



Role of active clays on alkaline–surfactant–polymer formulation performance in sandstone formations

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HIGHLIGHTS

- ▶ We ran experiments on two reservoir rocks to demonstrate impact of active clays on recovery.
- ▶ We demonstrate that active clays can hinder the performance of alkaline–surfactant–polymer.
- ▶ Geochemical model predicts relatively well effluent chemistry during corefloods.
- ▶ Detailed experimental and modeling work lead the way in generating predictive EOR models.

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ABSTRACT

Enhanced-oil recovery by means of chemical methods such as alkali–surfactant–polymer (ASP), surfactant–polymer (SP) and also alkali–polymer (AP) flooding have been reported as an effective strategy to increase oil recovery. Despite promising results of ASP floods in numerous formations, ASP projects can be plagued with severe scale formation and injectivity losses during the flooding period. Our current approaches have limited ability to predict these problems. Clay type and amount have been claimed as key in the performance of chemical floods. In this study, single- and two-phase flow experiments were carried out to study how ASP blends performed in the presence of clays using rock samples from two different oil-producing formations located in South America and Wyoming, respectively. To support speculations on the role of clays, in addition to XRD and SEM, effluent water samples as well as production data were also analyzed after each flooding step. Numerical simulations based on production data and water composition analysis were built and run to show the importance of clay presence in reactive transport modeling. Results show that the performance of ASP flooding is affected significantly by the presence of active clays.

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1. Introduction

After primary depletion and secondary waterflooding of oil reservoirs, significant amount of oil can still remain in the reservoir due to capillary trapping as well as bypassed oil as a result of viscous fingering. This amount of oil is often the target for enhanced oil recovery (EOR) methods. Alkali–surfactant–polymer (ASP) flooding has been claimed as a very promising EOR method and has been studied and tested vastly for more than two decades [1–10]. In this process, a blend of an alkaline agent, surfactant (S) and a polymer is injected into the reservoir, usually chased with a polymer drive. The main function of the ASP blend is to increase the in situ Capillary Number (CN) by reducing interfacial tension between oil and water to ultra-low values and also by increasing

the viscosity of the displacing fluid [4,11]. An inversely proportional relationship between CN and residual oil saturation has been found experimentally [12,13].

In this complex chemical treatment, the mineralogy and clay content of the formation have been found to be detrimental to floods. These problems can be summarized in terms of undesirable surfactant retention, polymer adsorption, alkali consumption, fine migration, scale formation and permeability damage [14]. Due to the large effective surface area of clays and the high degree of reactivity of such surfaces, clays can strongly influence the success of ASP floods. Therefore, rock mineralogy and clay content should be considered carefully as two key screening considerations when designing ASP floods [15].

Additionally, ASP flooding often requires injection water treatment in the form of either fresh or softened waters to avoid precipitation of scales during chemical mixing and also to prevent early chemical degradation of polymer. However, once the chemical slug

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is injected in fresh water, its effects while mixing with the reservoir waters is not well understood, particularly in the case of high divalent cations content.

In addition to the aforementioned problems caused by clays, formations with active clays are subject to permeability damage during low salinity waterflooding when water-sensitive/swelling clays are present [16,17]. Quirk and Schofield [18] showed that the hydraulic conductivity of a soil decreased with increasing exchangeable sodium percentage and decreasing ionic strength of the percolate. Frenkel et al. [19], Pupisky and Shainberg [20] and Alperovitch et al. [21] showed that permeability dropped for loamy sand soils flooded by de-ionized water. McNeal and Coleman [22], and Yaron and Thomas [23] concluded that most soils with high exchange capacity were those rich in 2:1 layer silicates, especially montmorillonite and the least labile were those rich in kaolinite and sesquioxides. Clay swelling has been one of the main causes for formation damage in oil reservoirs and it occurs mostly in the vicinity of the wellbore during well operations (e.g. drilling and completion) [16,24].

Mungan [25] found that increasing pH and reducing salinity of injected fluid can reduce the permeability of Berea cores. This rock is known to have minute or negligible amounts of clay with high cationic exchange capacity (CEC). Mechanisms of permeability reduction are different between fine migration and high CEC clays. Mungan [25] found that injection of high pH blend through Berea core causes dissolution of silicate cements leading to fine migration and consequently pore plugging. However, injection of low-salinity brine is frequently responsible for clay swelling and also fine migration. Mungan et al. also found that when alkali injection is chased with distilled water, further permeability reduction took place. They proposed that such reduction could be caused by dispersion of Na⁺ saturated clays in distilled water.

