Journal of Engineering

journal homepage: www.joe.uobaghdad.edu.iq

Volume 30 Number 2 February 2024

Experimental Evaluation of Stability and Rheological Properties of Foam Cement for Oil Wells

Qassim Mohammed Sayed[1,*], Hassan Abdul Hadi Abdul Hussein[2]

Department of Petroleum Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
qasem.sayed2108m@coeng.uobaghdad.edu.iq[1], hasanaltee@coneng.uobaghdad.edu.iq[2]

ABSTRACT

Oilwell cementing operations are crucial for drilling and completion, preserving the well's productive life. However, weak and permeable formations pose a high risk of cement slurry loss, leading to failure. Lightweight cement, like foamed cement, is used to avoid these difficulties. This study is focused on creating a range of foamed slurry densities and examining the effect of gas concentration on their rheological properties. The foaming agent and foam stabilizer are tested, and the optimal concentration is determined to be 2% and 0.12%, respectively, by the weight of the cement.

Furthermore, the construction of samples of foam cement with different densities (0.8, 1.0, 1.2, 1.4, and 1.6) g/cc is performed to find the relation with different volumetric percentage gas in foamed cement slurry (57.5, 47, 36, 25.5, and 15%). The relationship between rheological properties and foam quality is discussed, as the presence of gas plays a significant role in enhancing rheological properties. The rheology of foam cement increases proportionally with increasing foam quality, especially the plastic viscosity, which is 26 cp at 0% foam quality and 50 and 65 cp at 15% and 57.5% foam quality, respectively. Also, yield points increase as foam quality improves. Therefore, it is feasible to exclude certain cement additives that increase viscosity.

Keywords: Cement, Foam quality, Foamed cement, Rheology properties, Stability.

*Corresponding author
Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2024.02.12

Article received: 25/10/2023
Article accepted: 24/12/2023
Article published: 01/02/2024

تقييم تجريبي للثبات والخصائص الريولوجية للسمنت الرغوي لآبار النفط

قاسم محمد سيد*، حسن عبدالهادي عبدالحسين

قسم هندسة النفط، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

تعد عمليات تدعيم آبار النفط أمرًا بالغ الأهمية للحفر والإكمال، مما يحافظ على العمر الإنتاجي للبئر. ومع ذلك، تشكل التكوينات الضعيفة والنفاذة خطرًا كبيرًا لفقد ملاط الاسمنت، مما يؤدي إلى الفشل. ويستخدم الاسمنت الخفيف الوزن، مثل الاسمنت الرغوي، لتجنب هذه الصعوبات. الهدف من البحث هو إنشاء مدى واسع من كثافات الملاط الرغوي والتحقيق في كيفية تأثير تركيز الغاز الموجود فيها على خصائصها الريولوجية. تم اختبار عامل الرغوة ومثبت الرغوة، وتم تحديد التركيز الأمثل ليكون 2% و0.12% على التوالي من وزن الاسمنت. علاوة على ذلك، تم بناء عينات من الاسمنت الرغوي بكثافات مختلفة (0.8، 1.0، 1.2، 1.4، 1.6) غم/سم لإيجاد العلاقة مع النسبة الحجمية للغاز في ملاط الاسمنت الرغوي (57.5، 47، 36، 25.5، 15%) ومناقشة الخواص الريولوجية وعلاقتها بزيادة كمية الرغوة حيث أن وجود الغاز يلعب دوراً هاماً في تحسين الخواص الريولوجية. تزداد ريولوجية الاسمنت الرغوي بشكل متناسب مع زيادة نسبة الرغوة، خاصة اللزوجة البلاستيكية، والتي تبلغ 26 سنتي بويز عند نسبة رغوة 0٪ و50 و65 سنتي بويز ولجودة رغوة 15٪ و57.5٪، على التوالي. كما تزداد نقاط الخضوع مع زيادة كمية الرغوة. لذلك، من الممكن استبعاد بعض إضافات الاسمنت التي تؤدي إلى زيادة اللزوجة.

