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Rheology of foamed cement

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ABSTRACT

Foams are being used in a number of petroleum industry applications that exploit their high viscosity and low density. Foamed cement slurries can have superior displacement properties relative to non-foamed cement slurries. This article presents results of an experimental study of foamed cement rheology. Viscosity curves of foamed cements were obtained using a flow-through rotational viscometer. Foamed cements with different foam qualities were generated under different pressures using a foam generator/viscometer apparatus. The foam qualities during the tests ranged from 0% to 30%, and the shear rate varied between 5 s^{-1} and 600 s^{-1}. Experimental results indicate that: i) unlike conventional aqueous foams, low-quality cement foams have a lower viscosity than the base fluid; ii) as the cement foam quality (gas volumetric fraction) increases from 10% to 30%, the viscosity also increases; and iii) the viscosity of low-quality cement foam slightly increases after depressurization or expansion.

1. Introduction

Cementing of a well is normally undertaken to fill and seal the annulus between the casing string and the drilled hole. Properly placed cement can effectively isolate different formation zones (i.e. zonal isolation). Adequate zonal isolation allows the production of oil and gas from the producing formations and prevents leaks into the surface and to other subsurface formations. During cementing operation, the volume and physical properties of the cement slurry are determined before starting the operation. Then, the slurry is pumped into the wellbore to displace drilling fluids and place cement in the annulus.

Foam cement is often considered as an alternative to conventional cement when lower slurry densities are required or when good long-term performance is required as in cementing high-pressure high-temperature zones. Especially, low-density foamed cement meets challenges of weak formations and low-pressure depleted zones. Foamed cement is a compressible fluid; as a result, the density and quality (i.e. volume fraction of the gas phase) changes during its circulation in the well due to significant pressure variations. During foam cementing operation, foam is generated at the surface and injected into the casing. It flows down the inside of the casing and then up the annulus formed between the casing and the drilled hole. As it flows down the casing, the pressure increases, resulting in decrease in foam quality. After reaching the bottom of the hole, the quality will then increase again when the foam flows up in the annulus due to reduction in pressure (depressurization).

A number of field studies indicate that foamed cement may outperform conventional cement for zonal isolation. Large-scale laboratory testing has shown that foamed cement is ductile and can deform as casing is pressurized, but it will not crack like conventional cement [1]. However, flow behavior of foamed cements is not well understood. Therefore, studies of cement foam rheology are necessary to improve our understanding of foamed cement and the quality of foam cementing jobs. Foamed cement slurries are considered to have better drilling-fluid displacement properties than non-foamed cement slurries. This is because foamed cement is expected to have higher viscosity (shear viscosity) than the base slurry. In addition to the viscosity, the extensional viscosity (i.e. the resistance of fluid to an imposed elongation rate) may affect fluid displacement efficiency of oil well cements. Moreover, foamed cements lower the overall slurry fluid loss and thereby help to control gas and fluid influx into the setting cement [2–5].

Viscometeric measurements performed under controlled conditions can be useful to understand physical mechanisms that determine the rheology of foamed cement. This study has been conducted to investigate the rheology of foamed cement under different foam generation conditions. The overall objectives of this study are: i) to investigate effect of foam quality on the rheology and flow properties of foamed cement; and ii) to study the secondary effect of pressure (the effect of pressure under constant foam quality) on the rheology of foamed cement.

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2. Foams and foam cements

The rheological behavior of foams is unlike that of single-phase homogenous fluids. The difference arises from many factors. Foams are compressible, heterogeneous, and unstable fluids. They are considered as shear-history-dependent fluids in which the foam structure may be continuously changed [6]. Because foams are unstable, rotational viscometers with a fixed amount of sample are not suitable for rheological measurements of foams [7]. Flow characteristics of foam in a Couette viscometer demonstrate a strong localization of the flow at the moving inner wall [8]. A recent study [9] conducted using NMR and a rotational viscometer shows that foam cannot flow steadily below a critical shear stress. At low rotational speeds, the shear localizes in a layer of thickness decreasing with the shear rate. When this thickness becomes smaller than a critical value (about 25 bubble diameters), the continuum assumption is no longer valid [9].

Flow properties of foams are significantly influenced by foam quality (i.e. gas volumetric fraction). The quality of foam at given pressure and temperature is expressed as:

$$\Gamma = \frac{V_g}{V_L + V_g}, \tag{1}$$

where V_g and V_L are the volume of gas and slurry [m^3], respectively. In addition to the quality, the flow properties of foams/emulsions at lower volume fractions of dispersed phase are also dependent on both the size of the bubbles/droplets and the distribution of their sizes. Bubbles or droplets can be deformed or rearranged by the applied shear [10,11]. At low shear rates, spectroscopy measurements of continuously sheared aqueous foam [11] show isolated clusters of bubbles intermittently rearrange from one solidly packed configuration to another even though the macroscopic flow appears continuous. Due to the instability of foams, the mean bubble size varies as the foam is being continuously sheared. Variation in the bubble size results in considerable change in the rheological properties of the foam [12].

Literature concerning the flow of aqueous foams is abundant; however, studies of the rheology of foamed cement are limited. Al-Mashat [13] reported flow experiments on foamed cement performed in two capillary tubes with diameters of 2.3 mm and 3.4 mm. The foam qualities during the tests ranged from 30% to 65%, and the shear rate varied between 1000 s^{-1} and 10 000 s^{-1}. His results suggested that the plastic viscosity of foamed cement increases with the foam quality and decreases with an increasing shear rate to an almost constant value, thus indicating Newtonian behavior at high shear rates. Viscometric flow curves showed the dependency of viscosity measurements on pipe size and the size of foam bubbles.

More recently, Griffith et al. [14] discussed the performance of cement foams under high-temperature, high-pressure (HTHP) conditions. They investigated the solubility of nitrogen in water and cement slurries. Their study indicated that the effect of nitrogen solubility on the foam quality is minimal under HTHP conditions.

