Journal of Petroleum Research and Studies

journal homepage: https://jprs.gov.iq/index.php/jprs/

Print ISSN 2220-5381, Online ISSN 2710-1096

An Experimental Investigation of Rheological and Free Water of Foam Cement System

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Article Info

Received 09/06/2024
Revised 01/02/2025
Accepted 02/02/2025
Published 21/12/2025

DOI: http://doi.org/10.52716/jprs.v15i4.978

Abstract

Foamed cement system is one of the types of lightweight cement used in the process of cementing oil wells in weak formations which is exposed to lost circulation problems. This study aims to determine the closest rheological model to the foamed cement system and the extent of the effect of the presence of foam and its concentration on the plastic viscosity and stability of the foamed system as well as free water. We conducted experiments on a sample of base cement and several samples of foamed cement, a foam quality (injected air as a percentage) of 15, 25, 36, and 47 is injected into the base cement slurry to obtain different densities of foamed cement of 1.6, 1.4, 1.2, and 1.0 g/cc respectively. For selecting the best rheological model purpose, an absolute average percentage error (EAAP) criterion and R2 of four rheological models (Bingham plastic, Power law, Herschel-Bulckley, and Casson) is applied. The results indicated that the Herschel-Bulckley model exhibited the closest rheological model with the lowest value of (EAAP) around 5% and R2 greater than 0.989. In addition, an increase of the foam quality will improve the plastic viscosity and at the same time the stability of the foam cement system increased, as the volumetric percentage of released microbubbles decreased from 5.3% to 4.3% when the foam quality increased from 15 to 47. The free water for base cement slurry was 2.08% and disappeared completely when foam quality increased above 15%. Experimental data demonstrated a direct correlation between foam quality with plastic viscosity, stability of foamed cement and free water, where enable the establishment of a reliable model for predicting cement performance and use in cementing operations of wells suffering from lost circulation problems. The compressive strength of foamed cement was calculated for several densities in the master's thesis and excellent values were obtained, higher than other types of lightweight cement, and were published in another research. Foam cement is a new system in oil well cementing operations that has not been applied in Iraq at present. It is important to study it in advance to identify its rheological behavior as well as the problem of free water, which is a burden in cementing horizontal or inclined oil wells.

Keywords: Foamed cement, Foam quality, Stability, Free water, Rheological Properties.

دراسة مختبرية للخواص الريولوجية والماء الحر لنظام السمنت الرغوي

الخلاصة:

نظام السمنت الرغوي هو أحد أنواع السمنت الخفيف الوزن المستخدم في عملية تدعيم آبار النفط في التكوينات الضعيفة المعرضة لمشاكل الفقدان. تهدف هذه الدراسة إلى تحديد أقرب نموذج ريولوجي لنظام السمنت الرغوي ومدى تأثير وجود الرغوة وتركيزها على اللزوجة البلاستيكية واستقرار النظام الرغوي وكذلك الماء الحر. أجرينا تجارب على عينة من السمنت الأساسي وعدة عينات من السمنت الرغوي، تم حقن نسبة حجمية من الرغوة (هواء محقون كنسبة مئوية) 15، 25، 36، و 47 في ملاط السمنت الأساسي للحصول على كثافات مختلفة من السمنت الرغوي 1.6، 1.4، 1.2، و 1.0 غم/سم^3 على التوالي. لاختيار أفضل نموذج الريولوجي، تم تطبيق معيار متوسط الخطأ النسبي المطلق (EAAP) وR^2 لأربعة نماذج ريولوجية (بلاستيك بينغهام، قانون الطاقة، هيرشيل بولكلي وكاسون). أشارت النتائج إلى أن نموذج هيرشل-بولكلي أظهر أقرب نموذج ريولوجي بأقل قيمة لـ (EAAP) حوالي 5٪ و R^2 أكبر من 0.989. بالإضافة إلى ذلك، فإن زيادة نسبة الرغوة ستحسن اللزوجة اللدائنية وفي نفس الوقت تزيد استقرار نظام السمنت الرغوي، حيث انخفضت النسبة الحجمية للفقاعات الدقيقة المتحررة من 5.3٪ إلى 4.3٪ عندما زادت نسبة الرغوة من 15 إلى 47. كان الماء الحر لملاط السمنت الأساسي 2.08٪ واختفى الماء الحر تمامًا عندما زادت نسبة الرغوة عن 15٪. أظهرت البيانات المختبرية وجود علاقة مباشرة بين نسبة الرغوة واللزوجة اللدائنية واستقرار السمنت الرغوي والماء الحر، مما مكن من إنشاء نموذج موثوق للتنبؤ بأداء السمنت الرغوي واستخدامه في عمليات تسميت الآبار التي تعاني من مشاكل فقدان ملاط السمنت. تم حساب قوة ضغط الاسمنت الرغوي لعدة كثافات في رسالة الماجستير وتم الحصول على قيم ممتازة اعلى من انواع الاسمنت الخفيف الاخرى ونشرت في بحث اخر. السمنت الرغوي هو نظام جديد في عمليات تدعيم الآبار النفطية لم يطبق في العراق في الوقت الحاضر ومن المهم دراسته مسبقا للتعرف على سلوكه الريولوجي وكذلك مشكلة المياه الحرة والتي تشكل عبئا في تدعيم الآبار النفطية الأفقية أو المائلة.

1. Introduction

Oil well cementing has been played an essential part in producing the hydrocarbons from subsurface to surface successfully [1]. The cadres specializing in cementing oil wells suffer from problems of lost circulation and casing fallback, especially when cementing depleted productive layers with high permeability or low fracture gradients that cannot withstand the hydrostatic pressure of the cement column. Therefore, the cadres resort to using low-density cement slurry that ensures the safety of the formation and the cementing process successfully. Oil well cement slurry can be classified according to density into three categories; traditional cement slurry ranging from 1.9 to 2.1 g/cc [2], high dense cement slurry above 2.1 g/cc, and lightweight cement slurry less than 1.8 g/cc [3]. Foamed cement, which is one type of lightweight cement, is used in cementing processes in low fracture gradient sections in which lost circulation problems and fallback of casing occur, is a mixture of cement slurry with the addition of inert gases (usually nitrogen) with the assistance of a foaming agent as a surfactant. When mixed properly, the gas forms microbubbles distributed uniformly within the continuous phase, i.e., the cement slurry [4,5,6]. The term "Foam quality" is the ratio of gas volume to the total foam slurry volume expressed in percentage [7]. The new foamed cement technology was used for cementing in Colombia and gated excellent results in achieving isolation in difficult wells that other lightweight cement slurries did not achieve. The physical properties of foamed cement have proven its great specifications in achieving good area isolation, high compressive strength, high viscosity, low density, and great extensibility [6]. Foamed cement has many advantages that distinguish it from other types. It has a low weight, which allows for easy installation in weak formations. It also reduces the risk of damage to productive formations. It is also used in well abandonment operations, where it forms a permanent barrier used to plug old wells. There are some restrictions on the use of foamed cement, such as the cost of field equipment and the requirement for skilled operating personnel [8].

