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Research paper

Properties and plugging behaviors of smectite-superfine cement dispersion using as water shutoff in heavy oil reservoir

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ABSTRACT

The high viscosity of crude oil, high permeability and strong edge water in some heavy oil reservoirs usually result in the failure of traditional water shutoff agents. In this paper, a novel water shutoff agent, the smectite-superfine cement dispersion, was produced based on traditional cement plugging agent. The high temperature stability test, simulated formation injection test and plugging strength test were conducted to evaluate the water shutoff performance. The results showed that the smectite-superfine cement dispersion exhibited perfect water shutoff performance and could fit into reservoirs with different permeability values by adjusting the cement content. The SEM analyses indicated that the hydration productions of superfine cement and smectite grew in a crisscross way and formed a stable microstructure, which ensures the composite with high strength.

1. Introduction

Some heavy oil reservoirs are characterized by highly viscous crude oil, high permeability and strong edge water (Cansu and Serhat, 2016). During cyclic steam stimulation, the invading edge water helps drive the oil to the producing wells, meanwhile, leads to a steady rise in well's water cut (Briggs et al., 1988; Tang et al., 2011). It is a very common used method to increase oil recovery with blocking agent, which can plug the high permeable water channels effectively (Thomas, 1998). In the past, several blocking agents were used in heavy oil reservoirs to control the edge water fingering but their effects were not that satisfactory. Some of them including conventional amphoteric polymer gels (Thomas, 1998; Demir et al., 2016) and preformed particle gel plugging agents (Imqam et al., 2015) showed bad high-temperature stability, some of them exhibited poor injectivity behaviors (Garland, 1966), and the others like tannin extract (Al-Muntasheri et al., 2008) were less effective. As a summary, an idea plugging agent should possess good heat resistance, strong plugging strength, good injection performance and economic feasibility (Denney, 2001), according to which, cement is chosen as the most suitable component. Cement plugging agent is not only very cheap, but also has good ability to afford the negative pressure in near-wellbore area, strong plugging strength, and high resistance to both temperature, salt and acid (Teng et al., 2006). However, there are also some disadvantages, like poor suspending ability, which means the particles precipitate easily, thus hinders the transport of particles from entering into deep formation (Shidel, 1919). What's worse, normal cement system has very narrow selectivity (Van Eijden et al., 2006).

Superfine cement particle is much smaller than the ordinary ones, and has better flowing performance, higher strength and better stability (You et al., 2015; Eskişar et al., 2015). Because of its small particle size, the superfine cement has large specific surface area, which results in faster hydration and longer initial setting time than normal cement. Tests proved that superfine cement was an effective cementitious filler to improve cement packing density, rheology and strength (Chen and Kwan, 2012).

Usually some suitable materials are added into cement slurry to improve its properties for application. The smectite-superfine cement mixture material was recommended in few studies (Akbulut et al., 2015; Anagnostopoulos, 2015; Gupta and Kumar, 2017; Jenni et al., 2017). Using cement or lime to stabilize clay materials is a well-established technology to obtain superior engineering properties/performance. The basic layered structure of montmorillonite is composed of 2 silica tetrahedron slices and 1 alumina octahedral slice. Such material has excellent properties, such as small particle size, high specific surface area, aspect ratio, cation exchange capacity (CEC) and adsorption capacity, most importantly, it's cheap (Utracki, 2009; Alves et al., 2016).

Goodarzi et al. (2016) found that the silica fume binary system could expedite the process of stabilization and thus improve the engineering properties of clay with a smaller addition of binder. To

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investigate Metakaolin's (MK's) effect on the hydraulic conductivity of cement stabilized soil, the flexible wall permeameter was developed and mercury intrusion porosimetry (MIP) tests were performed. Deng et al. (2015) investigated Metakaolin's effect through testing the hydraulic conductivity of cement stabilized soil. Test proved that Phyllite smectite-superfine cement composites have eligible plasticity index, maximum dry density and a very low permeability. Thus, it could be applied to build roofs and flexible pavements (Garzón et al., 2015). Fan et al. (2014) discovered that the addition of clay can enhance both the early-age and long-term flexural strength of the cement paste. Nowadays, the smectite-superfine cement was widely used for shielding the radioactive material. Akbulut et al. (2015) found that the clay-white cement mixture was superior than some other samples in radioactive shielding. Eskander et al. (2013) proposed a mixture of clay, cement, liquid scintillator radioactive waste and water and found that it complied with the required specifications of the disposal process at very exaggerating conditions.

