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Experimental investigation of rheological properties of fiber-laden crosslinked fracturing fluids

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ABSTRACT

Proppant settling is a critical issue in hydraulic fracturing and this is found to be a strong function of rheological properties (viscosity and elasticity) of fracturing fluids. In order to improve proppant-suspension capacity of fracturing fluids, fiber materials are often added into fracturing fluids, such as in FiberFRAC and channel fracturing. However, only few studies have currently dealt with the rheological properties of crosslinked fracturing fluids containing fiber. In this paper, a comprehensive study was performed to investigate the influence of fiber on the rheological properties (apparent viscosity and viscoelasticity) of borate crosslinked hydroxypropyl guar (HPG) gels by using a HAAKE MARS III rheometer with different geometries (a concentric-cylinder geometry, a vane geometry and a parallel-plate geometry). It was found that the addition of fiber did not have a significant influence on the apparent viscosity of crosslinked fracturing fluid, which was due to the high viscosity of borate crosslinked fracturing fluids and low dosage of fiber. However, the addition of fiber caused an obvious increase in the elastic modulus of crosslinked fracturing fluid. Significant increment in elastic modulus was observed at high fiber concentration and long fiber length.

1. Introduction

Hydraulic fracturing is widely used to enhance oil/gas production in low permeability reservoirs. Typical hydraulic fracturing treatment consists of pumping large quantity of high viscosity crosslinked fracturing fluid along with large quantity of proppants to create a conductive proppant pack. In order to maximize the productivity in fractured wells, it is highly desirable to transport proppants further and to place them evenly within the created fractures, which provide long and highly conductive passages for hydrocarbons to flow from reservoir into wells. Proppant settling is a critical issue in proppant transport. Rapid proppant settling would reduce effective fracture length and results in less coverage in fracture height, which drastically reduces the effectiveness of hydraulic fracturing. In worst-case scenario, fast settling of proppants would even result in screenout in the near wellbore region, causing failure of fracturing treatment.

It is widely accepted that the settling velocity of proppants could be calculated through the classical Stokes law (Eq. (1)), which shows that proppant settling velocity is inversely proportional to the fracturing fluid viscosity (Acharya, 1986; Daneshy, 1978; Gadde et al., 2004; Novotny, 1977).

$$V_s = \frac{\left(\rho_p - \rho_f\right) g d_p^2}{18\mu_a} \tag{1}$$

However, recent researches have shown that borate crosslinked Hydroxypropyl guar (HPG) gels, which are the most commonly used fluids in hydraulic fracturing treatments, are viscoelastic in nature, displaying both viscous and elastic properties (De Kruijf et al., 1993; Harris et al., 2005; Prud'homme et al., 1988, Wang et al., 2014). The elastic property can better describe the proppant-suspension capacity of crosslinked fracturing fluids (Acharya, 1986, 1987; De Kruijf et al., 1993; Goel et al., 2002; Power, 1997). Acharya (1987) investigated the effect of viscosity and elasticity of fracturing fluids on the settling rate of single proppant. He proposed that the elasticity also affected the proppant-suspension capacity and this property might be more important. De Kruijf et al. (1993) showed that the static proppant settling in borate crosslinked HPG gels was not controlled by the viscous modulus but by the elastic modulus of gels. Goel et al. (2002) performed proppant settling experiments in non-crosslinked and crosslinked guar gels using a high-pressure simulator and found

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that the fracturing fluids which satisfactorily transported proppants through the slot had similar elastic modulus. They concluded that compared to apparent viscosity, the elastic modulus was a more appropriate parameter to represent the proppant-suspension capacity of fracturing fluids.

In order to improve the proppant-suspension capacity of fracturing fluids, fiber materials are often added into fracturing fluids, such as in FiberFRAC (Bulova et al., 2006; Engels et al., 2004; Guo et al., 2012; Vasudevan et al., 2001) and channel fracturing (Ejofodomi et al., 2014; Gillard et al., 2010; Johnson et al., 2011; Medvedev et al., 2013). Although many proppant settling experiments have confirmed that the addition of fiber could effectively decrease the settling velocity of proppants (Engels et al., 2004; Guo et al., 2012; Medvedev et al., 2013; Vasudevan et al., 2001). The reasons why this happens, the effect of fiber on the rheological properties and the effect of fiber on the proppant-suspension capacity of fracturing fluids are still unclear.

A few articles have reported the influence of fiber on the apparent viscosity of fracturing fluids. Vasudevan et al. (2001) initially proposed that addition of fiber significantly increased the apparent viscosity of linear guar gels. Recently, the study of Guo et al. (2015) demonstrated that adding fiber to HPG base gels caused a significant increase in apparent viscosity. However, studies of Engels et al. (2004) and Bulova et al. (2006) showed that the addition of fiber had almost no influence on the apparent viscosity of borate crosslinked gels. Guo et al. (2012) also reported that adding 1 wt% concentration of PP/PET fiber and PP/PET/SIO2 fiber resulted in increases of 6–9 mPa s and 12–15 mPa s respectively in apparent viscosity of crosslinked fracturing fluids. This therefore indicated that the addition of fiber did not have a significant effect on the viscosity of crosslinked fracturing fluids whose apparent viscosity was high.