Typically, rheology studies the deformation of those materials whose behavior falls between solids and fluids (viscoelastic materials) [9]. The study of rheological properties attempts to determine the intrinsic fluid properties; mainly viscosity, which is necessary to determine the relationships between the flow rate (shear rate) and the pressure gradient (shear stress) that causes the movement of a fluid [10]. The science of rheology can be employed for instance for achieving the following goals: evaluating the mixability and pumpability of a slurry, determining the frictional pressure when a slurry flows in pipes and annuli and designing a processing equipment such as selecting the appropriate pump to provide sufficient power for a material to flow over a certain distance in pipelines [11]. The density and rheological properties will determine the success of the initial placement of the cement [12].

Well cementing operations require good displacement of drilling fluid, which in turn requires a high viscosity cement slurry to ensure adhesion between the cement-well wall and the cement-casing [11]. The foam cement's high apparent viscosity and two-phase composition result in much improved mud removal compared to traditional slurry cementing. An increase in bubble concentration leads to an increase in viscosity, resulting in improved mud removal in most situations due to increased foam quality [3,13]. The rheological specifications of foamed cement improve with foam presence, also by improving the specifications of the base cement slurry [14]. Free water separation occurs in traditional cement, especially in cementing of horizontal and directional wells, where channels are formed above the cement, connecting different regions [11].

This laboratory work is considered a recent experience, as it constitutes a challenge in manufacturing the preparation device according to API specifications, the chemicals that used to prepare foamed cement, as well as the method of preparation and dealing with this new system. The base cement slurry with foam forms a highly viscous tissue structure that adds high stability to the foam cement system so that free water and settling disappear. This in turn prevents the forming of channels behind the casing and thus prevents the leakage of fluids between adjacent formations, especially in horizontal and inclined wells. This feature is not found in other types of lightweight cement. Also, the high viscosity plays a major role in the process of displacing the drilling fluid during the cementing process, in addition to the high expandability of foam cement and its role in compensating for the lost volume during the cementing process. It also enhances the adhesion of the cement with the casing on the one hand and with the formation wall on the other hand.

2. Materials, Apparatuses and Methods

2.1. Materials

The materials that were utilized to prepare the foam cement slurry samples to be tested are:

2.1.1. High-Resistant Sulfate G-Class Cement

Oil well cement (class G) is used in this work. It was manufactured in Germany by the Dyckerhoff Company. Their oil-well cements are tested and produced in strict accordance with the following standards:

- API Specification 10A, 24th Ed. (2010).
- ISO 10426-1:2009.

2.1.2. Water

According to the API, distilled water has been used for testing. There is no problem in choosing distilled water or reverse osmosis water. The important thing is that the concentration of salts is low. In most laboratories, distilled water is used to obtain accurate results. The high concentration of dissolved salts in the water used in cementing processes affects the performance of the foaming agent and thus affects the calculations of the volume and density of foamed cement required in cementing processes.

2.1.3. Foaming Agent

A foaming agent belongs to the surfactant agent family of materials that help with foam formation. It is the job of surfactants, which are chemical compounds, to lower the interfacial tension or surface tension between different liquids or between liquid and gas. The chemical material that was used in tests as a foam agent has a trade name called CHRYSO® Poresin 88. It has the following physical properties:

- Nature: transparent liquid
- Density at 20°C (68ºF): 1.02 g/cc ± 0.02
- pH: 8.0 ± 1.0

- Chloride free
- Equivalent Na2O: ≤ 1.0%

2.1.4. Foam Stabilizer (Low Viscosity Carboxymethyl Cellulose CMC-LV)

CMC is an acronym for carboxymethyl cellulose, which consists of carboxylate plus hydroxyl [15]. It is considered a polymer extracted from cellulose and insoluble in water. Thus, in order to make it soluble, it is adjusted to the polyelectrolyte form, which increases liquid-phase effective viscosity and filtration [16].

2.1.5. Air or Nitrogen Gas

Air is naturally composed of nitrogen (78%), oxygen (21%), various gases, and water vapor. Nitrogen is the main and desired gas for foam cement operations [13].

2.2. Apparatuses

2.2.1. Constant speed Mixer; For mixing oil well cement slurries, a cement mixer model 30-60 manufactured by Chandler Company was used as shown in Figure (1-b). It has all the requisite functions to mix water and cement slurries in accordance with API Spec. 10.

2.2.2. Multi-Blade Blender; The mixing apparatus used to prepare foamed cement slurry has specifications: container with sealing lid, threaded cap, O-ring seal, hole with plug, and five mixing blades rotating anticlockwise, as shown in Figure (1-a).

2.2.3. Graduated Cylinder; 250 ml graduated cylinder is used for stability testing, free water and determine of foamed cement density, as shown in Figure (1-c).

2.2.4. Viscometer; A viscometer model 3500 manufactured by Chandler company was used to measure the rheology properties and gel strength of oil well cement slurry, as shown in Figure (1-d).

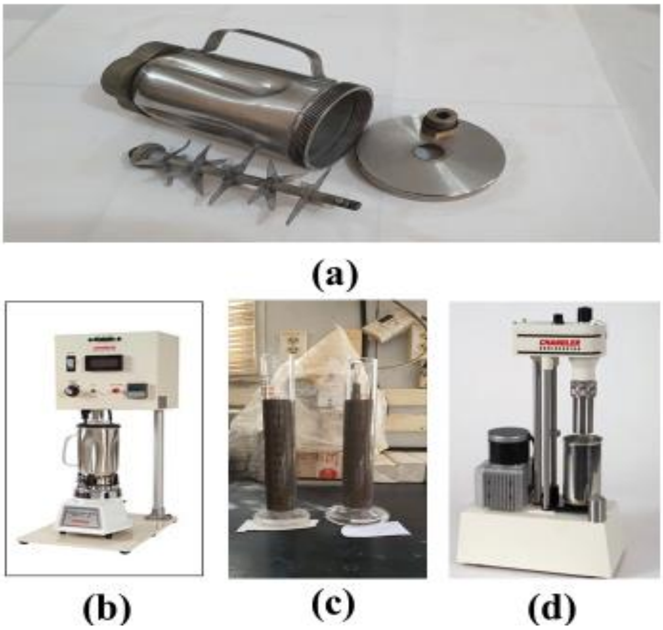

Fig. (1): Apparatuses that used in experimental work.

