Journal of Petroleum Science and Engineering 135 (2015) 50–58

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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

Smart cement rheological and piezoresistive behavior for oil well applications

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ARTICLE INFO

Article history:
Received 12 April 2015
Received in revised form
24 July 2015
Accepted 18 August 2015
Available online 20 August 2015

Keywords:
Water-to-cement ratio
Yield stress
Maximum shear stress
Curing time
Electrical resistivity
Models

ABSTRACT

Behavior of smart oil well cement with varying water-to-cement ratio (w/c) was investigated. The oil well cement (Class H) was modified with 0.1% conductive filler (CF) to make the cement very sensing and smart and the rheological properties and piezoresistivity behavior with water-to-cement ratios of 0.38, 0.44 and 0.54 at two different temperatures (25 °C and 85 °C) were investigated. Electrical resistivity was identified as the sensing and monitoring property for the smart cement. The shear thinning behavior of the smart cement slurries have been quantified using the new hyperbolic rheological model and compared with another constitutive model with three material parameters, Herschel–Bulkley model. The results showed that the hyperbolic model predicated the shear thinning relationship for the smart cement slurries very well. The hyperbolic rheological model has a maximum shear stress limit were as the other model did not have a limit on the maximum shear stress. The electrical resistivity changes of the hydrating cement was influenced by the water-to cement ratio. The minimum electrical resistivity of the cement slurry was linearly related to the water-to-cement (w/c) ratio of the cement slurry and it decreased with increased w/c ratio. Additional of 0.1% CF also increased the 28 day compressive strength of the smart cement by over 10%. The piezoresistivity of smart cement at peak compressive stress was over 700 times higher than the unmodified cement which was less than 0.7%, making the smart cement very highly sensing. The piezoresistivity of the smart cement was influenced by the curing time and w/c ratio. A nonlinear piezoresistivity model has been developed to predict the compressive stress – electrical resistivity relationship for the smart cement.

1. Introduction

With some of the reported failures and growing interest in environmental and economic concerns in the oil and gas industry, integrity of the cement sheath is of major importance. Oil well cement serves many purposes in the cemented oil and gas wells. Foremost important among these is to form a sealing layer between the well casing and the geological formation referred to as the zone of isolation. Two studies done on blowouts on the U.S. outer continental shelf during the period of 1971–1991 and 1992–2006 clearly identified cementing failures as the major cause for blowouts (Izon and Mayes, 2007). Cementing failures increased significantly during the second period of study when 18 of the 39 blowouts were due to cementing problems (Izon and Mayes, 2007). Also the deep-water horizon blowout in 2010 in the Gulf of Mexico was due to cementing issues (Kyle and Eric, 2014). The explosion at the drilling rig, Deepwater Horizon, which explored oil and gas at the Macondo well claimed eleven lives and caused severe injuries and record-breaking sea pollution by the release of about five million barrels of crude oil (Cristou and Konstantinidou, 2012). Therefore, proper monitoring and tracking the process of well cementing and the performance during the entire service life has become important to ensure cement integrity (Vipulanandan et al., 2014).

The viscosity of cement affects its pumping properties. The viscosity must be kept low enough to ensure pumpability of the slurry during the entire operation period. In deeper wells, because of the increased temperature, the viscosity decreases due to thermal thinning. This leads to an unwanted flow characteristic. Knowledge of the rheological properties of oil well cement are important to optimize cement slurry viscosity to maximize the displacement and safe circulating pressures. Undesirable cement rheological properties results in the settling of solids in cement compositions, which results in defective cementing and failure of the set cement to provide zonal isolation (Reddy and Riley, 2004).

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http://dx.doi.org/10.1016/j.petrol.2015.08.015
0920-4105/

Current empirical and time-independent rheological models (Power law, Bingham, Herschel–Bulkley) represent the shear stress-shear strain rate relationship, yield stress and apparent viscosity. The estimated rheological properties can vary significantly based on the models (Reddy and Riley, 2004). The Bingham plastic model and the Power law model are widely used in the petroleum industry to describe the flow properties of cement slurries (Guillot, 1990). The Bingham plastic model includes both yield stress and a limiting viscosity at finite shear rates, which the Power law model fails to consider. Herschel–Bulkley model does not have such limitation and can predict the nonlinear shear-thinning/shear-thickening behavior of OWCs. The hyperbolic model was effective in predicting the shear stress–shear strain rate shear thinning behavior and based on the root mean square error (RMSE) was predicting better than Herschel–Bulkley and Casson models also the hyperbolic model predicted the maximum shear stress tolerance of drilling mud other two models predicated infinite shear stress tolerance for the drilling mud (Vipulanandan and Mohammed, 2014).

