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Full Length Article

Vipulanandan model for the rheological properties with ultimate shear stress of oil well cement modified with nanoclay

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ABSTRACT

In this study, the effect of clay nanoparticles (NC) and temperature on the rheological properties with ultimate shear stress and weight loss of the oil well cement (class H) modified with NC was investigated. The NC content was varied between 0 and 1% by the weight of the cement. The total weight loss at 800 °C for the oil well cement decreased from 6.10% to 1.03%, a 83% reduction when the cement was mixed with 1% of NC. The results also showed that 1% of NC increased the rheological properties of the cement slurry. The NC modification increased the yield stress (τ_o) and plastic viscosity (PV) by 5%–65% and 3%–16% respectively based on the NC content and the temperature of the cement slurry. The shear thinning behavior of the cement slurry with and without NC has been quantified using the Vipulanandan rheological model and compared with the Herschel-Bulkley model. The Vipulanandan rheological model has a maximum shear stress limit were as the Herschel-Bulkley model did not have a limit on the maximum shear stress. Based on the Vipulanandan rheological model the maximum shear stress produced by the 0% and 1% of NC at the temperature of 25 °C were 102 Pa and 117 Pa respectively hence an increase of 15% in the ultimate shear stress due to the addition of NC. The addition of 1% of NC increased the compressive strength of the cement by 12% and 43% after 1 day and 28 days of curing respectively. The modulus of elasticity of the cement increased with the additional of 1% NC by 6% and 76% after 1 day and 28 days of curing respectively. Effects of NC content and the temperature on the model parameters have been quantified using a nonlinear model (NLM). The NLM quantified the effect of NC treatment on all the model parameters.

1. Introduction

Cement slurry in oil well cementing is pumped through a steel casing to the bottom of the well and then up through the annulus between the casing and the surrounding formations. The two principle functions of the primary cementing process are to restrict fluid movement between formations and to bond and support the casing [1]. As cement descends into the well, the slurry is hydrating under elevated temperature. The high temperature, high pressure, and the additives involved make oil well cementing a challenging process. The rate of increase in viscosity is the most important property in the well-cementing operation. When the viscosity of the slurry exceeds a few Pa.s, it becomes difficult to pump, so it is essential that this limit not was reached before the cement paste fills the annulus [2,3].

Rheology is defined as the science of deformation and flow of materials in response to applied stresses. The rheological properties through equations giving the relation between shear stress and shear strain rate for concentered suspensions of cementitious materials. These are suspensions that rheologically behave mostly in a non-Newtonian way such as the deformation and flows of the suspicions depend on the applied stress in a non-linear way. Being able to predict the rheological behavior of cementitious suspensions is important for the design, execution, and evaluation of a primary cementing operation [4]. A number of shear stress and shear strain rate relationships have been developed for cement slurries, but there is a lack of understanding of the relationships among the materials used for preparing such as slurries and test conditions such as temperature and shear rate. The power-law, Bingham, and Herschel-Bulkley models are the most commonly used in the well-cementing industry [5]. The rheological properties of oil well cement slurries are important in assuring that the slurries can be mixed at the surface and pumped into the well with minimum pressure drop and must be optimized to achieve effective well-cementing operation [2].

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1.1. Nanomaterials

Several reasons nanoparticles have had such a strong influence on the mechanical properties of cementitious materials become the nanoparticles have a high surface area, providing high chemical reactivity. Also owing to the fact that the C-S-H gel diameter is approximately 10 nm, the dispersed nanoparticles can fill the voids between cement grains, resulting in the denser material. Well-dispersed nanoparticles act as reaction centers, accelerating cement hydration because of the high reactivity of nanoparticles. Also, highly reactive nanoparticles accelerate the pozzolanic reaction and also react with $Ca(OH)_2$ [6,7]. Nanoparticles have been also added to drilling muds in small amounts, with amounts of the order of 1% to enhance the performance based on the environmental conditions [8–10]. Nanotechnologies are also being developed to enable and enhance down-hole sensors and actuators that can operate in chemically harsh environmental at high pressures and temperatures [11].