2.3. Methods

2.3.1. Rheological Models

Rheological Models are mathematical expressions that related the shear stress to shear rate these models take different forms based on behavior of shearing fluid.

The rheology of cement slurry depends on various factors, such as the water-cement ratio, chemical composition of the cement, grain size and shape, the distribution of its components, existence of additives, the procedure of mixing and testing, etc. [17,18].

2.3.1.1. Bingham Plastic Model [19]

The Bingham model may be characterized by two parameters: plastic viscosity and yield point as shown in Figure (2). The first factor is dependent upon the size, concentration, shape of solid particles, and the viscosity of the liquid phase. The yield point is created by the forces of attraction between solid particles due to the presence of charge on their surfaces. The mathematical representation is as follows [20]:

$$\tau = \tau_y + \mu_p * \gamma \quad \text{......} \quad (1)$$

$$\mu_p = (\Theta_{600} - \Theta_{300}) \quad \text{......} \quad (2)$$

$$\tau_y = \Theta_{300} - \mu_p \quad \text{......} \quad (3)$$

Where τ is shear stress, γ is shear rate, τ_y: is yield stress,and μ_p is the plastic viscosity.

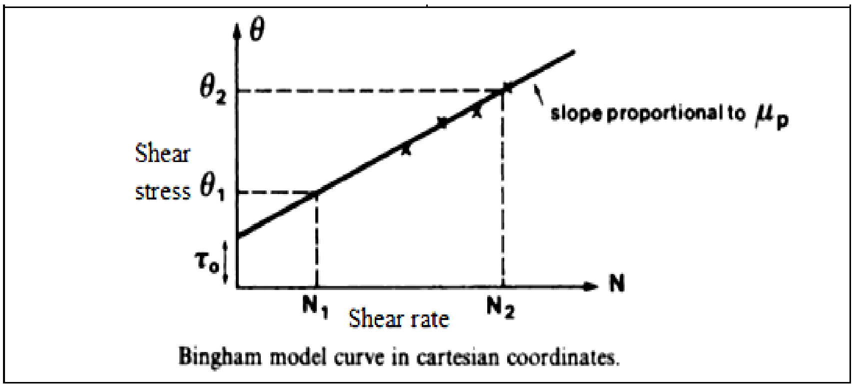

Fig. (2): Bingham plastic model [11]

2.3.1.2. Power Law Model [21]

The power law model may be determined by two variables: the consistency index ($pa*s^n$) and the power law index (dimensionless), as shown in Figure (3). The mathematical representation is as follows:

$$Ʈ= k^* \gamma^n \ldots\ldots (4)$$

γ: shear rate (s^{-1})

Ʈ: shear stress ($Ib/100ft^2$)

n: power law exponent (dimensionless)

k: Consistency index ($(Ib/100ft^2) *s^n$)

Equation (4) was linearized as follows:

$$\log Ʈ= \log k+ n^*\log\gamma \ldots\ldots (5)$$

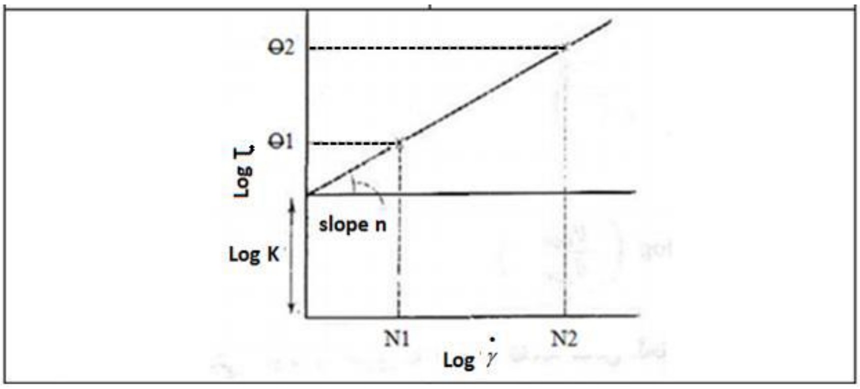

Fig. (3): Power law logarithmic graphical representation [11]

2.3.1.3. Herschel-Bulkley Model [22]

By using three parameters, Herschel-Bulkley model shows the rheology behavior of fluid. It can be represented mathematically as follows [11]:

$$Ʈ= Ʈ_{0H}+ k^* \gamma^n \ldots\ldots (6)$$

γ: shear rate (s^{-1})

Ʈ: shear stress ($Ib/100ft^2$)

n: fluid´s flow index (dimensionless)

k: Consistency index ($Ib/100ft^2$) $*s^n$

$Ʈ_{0H}$: Herschel yield stress ($Ib/100ft^2$), (The Yield stress is normally taken at 3 rpm reading) [23].

Equation (6) was linearized as follows

$$\text{Log}(Ʈ - Ʈ_{0H}) = \log k + n*\log\gamma \quad (7)$$

Figure (4) shows the graphical representation of this model.

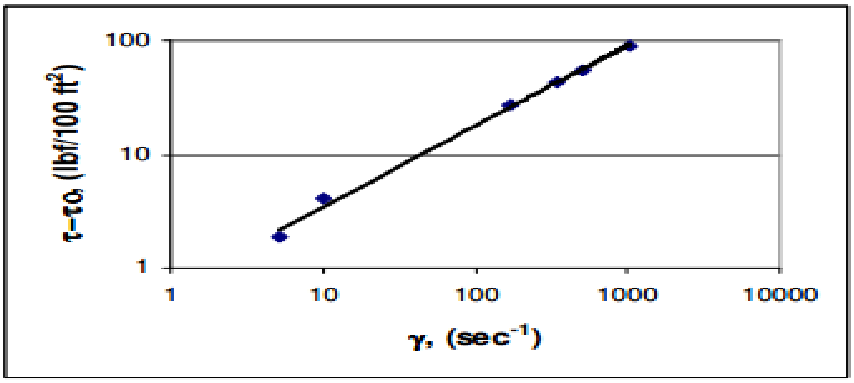

Fig. (4): Herschel-Bulkley fluid rheogram [11]

2.3.1.4. Casson Model [24]

The Casson model is a structural model that elucidates the flow behavior of viscoelastic fluids. The Casson model exhibits a more gradual transformation from the Newtonian region to the Yield region. The Casson model is mathematically represented as explained in equation 8 and Figure (5).

