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The Effect of Water-Cement Ratio and Temperature on Density and Rheological Properties of Oil Well Cement Slurry

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Abstract: ***Oil well cementing has always been a vital, indispensable, and costly part of drilling and wellbore completion. Ensuring high-quality cement slurry is crucial for safe and economical oil production over the well's entire lifespan. However, designing the optimal cement slurry for oil wells is challenging due to the several parameters that must be considered to achieve successful cementing. This study examines the effects of water-cement ratio and temperature on the density and rheological properties of class G cement slurry. Four cement samples with water-cement ratios of 0.34, 0.39, 0.44, and 0.49 were tested at 25 °C and 45 °C. A homogenous mixture of the slurries without additives was obtained by following American Petroleum Institute (API) standards. The study showed that the density of oil well cement slurries decreased as the water-cement ratio increased. The rheological properties of the slurries decreased with higher water-cement ratios. However, the rheological properties of each water-cement ratio increased as the temperature rose. This demonstrates that the water-to-cement ratio and temperature strongly influence the rheological properties of oil well cement slurries.***

Keywords: Cement Slurry, Density, Rheology, Temperature, Water-to-Cement Ratio.

I. INTRODUCTION

In oil well cementing, cement slurry is injected from the surface to depths extending several thousand feet below ground [1]. It is pumped down the casing and back up through the annulus [2], where it solidifies and hardens [3]. In the oil and gas industry, the slurry is mainly composed of cement, water, and additives that enhance performance [4]. The quality of the cement slurry behind the casing is critical during the drilling of subsequent wellbore sections and the well's production period, significantly impacting secondary cementing [5], workover, and stimulation operations [6].

High-quality cement slurry ensures economical and safe oil production throughout the well's lifetime [7], providing long-term wellbore durability by creating a robust casing [8]. Conversely, poor-quality cement slurry can necessitate remedial cementing, increasing the time and cost of the operation [9]. As a result, oil well cement slurry must be carefully engineered to fulfill several critical requirements [10], including consistent thickening time (setting time), low viscosity, minimal free fluid, sufficient strength development, and reduced fluid loss [4]. Designing an effective cement slurry involves accounting for various factors, such as well depth, temperature, mud column pressure, slurry viscosity, water content, and the quality of the available mixing water [11].

Due to the capital-intensive nature of wellbore cementing, careful attention must be paid to these factors to ensure the effectiveness of the designed and prepared cement slurry. The success of the initial cement placement depends on its density and rheological properties [12]. This study aims to examine the effects of water-cement ratio (w/c) and temperature on density and rheological properties of class G cement slurry, assisting operators in making informed decisions.

A. Cement Slurry Density

Cement slurry density refers to the weight of the slurry per unit volume. It has a direct impact on its other properties as well as those of the set cement. The density of cement slurry must exceed that of the drilling fluid to ensure effective displacement, but it should remain low enough to avoid fracturing the formation. Additionally, it must provide adequate strength to the set cement while maintaining the slurry's pumpability. Under normal conditions, to balance strength, flowability, and ease of property control, the slurry density is typically maintained between 1.80 and 1.90 g/cm³, significantly higher than the density of drilling fluid. In practice, a wider range of slurry density is often required in the field. Geopolymer cement/binder formulations have demonstrated densities ranging from 1.45 g/cm³ to 1.84 g/cm³, achieved by altering water content or adding fillers.

The most extreme densities reported vary from 0.9 g/cm³ to 3.2 g/cm³. However, densities above 2.0 g/cm³ can impair the slurry's rheological properties, potentially reducing displacement efficiency [13].

B. Rheology of Oil Well Cement Slurry

The rheological properties of cement slurry refer to its ability to deform and flow under applied shear stress. These properties can be measured using rheological parameters associated with specific rheological models [14]. The rheology of cement slurry plays a vital role in the design, execution, and quality of primary cementing.