الكلمات المفتاحية: اسمنت، جودة الرغوة، اسمنت الرغوي، خواص ريولوجية، استقرارية

1. INTRODUCTION

Cementing casing is a crucial stage in the drilling and completion of gas and oil wells, involving engineering and scientific disciplines **(Hadi and Ameer, 2017; Wang et al., 2017)**. It involves placing a cement slurry in the annulus between the well casing and geological formations to create a solid mass for supporting and sealing **(Thiercelin et al., 1998; Singamshetty et al., 2004; Hernandez and Nguyen, 2010; Ibrahim and Almahdawi, 2016).** The cement's ability to maintain annular isolation depends on the formation's mechanical behaviour, cement, and stress conditions **(Mueller and Eid, 2006)**. The cement must provide enough strength to sustain the casing and resist the stresses it will encounter over its lifecycle **(Smith, 1991)**. Failure of a cement sheath can be caused by pressure- or temperature-induced strains, which are common in well operations **(Griffith et al., 2004)**. Portland cement is widely used in oil well operations, accounting for about 99% of primary cementing operations. "G-class cement" is used in well cementing processes, meeting API standards **(Assi and Almehdawi, 2021)**. Conventional cement slurry has a high-density range of (2.1–1.9) g/cc, which may cause lost circulation problems, therefore, lightweight cement slurries can be used to avoid these problems **(Al-Hiti and Hana, 2003)**. Oil wells with low fracture gradients, high permeability formations, or fragile zones cannot withstand the weight of a cement column with a standard density. To cement these areas, a lighter slurry is needed. One potential method is to increase the water-to-cement ratio (WCR), which is crucial in concrete mix design. However, this approach may not always yield optimal results as it reduces the viscosity of the slurry, causing the settling of suspended particles and delaying the thickening time of the slurry. Various techniques are used to reduce the weight of cement slurry, such as using extenders with water-absorbing properties. These extenders increase the water requirement for producing the cement slurry, reducing its weight. Bentonite, fly ash, silicates, diatomaceous, earth, pozzolans, oil emulsions, and perlite are widely recognized additives for oil well cement **(Harms and Febus, 1985)**. Another strategy is to incorporate light additives into the cement slurry. Gilsonite, a solid hydrocarbon belonging to the asphaltenes family, is the most effective option. Its small, black, and rough seeds have a very low density (SO= 1.07), and it does not exhibit water absorption or swelling properties. Gilsonite has effectively managed and prevented cement slurry leakage inside geological formations **(Wu and Onan, 1986; Al-Hiti and Hana, 2003)**. A lightweight cement mixture known as foam cement combines cement slurry, inert gases (usually nitrogen), and a foaming agent **(Harms and Febus, 1985; Nelson and Cementing, 1990; Crandall et al., 2014; Vela et al., 2020)**. Foam quality is defined as the volumetric percentage of gas in the cement slurry. Cementing weak formations that cannot support high hydrostatic pressure is the purpose of this type of cement, which has a lower density **(Nelson and Cementing, 1990; Harlan et al., 2001).** In recent years, the use of foam cement in high-stress environments has increased in frequency **(Benge et al., 1996; Judge and Benge, 1998; White et al., 2000; Rae and Di Lullo, 2004).** Foamed cement is more elastic than traditional cement because of its foam network, which lowers Young's modulus **(Deeg and Griffith, 1999; Spaulding, 2015)**. It has a higher resistance to mechanical stresses from well operations and can deform without splitting when pressurized **(Bour and Rickard, 2000; Kopp et al., 2000)**. Zonal isolation depends on cement permeability and mechanical behaviour **(API, 1997).** To develop a foamed cement system with superior properties such as high compressive strength and low permeability, it is vital to keep gas bubbles from merging and moving around **(Kjøstvedt, 2011).** In oil well cementing, foam cement's compressive strength is crucial and can withstand deformation when a load is applied **(Falode et al., 2013)**. The composition of two-phase foam cement and its high viscosity makes it ideal for mud displacement, especially in boreholes with lost circulation zones or washouts. Expandable foamed cement provides strong zonal isolation and reduces thermal conductivity, making it useful in situations where cooling is not desired **(Kjøstvedt, 2011)**. Foamed cement slurries have improved drilling fluid displacement capabilities compared to base cement slurries due to their greater shear viscosity and extensional viscosity. Additionally, foamed cement lowers overall slurry fluid loss, helping to control fluid and gas inflow into the setting cement **(Aldrich and Mitchell, 1976; Davies et al., 1981; Montman et al., 1982).**