2.1. Rheology of low quality foams

Foams are complex mixtures of gases and liquids or slurries, whose rheological and hydraulic properties are largely influenced by foam quality, liquid-phase viscosity, temperature, and pressure. Beyer et al. [15] found that pressure and temperature influence foam rheology mainly by affecting foam quality and liquid-phase viscosity. A significant increase in pressure reduces the volume occupied by the gaseous phase and indirectly reduces the foam quality and viscosity. At constant pressure, often an increase in temperature decreases the viscosity of the liquid phase. Consequently, the foam viscosity predominately increases as the temperature decreases.

Rheological measurements performed on stable foam [16] indicated the presence of transient and steady state regimes when a constant shear rate is applied. In the transient regime, the measured stress varies with time at a constant shear rate and is followed by the steady state regime where the stress is stabilized. Janiaud et al. [17] formulated a continuum model that incorporates elasticity, yield stress, plasticity, and viscous drag. The model predicts exponentially decaying velocity profile and strain localization, which are observed from the experiments of Debregeas et al. [8].

A recent study [18] on rheology of low quality foams using an oscillatory rheometer shows increase in viscosity with increasing quality at low frequencies. However, results obtained at high frequencies indicate decrease in viscosity as the quality increases. Bubble deformation is one of the mechanisms that results in reduction of foam viscosity. Similar results have been obtained when suspensions of rhyolitic glasses of varying bubble concentrations were investigated [19] experimentally. Results show the negative effect of bubble concentration on the viscosity of the suspension.

Often, foam flows are characterized by bubble deformations and rupturing, which may have significant effect on the rheology. In steady, homogenous shear flow, a small change in bubble shape from sphericity depends upon the capillary number, C_a. The capillary number (Eq. (2)) is a relative measure of viscous forces that tend to distort the bubble and interfacial tension, which favors sphericity. The capillary number is given by:

$$C_a = \frac{a\dot{\gamma}\mu_L}{\sigma}, \tag{2}$$

where a, σ, and $\dot{\gamma}$ denote average bubble radius [m], interfacial tension [N/m], and shear rate [1/s], respectively. The rheology of bubbly suspensions was investigated numerically by Manga et al. [20]. For flows with low capillary number (i.e. $C_a<0.5$), simulation results indicate that the viscosity of bubbly suspensions is a weakly increasing function of quality. However, at higher capillary number, deformed bubbles become aligned in the direction of flow, reducing the viscosity of suspensions as the quality increases [20].

2.2. Rheology models for low quality foams

Rheological characteristics of low quality foams and dilute suspensions have been investigated experimentally and theoretically for several years. Both empirical and mathematical modeling approaches were considered to predict foam viscosity as a function of quality and liquid phase viscosity.

2.2.1. Empirical models

A number of studies have developed empirical rheology models for low quality foams. The modeling involves formulating a constitutive law based on experimental results. These models often do not have a physical basis. Mitchell [21] investigated the viscosity of low-quality foams ($\Gamma \leq 0.54$) using small-diameter pipe viscometers and developed an empirical equation for foam viscosity as:

$$\mu_f = \mu_L(1 + 3.6\Gamma), \tag{3}$$

where μ_f and μ_L are foam and base-fluid viscosities [Pa s], respectively; and Γ is foam quality or gas volumetric fraction. Eq. (3) indicates that the viscosity of low-quality foam increases linearly with foam quality. By contrast, experiments relating to the behavior of porous glasses show a decrease in viscosity with increasing bubble concentration. Rahaman et al. [22] presented the following correlation to predict the viscosity of porous glasses:

$$\frac{\mu_s}{\mu_L} = e^{-11.2\Gamma}, \tag{4}$$

where μ_s is suspension viscosity [Pa s].

2.2.2. Mathematical models

Mathematical modeling of foam rheology is a challenging task. Several mathematical models have been proposed to predict viscosity of foams based on flow properties of each phase, and foam composition and structure. The microscopic structure and fluid dynamics of foams are poorly understood. Based on the Navier–Stokes equations, Batchelor [23] developed a mathematical model for the viscosity of a dilute suspension of small particles. The model is developed based on the following assumptions: i) the effects of gravity and inertia on the motion of a particle are negligible; ii) the particles are assumed spherical; iii) and the capillary number is small compared with unity. Under these conditions, the viscosity of dilute suspension can be expressed as:

$$\frac{\mu_s}{\mu_L} = 1 + \Gamma\left(\frac{1 + 2.5\lambda}{1 + \lambda}\right) \quad (5)$$

where λ is the viscosity ratio, which is defined as the ratio of the viscosity of dispersed phase to that of continuous phase. For bubbly suspensions, the value of λ is negligible. Hence, according to this model, the viscosity of the bubbly suspension is greater than the viscosity of the base fluid by a fraction of Γ. The increase in viscosity with increasing quality prediction arises because flow lines are distorted around the bubbles. However, as the Capillary number increases, bubbles become increasingly deformed and this relationship is no longer valid [18].

Rheologies of diluted suspensions that are formed with highly viscous base liquid have been extensively studies to understand the dynamics of magmatic flows. The dependence of suspension viscosity on gas volumetric fraction for highly viscous base liquid differs from the relationship obtained for bubbly suspensions with low viscosity base liquid [19]. Theoretical analysis and experimental study conducted on bubbly glass suspensions [24] demonstrate the decrease of suspension viscosity when the gas fraction increases. Applying the viscous analogy of elastic stresses, Sura and Panada [24] developed the following equation for estimating the viscosity of bubbly glass suspensions:

$$\frac{\mu_s}{\mu_L} = \frac{3(1-\Gamma)^2}{3(1-\Gamma) + 2\Gamma} \quad (6)$$

Cement foam flows are expected to be dominated by high capillary numbers because foamed cements are generated using highly viscous base slurries. Barthes-Biesel and Chhim [25] developed a constitutive equation (Eq. (7)) for dilute suspensions that accounts for high values of capillary number. The equation is based on a mathematical analysis of the behavior of Newtonian liquid droplets, with elastic bounding membranes, that are suspended in a Newtonian viscous liquid. The Barthes-Biesel and Chhim [25] equation is expressed as:

$$\frac{\mu_s}{\mu_L} = 1 + \left(2.5 - \psi C_a^2\right)\Gamma, \quad (7)$$

The value of the dimensionless parameter ψ is determined using the following equation:

$$\psi = 68.5 + 21\varphi + 60\lambda, \quad (8)$$

where φ is a dimensionless constant that accounts for nonlinearity of the membrane material. The viscosity ratio (λ) for cement foam is on the order of 10^{-5}. For theoretical analysis, foam lamella can be considered as membrane materials. When the surface tension is assumed constant, the value of the nonlinearity constant becomes negligible. Therefore, a reasonable value of ψ is approximately 70 [26]. This suggests that there is a critical capillary number (i.e., $C_{a,crit} = \sqrt{2.5/\psi} \approx 0.19$) above which Eq. (7) predicts relative viscosity (μ_s/μ_L) of less than one. Consequently, for high capillary flows (i.e., $C_a > 0.19$), the viscosity of the foam can be less than the liquid-phase viscosity. Fig. 1 compares relative viscosity predictions of Barthes-Biesel and Chhim model (Eq. (7)) with other rheology models (Eqs. (5) and (6)).

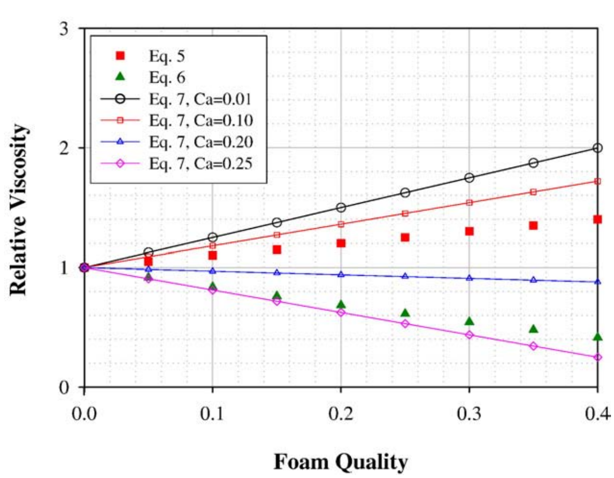

Fig. 1. Relative viscosity predictions of foam and suspension rheology models.

Table 1
Test matrix for foam cement rheology experiments.

Test type	Test fluid	Quality (%)	Pressure (MPa)
Tests conducted to study the effects of pressure and quality	Base slurry	0	0
	Foam 1	10	0.4
	Foam 2	10	7.0
	Foam 3a	10	7.0
	Foam 4	20	7.0
	Foam 5	20	3.5
	Foam 6	30	0.4
	Foam 7	30	2.4
	Foam 8	30	7.0
Tests conducted to study the effect of depressurization	Foam 3a*	10	7.0
	Foam 3b*	20	3.5
	Foam 3c*	30	2.4

*Depressurization tests performed under static conditions.

2.3. Non-Newtonian behavior of cement foam

Cement foams often show non-Newtonian behavior such as shear thinning and yield stress. As a result, non-Newtonian constitutive equations such as Bingham, Power Law, and Herschel–Bulkley models are applied in the petroleum industry. The Herschel Bulkley model is expressed as:

$$\tau = \tau_y + k\dot{\gamma}^m, \quad (9)$$

where τ and τ_y are shear and yield stresses [Pa], respectively; k is consistency index [Pas^m], and m is the flow behavior index. At present, this model is preferable because it combines the effects of Bingham ($\tau = \tau_y + k\dot{\gamma}$) and Power Law ($\tau = k\dot{\gamma}^m$) fluid models. Applying the Herschel–Bulkley model (Eq. (9)), the apparent viscosity of foam cement, η [Pas], can be expressed as:

$$\eta = \frac{\tau_y}{\dot{\gamma}} + k\dot{\gamma}^{m-1}. \quad (10)$$

According to Eq. (10), a plot of apparent viscosity versus shear rate on a log–log scale gives a straight line for power-law fluids. However, a similar plot for Herschel–Bulkley fluid forms a curve on a log–log scale.

2.4. Wall slip

Wall slip is normally considered one of the most important characteristics of foam flow. Foam rheology measurements present considerable experimental difficulties related to the phenomenon of wall slip. Slip occurs in foam flow because of the displacement of the

Table 2
Materials used to prepare 1 l of base slurry.

S/N	Material	Quantity
1	Tap water	401.56 g
2	Cement slurry foaming agent (B237*)	26.84 g
3	Dispersant/plasticizer (B165*)	31.80 g
4	Fluid loss control/water retention additive (D193*)	68.46 g
5	Cement class G	1521.35 g

*Liquid additives provided by Schlumberger.

gas phase away from the wall. A convenient description of the wall slip mechanism is based on the existence of a thin liquid film that does not itself slip but wets the wall and lubricates the bulk foam flow [27]. Because of wall slip, a higher foam flow rate is normally observed compared to that which would occur if the slip were not present. As a result, different flow curves are obtained when foam is tested with different pipe viscometers [28]. Moreover, rheology experiments conducted using rotational viscometers that have different dimensions indicate the presence of wall slip [29].

3. Experimental investigations

The viscosity curves of foams that contain different gas-phase concentrations were obtained using a flow-through rotational viscometer. A test matrix that shows the details of these experiments is presented in Table 1. Two types of rheology tests were carried out. The first type of test was conducted to investigate the effects of pressure and quality on the rheology of cement foams. The second type of test was performed to study the effects of depressurization on the rheology of foam. All the tests were conducted at ambient temperature (approximately 21 °C).

3.1. Materials used to prepare the foamed cement

All test foams were composed of cement base slurry and nitrogen. The base slurry consisted of a class G cement system containing appropriate levels of dispersant, foaming agent, and fluid-loss additives. The composition of the base cement slurry (Table 2) was the same throughout the entire study. Liquid–solid ratio and surface tension of the base slurry were 0.35 ml/g and 20 mN/m, respectively.