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Understanding this property is critical for evaluating the feasibility of mixing and pumping cement slurries, determining the pressure-to-depth relationship during and after compression, calculating return circulation during the "free fall" phase, predicting temperature profiles during slurry pumping, and planning the capacity needed for optimal slurry management [15]. For effective displacement of drilling fluid, the rheological properties of the cement slurry must be optimized [16]. These properties are also used to calculate friction losses during circulation, helping to prevent borehole leakage and enabling the selection of suitable operational equipment [17]. Furthermore, the rheological behavior of the slurry affects its adhesion to the casing and formation, which is essential for successful cementing [18].

Shahriar emphasizes that a thorough understanding of oil well cement slurry rheology is essential for assessing its mixability and pumpability, achieving effective mud removal, and optimizing slurry placement [19]. Inadequate mud removal can result in weak cement bonds, zone communication, and suboptimal stimulation treatments [20]. Rheological properties significantly influence the field performance of set cement and are strongly affected by the material choices, water-to-cement (w/c) ratio, and temperature [17].

Extensive research has led to the development of various mathematical models to describe the relationship between shear stress and shear rate. Time-independent rheological models enable experimental data on shear stress, shear rate, and viscosity to be aligned with specific patterns using rheological analysis software. However, all models inherently exhibit some degree of statistical error [21]. The primary rheological models for evaluating cement slurries are non-Newtonian, with the most common being the Bingham plastic and power law models [20]. The Bingham plastic model accounts for both yield stress and limiting viscosity at finite shear rates, unlike the power law model. However, the Bingham plastic model tends to overestimate shear stress at both low and high shear rates, a drawback not observed with the power law model [22]. To address this limitation, modified versions of the Bingham plastic friction pressure equations have been introduced to provide a more accurate representation of cement slurry friction pressures [23].

II. MATERIALS AND METHODS

Before cement slurry is pumped downhole, various laboratory tests must be conducted to predict its behavior and performance during pumping and after placement. Accordingly, a series of laboratory experiments were conducted to evaluate the density and rheological properties of cement slurry with different water-cement ratios at various temperatures.

A. Materials

The instruments used to conduct the experiments are electronic mass balance, speed mixer, measuring cylinder, rheometer, mud balance, slurry cup; thermo-cup; and stopwatch. The imported class G cement used was obtained from Schlumberger, Ghana.

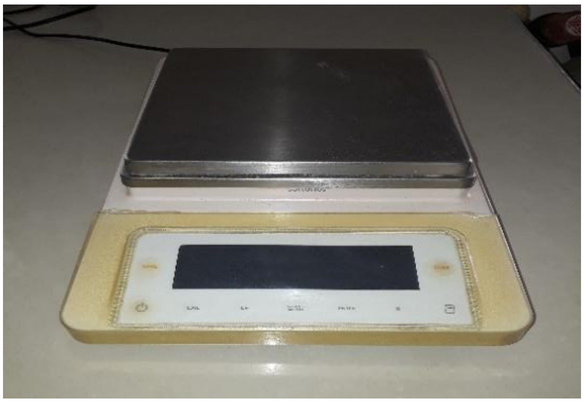
B. Methods

i. Cement Slurry Formulation

Table 1 represents the various water-cement ratios and their corresponding quantities of water and cement used for the experiment. The quantity of water needed was measured using a measuring cylinder while the cement powder (Class G) was weighed using the electronic mass balance shown in Fig. 1. The measured mix water was poured into the slurry blender and the speed mixer shown in Fig. 2 was set at 4,000 rpm for 15 seconds, and the cement sample was added within the 15 seconds after which the speed mixer was set at 12,000 rpm for 35 more seconds to form a homogeneous slurry mixture.

Table I: Cement Slurry Formulation

Sample	Water-Cement Ratio	Class G Cement (g)	Mix water (g)
A	0.34	396.50	*134.84*
B	0.39	396.50	154.67
C	0.44	396.00	174.50
D	0.49	396.59	194.33



[Fig.1: Electronic Mass Balance]

[Fig.2: Speed Mixer]

ii. Rheological Test

The rheological property test was performed using a rheometer at 25 ºC and 45 °C (Fig. 3). A quantity of cement slurry was poured into the sample cup of the rheometer. The sample cup was placed on a cup table under the sleeve of the rheometer and raised until the fluid level met the scribed line on the rotor. The locking nut on the sample was tightened and the rotary dial was turned to the desired speeds of 600, 300, 200, 100, 6, and 3 rpm. The dial readings for the various samples were taken by looking through the

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illuminated lens. The same procedure was repeated at a temperature of 45 ºC with the help of the thermo-cup. The temperature of the slurry was determined with the aid of a thermometer connected to the thermo-cup (Fig. 4).