In EOR, the potential of formation damage can be greater because fluid-rock interactions and incompatible fluid pairs (injected-formation waters) may cause secondary mineral precipitation, clay swelling, and fine migration and thus these interactions can be detrimental to formation permeability. Mayer et al. provide a good summary of EOR alkali field projects (70 s and 80 s) and possible explanations of fluid–fluid and fluid–rock interactions during alkali injection [26]. Southwick describes the impact of silica dissolution in pure quartz sand to impact 10–20% alkalinity [27]. Southwick contrasts the findings with modeling predictions by Bunge and Radke [28], in which the impact of slow quartz dissolution is significantly greater. Daqing Field (China) and Warner Field (Canada) are two examples of ASP floods that document scale (calcite and silica) formation [29]. These unexpected scale problems on the basis of lab results suggest that lab scale experiments might not be representative enough to generate the information needed to predict these types of fluid–rock interactions. Therefore, the use of reservoir rock for chemical floods is extremely important (if not mandatory) to evaluate chemical floods, especially for alkaline floods. Water compositional analysis of the effluents during ASP core floods to infer possible fluid–rock interactions using geochemical simulators and coupling key chemical reactions in commercial numerical simulations can provide information to better understand and potentially up-scale chemical floods.

ASP floods, not including polymer-induced permeability reduction, have high potential of causing permeability reduction. This is attributed to the presence of alkali agent and also injection of low-salinity brine through polymer drive step, particularly in formations with sensitive clays present.

The overall objective of this research is to determine the impact of mineralogy and clays on the performance of ASP floods in sandstone formations. To this end, rock samples from two distinctive sandstone formations were used in experiments. Several assays are used to study this problem. First, X-ray Diffraction (XRD) and

Scanning Electron Microscope (SEM) with the energy-dispersive analysis of X-rays (EDAXs) are employed to evaluate elemental composition and possible changes in rock mineralogy and clay content of each rock before and after flooding. Second, an ASP core-flood for each formation rock sample is completed. Collected results of these corefloods consist of production data and water inorganic analysis of effluent samples. Third, to better understand the impact of crude oil and water–rock interactions on results, single-phase flow experiments are carried out. One intent of these two floods is to determine differences in geochemical responses between the two sandstone formations, as the clay types are quite different. To evaluate our understanding of dominant flood controls from the point of view of geochemistry, numerical models using a pseudo-compositional commercial code (CMG-STARs) are developed to match two-phase flow coreflooding data and a geochemical commercial code (Geochemist's Workbench) is employed to match water chemistry data for single-phase flow experiments. Once models are history-matched, forward simulations serve to scrutinize our understanding of these multiphase flow recovery mechanisms.

2. Materials and methods

2.1. Materials

All the core samples used in this study were taken from two oil-producing formations located in South America and Wyoming. Composite cores were assembled using short plugs with similar properties. Core properties are summarized in Tables 1 and 2. Crude oils from the same formations are used in ASP floods. Basic crude oil properties are reported in Table 3 (resin and asphaltene fractions, in bold, are similar in the two crude oils). In the first ASP flood (ASP1) carried out on the South American formation, partially hydrolyzed polyacrylamide (HPAM), Na₂CO₃ and S3B are used as polymer, alkali and surfactant agents, respectively. In ASP1, produced water (PW1) had the same chemical composition of the formation water. Injection water (IW1) with the same composition of injected water in the field (Table 4) is used to saturate the composite core and setting initial water saturation (S_{wi}), and during the water flooding step (S_{or}) subsequently. For ASP flood,

Table 1
Properties of composite cores in ASP1 and ASP2 tests.

Test	ASP1	ASP2
Length of composite core (in)	10.42	10.09
Pore volume of composite core (cc)	51.85	42.31
Porosity of composite core (%)	17.7	14.87
Number of core plugs in the composite core	3	4
The length of each core plug from bottom to top (in)		2.45
	3.48	2.45
	3.46	2.62
	3.48	2.57
Air Permeability of each core plug from bottom to top (md)		148
	1142	130
	1021	119
	984	118

Table 2
Properties of used cores in single-phase flow experiments 1 and 2.

Test	ASP1	ASP2
Length (in)	2.56	2.42
Pore vol. (cc)	10.6	9.9
Porosity (%)	14.69	14.51
Permeability _{air} (md)	118	93

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