3.2. Experimental setup

Figs. 2 and 3 show a schematic and picture of the foam generator/viscometer apparatus. Some important features of this apparatus include the following: i) a cylinder with a movable dome-shaped piston inside, which separates the cylinder into two chambers (mixing chamber and pneumatic chamber); ii) a caliper attached to the piston rod to measure piston displacement; iii) a propeller/agitator to generate the foam; iv) a variable-speed drive motor that turns the propeller over a wide range of rotary speeds; v) a flow-through rotational viscometer; and vi) an electronic balance.

A flow-through rotational viscometer was specifically selected to measure viscosity of foams because it enables foam to enter at the top of the measurement cup and leave at the bottom (Fig. 4); thus, during the rheology measurement process, any foam degradation such as drainage and bubble coalescence is compensated by introducing new foam into the measuring cup, which has a diameter of 40 mm. For this investigation, a 36-mm-diameter rotor is used. Before conducting the rheology tests with foam cements, viscometric measurements were evaluated and verified for their accuracy using standard viscometer calibration fluids. The accuracy of the viscometer, based on the tests performed with standard calibration fluids, is 2.1% of the measured values.

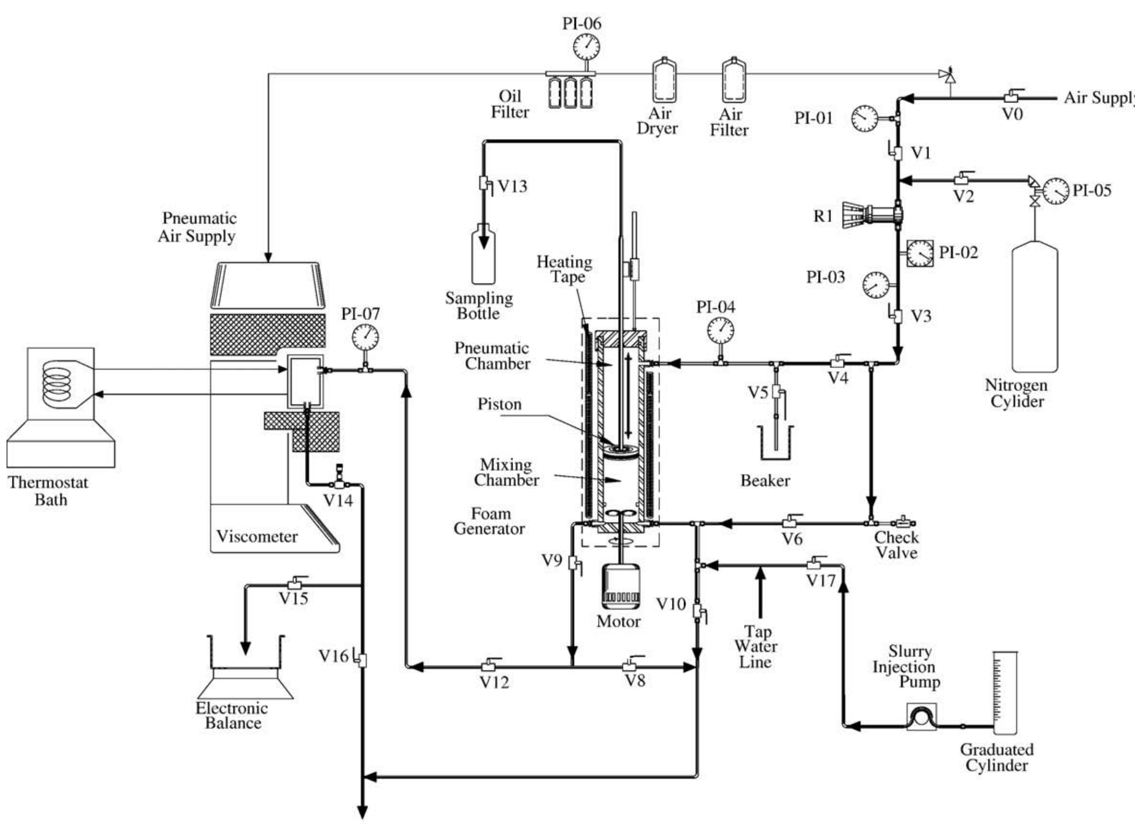

Fig. 2. Schematic diagram of foam generator/viscometer.

Some auxiliary components are necessary for proper functioning of the foam generator/viscometer; these are: i) a low-volume slurry injection pump that can pump the proper amount of slurry into the mixing chamber; ii) a gas source (nitrogen cylinder) with pressure regulators, gauges, and control valves to introduce gas at a selected pressure into the mixing chamber and the pneumatic chamber; and iii) a thermostatic bath to maintain constant temperature in the viscometer. The slurry injection pump transfers the required quantity of slurry from a graduated cylinder, which is connected to the inlet side of the pump as shown in Fig. 2. The quantity of the slurry injected to the chamber is accurately measured by recording the initial and final base slurry levels in the graduated cylinder.

An essential feature of the foam generator/viscometer shown in Fig. 2 is that, once constant-property foam is generated, valves are manipulated to inject gas to the pneumatic chamber to maintain constant pressure on the foam. Pressure in the pneumatic chamber is kept constant using the pressure regulator (R1). Hence, the pneumatic chamber can maintain constant pressure in the mixing chamber when foam flows continuously from the mixing chamber to the viscometer.

Foam flows from the generator to the viscometer when a micrometer valve (V14) downstream of the viscometer is opened. The rate at which the foam flows out of the generator is determined by measuring liquid-phase mass flow rate at the outlet of the viscometer with an electronic balance. It is important to maintain optimum flow rate (approximately 15 ml/min) through the viscometer. The optimum flow rate of 15 ml/min results in an axial shear rate (i.e. nominal Newtonian) of approximately 3 s^{-1} at the wall and an average foam residence time of 4 min in the viscometer. On trial experiments conducted as ambient conditions, foamed cement showed remarkably high stability with a half-life (i.e. the amount of time it takes for the foam to collapse to 50% of its original liquid volume) of more than 2 h. The electronic balance shown in Fig. 2 is used to determine mass flow rate of the base slurry passing through the viscometer. If we control the micrometer valve (V14), the foam flow rate is acceptably maintained at the desired level. The back-pressure in the viscometer is carefully monitored using the pressure gauge placed at the inlet (P0-07) of the viscometer. Backpressure monitoring helps to identify the presence of pipe plugging because of cement deposition/solidification. Plugging of the piping between the viscometer and foam generator can significantly increase the foam quality in the viscometer; thus, care is taken to avoid pipe plugging.