$$Ʈ^{0.5} = k_{0c} + k_c\, Ɣ^{0.5} \quad (8)$$

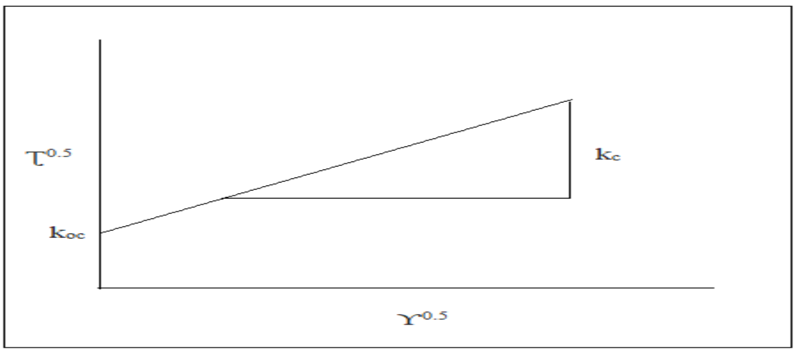

Fig. (5): Casson rheological model [23]

K_c and k_{oc} values can be determined by the linear relationship between the shear stress square root ($\tau^{0.5}$) and the shear rate square root ($\Upsilon^{0.5}$). The slope of this line represents k_c, while the intercept represents k_{oc}.

$$\text{Casson yield stress } \tau_{oc} \text{ (Pa)} = k_{oc}^2 \quad \ldots\ldots\ldots\ldots (9)$$

$$\text{Casson plastic viscosity } \eta_{ca} \text{ (mPa.s)} = k_c^2 \quad \ldots\ldots\ldots\ldots (10)$$

2.3.1.5. Absolute Average Percentage Error E_{AAP} [23]

The E_{AAP} is measure of deviation of models from measured stresses and its given by the equation 11.

$$E_{AAP} = \left[\frac{1}{N} \Sigma \left| \frac{(\tau \text{ measured} - \tau \text{ calculated})}{\tau \text{ measured}} \right| \right] * 100\% \quad \ldots\ldots\ldots (11)$$

2.3.2. Free Water Content

The reason of applying free water control is to address the problem of water getting out of the slurry and departing from the intended path of the well. This can result in the water rising, breaking out, and creating a channel on the higher side of the well, especially in decline and horizontal wells. Consequently, this leads to form of a connection between the high-pressure and the low-pressure zones in the formations, which is a significant challenge in cementing operations.

The free fluid quantity that collects on the top of cement slurry from the moment it is added until it sets is determined by this process [25]. According to API Spec.10A [26], the percentage of free fluid should not exceed 5.9%. To measure the free water content of the base or foam cement slurry the following steps are listed below:

1. Preparing cement slurry according to API procedures Placing cement slurry in an atmospheric pressure consistometer for 20 minutes at 190 ^{o}F maximum temperature.
2. Pouring of cement slurry into a 250 ml graduated cylinder. Closing the mouth of the cylinder and putting it on a vibration-free surface for 2 hours
3. Pulling free fluid from the highest point of the cement slurry to measure the percent of free water (ϕ) based on the weight and the specific gravity of the cement by utilizing the equation below.

$$\Phi = ((VFF * \rho) / MS) * 100 \quad \ldots\ldots\ldots\ldots\ldots\ldots (12)$$

Where;

VFF is the volume of free water, expressed in millilitres.

ρ is the specific gravity of cement slurry, expressed in g/cm^3.

MS is the mass of the cement slurry.

ϕ is the volume fraction of free water in cement slurry.

2.3.3. Foamed Cement Stability

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 providing a uniform distribution of bubble sizes. Typical foam stabilizers can be divided into three categories according to their mode of action:

1. Synergistic foam stabilizers enhance the interaction between surface adsorption molecules through synergistic action [27].
2. Viscosity-increasing foam stabilizers increase the viscosity of the liquid phase to reduce the discharge rate of foam [28].
3. The third category is the solid particle-type stabilizer [29].

The foamed slurry is placed into a graduated cylinder of 250 cc and covered from the top. For two hours, any decrease in the foam slurry height is recorded; whenever the decrease in slurry is small, 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, it means stability is excellent. 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. If foamed cement is unstable, gradually add a foam stabilizer until the best stability is obtained [30].

3. Results and Discussions

3.1. Rheological Properties Results

The purpose of this test is to examine the un-foamed and foamed cement slurry in order to identify the most effective model for this system. Additionally, the study aimed to investigate the impact of foam concentration on the model type choice. Four rheological models, which are Bingham plastic, power law, Herschel Bulkley, and Casson models, were used to determine the suitable rheological model of foamed cement. Results of this test are listed in Table (1) and illustrated in Figures (6) to (8) for cement slurry with foam agent and foam stabilizer.

Table (1): Rheological results of un-foamed cement slurry

Cement + water + foam agent + CMC-lv + 0% foam (1.88 g/cc)							
Dial speed RPM	Dial reading lb/100ft^2	Shear rate (s^{-1})	Shear stress(Pa) for models				
			measured	Bingham plastic	Power Law	Herschel-Bulkley	Casson
3	5.5	5.11	2.8	3	2.4	3.1	2.5
6	6.5	10.22	3.3	3.1	3.1	3.2	2.9
30	8.5	51.09	4.3	3.6	5.5	4.6	4.7
60	11	102.18	5.6	4.3	7.1	6	6.3
100	14.5	170.3	7.4	5.2	8.6	7.7	8.1
200	25	340.6	12.8	7.5	11	11.7	12.1
300	32	510.9	16.3	9.8	12.8	15.3	15.8
Absolute average percent error E_{AAP}				23.6	18.2	5.88	8.67
R^2					0.9059	0.9897	0.9839
Gel. Strength (Pa); 2.04 at 10 sec. 4.08 at 10 min.							

Model	PV (mPa.s)	Yp (Pa)	K (pa.s^n)	N
Bingham plastic	0.01339	2.933		
Casson	0.01364	1.767		
Power Law			1.3166	0.3645
Herschel-Bulkley			2.861	0.854

The rheological properties testing showed the unfoamed cement slurry behavior is closely related to the Herschel Bulkley model, with a 5.88 E_{AAP} and 0.9897 R^2. Following is the Casson model, which is slightly higher E_{AAP} and lower R^2. While the Bingham plastic and power law models indicate a large difference when compared to the measured reading, the absolute average percentage errors were greater than 18.