[Fig.3: Rheometer]

[Fig.4: Thermo-Cup]

iii. Density Test

The density for all the slurry samples was determined at room temperature (25 ºC). The mud balance base was placed on a flat-level surface. The clean, dry cup was filled with a freshly designed cement sample. The lid was placed on the cup, and any excess cement was wiped off. The mud balance (Fig. 5) was then positioned on the knife edge, and the rider was moved along the arm until the bubble indicated that the arm and cup were balanced. The mud weight was read at the edge of the rider nearest to the mud cup in specific gravity.

[Fig.5: Mud Balance]

iv. Gel Strength Test

The slurry sample was placed in a slurry cup and the rheometer was set at 600 rpm for 15 seconds. The rheometer was then turned to the 'STOP' position then set at 3 rpm for an extra 10 seconds. The rheometer was then turned on and the maximum deflection of the pointer was recorded as gel strength in lb/100ft^2. The same procedure was repeated for 10 seconds gel strength but this time round the rheometer was set to 'STOP' position for 10 minutes. This was done at 25 ºCand 45 ºC with the help of the thermo-cup. The plastic viscosity was obtained using the dial readings at 300 rpm and 100 rpm with the help of Equation 1 [24]. The yield point and annular viscosity were calculated using Equations 2 and 3 respectively [25].

$$PV = 1.5 \times (300\text{ rpm} - 100\text{ rpm}) \quad \ldots \quad (1)$$

$$YP = 300\text{ rpm reading} - PV \quad \ldots \quad (2)$$

$$AV = 600\text{rpm reading} / 2 \quad \ldots \quad (3)$$

III. RESULTS

This section presents the results of the density and rheological properties of the cement slurry samples.

A. Density Result

The densities of the various cement slurry samples are shown in Table 2.

Table II: Density of the Samples

Water-Cement Ratio (W/C)	0.34 (A)	0.39 (B)	0.44 (C)	0.49 (D)
Density (lb/gal)	17.02	16.27	15.69	15.02

B. Rheology Result

Tables 3 and 4 display the shear rates and shear stresses of the slurry samples at 25 °C and 45 °C, respectively. The plastic viscosities, apparent viscosities, and yield points are also provided in Tables 3 and 4.

Table III: Rheological Properties of the Samples at 25 °C

Sample	A (0.34)	B (0.39)	C (0.44)	D (0.49)
600	300	260	120	80
300	245	170	80	52
200	203	142	65	42
100	144	104	45	33
6	36	29	17	14
3	24	18	12	11
10s gel strength (lb/100ft^2)	28	20	11	8
10m gel strength (lb/100ft^2)	58	24	18	15
Plastic Viscosity (cP)	151.5	99.0	52.5	28.5
Yield point (lb/100ft^2)	93.5	71.0	27.5	23.5
Apparent Viscosity (cP)	150.0	130.0	60.0	40.0

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Table IV: Rheological Properties of the Samples at 45 °C

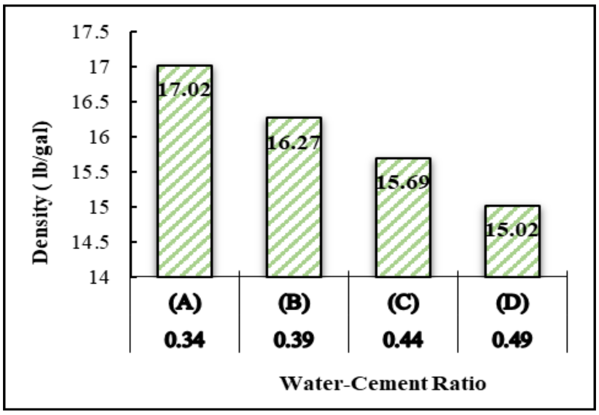
Sample	A (0.34)	B (0.39)	C (0.44)	D (0.49)
600	300	279	119	95
300	300	202	105	60
200	281	175	85	52
100	188	125	65	38
6	40	32	25	19
3	26	23	14	12
10s gel strength (lb/100ft^2)	44	30	14	13
10m gel strength (lb/100ft^2)	168	50	21	16
Plastic Viscosity (cP)	168.0	115.5	60.0	33.0
Yield point (lb/100ft)	132.0	86.5	45.0	34.5
Apparent Viscosity (cP)	150.0	139.5	59.5	47.5