The aim of this study is to create a lightweight cement system that is foam cement with a wide range of densities that exhibits high stability by using a foam stabilizer. The majority of the mechanical and physical properties are directly related to stability. Additionally, it investigates the rheological behavior and its correlation with foam percentage due to its advantageous role in cementing jobs, significantly displacing drilling fluid.

2. MATERIALS AND METHODS

In this work, the materials utilized are:

- Cement: G-class cement is used; it was manufactured in The United Arab Emirates with a high sulfate resistance type (HSR).

- Foaming agent: A surfactant compound (transparent liquid, Density at 20° C: 1.02 g/cc ± 0.02, pH: 8 ± 1, Chloride-free, Equivalent Na2O: £ 1.0%).
- Foam stabilizer: CMC Low Viscosity, Carboxymethylcellulose **(Brito et al., 2018; Hammood and Al-Qaisi, 2019)**.

2.1 Foam Capability

The foam capability test checks whether the foaming agent and stabilizer are compatible, as well as the foam system's foaming capability and stability, if applicable. This test was done in accordance with ISO 10426-4, also called ANSI/API-recommended practice 10B-4: preparation of foamed cement slurry and testing it at atmospheric pressure **(RP API, 2015)**. The special equipment for preparing foamed cement in the laboratory is a multi-bladed, tightly sealed blender of a known volume, as shown in **Fig. 1**. A specific weight of cement slurry and a weight percentage of the foaming agent is placed in the blender, which rotates at a speed of 12,000 rpm for 15 seconds. When the blender is filled with foamed cement, the foaming agent concentration is optimal; if not, the cement slurry must be redesigned. Foam system stability refers to the ability to sustain the initial structure of the foam system by preventing the coalescence or migration of microbubbles while also providing a uniform distribution of bubble sizes. The foamed cement slurry is placed into a large 250-ml graduated cylinder and covered from the top, as shown in **Fig. 2**, and stays for two hours; any decrease in the foam slurry height is recorded; whenever the reduction in the slurry is slight, it means good stability. Two samples can be taken from the top and the bottom, and their densities can be compared; if they are equal, stability is excellent. In addition to stability, Unstable foamed cement with no spherical and linked voids may generate well channeling and density inhomogeneity, resulting in poorly contained sections **(De Rozieres and Ferrière, 1991). T**he following may be measured: free fluid, settling, bubbles coalescing, etc. The test must be conducted at the ambient temperature; however, a water bath may be used to keep the temperature steady while keeping vibration to a minimum**(Kjøstvedt, 2011)**.

Figure 1. Multi-bladed blender.

Figure 2. Graduated cylinder used for stability test.

2.2 Foamed Cement Density And Foam Quality

The un-foamed or base cement slurry density is determined by a pressurized fluid density device, as shown in **Fig. 3**.

Figure 3. Pressurized fluid density device.

