited better workability as compared to the rest.

Table 18: summary of plastic viscosity and yield point values for the 3 different cement systems

Water-cement ratio	**0.4**	**0.5**	**0.6**
PV @ 80 ^{o}F	24	19.5	9
PV @ 150 ^{o}F	15	6	6
YP @ 80 ^{o}F	4	0.5	3
YP @ 150 ^{o}F	3	2	4

- The thickening time (also called pumping time) was assessed under estimated downhole conditions of 150^{o}f and 4500 psi using a consistometer. The end of thickening time is recognized to be about 50BC or 70 BC for most applications. It is necessary to test for thickening time as it helps to ascertain if the cement slurry would remain fluid enough to be pumped downhole. As seen in table 19, the cement system with the lowest water cement ratio had the highest thickening time compared to the others, due to its low water content.

Table 19: summary of thickening time values for the 3 different cement systems

Water-cement ratio	**0.4**	**0.5**	**0.6**
TIME @ 30 BC	19H:40M	17H:27M	11H:55M
TIME @ 40 BC	19H:49M	17H:32M	12H:04M

TIME @ 50 BC	19H:57M	17H:33M	12H:20M
TIME @ 70 BC	20H:06M	17H:38M	13H:01M
TIME @ 100 BC	20H:16M	17H:43M	13H:05M

- The cement gel strength is a physical property that measures the transition of the cement slurry from the fluid to solid phase. It is an indicator of attractive forces that exists between the particles in the mixture. When water is mixed with cement, a hydration reaction occurs resulting in a cement gel. This cement gel is responsible for the strength and binding in the cement structure. According to API standards, it is measured at 10 seconds and 10 minutes. Furthermore, the gel strength developed and the speed at which it occurs is used by service companies to measure a slurry's ability to resist gas intrusion and develop mitigative strategies when operating in high-risk formations. A lower water content results in higher gel strength.

Table 20: summary of gel strength values for the 3 different cement systems

Water-cement ratio	**0.4**	**0.5**	**0.6**
10 sec gel strength (lbf/100ft^2)	4	4	4
10 mins gel strength (lbf/100ft^2)	16	12	4

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