Cement foam with different qualities can be generated by varying the total volume of the foam-generating chamber (mixing chamber). The total volume of the mixing chamber can be adjusted by controlling the piston level in the chamber. Thus, to generate a given quality foam, the initial location of the piston is back-calculated from the volume of the base slurry and desired foam quality. A constant base slurry volume of approximately 900 ml was used for the entire test. Average bubble size for the test foams was approximately 50 µm.

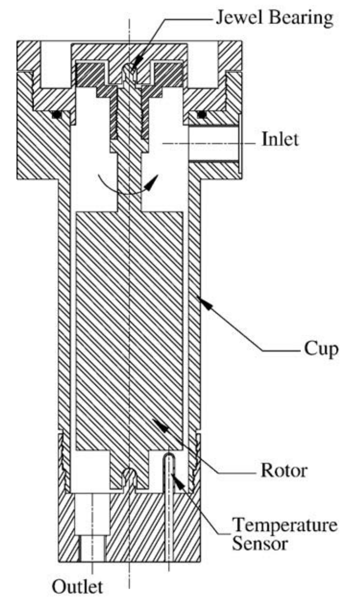

Fig. 4. Cup-rotor assembly of a flow-through viscometer.

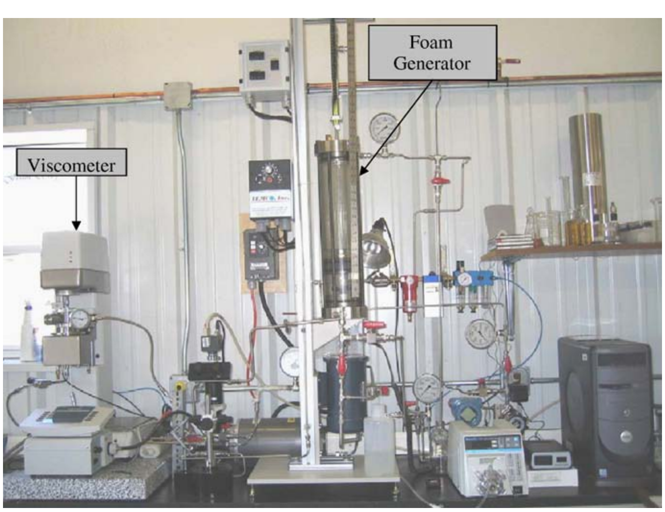

Fig. 3. Foam generator/viscometer apparatus.

3.3. Test procedures

A stepwise test procedure was developed to conduct foam cement rheology measurements using the foam generator/viscometer apparatus. The test procedure includes the following six major stages:

Stage I. Prepare base slurry: A foam rheology experiment begins by mixing water, dispersant and fluid loss additive in a 2-liter beaker at 21 °C. A multispeed stirrer was used to disperse the chemicals at 200 rpm. After mixing the solution for approximately 1 min, cement powder was slowly added to the beaker while the mixture was agitated at 200 rpm for 50 s. Then the mixture (water, dispersant, fluid-loss additive and cement) was agitated at high speed (1500 rpm) for 5 min.

Stage II. Measure base slurry rheology: Viscosities of the base slurries were measured using a regular rotational viscometer. The viscometer was run at the maximum speed to break the structure of the fluid and maintain a constant slurry level between the viscometer cup and

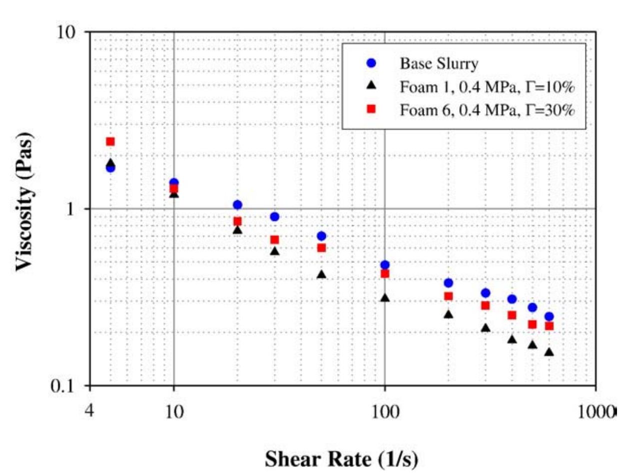

Fig. 5. Viscosity of cement foam at low pressure (0.4 MPa).

Table 3
Herschel Bulkley model parameters for test fluids.

Parameter	Base fluid	Foam 1	Foam 2	Foam 3a	Foam 4	Foam 5	Foam 6	Foam 7	Foam 8	Foam 3a*	Foam 3b*	Foam 3c*
τ_y [Pa]	0.00	5.50	3.20	3.40	5.00	2.60	8.30	0.90	2.70	4.79	3.36	4.95
m	0.59	0.66	0.79	0.86	0.69	0.75	0.76	0.60	0.57	0.86	0.89	1.02
k [Pas^m]	3.48	1.26	0.49	0.38	1.34	0.93	0.95	2.73	3.81	0.78	0.35	0.18

rotor. Then the speed was reduced to the minimum, and measurements (angular displacements) were taken for different rotation speeds of the cup.

Stage III. Mix the base slurry with the foaming agent: After measuring the rheology, the slurry sample in the viscometer cup was mixed with the remaining slurry in the beaker. The foaming agent was added while the slurry was being agitated carefully using a laboratory spatula to avoid the formation of foam.

Stage IV. Inject the slurry into the foam generator: After mixing the foaming agent with the base slurry, the desired quantity of cement slurry was injected into the mixing chamber. The piston position (the volume of the mixing chamber) was carefully adjusted to the desired level by carefully venting nitrogen from the pneumatic chamber.

