Applied Clay Science 104 (2015) 309–317

Contents lists available at ScienceDirect

Applied Clay Science

journal homepage: www.elsevier.com/locate/clay

Research paper

Stability and ageing behaviour and the formulation of potassium-based drilling muds

Karime Sehly [a], Hui-Leng Chiew [a], Heng Li [a], Alexander Song [a], Yee-Kwong Leong [a,*], Weian Huang [b]

[a] School of Mechanical and Chemical Engineering, The University of Western Australia, Crawley 6009, Australia
[b] School of Petroleum Engineering, China University of Petroleum, Qingdao 266580, China

ARTICLE INFO

Article history:
Received 31 March 2014
Received in revised form 4 December 2014
Accepted 7 December 2014
Available online 23 December 2014

Keywords:
Yield stress
Zeta potential
Thixotropy
Leong model
Bentonite
CMC fluid lost prevention additive

ABSTRACT

The formulation of drilling muds is currently driven by a trial-and-error process. This study aims to provide generic knowledge that helps to develop a systematic approach towards mud formulation producing muds that achieve most, if not all of their specific functionalities. The effect of KCl on the stability, viscosity and ageing behaviour of composite bentonite–barite–pyrophosphate muds was evaluated first. The ageing behaviour represented by a yield stress increasing with time was most pronounced for the 0.1 M KCl mud. At 0.2 M KCl and higher, the muds became unstable forming a two-phase suspension. The zeta potential was very small and essentially pH independent for both the 0.01 M and the 0.1 M KCl muds. Leong and Nguyen–Boger models described the ageing behaviour well, although the Leong model was found to perform better. In stage two, the effect of polyanionic carboxymethylcellulose (CMC) fluid loss prevention additives on the bentonite–barite–pyrophosphate–0.1 M KCl mud was evaluated. High molecular weight (Mw) CMC produced a thickening effect increasing both the viscosity and yield stress of the mud. Low Mw CMC (commercially known as PAC) only increased the mud yield stress marginally. All of these composite muds displayed a very similar ageing behaviour that is well described by the Leong model. The time scale-structural recovery increased with KCl and high Mw CMC concentration. All muds displayed shear thinning plastic behaviour.

1. Introduction

1.1. Background

Drilling muds, especially the heavy muds, have gained considerable worldwide attention recently from two major incidents as a means of stemming the flow of oil and gas from blowout wells located kilometres beneath the seabed. These blowout incidents occurred at the Montara well located off the coast of Western Australia in 2009, and at the Deepwater Horizon well in the Gulf of Mexico in 2010. These muds must therefore possess the relevant density and essential rheological and thixotropic properties. Bentonite, comprising 70–90% of montomorillonite, is the most important ingredient of drilling muds. It imparts thixotropic and yield stress properties to the mud. Thixotropy is due to the temporal evolution of the gel structure in shear and at rest. The processes of gel structure breakdown in shear and recovery at rest occur at a finite time scale (Barnes, 1997; Nguyen and Boger, 1985). Ageing is a study of the structural recovery behaviour at rest or at a low shear rate condition.

Drilling muds are formulated to serve multiple functions simultaneously in a drilling environment in addition to providing an adequate hydrostatic head (Skalle, 2011). They must be able to remove drill cuttings, cool drill bits, stabilise wellbores, minimise formation damage, seal permeable formations, control well formation pressure and minimise corrosion. As a result these muds are composed of several essential ingredients such as bentonite as a thixotropic agent (Brandenburg and Lagaly, 1988; Norris, 1954; van Olphen, 1955), barite or even kaolin as weighting agent (Au and Leong, 2013), dispersant, salt, fluid loss prevention additives and corrosion inhibitors. Shales make up over 75% of the rock types encountered while drilling for oil and gas and give rise to more problems per metre drilled than any other type of formation (Bloys et al., 1994). The poor wellbore quality of shale formations can cause wellbore collapse or closure as a result of chemical infiltration of the mud filtrate containing water. The realisation of the lasting negative impacts that the disposal of oil-based mud cuttings has on the environment has led to a severe loss in its popularity as a drilling fluid, which has then stimulated interest to find environmentally friendly water-based mud alternatives. Water-based potassium drilling muds are now the most popular mud type used in the industry adopted for their ability to create a more stable, hydration-resistant rock, especially in the case of shales (Khodja et al., 2010). These muds hold the cutting together when drilling through water-sensitive shales (Clark et. al., 1976; O'Brien and Chenevert, 1973). Chang and Leong (2014) reported that bentonite gels became unstable and separated into two phases, liquid and sediment, at a high KCl concentration of 0.5 M. Unstable muds will experience large fluid loss to the formation in the well, which is