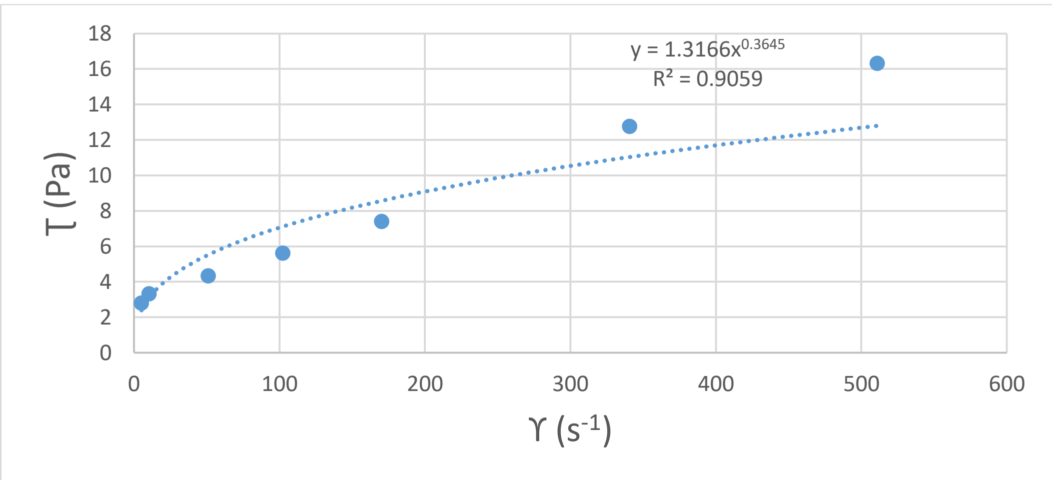

Fig. (6): Power law model for un-foam cement slurry

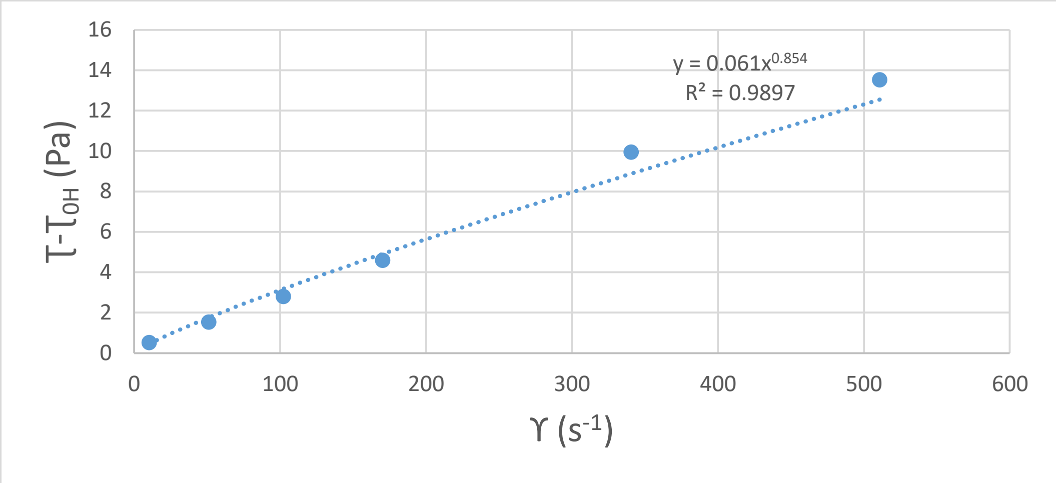

Fig. (7): Herschel Bulkley model for un-foam cement slurry

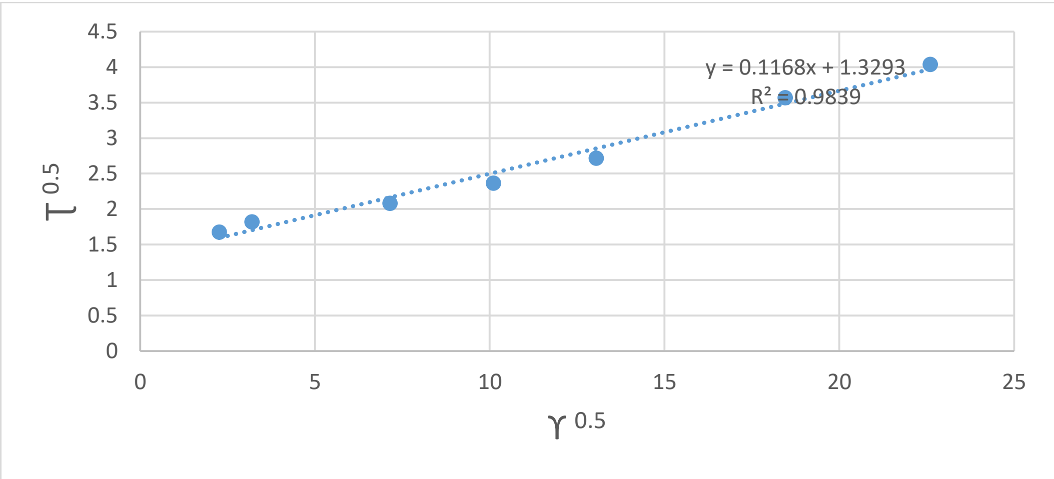

Fig. (8): Casson model for un-foamed cement slurry

In the next step, foam quality of 15% was injected into the slurry, reducing the density to 1.6 g/cc, and the results of testing are shown in Table (2) and in Figures (9) to (11).

Table (2): Rheological results of foam cement slurry contain 15% foam

Cement + water + foam agent + CMC-lv + 15% foam (1.6 g/cc)							
Dial speed RPM	Dial reading lb/100ft^2	Shear rate (s^{-1})	Shear stress(Pa) for models				
			measured	Bingham plastic	Power Law	Herschel-Bulkley	Casson
3	8	5.11	4.1	3.8	3.5	4.5	3.7
6	9.5	10.22	4.9	4	4.6	4.8	4.3
30	13.5	51.1	6.9	5	8.6	7	7.2
60	18	102.2	9.2	6.2	11.3	9.5	10
100	23.5	170.3	12	7.9	13.8	12.5	13.1
200	37.5	340.6	19.1	12.2	18.1	19.5	20
300	56	510.9	28.6	16.4	21.3	26	26.3
Absolute average percent error E_{AAP}				28.19	16.34	4.28	8.11
R^2					0.9233	0.9968	0.985
Gel. Strength (Pa); 4.08 at 10 sec. 10.2 at 10 min.							