To get the anticipated density, we assess the weight of cement slurry plus foaming agent and foam stabilizer by multiplying the volume of the multi-bladed blender with the required density value. This is called the expected density, such as:

Weight of cement slurry = volume of blender *expected density (1)

Determining an actual density involves the measurement of mass and volume in Eq. (2). The foamed cement slurry is placed into a graduated cylinder with a capacity of 250 ml and afterward weighed. Due to the foam slurry's expansion due to a rise in temperature from rapid rotation, the actual density is lower than anticipated. Determining the difference between the two densities is crucial for proper consideration. Several foamed cement samples with different gas concentrations are being created, as shown in **Fig. 4**.

$$\rho_{FS} = \left(\frac{m}{v}\right) \quad (2)$$

Pressurized fluid density balance cannot be used, and Atmospheric fluid density balance is not recommended; holes may create restrictions leading to incorrect results. The concept of foam quality pertains to the volumetric percentage of gas in foamed cement slurry, as in Eqs. (3) and (4).

$$FQ = (\frac{V_{gas}}{V_{gas}+V_{BS}}) * 100 = \frac{V_{gas}}{V_{FS}} * 100 \quad (3)$$

$$FQ = (\frac{\rho_{BS}-\rho_{FS}}{\rho_{BS}-\rho_{gas}}) * 100 \quad (4)$$

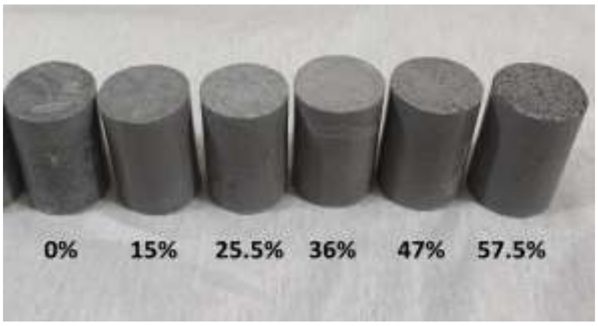

Figure 4. Foam cement samples with different foam quality.

2.3 Rheology Properties

The rheological properties of foamed cement slurries play an essential role in assessing the adequacy of the slurry design in terms of viscosity characteristics. A foamed cement system has to have enough viscosity to keep the foamed slurry stable. Therefore, fine-tuning the base cement slurry is necessary to achieve the desired rheological qualities. The rheology is evaluated at room temperature and bottom hole circulating temperature (BHCT), with and without the former, using a viscometer device 3500 from CHANDLER company, as shown in **Fig. 5**. Rheological testing can be done on foamed cement. The traditional bob/sleeve rheology uses statistical regression to determine shear stress vs. shear rate. The issue with foamed slurry is insufficient shear stress between the bob and sleeve, leading to lower torque values. Wall slipping concerns traditional bob and sleeve, even for conventional slurries. The phenomenon is significantly more pronounced in two-phase fluids like foamed cement. Foam's rheological behavior is different from that of homogeneous, single-phase fluids.

The difference comes due to several factors. Foams are fluids that are unstable, heterogeneous, and compressible **(Kopp et al., 2000)**. Rotational viscometers with a fixed sample volume are unsuitable for measuring the rheological properties of foams due to their instability **(Ahmed et al., 2009).** Foam's flow characteristics in a Couette viscometer show that the flow is highly localized at the inner wall's motion **(Debregeas et al., 2001)**. A Fann Yield Stress Adapter (FYSA) is designed to reduce this issue and is recommended for direct yield point measurement and improved readings at low shear **(Olowolagba and Brenneis, 2010)**, as shown in **Fig. 6.** A Chandler 3500 viscometer device is used because no FYSA device is available.

Figure 5. CHANDLER device 3500.

Figure 6. FYSA viscometer device **(Kjøstvedt, 2011).**

3. RESULTS AND DISCUSSION

3.1 Foam Capability

An essential factor in foamed cement applications is the ability to efficiently create microbubbles with high stability in the cement slurry in laboratory conditions. The first step is determining the optimal amount of a foaming agent, as an increase in concentration has been shown to affect the properties of foamed cement systems adversely. In contrast, a reduction in concentration limits the ability to generate the foam and cannot reach the required density. The test started by adding a foaming agent at a concentration of 1% BWOC, and the concentration was increased gradually until the blender was full of foamed cement slurry. The results showed that a concentration of 2% BWOC was ideal for the foaming agent to create foam cement slurry, filling the mixer, regardless of the amount of the base cement slurry to be foamed.