* Corresponding author.
E-mail address: yeekwong.leong@uwa.edu.au (Y.-K. Leong).

http://dx.doi.org/10.1016/j.clay.2014.12.013

an undesirable property. The effect of KCl concentration on the ageing and stability behaviour of bentonite-based drilling mud was evaluated.

The cleansing of the well bore of loose cuttings is accomplished by circulating the drilling mud through the drill string, out of the drill bit and up through the well annulus (space between drill string and well wall), thereby lifting the loose material to the surface (Adams and Charrier, 1985; Bourgoyne et al., 1986; Luckham and Rossi, 1999). Drilling muds are designed to form a stronger gel structure at rest, so as to hold the cuttings and weighing material in suspension should mud circulation cease, and therefore preventing them from falling to the well bottom. The gel structure is broken down by using a pump to create axial movement of the drill string, thus shearing the mud. Too high a gel strength means a high pump pressure is needed to create the required axial movement, which may in turn damage the formation while too low a gel strength could lead to the suspensions sinking to the well bottom (Zheng and Ma, 2010). It is therefore crucial to be able to quantify the evolving gelling strength of the chosen drilling fluid at all stages of rest time so as to determine influential factors such as optimum shear time and required shear pressure. An ageing study involving the direct yield stress measurement of the mud as a function of ageing time need to be conducted to address this issue.

The thixotropic behaviour of bentonite slurries has been studied extensively for over 70 years (Abend and Lagaly, 2000; Brandenburg and Lagaly, 1988; Briscoe et al., 1992, 1994; Broughton and Squires, 1936; Dolz et al., 2007; Galindo-Rosales and Rubio-Hernandez, 2006; Hauser and Reed, 1937; Kelessidis and Maglione, 2008; Lagaly, 1989; M'Ewen and Mould, 1957; van Olphen, 1955), and yet this behaviour is still not well understood. The approaches to the various thixotropic studies are quite different, with some involving the application of continuous shear such as the hysteresis loop method and step-up and step-down shear rate method and others that allowed the structural recovery to occur without any disturbance. In ageing, a number of rheological parameters have been employed to monitor the structural recovery process. These are the yield stress (Abu-Jdayil, 2011; Kelessidis and Maglione, 2008; Lee et al., 2012), elastic modulus (van Olphen, 1955; Yoon and El Mohtar, 2013) and viscosity (Abu-Jdayil, 2011). The yield stress can be measured directly (Goh et al., 2011; Lee et al., 2012) or obtained from model fit to the flow data (Abu-Jdayil, 2011; Brandenburg and Lagaly, 1988; Kelessidis and Maglione, 2008). The use of the flow or viscosity method is not an ideal mode of structural recovery study because of the severe damage to the structure in shear and during its transfer to the viscometer.

As a consequence, it is difficult to quantitatively compare structural recovery results of the different studies. In addition, in most cases, the initial state of the gels prior to the structural recovery experiment is not well defined (Nguyen and Boger, 1985). Leong and co-workers (Chang and Leong, 2014; Lee et al., 2012; Yap et al., 2011) applied a different approach where this initial state is well defined. This state is where the freshly prepared gel has reached a surface chemistry equilibrium (Goh et al., 2011). At this equilibrium state, the gel yield stress measured immediately after agitation remained unchanged. As part of this approach, the yield stress must be measured in the gel region which has not been disturbed by a previous measurement (Chang and Leong, 2014). This approach will be employed here and is quite similar to that employed by van Olphen (1955). He characterised the ageing behaviour of bentonite gels without disturbing the structure at rest using a shear wave modulus method. The increasing modulus with ageing time was evaluated as a function of NaCl concentration ranging from 0.03 to 0.134 M. The modulus was found to increase with NaCl concentration. Structural recovery behaviour was however not observed with the Ca-bentonite slurries (van Olphen, 1957). Also the viscosity and yield stress of these Ca-bentonite slurries were much lower. Van Olphen attributed this behaviour to a coarser particle size distribution of the Ca-bentonite suspension.