Model	PV (mPa.s)	Yp (Pa)	K (pa.s^n)	N
Bingham plastic	0.02486	3.69		
Casson	0.02477	2.454		
Power Law			1.8283	0.3935
Herschel-Bulkley			4.1939	0.8744

The Herschel Bulkley model gives calculated shear stresses that are almost identical to the measured shear stresses and have the lowest E_{AAP} 4.28 and 0.9968 R^2, followed by the Casson model of 8.11 E_{AAP} and 0.985 R^2. Bingham and power law models exhibit large E_{AAP}, above 16.

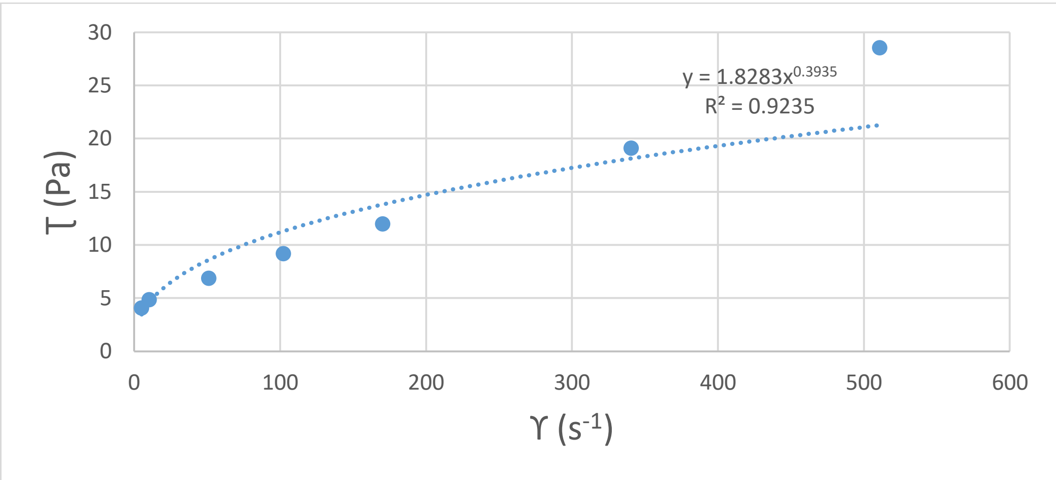

Fig. (9): Power law model for cement slurry contain 15% foam

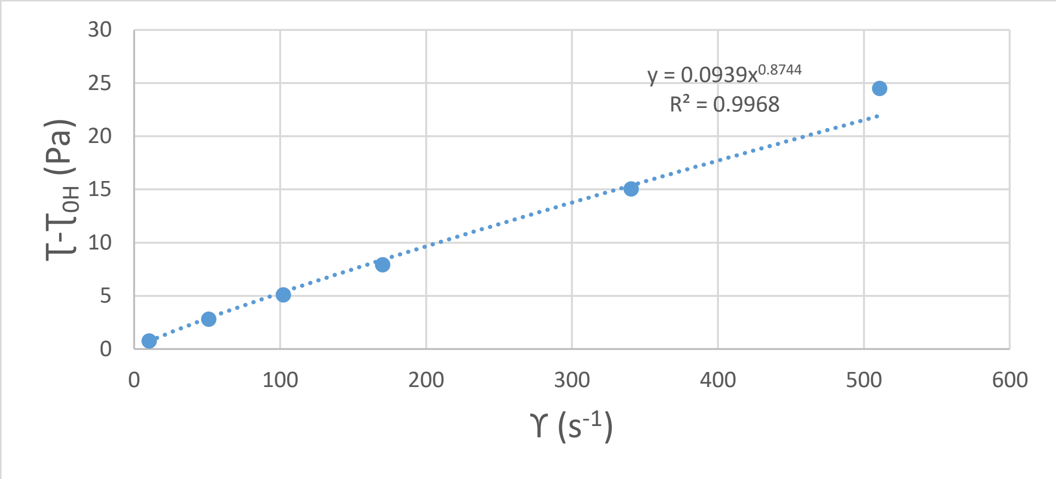

Fig. (10): Herschel Bulkley model for cement slurry contain 15% foam

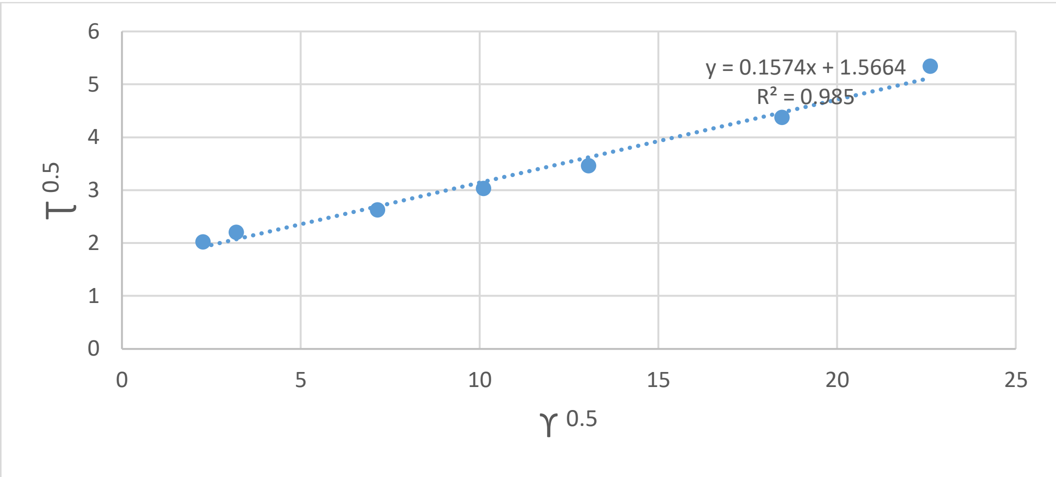

Fig. (11): Casson model for cement slurry contain 15% foam

Table (3): Absolute average percentage error and R^2 for rheological models

Density g/cc	Foam quality	Bingham	Power law		Herschel-Bulkley		Casson	
		E_{AAP}	E_{AAP}	R^2	E_{AAP}	R^2	E_{AAP}	R^2
1.88	0	23.6	18.2	0.9059	5.88	0.9897	8.67	0.9839
1.6	15	28.19	16.34	0.9233	4.28	0.9968	8.11	0.985

As shown in Table (3), the lowest E_{AAP} and higher R^2 in all models is the Herschel Bulkley model, so it can be considered the most appropriate model for the foam cement system, followed by the Casson model with a slightly higher E_{AAP} and lower R^2 while the Bingham and power law models have the highest difference with measured stresses, as shown in Figures (12) and (13). Also, unfoamed and foamed cement have the same rheological model.