Electrical resistivity measurement has been used by many researchers to characterize the cement concrete and in other cement applications (McCarter et al., 2000; Wei et al., 2008; Azhari and Banthia, 2012; Vipulanandan et al., 2014; Liao and Wei, 2014). Limited studies have used electrical measurement methods to study the microstructural evolution in hydrating cement-based material systems (Wei et al., 2008; Han et al., 2012; Zuo et al., 2014). However, there is no information in the literature on electrical resistivity for characterizing oil well cements (Mangadlao et al., 2015).

Past studies have investigated the changes in electrical resistivity with applied stress referred to as piezoresistive behavior of modified cement-based and polymer composites (Vipulanandan et al., 2008). These studies showed that the changes in resistivity with the applied stress were 30 to 50 times higher than the strain in the materials. Hence the change in resistivity has the potential to be used to determine the integrity of the materials. Past studies have reported that the interfacial factors are important in obtaining electrical resistivity from electrical resistance (Chung, 2001). Due to the voltage present during electrical resistance measurement, electric polarization occurs as the resistance measurement is made continuously. The polarization results in an increase in the measured resistance. The conventional methods of measuring the electrical resistivity of cementitious materials can be categorized into direct-current (DC) methods and alternating-current (AC) methods, both of which require electrodes for their measurements. Therefore, there is the potential for contact problems between the electrodes and the matrix, which could completely affect the accuracy of the measurement. Recent studies have suggested that replacing the DC measurement with the AC measurement can eliminate the polarization effect (Zhang et al., 2010, Mohammed and Vipulanandan, 2013).

The compressive stress–strain behavior of strain softening materials such as concrete, glass-fiber-reinforced polymer concrete, fine sands grouted with sodium silicate and cement mortar have been predicted using the *p*–*q* model (Mebarkia and Vipulanandan, 1992; Vipulanandan et al., 2008). Also the stress–strain behavior of Portland cement stabilized sand has been modeled using the *p*–*q* model (Usluogullari and Vipulanandan, 2011). Also the *p*–*q* model was used to predict the compressive strength behavior of the sulfate contaminated CL soil treated with polymer and lime (Vipulanandan and Mohammed, 2014).

1.1. Objectives

The overall objective was to quantify the effect of different w/c ratio on the electrical resistivity and piezoresistive behavior of smart oil well cement. The specific objectives are as follows:

(1) Characterize the shear stress–shear strain rate relationship of smart oil well cement at different water-to-cement ratios and different temperature and model the behavior using hyperbolic model and Herschel–Bulkley model.
(2) Investigate the relationship between the electrical resistivity of initial curing (1 day) of smart cement with water-to-cement ratios.
(3) Test and quantify the piezoresistive behavior of smart cement with different water-to-cement ratios up to 28 days of curing.

2. Materials and methods

In this study, Class H cement with water-to-cement of 0.38, 0.44 and 0.54 was used. The samples were prepared according to the API standards (API 1997, 2002). To improve the sensing properties and piezoresistive behavior of the cement modified with 0.1% of conductive fillers (CF) by the weight of cement was mixed with all the samples. After mixing, cement slurries used for rheological, curing and piezoresistivity studies. For the curing and compression piezoresistivity studies cement slurry was placed in plastic cylindrical molds with diameter of 50 mm and a height of 100 mm. Two conductive wires were placed in all of the molds to measure the changing in electrical resistivity. At least three specimens were used for each type of test for all the water-to-cement ratio mixes investigated in this study.

2.1. XRD characterization

An X-ray diffraction (XRD) analyses was performed in order to determine the chemical composition of oil well cement at 25 °C. The XRD pattern of the particles was obtained by using Siemens D5000 powder x-ray diffraction device. XRD analyses were performed on cement passing sieve No. 200 (75 µm). The powder (≈ 2 g) was placed in an acrylic sample holder (3 mm) depth. The sample was analyzed by using parallel beam optics with CuKα 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.

2.2. Rheological test

The rheology tests for smart cement with different water-to-cement ratios at two different temperature of 25 °C and 85 °C were tested using a viscometer in the speed range of 0.3–600 rpm (shear strain rate of 0.5–1024 s^{-1}) with a heating chamber. The speed accuracy of this device was 0.001 rpm. The temperature of the slurry was controlled to an accuracy of ± 2 °C. The viscometer was calibrated using several standard solutions. All the rheological tests were performed after 10 min of mixing of the cement slurries.

2.3. Electrical resistivity

It was very critical to identify the sensing properties for the cement that can be used to monitor the performance. After numerous studies and based on the current study on oil well cements, electrical resistivity (ρ) was selected as the sensing property for cement-based materials. Hence two parameters (resistivity and change in resistivity) were used to quantify the sensing properties of cement. Electrical resistivity is given by:

$$R = \rho * K \tag{1}$$

where R is electrical resistance. The calibration parameter K was determined based on the resistance measured at 300 kHz of