However, with respect to the effect of fiber on the viscoelastic properties of fracturing fluid, there was almost no work reported. But in other industries, such as paper manufacture and fiber-reinforced composites, many researchers have done studies focusing on viscoelasticity of fiber suspensions (Advani, 1994; Cui and Grace, 2007; Derakhshandeh et al., 2011; Keshtkar et al., 2009; Swerin et al., 1992). Swerin et al. (1992) used a parallel-plate rheometer to study the viscoelastic properties of pulp suspensions at mass concentrations ranging from 3 wt% to 8 wt%. The experimental results indicated that the viscous and elastic modulus increased with fiber mass concentration and did not vary with the frequency. In a study on the influence of fiber aspect ratio (the ratio of fiber length to fiber diameter) on the viscoelastic properties, Guo et al. (2005) measured the glass fiber suspensions consisting of the polyethylene and fibers of different aspect ratios. They proposed that the viscous and elastic modulus increased with the fiber aspect ratio. Rajabian et al. (2008) investigated the viscoelasticity of polyethylene composites filled with Kevlar fibers at volume fractions of 5% and 10% by small-amplitude oscillatory shear tests (SAOS). They demonstrated that the addition of fiber significantly increased elastic modulus and complex viscosity of composites and explained that it was due to the strong interactions between the fibers and polyethylene matrix. Keshtkar et al. (2009) studied the rheological behavior of various suspensions composed of different kinds of fibers in silicone oil with a parallel-plate geometry. The experimental results showed that the elastic modulus and complex viscosity of fiber suspensions increased with the fiber aspect ratio and flexibility, which were a result of formation of a network-like structure of fibers.

In our previous paper, we focused on the effect of fiber on the apparent viscosity of HPG base gels (Guo et al., 2015). In this current paper, a comprehensive study was performed to investigate the influence of fiber on the rheological properties (apparent viscosity and viscoelasticity) of borate crosslinked HPG gels by using a HAAKE MARS III rheometer equipped with a variety of geometries (a concentric-cylinder geometry, a vane geometry and a parallel-plate geometry). Specially, the effect of fiber variables (fiber concentration and fiber length) on the elastic modulus of crosslinked fracturing fluids were discussed experimentally.

2. Experiments

2.1. Experimental materials

0.35 wt% HPG solutions crosslinked with borate were used as the base fluids. To simplify the solution, only HPG, borate and sodium bicarbonate, which affected the crosslinking reaction, were added into the distilled water. The crosslinked HPG gels were viscoelastic fluids displaying both viscous and elastic behavior (Goel et al., 2002).

One kind of polyester fiber, which was commonly used in channel fracturing in China, was used in our experiments (Fig. 1A). Dispersion tests showed that the fiber could be evenly dispersed both in the HPG base gels (Fig. 1B) and in the crosslinked HPG gels (Fig. 1C). Through crosslinking experiment and gel breaking test, it was found that addition of fiber almost had no effect on the crosslinking reaction and gel breaking reaction of fracturing fluids. Because fiber concentrations (C_f) used in the field were between

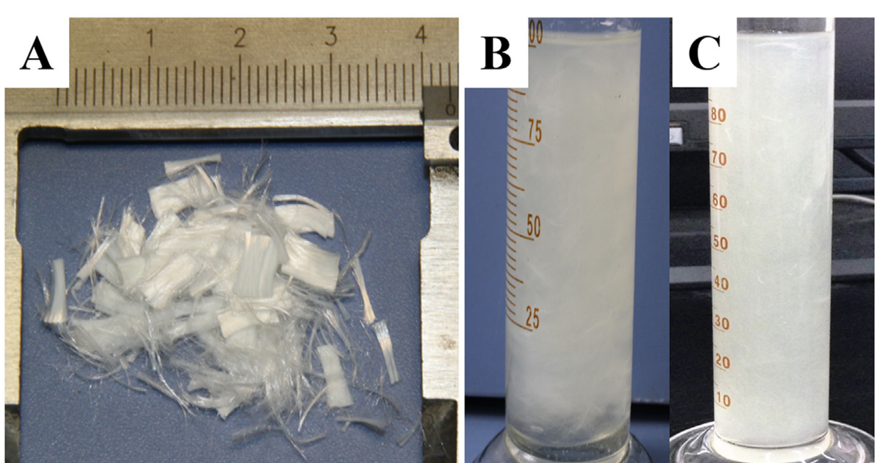

Fig. 1. The fiber used in the experiments (A) and dispersion test: (B) in HPG base gels and (C) in crosslinked HPG gels.