Journal of Natural Gas Science and Engineering 35 (2016) 836–850

Contents lists available at ScienceDirect

Journal of Natural Gas Science and Engineering

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

Optimum particle size distribution design for lost circulation control and wellbore strengthening

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ARTICLE INFO

Article history:
Received 21 April 2016
Received in revised form
11 July 2016
Accepted 12 August 2016
Available online 16 August 2016

Keywords:
Wellbore strengthening
Lost circulation material
Optimum particle size distribution
Maximizing fracture propagation pressure
Large scale fracturing experiments

ABSTRACT

In this paper, we have experimentally studied the impact of particle size distribution (PSD) on the fracture sealing capability of lost circulation material (LCM) blends. Our primary aim was to determine the PSD which maximizes the Wellbore Strengthening (WBS) benefits obtained from fracture sealing. High-pressure borehole fracturing experiments were conducted on Berea sandstone samples under atmospheric pore pressure and various confining pressures to investigate the WBS effects of several LCM blends. Post-fracturing methods such as Computerized Axial Tomography (CAT) scan and thin-section imaging were used to investigate the geometry of induced fractures and formed seals within them. Based on the conducted experiments and post-fracturing analyses, we have evaluated and re-assessed well-known theories applicable to the design of LCM blends, such as the one-third rule, the ideal packing theory, and the Vickers criteria. Our experiments indicate that for any rock with a given set of rock strength and failure parameters, there exists an optimum PSD to maximize WBS benefits. Optimum PSD appears to be of primary importance, almost independent of LCM type. In addition, we have shown that the optimum PSD should have a bimodal structure, with sufficient concentrations of properly sized fine and coarse particles. Although the one-third rule, the ideal packing theory, and the Vickers criteria may provide some basic PSD guidelines, these theories are mainly empirical relationships based on conventional particle plugging experiments. As shown here, they do not properly represent the physics of fracture sealing. To remedy this situation, we are introducing a new family of design curves for optimum PSD, based on the underlying physics of fracture sealing observed in the WBS experiments.

1. Introduction

WBS is an effective technique to help negotiate challenging wells with narrow drilling margin (van Oort and Razavi, 2014). It can be defined as the extension of the drilling margin through enhancement of the fracture pressure. Fracture pressure enhancement is usually achieved by plugging the fractures (whether these are drilling-induced or natural) existing in the proximity of the borehole. The plugging solids used for WBS are generally known as LCM in the drilling industry. Since the introduction of the LCM to the industry, numerous experimental investigations have been conducted to understand the true underlying mechanics of fracture bridging which occurs due to the presence of LCMs in drilling fluids (e.g., Drilling Engineering Association (DEA) 13 (1985 and 1988), Dudley et al. (2000), Guo et al. (2009, 2014)). Building on the results of these experimental investigation, several theoretical studies were conducted to determine the fracture pressure of boreholes with various formation types, inclination angle, and in-situ stress values (e.g., Morita et al. (1990), Chen et al. (2015), Dokhani et al. (2014, 2015), Mehrabian et al. (2015)).

Several design guidelines were introduced to determine the optimum PSD, concentration, type, and shape of the LCMs required for WBS applications. Abrams (1977) pioneered the work on the design of bridging solids. His work led to the introduction of the well-known “one-third rule”, aka the Abrams' rule. The one-third rule recommends the following guidelines for the size and concentration of bridging materials:

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http://dx.doi.org/10.1016/j.jngse.2016.08.038
1875-5100/

1 The median particle size of the bridging additive should be equal to - or slightly greater than - one-third the median pore size of the formation.
2 The concentration of the bridging size solids must be at least 5 percent by volume of the solids in the final mud mix.

Abrams' work was primarily aimed at reduction of formation damage due to reservoir impairment. However, the one-third rule can be applied to determine the size of bridging solids used for various particle plugging applications, including WBS. Building on Abrams' work, Vickers et al. (2006) employed the Pore Plugging Apparatus (PPA) and return permeability testing to minimize fluid loss. This work resulted in the introduction of the "Vickers criteria", which prescribes the following standards for the PSD of the bridging LCM blends:

- D_{90} = largest pore throat
- D_{75} < 2/3 pore throat
- D_{50} = 1/3 of the mean pore throat
- D_{25} = 1/7 of the mean pore throat
- D_{10} > smallest pore throat

In addition, the authors recommended that the concentration of bridging material needs to be greater than 30 pounds per barrel (ppb) for water based mud (WBM) (this may be reduced for oil-based mud). This concentration, however, is lower than the 5 percent solid volume recommended by the Abrams' rule.

Fuh et al. (1993) patented a method for inhibiting the initiation and propagation of fractures by using LCM of a specific size. Their method was the result of the experiments conducted at the DEA 13 investigations (1985 and 1988) and several field applications, which employed the LCMs for WBS purposes. The patent prescribes adding 30–50 ppb of LCM with a critical size ranging from 250 to 600 μm to the drilling fluid. The preferred LCM types are nut shells or calcined petroleum coke.