Stage V. Generate foam in the mixing chamber: The mixer was turned on to generate foam at the desired pressure. After agitating the mixture of nitrogen and cement slurry for approximately 5 min at 1600 rpm, agitator torque readings were stabilized and the mixer was stopped.

Stage VI. Measure the foam rheology: While maintaining approximately constant flow through the viscometer, the viscometer was turned on to measure the viscosities of the foam at different shear rates.

3.4. Results and discussion

Different sets of rheology experiments (low-pressure tests, high-pressure tests, and different-pressure tests) were carried out by varying cement foam quality and static pressure. Additional rheology tests were conducted to investigate the effect of expansion or depressurization. Base slurry compositions were the same for all the tests.

3.4.1. Low-pressure tests

The first set of tests was conducted under low-pressure conditions (approximately 0.4 MPa) and the foam quality was varied from 10% to 30%. A static pressure of 0.4 MPa is the lowest pressure that is required to maintain a constant flow of cement through the viscometer. The results of these measurements are presented in Fig. 5. The results indicate that both foams (Foam 1 and Foam 6) have less viscosity than the base slurry. It is apparent from the logarithmic plot (Fig. 5) that almost all the data points of the base slurry lie on a straight line, thus indicating that the material is a Power Law fluid. However, viscosity measurements of the cement foams at low shear rates indicate the presence of yield stress. Herschel–Bulkley model parameters determined for each test fluid are presented in Table 3. All the test fluids with the exception of the base fluid exhibit strong yield stress. It is also important to note that the foam flows generally show slip at the wall, which occurs as a result of the presence of a thin fluid layer as presented in Section 2.4. Because of wall slip, the measured shear rate (i.e., total shear rate) is slightly higher than the actual shear rate. The contribution of the wall slip to the total shear rate may be significant at low shear rates.

3.4.2. High-pressure tests

As foam flows down the casing, the pressure increases with the depth of the well. The maximum pressure occurs at the bottom of the hole where flow properties of foamed cement is critical. Thus, the second set of rheology tests was carried out under high-pressure conditions. Three foam qualities were tested. The results of these experiments are presented in Fig. 6. At high pressure, 30%-quality foam and the base fluid have similar rheological curves. However, 30%-quality foam has higher viscosities at lower shear rates (i.e., less than 50 s^{-1}). In agreement with the low-pressure tests, the viscosities of foams under high-pressure conditions increase with increasing quality.

3.4.3. Tests under different pressures

The third set of rheology tests was conducted by varying both foam quality and static pressure. The results of these experiments are presented in Fig. 7. All the foams have less viscosity than the base slurry. This results suggest that the viscosity of cement foams increases as the quality increases from 10% to 30%. Fig. 8 presents the viscosities of 30%-quality foams (Foam 6, 7, and 8) measured in this investigation. Except for the lowest shear rate (i.e., 5 s^{-1}), Foam 6

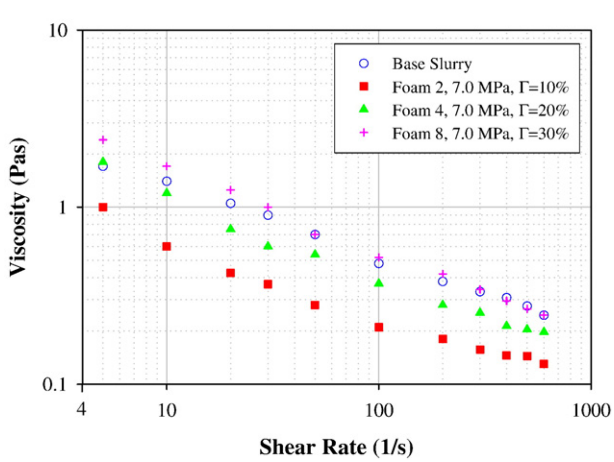

Fig. 6. Viscosity of different quality cement foams at 7 MPa pressure.

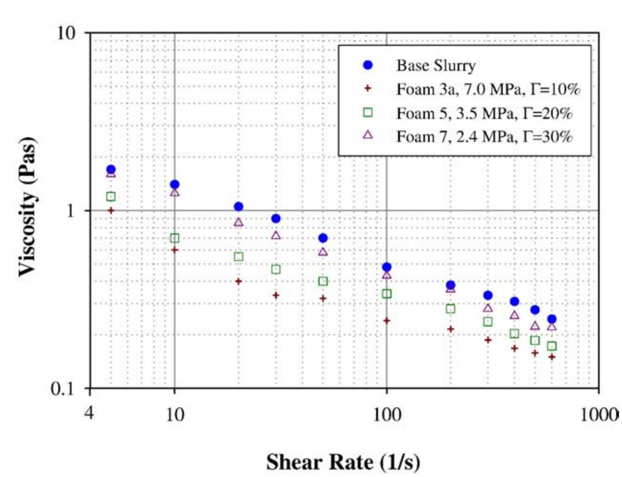

Fig. 7. Viscosity of cement foam at different pressures and foam qualities.

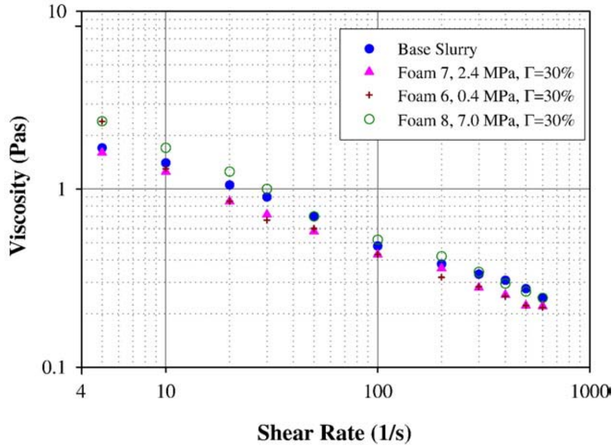

Fig. 8. Viscosity of 30%-quality cement foams at different pressures.