Drilling fluid formulation intended to achieve the desired mud properties is currently based on knowledge gained from extensive mud formulation testing by mud companies over the years. Leong and co-workers (Chang and Leong, 2014; Goh et al., 2011; Lee et al., 2012; Yap et al., 2011) have recently focussed their research attention towards achieving a comprehensive understanding of the effects of individual additives so that a new systematic and scientific approach of drilling mud formulation and preparation can be developed. They have previously investigated the rheological and ageing properties of bentonite gels with and without pyrophosphate dispersant (Goh et al., 2011; Lee et al., 2012) and salts (Chang and Leong, 2014) as well as composite bentonite suspensions such as bentonite–barite with and without phosphate-type dispersants (Yap et al., 2011). In this current follow up study, the effects of KCl salt and two fluid loss prevention agents (both anionic cellulose additives) will be evaluated.

One of the objectives of this investigation is to evaluate the effect of KCl concentration on drilling fluid gelling and rheological properties. The density of drilling mud is controlled by the addition of an inert weighting agent, usually barite (specific density of 4.5 g/cm^3). Drilling mud densities must match the formation pressure encountered so as to prevent fluid influx into the well or loss of fluid into the formation. Dispersants such as pyrophosphate and polyphosphate are often added to thin the mud or to increase the mud density by loading more weighting agent and maintaining the same viscosity behaviour. Fluid loss prevention additive is another important ingredient used to stabilise the wellbore, minimise formation damage and seal permeable formations. They are generally anionic polyelectrolytes such as acrylates, polyphosphates, lignosulfonates, carboxymethylcellulose (CMC) or polyanionic cellulose and others. In this investigation the effects of CMC on the ageing and rheological behaviour of drilling muds were evaluated. Two different molecular weight (Mw) CMC additives were evaluated.

This study will help develop a better understanding of the effects of potassium concentration on the ageing and stability behaviour of drilling mud and also aid in the development of a systematic approach to the formulation of drilling mud. The popularity of KCl additives in the industry and the lack of research conducted on the thixotropic behaviour of potassium mud were the main motivations for going forward with this investigation.

1.2. Modelling of structural recovery or ageing behaviour

There are a number of ageing or structural recovery models based on storage or elastic modulus, yield stress and viscosity (Barnes, 1997). Currently, there are only three models based on yield stress; a two-parameter (Pujala and Bohidar, 2013; Rich et al., 2011) and 2 three-parameter models (de Kretser and Boger, 2001). The origin of the two-parameter model can be traced to polymer ageing theory and analysis (Chow, 1994). The three parameter models are the Nguyen–Boger model and the so-called Leong model (de Kretser and Boger, 2001).

The Nguyen–Boger (NB) model is based on first-order structural recovery kinetics (Nguyen and Boger, 1985) and is given by

$$\tau_y(t) = \tau_{yoc} - \left(\tau_{yoc} - \tau_{y0}\right)e^{-Kt} \tag{1}$$

The Leong model, based on second-order aggregation kinetics (Hattori and Izumi, 1982), is expressed by (de Kretser and Boger, 2001)

$$\tau_y(t) = \tau_{y\infty}\left(\frac{1-\left(\frac{\tau_{yo}}{\tau_{y\infty}}\right)^{3/2}}{1+K_r t}\right)^{2/3} \tag{2}$$

where $\tau_y(t)$ is the time-dependent yield stress, τ_{y0} is the equilibrium structural breakdown (agitated) state yield stress, $\tau_{y\infty}$ is the yield stress at complete structural recovery, $1/K$ is the Nguyen–Boger model time constant and $1/K_r$ is the Leong model time constant. The methods employed to determine the parameters of both models have been