Journal of Petroleum Science and Engineering 130 (2015) 86–95

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Effect of nanoclay on the electrical resistivity and rheological properties of smart and sensing bentonite drilling muds

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A R T I C L E I N F O

Article history:
Received 18 November 2014
Accepted 19 March 2015
Available online 31 March 2015

Keywords:
Bentonite
Nanoclay
Electrical resistivity
Rheological properties
Temperature
Modeling

A B S T R A C T

In this study, the effect temperature on the electrical resistivity and rheological properties of a water based bentonite drilling mud modified with nanoclay was investigated. Based on the experimental and analytical study the electrical resistivity was identified as the sensing property of the smart drilling mud so that the changes in the properties can be monitored in real-time during construction. The bentonite contents in the drilling muds were varied from 2% to 8% by the weight of water and temperature was varied from 25 °C to 85 °C. The nanoclay (particle size in range of 12 nm to 20 nm) content was varied between 0 and 0.6% by the weight of the drilling mud to modify the rheological properties and enhance the sensing electrical resistivity of the drilling mud. The nanoclay and bentonite clay were characterized using the X-ray diffraction analysis (XRD) and thermal gravimetric analysis (TGA). Based on the X-ray diffraction (XRD) analyses the major constituents in the nanoclay were montmorillonite (MMT) (hydrated sodium calcium aluminum magnesium silicate hydroxide, $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$)), quartz ($SiO_2$), magnesium aluminum silicate ((MgAl) SiO_3) and calcium–aluminum silicate hydrate ($CaAl_2$ $(SiO4)_2(OH)_4$). The TGA analyses on the bentonite and nanoclay showed weight loss in the temperature range of 600 °C to 800 °C, which supported the presence of montmorillonite. The weight loss up to 120 °C represented the loss of moisture (free water) in both bentonite and nanoclay which was 6.4% and 12.8%, respectively. The total weight loss at 800 °C for the bentonite decreased from 12.9% to 7.15%, about 45% reduction, when the bentonite clay was mixed with 0.6% of nanoclay. The results also showed that 0.6% nanoclay decreased the electrical resistivity of the drilling mud from 15% to 36% based on the bentonite content in the drilling mud. The electrical resistivity of the drilling mud with and without nanoclay decreased with the increase in the temperature. The nanoclay modification increased the yield point (YP) and plastic viscosity (PV) by 30% to 61% and 12% to 37% respectively based on the bentonite content and temperature of the drilling mud. Addition of nanoclay also increased the apparent viscosity and gel strength of the drilling muds. The rheological properties of the drilling muds have been correlated to the electrical resistivity of the drilling mud using nonlinear power and hyperbolic relationships. The model predictions agreed well with the experimental results. Hence the performance of the bentonite drilling muds with and without nanoclay can be characterized based on the electrical resistivity which can be monitored real-time in the field.

1. Introduction

Water based drilling fluids, especially water–bentonite suspensions have been used in the oil, gas and geothermal drilling industry for decades. Multi-functional drilling muds are required to transport the rock cuttings to the surface, lubricate and cool the drill bit and apply hydrostatic pressure in the well bore to ensure well safety. The deeper wells that are being drilled calls for more advanced drilling fluids because of the changes in pressure, temperature and geology with depth. Common viscosifyers used in water based drilling muds are bentonite and/or polymers. The drilling fluid can react with certain types of formation or the pressure can cause the rock to crack, leading to massive loss of fluid into the formation (Riveland, 2013). Hence there needs to not only enhance the performance of bentonite-based drilling mud but also monitor the performance of the drilling muds during the drilling operations.

Bentonite has been used worldwide as drilling fluid additive (Abdou et al., 2013; Vipulanandan and Mohammed, 2014). The main function of the bentonite is to increase the viscosity of the mud and to reduce the fluid loss to the formation. A good quality bentonite should contain mainly montmorillonite (Brigatti et al., 2006). Bentonite often contains other clay minerals such as illite

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http://dx.doi.org/10.1016/j.petrol.2015.03.020
0920-4105/

and kaolinite and non-clay components such as quartz and feldspar. Because the sodium based montmorillonitic clays have the highest swelling capacity (which is responsible for viscosity build up and formation of low permeability filter cake); the presence of other materials will have an adverse effect on bentonite quality (Abdou et al., 2013). The type of exchangeable ions has a great effect on the swelling capacity of the montmorillonite. If the mineral composition of bentonite is such that its viscosifying power is insufficient, various additives such as nanoclay or polymer can be added (Murray, 2006).