Dick et al. (2000) conducted another major effort for the selection of bridging particles by adopting the "ideal packing theory" from the paint industry to practical oilfield use. Originally, the ideal packing theory was introduced by Andreasen and Andersen (1930) who proposed a power law relationship between the Cumulative Volume, CV, and the particle size, d, ($CV \propto d^x$) for effective bridging. The exponent value (x) typically ranges between 0.5 and 1. Kaeuffer (1973) states that ideal packing occurs when the CV varies linearly with the square root of the particle size ($CV \propto d^{\frac{1}{2}}$). More recently, Chellappah and Aston (2012) improved upon this power law model by employing particle plugging apparatus (PPA) testing and suggesting that the optimum value of exponent (x) is closer to 1 than to 0.5.

Although LCMs have become a standard part of fluid design for drilling formations with a narrow drilling margin, the industry still lacks a comprehensive framework to optimally select LCMs for WBS applications. Confusions persist on the underlying mechanics of fracture sealing and the true location of the seal formation along the fracture length. Very few in-depth experimental studies have been carried out to evaluate the validity of the proposed mechanisms. Furthermore, the above-mentioned guidelines for LCM concentration and PSD have not been examined independently in realistic fracturing experiments.

In this paper, we apply an experimental approach to study the fracture plugging during the WBS phenomenon. In section 2, we briefly describe the experimental set up, the tested fluid system and rock samples, and the testing procedure. In section 3, we present the results of parametric studies using synthetic-based fluids loaded with graphite- and Gilsonite-based LCMs. Post-fracturing analyses such as thin-section and CAT scanning imaging were conducted to study the geometry and structure of formed plugs on the fracture surface. In addition, the existing models to design the bridging blends are evaluated based on the conducted WBS experiments and post fracturing analyses. Finally, we propose a novel method to determine the optimal LCM PSD which maximizes the strengthening benefits. In section 4, we list a summary of our finding and conclusions.

2. Approach

2.1. Experimental set up: the UT MudFrac system

A state-of-the-art experimental set up was designed and manufactured for in-depth WBS investigations. The UT MudFrac hydraulic fracturing system (Fig. 1a–b) is a dual flow-loop and pressure-intensifying system which tests 4 inches diameter x 6 inches length cylindrical rock samples. A 9/16 inch borehole is drilled and flow lines are inserted 2.5 inches into each end of the sample, leaving 1 inch of the rock surface for fracture initiation and propagation. The flow lines are epoxied to the rock sample to prevent pressure communication between the borehole and the vessel. The sample is isolated by using two steel end-caps in the axial direction and a rubber sleeve in the radial direction (Fig. 1c–d). The UT MudFrac system applies isostatic confining pressure to the sample by compressing the confining fluid (water). Positive displacement pumps are used to control the borehole injection and confining pressure. A more detailed description of the experimental set up is presented in Razavi et al., 2015.

2.2. Rock and fluid samples

Berea sandstone samples were selected to represent permeable rock formations. Typical material properties of the samples are presented in Table 1. The permeability and porosity measurements were provided by the rock sample supplier. Brazilian tensile strength and fracture toughness measurements were performed on three intact cores and the average values are reported in Table 1. In addition, the compressive strength and elastic moduli (Young's modulus and Poisson's ratio) of Berea sandstone samples were measured at 0, 500, 750, and 1000 psi confining pressures (Fig. 2). Synthetic based mud (SBM) was used as the base fluid system during the fracturing experiments. Mud density was maintained at 12 pounds per gallon (ppg) using Barium Sulfate (barite) as the weighting agent. Commercial grades of graphite- and Gilsonite-based LCMs, which are routinely used in field practice for lost circulation control purposes, were used. Rheological properties of the drilling fluids were measured before and after each experiment. Typical values for plastic viscosity (PV), yield point (YP) and gel strengths (10-sec and 10-min) are reported in Table 2.

2.3. Testing procedure: fracture initiation and propagation injections

Each fracturing experiment with the UT MudFrac system includes one fracture initiation and several fracture propagation injections on an intact Berea sandstone sample. Fracture initiation injection was performed by pressurizing the closed borehole at a rate of 1 cc/sec and 100 psi confining pressure. Subsequently, fracture propagation injections were carried out on the sample at a rate of 0.1 cc/sec and at confining pressures of 100, 200, 300, 400, and 500 psi. All experiments were conducted at atmospheric pore pressure and room temperature.

In Fig. 3a, the fracture initiation injection results are shown for two distinct drilling fluid systems: SBM without LCM, and SBM loaded with 30 ppb of graphite-based LCM. The injection and