Because of the excellent properties of the clay-cement composites, its mechanism of action was also studied by many researchers (Yoobanpot et al., 2017; Jiang et al., 2017; Yadav and Tiwari, 2017). Based on the XRD and SEM analyses, the incorporation of silica fume and cement matrix extended the formation of new cementing compounds and provided a much denser microstructure (Goodarzi et al., 2016). The impact of adding kaolinite clay was investigated to enhance the chloride penetration resistivity of concrete structures, and the SEM pictures suggested that the kaolinite clay acted as a filler, as well as an accelerator of cement hydration (Fan et al., 2014).

Unfortunately, we found no published work in literatures concerning the plugging performance of composites prepared using smectite and superfine cement additive. Therefore, the formula of smectite and superfine cement needs to be optimized for better performance in application. As one potential water shutoff agent for high oil reservoir, this paper reports a new experimental study on smectite-superfine cement composites to examine the improvement in selected engineering properties and plugging performance. The reaction mechanism of the two main materials was also investigated.

2. Experimental materials and procedures

2.1. Materials

In the present investigation, selected smectites, sourced from Dongying Province, was used. The physical properties and chemical compositions of superfine cement were listed in Tables 1 and 2. The major oxide compositions of this smectite were analyzed by X-ray fluorescence spectrometer (ARL-9800, Switzerland) and the result is show in Table 3. The specific surface area (SSA) of smectite and cement was measured using N_2 adsorption/desorption (Tristar 3000, Micrometrics, Norcross, GA U.S.A.). WINNER2000 laser particle size analyzer was adopted for particle size analysis, with transmittance of 2.5–3.5 and ultrasonic vibration time of 1–2 min

2.2. Procedures

In preparing for the composite, the specific amount of smectite was added to water and stirred for 24 h to ensure fully hydrated before cement was added. The mixture was characterized by its strength, condensate rate, viscosity, particle size and plugging performance.

Table 2
The chemical composition of superfine cement.

Composition	Loss	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O
Mass (%)	1.93	19.69	4.53	3.20	66.61	1.61	0.13

Table 3
The chemical composition of smectite.

Composition	Al_2O_3	SiO_2	Fe_2O_3	CaO	Na_2O	K_2O	MgO
Mass (%)	18.45	63.22	11.68	0.42	4.58	0.89	0.76

The viscosities and rheological behaviors of samples with 10% smectite and different superfine cement contents (1%, 3%, 5%, 7%, 9% by weight) were measured by DV-III viscometer at six different rotate speed (ranging from 1.5 r/min to 60 r/min).

In the strength and stability tests, the separated water ratio of the smectite-superfine cement dispersions (smectite concentration from 5% to 12.5% and cement addition from 1% to 5% by weight) were tested to determine the optimal ratio. Also, ten samples (10% smectite dispersions with 0 to 10% superfine cement) were sealed in penicillin bottle and placed in 60 °C. A 5.00 g heft needle was used to measure the penetration depth at various curing time. The strength is inversely proportional to penetration depth.

For the injection behavior and plugging performance tests, 11 samples with different solid ratios (the superfine cement content ranged from 1% to 8%). Sand pack (Φ2.5 cm × 50 cm) was used to evaluate the plugging performance of the dispersion. Formations with different permeability (6 μm^2, 12 μm^2, 18 μm^2, 24 μm^2) were simulated by filling quartz sands with different particle sizes. The samples were injected into the sand pack at a constant speed (2 mL/min) and the injection pressure was recorded.

Measurements were performed using a D8 ADVACE X-ray diffractometer with CuKα radiation. Spectra were obtained in the range $5^\circ < 2\theta < 80^\circ$. The mineralogical changes of smectite-superfine cement dispersions were determined after 1 day and 5 days placed in 60 °C thermostat. When studying the microstructure of the clay paste samples with superfine cement addition, a JSM-6360LV SEM system was used to observe the samples. The applied accelerating voltage is 20 kV. The EDAX technique was applied to analyze the element distribution in the samples, as well. The EDAX plots provide the presence of chemical elements, which can confirm the composition of crystal in the concrete samples. Small fractured samples or powder samples were coated with 5 to 10 nm thickness gold to make it conductive.

3. Results and discussions

3.1. Characterization of the smectite and superfine cement

The particle size distribution of smectite and cement were shown in Fig. 1. The result of particle size analyses showed that the Dv95 of the cement was 11.849 μm and the specific surface area was 976.6 m^2/kg, which meant that the cement was superfine cement according to the European Standard for grouting (SFS-EN 12715). The Dv95 of the smectite was 36.681 μm and the specific surface area was 422.9 m^2/kg.

Table 1
The physical properties of superfine cement.

Specific surface area (m^2/kg)	Density (g/cm^3)	Cement standard thickness (%)	Jelling time (min)		Flexural strength (MPa)		Compressive strength (MPa)	
			Presetting	Final set	3d	28d	3d	28d
976.6	3.11	28.8	137	192	7.3	10.4	37.8	60.4