C. Discussion

This section presents the results obtained from the tests conducted on the cement slurry samples, ranging from the density test to the rheological properties test.

i. Density

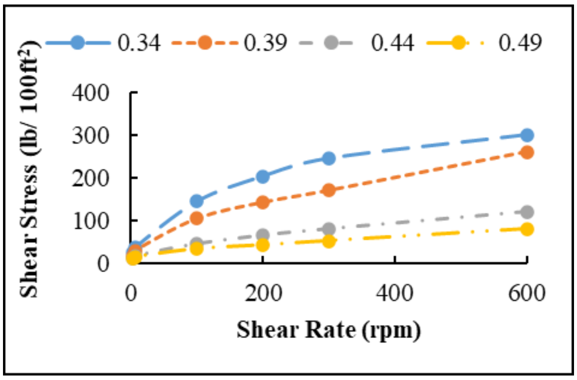
Slurry density refers to the weight of the cement per unit volume of water and is a critical parameter in cementing operations. Maintaining the cement slurry density equal to the drilling fluid's is essential to reduce the risk of formation fracture, kicks, and lost circulation [26]. Results from the test indicate that the density of the cement slurry samples decreased with increased water-cement ratio (Fig. 6). From Fig. 6, it is evident that a water-cement ratio of 0.34 has the highest density, while 0.49 has the lowest density. Excessive water can segregate cement slurry components, while too little water reduces cement slurry pumpability. According to Memon et al. [27], typical cement slurry density ranges from 14 to about 17 lb/gal, and all the cement slurry samples fall within this range. This indicates that any of these water-cement ratios are suitable for cementing operations in terms of density.



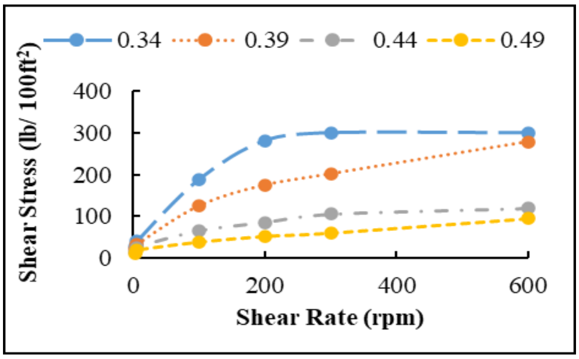
[Fig.6: Density of Cement Slurry Sample]

ii. Rheological Properties

The fundamental reason for determining the rheological properties of the cement slurries is to predict the flow characteristics using Plastic Viscosity (PV), Yield Point (YP) and Apparent Viscosity (AV). Figs. 7 and 8 depict the shear stress and shear rate behavior of oil well cement slurries with varying water cement ratios at different temperatures. The results suggest that a higher water-to-cement (w/c) ratio reduced the rheological values of the cement slurries. Memon et al. state that almost all fluids and cement slurries for drilling and cementing operations are non-Newtonian fluids and are treated using a Bingham plastic or power law type model [28]. This is evident in Figs. 7 and 8.