Nanotechnology has shown great potential in wide-ranging applications and can provide solutions to some of the upstream and downstream challenges in the oil and gas industry. Nanomaterials, having a particle size in the range of 1–100 nm, are now being commercially used in several applications [12]. Nanomaterials with large surface area are very reactive and have the potential for improving cement slurry properties such as high early strength, controlling fluid loss, accelerating cement hydration and reducing permeability [10,12]. The addition of nanomaterials such as nano silica and nanoclay resulted in a significant increase in the compressive strength of the cement and prevents strength retrogression at high temperature [13,14,15]. In addition to many advantages of using nanoparticles in the cement slurry, it is safer than conventional mud from the point of environmental view. Most of the proposed applications of nanotechnology in the oil field can be classified into the following areas of sensing or imaging, enhanced oil recovery, gas mobility control, drilling, and completion and produced fluid treatment [16]. 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 [17,18]. Montmorillonite based NC chemically is hydrated sodium calcium aluminum magnesium silicate hydroxide $(Na, Ca)_{0.33}(Al, Mg)_2\ (Si_4O_{10})\ (OH)_2{\cdot}nH_2O$ [16]. Nanoclay is a unique clay having a platy structure with a unit thickness of one nanometer or less. Because montmorillonite clay is hydrophilic, it is not compatible with most polymers and must be chemically modified to make its surface more hydrophobic [19]. The nanoparticles are smaller than the micro particles used in the slurry and have a higher area to volume ration which gives the surface properties more influence than the same particle with a larger size. 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 the virgin polymer or conventional micro and macro-composites [20,21]. The performance of nanoscale materials in the cement mortars was experimentally studied. The experimental results illustrate that the nanoscale structures, which was mixed with the cement mortars were highly beneficial in improving the rheological properties of the cement slurry, concurrently producing an increase in the compressive and flexural strengths of the cement mortar Due to calcination, the amorphous contents of nanoclay was increased, which later reacted with $Ca(OH)_2$ of the cement hydration products and formed additional calcium-silica-hydrate (CSH) gel. The benefit of the use of nanoclay was the improvement of the microstructure of the cement nanocomposite [22].

2. Objectives

The overall objective was to quantify the changes in the rheological properties of the oil well cement slurry modified with NC under different temperatures. The specific objectives are as follows:

(i) Investigate the effect of the nanoclay (NC) on the rheological properties of the oil well cement slurry at different temperature conditions.
(ii) Quantify the shear stress-shear strain rate relationship of cement slurry modified with varying amounts of NC at different temperature using the Vipulanandan rheological model and compare it to the Herschel-Bulkley model.
(iii) Investigate the relationship between the shear stress limit of the cement slurry and the NC and temperature.
(iv) Investigate the effect of the NC on the compressive strength of the cement at different curing time.

3. Materials and methods

3.1. Oil well cement

Commercially available oil well cement (Class H cement) was modified with NC used in this study. The chemical composition of the cement has been identified using X-ray diffraction as shown in Fig. 1(a).

3.2. Clay nanoparticles (NC)

Clay nanoparticles (NC) with the grain size of 25 nm and bulk density varied from 0.6–1.1 gm/cm^3 and purity of 99.0+% were purchased from Aldrich, USA and used for this study. The chemical composition of the NC has been identified using X-ray diffraction as shown in Fig. 1(b).

3.3. Sample mixture

In this study, oil well cement (Class H) with the water-to-cement ratio of 0.38 was used. The samples were prepared according to the API standards [23,24]. Three series of oil well cement slurries were prepared with varying amounts of NC up to 1% (by the weight of the cement) At least three samples were tested under each condition.

3.4. XRD analysis

An X-ray diffraction (XRD) analyses were performed in order to determine the chemical composition of cement at 25 °C. The powder (≈2 g) was placed in an acrylic sample holder (3 mm) depth. The samples were analyzed by using parallel beam optics with CuKα radiation at 40 kV and 30 mA. The samples were scanned for reflections (2θ) from 0° to 90° in steps of 0.02° and a 2 sec count time per step [25].

3.5. Thermogravimetric analysis (TGA)

Thermogravimetric analysis curves, mass loss (TGA) and its derivative (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 (¾ full). This was followed by the introduction of N_2 gas into the TGA compartment for 5 minutes 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 [16]. The weight loss percentage and temperature relationships were obtained for the sam-

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