Stability is the second thing that keeps the initial structure of a foam cement system. This is important for the success of a foam system because, once it's made, the gas bubbles tend to stick together and escape. After all, the gas and cement slurry have different densities. A suitable viscosity of the foam system is necessary to keep the bubbles suspended and minor within the continuous phase. The experiment used carboxymethyl cellulose (CMC) as a foam stabilizer. CMC was added at a concentration of 0.04% by weight of cement (BWOC). As the concentration of CMC gradually increased, the system tended to achieve optimal stability. The stability of the foam system was seen to stop at a CMC concentration of 0.12% by weight of cement, as shown in **Fig. 7**. The foam stabilizer that exceeds the optimal concentration value is not beneficial but affects the properties.

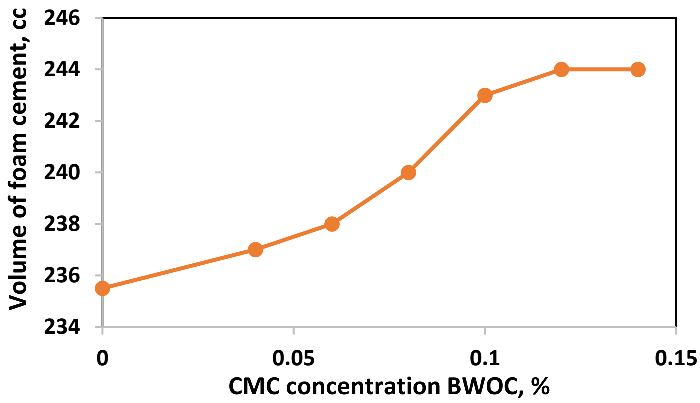

Figure 7. Relation between CMC concentration and volume of foamed cement slurry.

3.2 Foamed Cement Density and Foam Quality

The base cement slurry density was determined by a pressurized fluid density device, which is 1.88 g/cc, while the foam cement density was determined by Eq.(2), also foam quality was determined by Eq. (3) or Eq. (4), as shown in **Table 1.**
The density of foamed cement is directly proportional to the quantity of gas distributed within the foaming system, affecting the cement's significant physical, mechanical, and rheological properties. Acknowledging the correlations between the gaseous content and other properties is important. The volume of gas in foamed cement slurry is known as foam quality. According to laboratory results, increasing the foam quality makes the continuous phase (i.e., base cement slurry) occupy less space in the system; therefore, as noted, the percentage gas volume has an inverse relationship with density, as shown in **Fig. 8.** The compressibility of the foam is a crucial factor in enhancing the cementing process, as it enables the foam cement to expand and compensate for any slurry loss.

Table 1. Relation between foam slurry and foam quality.

Foam cement density (g/cc)	Foam quality (%)
1.88	0
1.6	15
1.4	25.5
1.2	36
1.0	47
0.8	57.5

Additionally, it can pass through small passageways and caves, applying pressure to both the casing and the wall of the formation. This process effectively prevents the creation of channels that would allow the passage of gas or water between the layers.

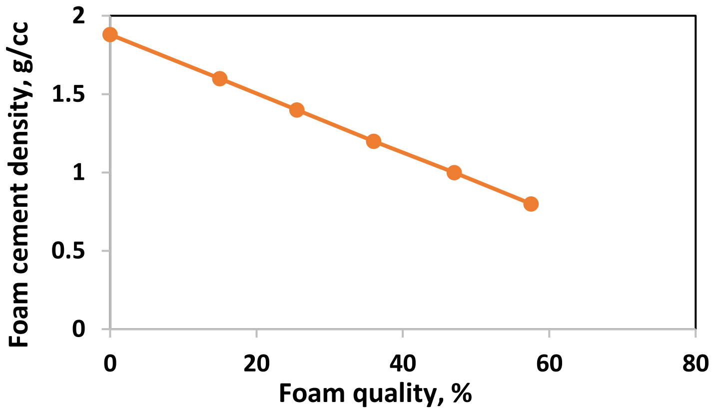

Figure 8. Relation between foam quality and foamed cement density.