[Fig.7: Shear Stress Against Shear Rate at 25 °C]

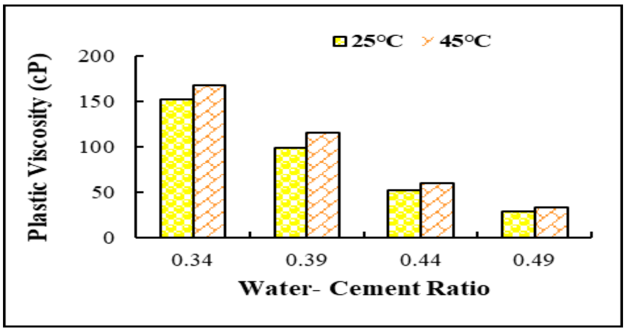


[Fig.8: Shear Stress Against Shear Rate at 45 °C]

iii. Plastic Viscosity

From Fig. 9, it is seen that plastic viscosity decreases with increasing w/c. As indicated in Fig. 9, the plastic viscosity dropped sharply at all the temperatures when the w/c was increased from 0.34 to 0.49. This is because as the w/c increases, we have less viscous cement slurry. This is consistent with a study conducted by Shahriar and Nehdi [29]. Also, it can be seen that the plastic viscosity of the cement slurries increased with increased temperature at the different w/c ratios. As the temperature increases, the cement hydration increases and the cement becomes more viscous.

According to Broni-Bediako et al. [4], a plastic viscosity of more than 100 cP is undesirable for pumping slurry downhole. At 25 ºC the cement slurry with w/c of 0.39, 0.44 and 0.49 appeared to be pumpable. At 45 ºC, samples with w/c of 0.44 and 0.49 indicated it is pumpable.



[Fig.9: Variation of Plastic Viscosity with Temperature and Water-Cement Ratio]

iv. Yield Point

According to Shahriar and Nehdi, yield stress is the

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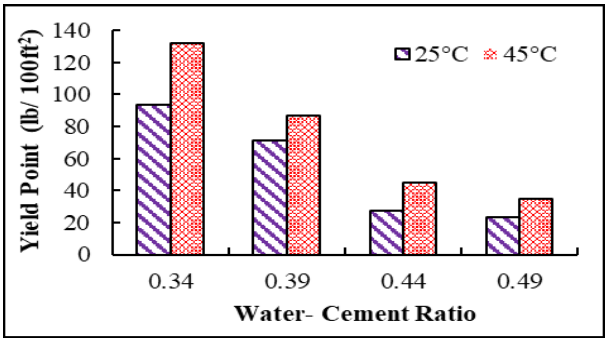
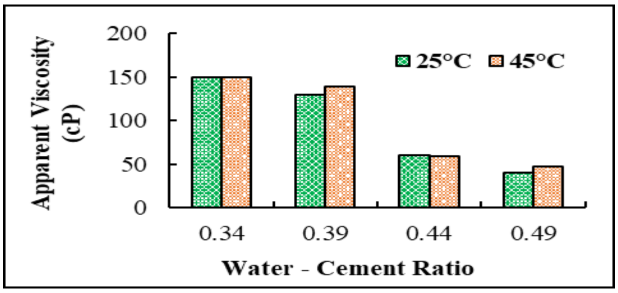
minimum force needed for a material to start flowing. Cement slurries exhibit solid-like behavior below this yield stress. In this study, yield stress decreases as the water-to-cement (w/c) ratio increases due to the slurry's lower viscosity. Conversely, yield stress values increase with higher temperatures across all w/c ratios because the slurry becomes denser, requiring more energy to initiate flow, as it behaves like a solid below a certain yield point (stress) (Fig. 10) [32]. The increase in yield stress with rising temperature is likely due to the accelerated rate of cement hydration at higher temperatures compared to lower ones [33]. It is also noteworthy that the impact of temperature was more significant at lower water-to-cement ratios in all observed cases. To prevent the slurry from settling, the yield stress should exceed 15 lb/100ft² [11]. According to Fig. 10, the yield stress for all w/c ratios at all temperatures was above 15 lb/100ft², indicating that all the cement slurry samples are suitable for cementing operations [34]. However, additives may be needed to ensure the yield stress remains above 15 lb/100ft². This yield stress trend is consistent with the previous findings of Shahriar and Nehdi [29].