Nanoparticles with noticeable alterations in optical, magnetic and electrical properties are excellent tools for the development of sensors and the formation of imaging contrast (Krishnamoorti, 2006). Since the nanoparticles are extremely small in size, nanoparticles are preferred to be used in drilling mud design as their abrasive forces are negligible with less kinetic energy impact. In addition to many advantages of using nanoparticles in mud design it is safer than conventional mud from the point of environmental view. The nanoparticles are added to mud in small amount, with low concentration of the order of 1%. Nano-based drilling muds could be the fluid of choice in conduction drilling operations in sensitive environments to protect other natural resources (Amanullah and Al-Tahini, 2011). The nanoclay particles can go in between the larger particles and block the flow through them (Riveland, 2013). During the past decade the nanomaterial has been used to improve the performance and functionality of a variety of engineering materials used in solar, biomedical, thermoelectric and environmental applications (Liu et al., 2013; Nazzal et al., 2013). Nanoclay is defined as having particle size in the range of 1 to 100 nm. Montmorillonite based nanoclay is chemically a hydrated sodium calcium aluminum magnesium silicate hydroxide $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$. Nanoclays are unique clays having platy structure with a unit thickness of one nanometer or less (Kosuri, 2008). Because montmorillonite clay is hydrophilic, it is not compatible with most polymers and must be chemically modified to make its surface more hydrophobic (Bhat et al., 2008). The nanoparticles are smaller than the micro particles used in the mud and have a higher surface area to volume ratio which gives the surface properties more influence than the same particle with a larger size. The nanoparticles in the drilling mud may also give better control of both the fluid loss to the formation and the initial spurt loss. Thus the right combination of mud particles and nanoparticles can be economically beneficial. Previous studies have shown that the nanoclay reduced friction between steel and paraffin as base fluid (Cheng et al., 2007). The use of nanoclay has attracted great interest in the polymer industry during the past decade as polymer modified clay exhibited much better mechanical properties when compared with virgin polymer or conventional micro and macrocomposites (Rehab and Salahuddin, 2005; Mohammed and Vipulanandan, 2014). Based on literature review of rheological models used for drilling muds (oil-based muds, water-based muds), Livescu (2012) concluded that the most popular once were Bingham, Herschel–Bulkley or power law. The limitations of these mathematical models are that they do not account for complex rheological effects such as thixotropic behavior of the drilling muds (Livescu, 2012).

In this study, enhancing the sensing and rheological properties of bentonite drilling mud modified with nanoclay at different temperatures were tested and quantified with the electrical resistivity of the drilling mud.

2. Objectives

The overall objective was to quantify the effect of temperature on the electrical resistivity and rheological properties of bentonite drilling mud modified with nanoclay. The specific objectives are as follows:

(i) Evaluate the effect of nanoclay on the electrical resistivity (nondestructive and sensing properties) and rheological properties of the bentonite drilling muds at different temperatures.
(ii) Investigate the relationship between electrical resistivity of the drilling mud and the rheological properties of the bentonite drilling mud so that it can be used as a real-time monitoring parameter.

3. Materials and methods

3.1. XRD characterization

An X-ray diffraction (XRD) analyses was performed in order to determine the chemical composition of bentonite at 25 °C. The XRD pattern of the particles was obtained using the Siemens D5000 powder x-ray diffraction device. XRD analyses were performed on bentonite passing sieve no. 200 (75 μm). The powder ($\approx$ 2 g) was placed in an acrylic sample holder (3 mm) depth. The sample was analyzed by using parallel beam optics with Cu$K\alpha$ radiation at 40 kV and 30 mA. The sample was scanned for reflections (2θ) from 0° to 80° in steps of 0.02° and 2 s count time per step.

3.2. Thermogravimetric analysis (TGA)

Thermogravimetric analyses curves, mass loss (TGA) and rate of mass loss (derivative with respect to temperature) (DTG) were quantified using a Setaram TGA 500 apparatus at a heating rate of 10 °C/min for a mass sample of about 20 mg. The sample was loaded in a platinum pan (3/4 full). This was followed by introduction of N_2 gas into the TGA compartment for 5 min to purge the likely oxygen in the environment of the system. After the purging, the sample was heated in the N_2 atmosphere from room temperature to the maximum of 800 °C. The weight loss percentage and temperature relationships were obtained for the samples. In this study, the TGA and DTG curves were obtained for bentonite, nanoclay and bentonite modified with 0.6% of nanoclay.

4. Electrical resistivity of drilling mud

In this study, two different resistivity devices were used to measure the electrical resistivity of drilling mud. A digital resistivity meter was used to measure the resistivity of fluids, slurries, and semi-solids with resistivity in the range of 0.01 Ω m to 400 Ω m. Also a conductivity meter with conductivity (inverse of resistivity) in the range of 0 to 199.9 μS/cm was also used to compare the results. The electrical resistivity of the modified drilling mud with nanoclay was measured using the resistivity meter and conductivity meter at various temperatures. Both of the devices were calibrated using standard sodium chloride (NaCl) solution.

5. Rheological properties

The rheological properties yield point (YP), plastic viscosity (PV), apparent viscosity (AV), gel strength 10 s (Gel10″) and gel strength 10 min (Gel10′) of the drilling mud were measured. In this study the bentonite content in drilling mud was varied up to 8% by the weight of water. Bentonite drilling mud modified with varying amount of nanoclay up to 0.6% by total weight of drilling mud were tested in the temperature range of 25 °C to 85 °C using a