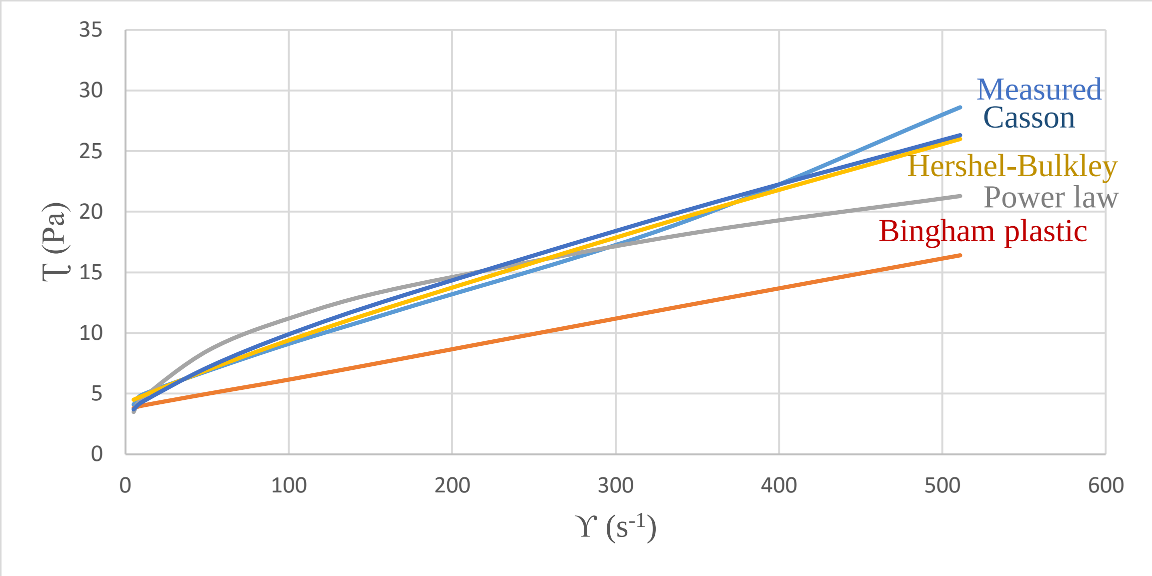

Fig. (12): Shear stresses vs. shear rate for base cement slurry

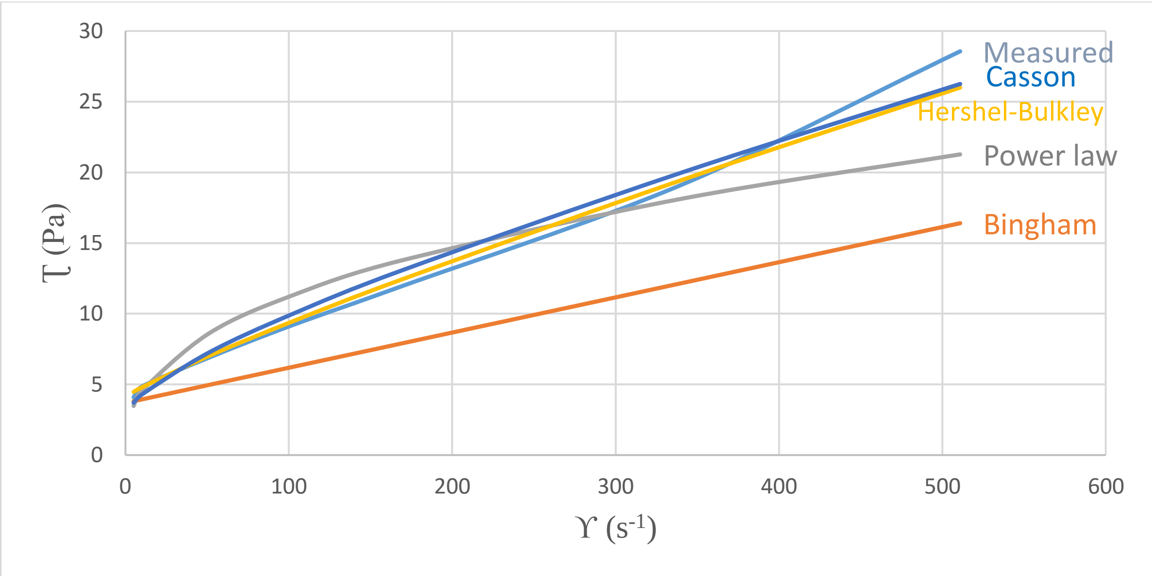

Fig. (13): Shear stresses vs. shear rate for cement slurry contain 15% foam

3.2. Effect of Foam Quality on Stability

One of the important factors in the foam cement system is stability, as it directly affected some properties such as free water and settling, as well as permeability and compressive strength. Table (4) and Figure (14) presents the results of this trend of tests .The results showed that stability increases with increased foam quality, and this indicates that the amount of foam is considered a second stabilizing factor with the foam stabilizer (CMC-lv).

Table (4): Foam cement stability with foam qualities

Density g/cc	Foam quality%	Foam slurry initial vol.cc	Foam slurry final vol. 2 hr. cc	Free foam cc	(Free foam /total foam) %
1.6	15	250	248	2	5.3
1.4	25.5	250	247	3	4.7
1.2	36	250	246	4	4.4
1.0	47	250	245	5	4.3