[Fig.10: Variation of Yield Stress with Temperature and Water-Cement Ratio]

v. Apparent Viscosity

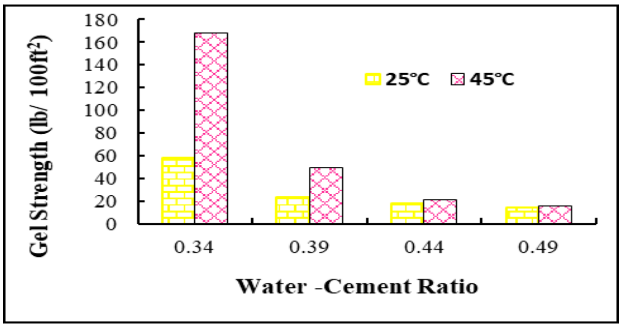
Apparent viscosity represents the combined effect of plastic viscosity and yield point. An increase in either or both factors will result in a higher apparent viscosity [30]. From Fig. 11, the apparent viscosity decreased with increasing water-cement ratio because of the decrease in the viscosity and hydration reaction rate of the cement slurry. Also, the apparent viscosity appeared to increase with increased temperature for all w/c except at 0.44. The increase in value as temperature increases is due to the increase in hydration and increase in viscosity that occurs when cement slurry is subjected to high temperatures. The sample with w/c of 0.44 had an irregular pattern, in that apparent viscosity decreased from 25 ºC to 45 ºC. At w/c of 0.34, apparent viscosity remains constant for all the two temperatures.



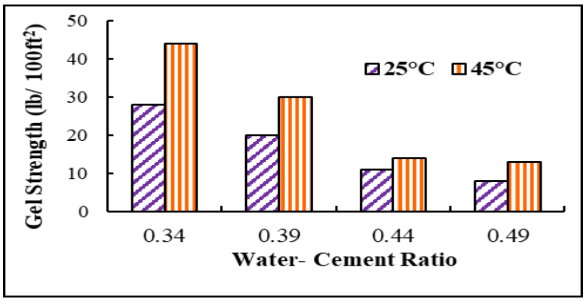
[Fig.11: Variation of Apparent Viscosity with Temperature and Water-Cement Ratio]

vi. Gel Strength

Gel strength is a rheological property that reflects the strength of attractive forces in a fluid when it is static. Both gel strength and yield point measure the attractive forces within a mud or cement system, and a reduction in one typically leads to a reduction in the other [31]. Fig. 12 and 13 show the gel strength at 25 ºC and 45 ºC at 10 minutes and 10 seconds respectively. From Figs. 12 and 13, gel strength decreased with increased w/c because the slurry becomes less viscous with increased w/c. For all w/cs, gel strength increased with increased temperature due to excessive gelation. The gelation was more pronounced at low w/c and high temperature as indicated in Figs. 12 and 13 in both the initial and final gel strengths.



[Fig.12: 10-Minute Gel Strength with Temperature and W/C Ratio]



[Fig.13: 10-Second Gel Strength with Temperature and W/C Ratio]

IV. CONCLUSION

Designing the optimal cement slurry for oil wells is challenging due to the need for slurry stability to achieve successful cementing. Therefore, parameters such as well depth, temperature, mud column pressure, viscosity and water content of cement slurries, and the quality of mixing water should be properly selected. The study was carried out to examine the effect of water-cement ratio and temperature on the density and rheological properties of class G cement slurry. Following API mixing procedures, four cement samples without additives were prepared with multiple water-cement ratios and tested at different temperatures. The density of all the cement slurries decreased with increased water-cement ratios. Regarding the rheological properties, the plastic viscosity, yield point, apparent viscosity and gel strength decreased with increased water-cement ratio. However, the rheological properties increased with increased temperature for each water-cement ratio.

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DECLARATION STATEMENT

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

- **Conflicts of Interest/ Competing Interests:** Based on my understanding, this article has no conflicts of interest.
- **Funding Support:** This article has not been sponsored or funded by any organization or agency. The independence of this research is a crucial factor in affirming its impartiality, as it has been conducted without any external sway.
- **Ethical Approval and Consent to Participate:** The data provided in this article is exempt from the requirement for ethical approval or participant consent.
- **Data Access Statement and Material Availability:** The adequate resources of this article are publicly accessible.
- **Authors Contributions:** The authorship of this article is contributed equally to all participating individuals.

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