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Modeling the flow behavior of cement slurry with temperature

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Abstract

This research work investigated the flow behavior of API Class G (Easy to disperse) cement slurry at different temperatures and modeled the flow behavior parameters as functions of temperature. The cement slurry used contained only API class G cement, fresh water and antifoam additive only. The flow behavior of the cement slurry was measured at 27, 38, 49, 60 and 71^{o}C in accordance with American Petroleum Institute (API) Recommended Practice 10B-2. The cement slurry, being a Bingham Plastic fluid, the flow parameters chosen for this study is Plastic viscosity, yield stress and critical velocity. Each parameter was found to increase with rise in temperature. Mathematical model equations relating the flow parameters with temperature were also derived.

Keywords: cement slurry, plastic fluid

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Introduction

API Class G cement (Easy to disperse) is used abundantly for primary cementing and remedial cementing operations in the oil and gas industry. The conditions to which cement is subjected during oil or gas well cementing operations differ considerably from those encountered at ambient conditions during construction operations and owing to the harsh conditions encountered in the wellbore, special cements are manufactured for use as oil and gas well cements. The rheology of cement slurry is a measure of its flow behavior. Rheology is the study of the flow and deformation of matter in response to applied stress. Cement slurry rheology is critical for the design, execution and evaluation of oil or gas well cementing operation. The rheology depends on many factors such as temperature, water-to-cement ratio, specific surface of the cement powder (size and the shape of cement grains), chemical composition of the cement, the relative distribution of the components at the surface of the grains, presence of additives, mixing and testing procedures. A sound knowledge of cement slurry rheology is required for successful primary or remedial cementing operation in the oil and gas industry because of the following reasons: evaluation of cement slurry mixability and cement slurry pumpability, determination of appropriate flow regime for placement of cement slurry, determination of the displacement rate required to achieve optimum mud removal, determination of the pressure versus depth relationship during and after cement slurry placement, calculation of the return rate when free fall is occurring and prediction of down-hole temperature profile when placing cement slurry in the annulus (Nelson and Guillot, 1990).

Temperature can have drastic effect on cement slurry rheology but the extent of this effect is highly dependent on the type of cement and the additives in the cement slurry, the hydration rate of the cement, the nature, stability and morphology of the hydration products (Nelson and Guillot, 1990). Turbulent flow is preferred over laminar flow as placement flow regime for cement slurry partly because of its flat velocity profile and the attendant scouring action of cement slurry particles on the casing and walls of the wellbore which aids mud removal. Laminar flow placement regime increases chances of contamination of cement slurry with drilling mud partly because of its bullet shaped velocity profile which promotes contact/mixing of cement slurry with drilling mud as the cement slurry channels through the drilling mud leaving mass of immobile mud with patches of cement slurry on the sides of the casing and walls of the wellbore. The presence of some additives such as viscosifiers and dispersants affect the flow behavior of cement slurry. Viscosifiers are viscosity-building additives while dispersants are viscosity-reducing additives. Hence, to enable investigation of the native flow behavior of the cement slurry as a function of temperature, the cement slurry chosen for this research project contains cement, freshwater and antifoam additive only. The antifoam additive has no effect on the flow behavior of cement slurry.

Cement slurry is a Bingham Plastic fluid. Other Bingham Plastic fluids are drilling mud, paints, toothpaste, ketchup and many colloidal suspensions. Bingham Plastic fluids posses a yield stress or threshold stress τ_0 which must be exceeded before they begin to deform (flow). Below τ_0 they behave like solids and at stresses greater than τ_0 they flow, exhibiting linear relationship between shear stress and shear rate. When plotted on Cartesian (rectangular) coordinates, the shear stress versus shear rate relationship of Bingham plastic fluids result in a straight line with a positive shear stress (intercept) at zero shear rate referred to as yield stress or yield point, τ_0. Above the yield point, the shear stress of the fluid is proportional to the shear rate and the proportionality constant is called the plastic viscosity (μ_p). The plastic viscosity is the slope of the graph. Thus the shear stress of this class of materials can be represented by the equation below:

$$\tau = \tau_0 + \mu_p \frac{du}{dy} \qquad (1.0)$$

Where τ_0 = Yield stress and μ_p = Plastic viscosity

Critical velocity is the velocity attained at critical Reynolds number. The critical Reynolds number is the Reynolds number at which transition from Laminar to turbulent flow occurs (Iyagba, 1997). Assuming critical Reynolds number of 3000, critical velocity is given by,

$$V_c = \frac{Re_{3000}\mu}{\rho L} \qquad (2.0)$$

Where, V_c = Critical velocity; ρ = Density of fluid; L = Characteristic length (m); μ = Viscosity; R_{3000} = Critical Reynolds number = 3000

The above equation applies to Newtonian fluids. For Bingham plastic fluids, the simplest method (Hedstrom, 1952) consists of assuming that once turbulent flow is reached, the fluid behaves like a Newtonian fluid with a viscosity equal to its plastic viscosity (Guillot and Nelson, 1990). Cement slurry with high plastic viscosity would have high critical velocity and would require high pump capacity (horse power) for turbulent flow placement and the attendant high friction pressure is a potential danger that could result in fracturing of fragile formations in a wellbore. Placement of such cement slurries is done in laminar flow regime in oil/gas wells with low fracture gradient. Mathematical models are mathematical relationships between process or system variables that describe the behavior of the process or the physical system. Mathematical models can be developed for the flow parameters of any cement slurry prepared from a particular batch or type of cement to enable prediction of the flow behavior at higher or lower temperatures.