3.3 Rheology Properties

Determining rheological characteristics is essential for achieving a successful oil-well cement system. Specifically, understanding the behavior of rheological properties concerning the gas volume percentage in the foamed slurry is essential. The study results indicate a notable increase in plastic viscosity as foam quality increases. At a foam quality of 57.5%, the plastic viscosity was measured to be 64.5 centipoise, while the base slurry exhibited a plastic viscosity of 26.3 centipoise.

Additionally, foam quality impacted yield points because it showed a slight increase as foam quality increased. It was 5.8 Ib/100 ft^2 at base slurry and increased gradually until it reached 12.5 Ib/100 ft^2 at foam quality 57.5%, as shown in **Fig. 9**. This indicates that foam plays a role in increasing the plastic viscosity and yield point, as the foam forms a stable texture with the cement grains and water molecules, which is suitable for displacing the drilling fluid during the cementing process and thus providing excellent cohesion between the casing and the rock formations. It also has an advantage over some specifications, such as free water and settling, which are non-existent in the foam system.

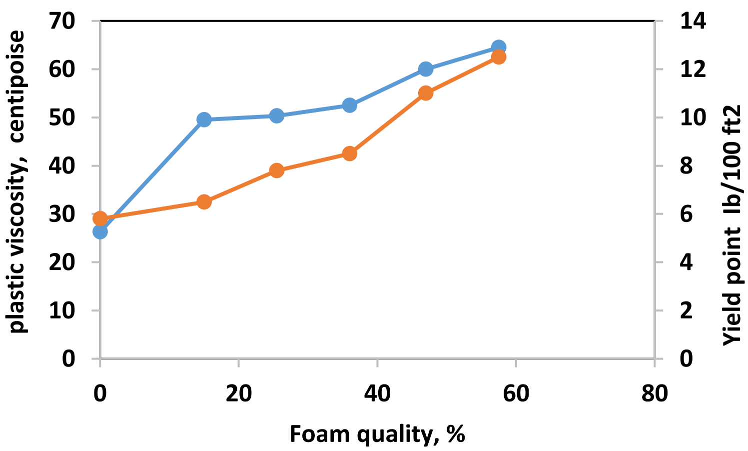

Figure 9. Relation between foam quality with plastic viscosity and yield point.

4. CONCLUSIONS

Tests were conducted on several chemicals, including a foaming agent and a foam stabilizer. Through laboratory work, one substance was identified for each function. Several important observations were noted, these are:

1. A high-speed device must create microbubbles to get a stable foam system. Additionally, a suitable foam stabilizer must be used.
2. The concentration of foaming agent and foam stabilizer cannot be increased above the ideal concentration because it negatively affects the other properties.
3. Determining foam system density involves measuring mass and volume, avoiding using other pressure-related devices. The relation between foam quality and foam system density is inversely proportional.
4. The plastic viscosity shows a noticeable increase as the foam quality increases.
5. The yield point exhibits a slight increase when the foam quality is improved.
6. The rheological properties of foamed cement can be improved by improving the base cement slurry.
7. The actual results of the rheological properties are greater than those measured with conventional equipment due to slippage between the bob and the sleeve.

NOMENCLATURE

Symbol	Description	unit	Symbol	Description	unit
BWOC	By weight of cement	%	V_{BS}	Base cement volume	cc
FQ	Foam quality	%	V_{FS}	Foam cement volume	cc
m	Mass	g	ρ	Density	g/cc
V	Volume	cc	ρ_{BS}	Base cement density	g/cc
V_{gas}	Gas volume	cc	ρ_{FS}	Foam cement density	g/cc

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