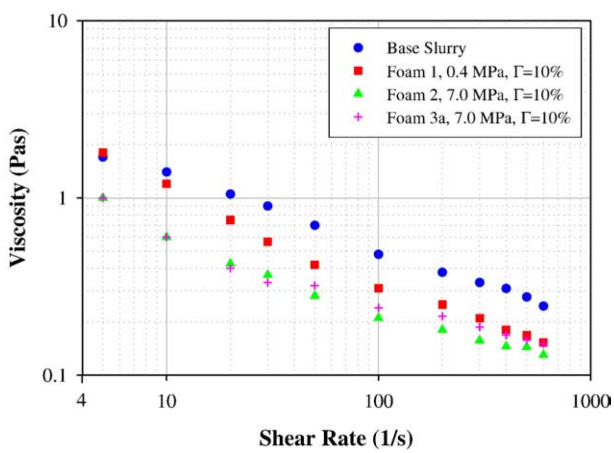

Fig. 9. Viscosity of 10%-quality cement foams at low and high pressure.

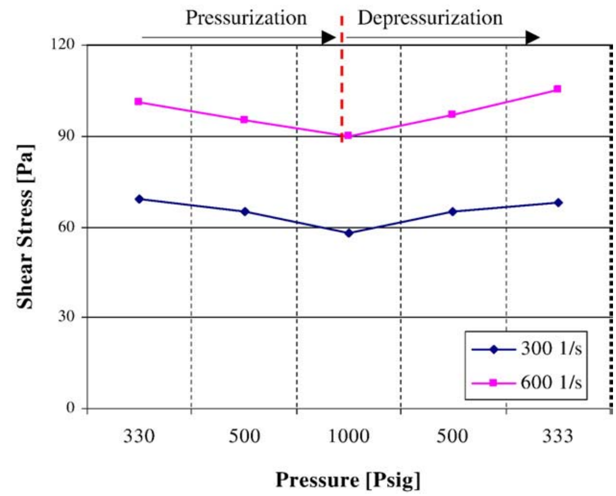

Fig. 11. Shear stress as a function of pressure at different shear rates.

and Foam 7 have approximately the same viscosity. Foam 8 has slightly higher viscosity than Foam 6 and Foam 7.

For low-quality foams (Foam 1, Foam 2, and Foam 3a), the viscosities at high pressures are lower than the viscosities at lower pressures (Fig. 9). The viscosity reduction could be caused by the effect of gas solubility at high pressure, which may reasonably reduce the quality of the foams at low gas volume fraction. However, as pointed out, the effect of nitrogen solubility on foam quality is minimal under HTHP conditions. It is important to note that results presented in Fig. 9 are obtained under ambient temperature conditions. Similar viscosity measurements (Fig. 8) obtained from high-quality foams indicate an increase in viscosity as the pressure increases. One possible explanation for this could be the presence of a sufficient amount of gas in high quality foams to minimize the effect of gas solubility. A similar increase in viscosity with increase in pressure has been observed with high quality water-based foams [30].

3.4.4. Depressurization test

Finally, a depressurization test was conducted to investigate the effects of expansion (pressure reduction) on the rheology of cement foams. This test was carried out under static conditions (flow through the viscometer was stopped during the expansion and rheology measurements). To reduce the effect of foam degradation, the test was conducted for a short time duration of about 4 to 5 min, which is approximately the same as the average foam residence time in the viscometer during the dynamic test. First, 10%-quality foam was generated in the mixing chamber at a pressure of 7 MPa and the rheology of the foam was measured. Then, the system was depressurized to 3.5 MPa and the rheology of the foam was measured. Again, the system was depressurized to 2.4 MPa and the rheology was measured. Test results are presented in Fig. 10. The viscosity of foam cement slightly increases when it is depressurized from 7 MPa (i.e., 10% quality) to 2.4 MPa (i.e., 30% quality). Note that the foam quality

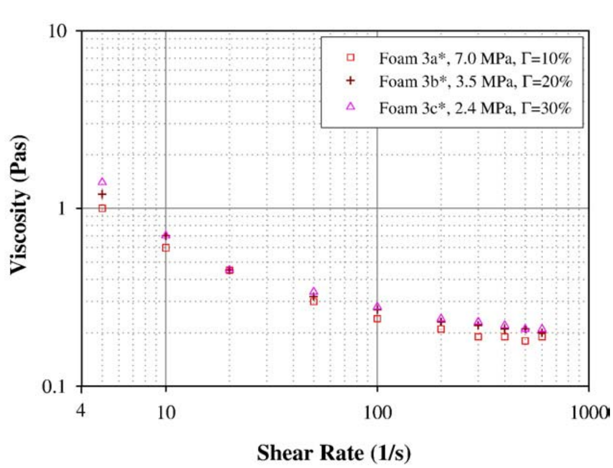

Fig. 10. Effect of depressurization on the viscosity of cement foam.

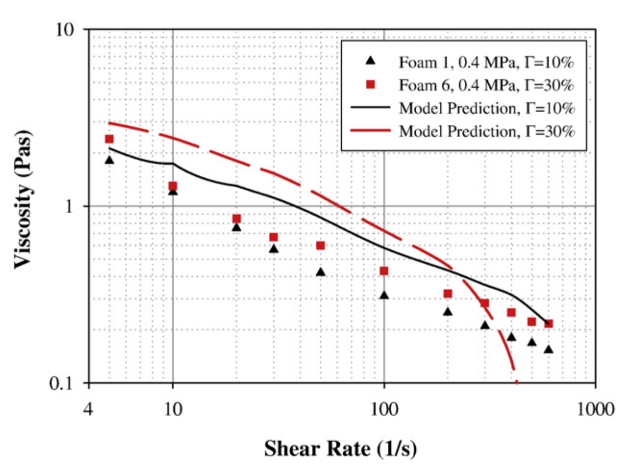

Fig. 12. Comparisons of measured data with model predictions at low pressure (0.4 MPa).