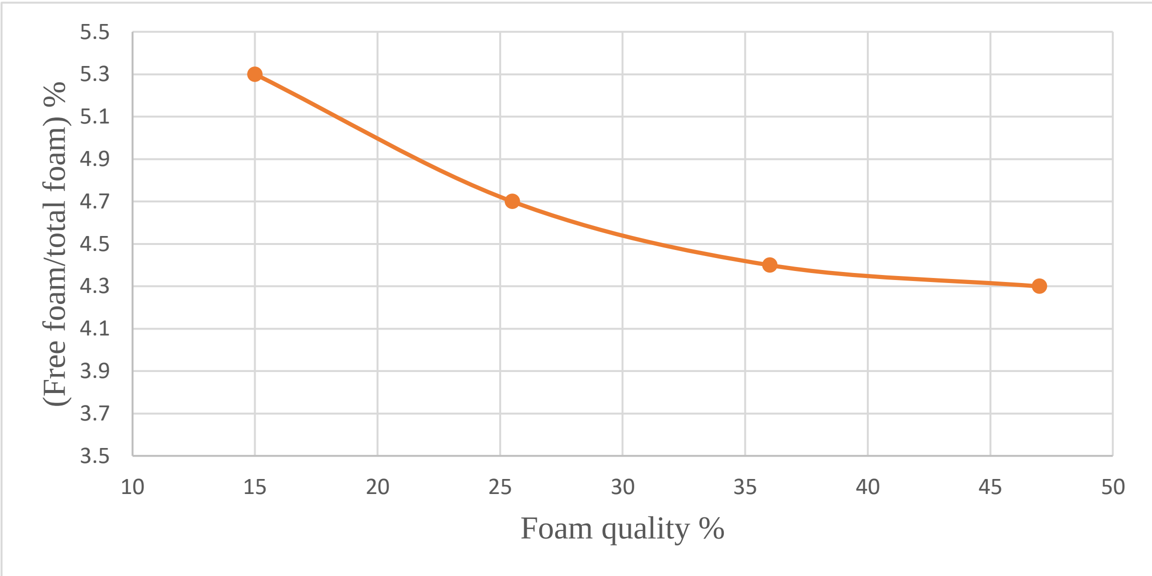

Fig. (14): Relation between foam cement stability and foam quality

3.3. Effect of Foam Quality on Free water

Free water volume is another important factor that should be tested in the formulation of foam cement. Table (5) and Figure (15) depicts the results of this trend. The results indicated that foam cement has higher stability than the base slurry. As the quality of foam cement increases, it exhibits enhanced stability by effectively holding water particles and cement grains between the bubbles. Therefore, the foam system becomes devoid of any free water.

Table (5): Free water with foam quality

Density g/cc	Foam quality%	Free water %
1.88	0	2.08
1.6	15	0.12
1.4	25.5	0
1.2	36	0
1.0	47	0

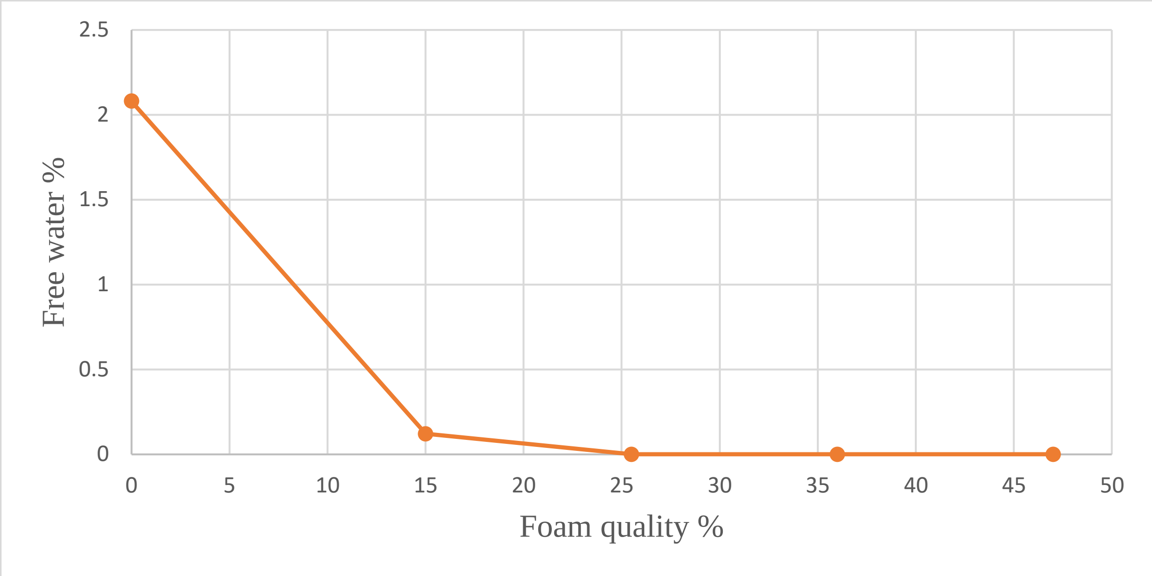

Fig. (15): Relation between free water and foam quality

Table (6): Effectiveness of foam quality with plastic viscosity, free water and stability

Density	Foam quality	Plastic viscosity	Free water%	(Free foam /total foam)%
1.88	0	0.01339	2.08	......
1.6	15	0.02486	0.12	5.3
1.4	25.5	0.02563	0	4.7
1.2	36	0.026775	0	4.4
1.0	47	0.0306	0	4.3

As shown in Table (6), increasing the foam quality leads to an increase in the viscosity of the foamed cement system, and thus the system is more stable, as shown in the stability results, notice a decrease in the released gas as a volumetric ratio to the total foam volume. Also, the percentage of free water disappears with the presence of gas bubbles spreading between Cement granules and water droplets. This means that the components of the foam system are in excellent compatibility and are useful in cementation operations in terms of displacing the drilling fluid, maintaining the properties of the cement, and not forming channels behind the cement shell.

4. Conclusion

1. Four rheological models were applied to the base and foamed cement to identify the most suitable model for the cement slurry to appear with the lowest error rate as well as to identify the rheological behavior of the cement slurry and the extent of the effect of adding foam in different proportions to the cement slurry. The rheological model closest to base and foamed cement is

Herschel-Bulkley, and the presence and concentration of foam does not change the rheological behavior of the cement system, as this model applies to cement in general.

2. The viscosity of the foam cement system increases with the increase in foam quality, which is an excellent and useful indicator in the process of displacing the drilling fluid during the cementing process, thus ensuring the adhesion of the cement to the casing and the formation wall, in addition to being lightweight, which enhances the cementing process in narrow areas and channels.
3. The foam system becomes more stable with the increase in foam quality, this is due to the small air bubbles and their regular distribution throughout the continuous phase, i.e., the base cement slurry. These bubbles hinder the movement of water towards the top and cement particles towards the bottom, so the system appears highly stable without free water and settling. This is a useful indicator as it gives enough time for the foam cement slurry to maintain its original shape until hardening.
4. There is a high compatibility between the components of the foam cement system, i.e., cement slurry with the foaming agent, CMC, and the foam, where the viscosity, stability, and free water are at their best. These materials formed a new, harmonious system in terms of the materials' harmony with each other without negatively affecting the function of each material. Therefore, the foamed cement system appeared with high stability, such that free water and cement deposits disappeared completely.

Author Contribution Statement: Qassim M. Sayed proposed to the conception of the research idea, design, data collection and processing, and data analysis and interpretation. Hassan A. Abdul Hussein, additionally contributed to the research design. All authors contributed collectively to the literature review, manuscript drafting, and the overall revision and proofreading of the final version.

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