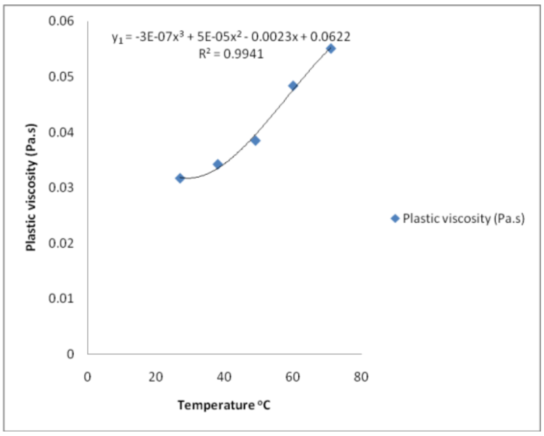
Materials and Methods

The composition of the cement slurry is as follows: API Class G Cement (Easy to disperse) = 1 tonne, Antifoam additive = 0.444 litre/tonne of cement and Fresh water = 451.88 litres/tonne of cement. The specific gravity of the cement slurry is 1.897. In accordance with API Recommended Practice 10B-2, 2005, the cement slurry was mixed in the Laboratory using the EG & G Constant Speed Mixer. The required quantity of water was poured into the Jar of the Constant Speed Mixer. While the mixer was running at 4000 RPM, the antifoam additive was added followed by the required quantity of cement. The mixture was further mixed for 15 Secs at 12000 RPM. The cement slurry was conditioned for 20 mins in Chandler EG & G Atmospheric Consistometer that has been pre-heated to the required temperature. At the end of the conditioning period, the rheology of the cement slurry was measured using Chandler EG and G Chan-35 Rheometer. For every temperature, fresh cement slurry was prepared. The rheology measurements were done at 27, 38, 49, 60 and 71°C.

Results and Discussion

The parameters used to measure the flow behavior of the cement slurry in relation to temperature are plastic viscosity, yield stress and critical velocity for turbulent flow through a 6.184” (0.157 m) ID pipe. The critical velocity for turbulent flow through a 6.184” (0.157 m) ID pipe was calculated from the measured experimental values of Plastic viscosity and density of the cement slurry.

Fig. 1. Plastic viscosity against temperature



$$y_1 = -3 \times 10^{-7}x^3 + 5 \times 10^{-5}x^2 - 0.0023x + 0.0622 \quad (3.0) \quad R^2 = 0.9941$$

Where y_1 = Plastic viscosity in Pa.s and x = temperature in °C

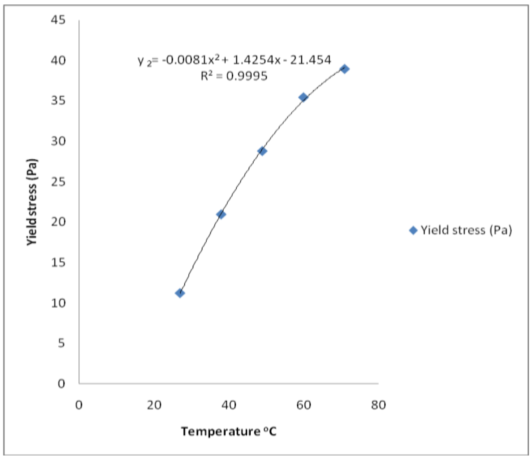


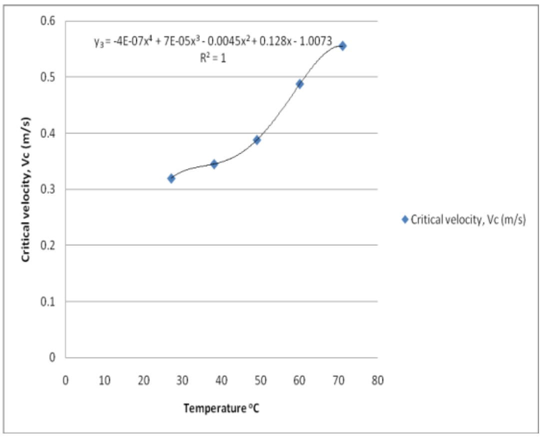
Fig. 2. Yield stress against temperature

$$y_2 = -0.0081x^2 + 1.4254x - 21.454 \quad (4.0) \quad R^2 = 0.9995$$

Where y_2 = yield stress in Pa and x = temperature in °C

The plastic viscosity, yield stress and critical velocity of the cement slurry were found to increase with rise in temperature. This is supportive of the fact that the rate of the hydration reaction or the rate of formation of hydration products in the cement slurry increase with rise in temperature. The mathematical model equations below were derived for the flow parameters through regression analysis using Microsoft Excel 2007.

Fig. 3. Critical velocity against temperature



$$y_3 = -4\,x10^{-7}x^4 + 7x10^{-5}x^3 - 0.0045x^2 + 0.128x - 1.0073$$

(5.0) $R^2 = 1$

Where y_3 = Critical velocity in m/s and x = temperature in °C

Conclusion

Temperature has effect on the flow behavior of cement slurry. The flow behavior of cement slurry changes with temperature. The flow behavior of cement slurry can be measured at different temperatures and mathematically modeled. For API class G (Easy to disperse) cement slurry (without viscosity-building or viscosity-reducing additives), the plastic viscosity, yield stress and critical velocity of the cement slurry increase with rise in temperature. Mathematical models can be developed for the flow parameters of any cement slurry and used to predict the flow behavior of the cement slurry at different temperatures.

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