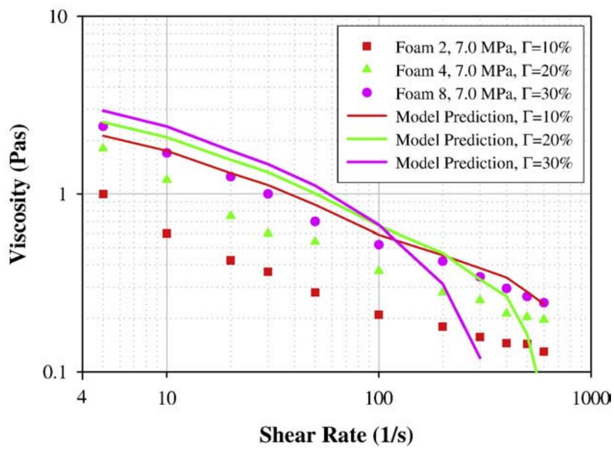

Fig. 13. Comparisons of measured data with model predictions at high pressure (7 MPa).

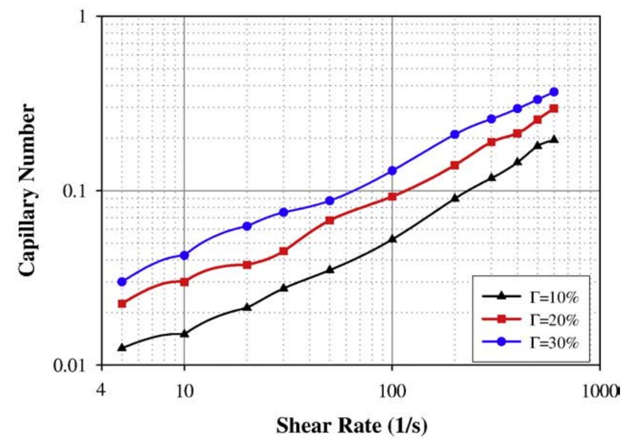

Fig. 15. Capillary number as function of shear rate for different quality foams at 7 MPa.

increases during depressurization because this is a closed system to which nothing was added. The depressurization procedure was carried out as a comparison because it is representative of conditions found in the field. The corresponding trend in viscosity change is in agreement with rheology measurements obtained without depressurization. However, the viscosity measurements obtained after the expansion are slightly lower than viscosity measurements obtained without foam expansion (Figs. 5–7 and 9). The reduction can be the result of foam degradation during the foam expansion process.

3.4.5. Pressurization and depressurization (pressure cycle) test

After completion of the depressurization test (Section 3.4.4), the static pressure of the system was increased from 330 psig to 1000 psig, then decreased from 1000 to 330 psig while measuring the torque/stress at constant shear rate. The results (Fig. 11) show that cement foam retains its rheological property after pressure cycle. Stress measurements at 600 1/s shear rate are slightly lower than the original measurements that are obtained before the pressure cycle tests. This could be due to foam drainage and segregation with time. Stress measurements at 300 1/s shear rate were taken immediately after completion of the depressurization test; thus, they are approximately the same as the original measurements.

3.4.6. Comparisons of measurements with model predictions

As presented in Fig. 1, the Barthes-Biesel and Chhim model [Eq. (7)] predicts both positive and negative effects of quality on foam viscosity. The model requires estimation of capillary number [Eq. (2)] for each measured data point. The capillary number is determined based on

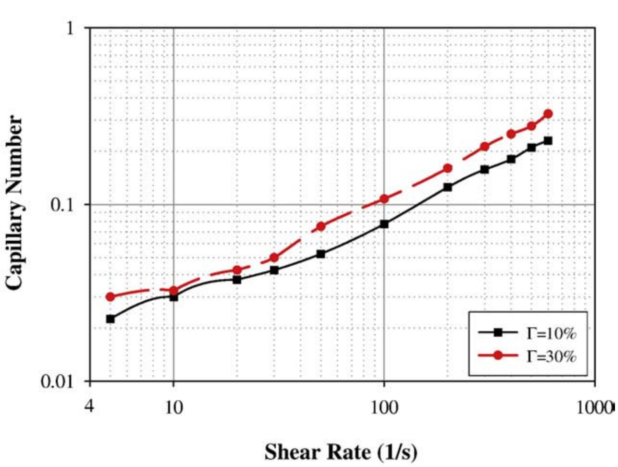

Fig. 14. Capillary number as function of shear rate for different quality foams at 0.4 MPa.

the apparent viscosity of the base slurry. Figs. 12 and 13 present measured results with predictions of the Barthes-Biesel and Chhim model [Eq. (7)] for low and high pressure tests, respectively. The model overpredicts the viscosity of 10%-quality foam. Model predictions for 20% and 30% quality foams show a different trend. At higher shear rates (i.e. $\gamma < 100$ 1/s), model predictions are substantially higher than the measurements. However, as the shear rate increases above 100 1/s, the predicted viscosity sharply deceases with an increase in shear rate. This significant reduction in viscosity prediction occurs when the capillary number (Figs. 14 and 15) approaches the critical value ($C_a = 0.19$). In general, the differences between measurements and model predictions are significant. For shear rate less than 100 1/s, the trend of viscosity changes with quality predicted by the model is not the same as the trend obtained with the measurements. These discrepancies could be due to the fact that the model has been developed assuming a Newtonian continuous phase while the base fluid used for the experiments was highly non-Newtonian (Table 3). In addition to non-Newtonian behavior, the cement slurry contains significant quantity of solids, which are not considered in the model.

4. Conclusions

Viscosity curves of foamed cements obtained using a foam generator/viscometer apparatus were investigated by varying the foam quality and static pressure. The following conclusions can be drawn from this investigation:

- Low-quality cement foams have less viscosity than the base slurry. Even though this result is theoretically possible according to the mathematical analysis of Barthes-Biesel and Chhim [25], this is the first time to our knowledge that base fluid viscosity is higher than that of the corresponding foamed system. This brings into doubt the general belief that foam cements provide better drilling fluid displacement than non-foamed cements unless the foams have different extensional viscosity properties than conventional cements slurries.
- Cement foam viscosity increases as the quality increases from 10% to 30%. This pattern is in agreement with the viscosity of aqueous foams.
- Rheology data of the base slurry best fits the Power Law rheological model. However, the rheological measurements of the cement foams at low shear rates indicate the presence of yield stress.

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