

Toward Reducing Surfactant Adsorption on Clay Minerals by Lignin for Enhanced Oil Recovery Application

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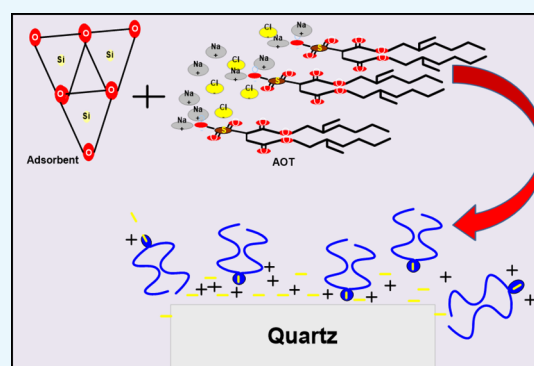
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ABSTRACT: The significant loss of surfactants during reservoir flooding is a challenge in oil field operations. The presence of clay minerals affects the surfactant performance, resulting in surfactant losses. This is because the mineralogical composition of the reservoir results in unpredicted adsorption quantity. Therefore, this paper seeks to investigate Aerosol-OT's adsorption on different quartz/clay mineral compositions during the flow. Also, it investigates adsorption mitigation by preflushing with lignin. The dynamic experiments were conducted on sand packs composed of quartz-sand and up to a 7% clay mineral content. The results obtained from the surfactant losses were compared with/without lignin preflush at different pH values. The main observation was the direct relationship between increasing the composition of clay minerals and the surfactant pore volume required to overcome the adsorption. The highest adsorption calculated was 46 g/kg for 7% kaolinite. Moreover, lignin successfully reduced the adsorption of Aerosol-OT by 60%. Therefore, the results demonstrate that the effects of the clay mineral content on adsorption could be efficiently minimized using lignin at a high pH.



1. INTRODUCTION

One of the critical screening parameters of surfactant usage in enhanced oil recovery (EOR) is surfactant performance.¹ During the flow in porous media, surfactants accumulate on the rock surface. This phenomenon is known as adsorption. Adsorption is considered as a hazardous factor affecting the economic feasibility of chemical enhanced oil recovery (CEOR) projects.² The surfactant adsorption tendency decreases its efficiency in decreasing the interfacial tension (IFT) between oil and water.³

The relationship between surfactant adsorption and rocks is conducted experimentally on different levels. The focus is generally on the sandstone reservoirs since most surfactant flooding projects are conducted on sandstones.^{4,5} However, there is less focus on carbonates due to infrequent EOR implementations.^{6,7} Due to the variety of rocks, adsorption remains a complex process that cannot be easily generalized or quantified. The degree of adsorption varies from one case to another, depending on various factors. Typically, these factors include the surfactant type, surfactant purities, chain length, salinity, and temperature.^{8–10} Adding to the previous factors, the clay minerals as part of rock constituents play a significant role in adsorption discrepancy.^{11–13} The static adsorption test has become compulsory during the pre-pilot stages because of the factors interfering.^{14,15}

Previous static adsorption tests have demonstrated that surfactants were adsorbed through several mechanisms, including ion exchange and the van der Waals interaction. Other notable mechanisms are chemical and lateral interactions, hydrogen bonding, electron polarization, and dispersion forces. Likewise, the adsorption process is significantly enhanced by increasing the concentrations of clay minerals.^{11,16,17} Furthermore, higher temperatures can reduce the adsorption on rock and clay mineral surfaces, whereas increasing the salinity increases adsorption.^{18,19}

Focusing on the dynamic flow, the adsorption might follow the same mechanisms, but the actual adsorption quantity increases by numerous factors.^{20–22} In other words, the relation between dynamic adsorption and static adsorption is not linearly proportional. The degree of adsorption during the flow alters for several reasons. These reasons include the physical properties of the core, distribution of clay minerals, oil presence, and existing phase flow rates.^{23–25}

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In conjunction with adsorption quantification endeavors, several researchers have focused on finding solutions to minimize adsorption during the flow.²⁶ These suggestions include optimizing the surfactants, using co-chemicals, and injecting preflush chemicals.²⁷ The injection of chemical preflush aims to mitigate surfactant sorption into a formation; these preflushes are known as sacrificial agents.²⁷ The sacrificial agent works based on different mechanisms like covering the mineral and rock surface by the physical spread. Also, it can build a chemical bond with the active sites and neutralize its effect. Moreover, few authors agreed on the possibility of competing mechanisms based on the surfactant-sacrificial agent and formation characteristic.

In previous studies, various substances such as alkali, low-cost surfactants, polybasic carboxylic acids, lignosulfonates, cellulose or cellulosic derivatives, starch, or starch-based derivatives have been used as sacrificial agents. Recent findings have demonstrated the potential of novel chemicals such as sodium polyacrylate²⁸ and ionic liquids²⁹ for minimizing adsorption.

Furthermore, natural sacrificial agents such as lignin and its derivatives have been endorsed for reducing the adsorption of different types of surfactants at different compositions of clay minerals.³⁰ One of the pioneered research investigated the use of lignin with an anionic surfactant (TRS 10-180) at sodium montmorillonite surfaces. The adsorption of the surfactant was decreased from 0.24 Equ/kg clay to 0.16 Equ/kg after preflushing with Kraft lignin.³⁰ Similarly, modified lignin has been investigated to reduce the adsorption of the ORS-40 surfactant on Chinese rock formation. The study showed a significant adsorption reduction by 50%.³¹ However, the composition of the surfactant was not reported in detail. A low-price alkali-based lignin was used as a sacrificial agent.³² The surfactant used in the experiment was betaine, whereas the porous medium was sand. The results demonstrated a high capacity of alkali lignin to reduce the adsorption by 40%. However, the study was focused on the sand; hence, no clay mineral or its fractions were investigated.³³ Gan et al.³⁴ showed that carboxymethylated lignin was adsorbed on natural graphite, and the amount adsorbed on the solid surface was increased with increasing ionic strength. Moreover, the synthesis of alkali lignin through the amination process was proposed as an effective surfactant for Daqing field oil. The results showed that the alkali lignin could work both as a sacrificial agent and as a surfactant that is involved in reducing the IFT.³⁵

Despite the previous efforts, several new surfactants have not yet been examined. Hence, there is a critical need to perform a systematic study to quantify the adsorption of any new proposed surfactant. Also, stepping beyond the typical examination to investigate adsorption mitigation by sacrificial agent preflush is needed. Thus, the objective of this work is to quantify anionic di-chain surfactant adsorptions at different mineralogical characteristics. Both static and dynamic adsorption tests are performed to demonstrate the role of clay mineral composition on the adsorption. The second part of the study aims to evaluate the efficiency of using lignin to reduce adsorption at the dynamic flow level. The study also gives insights into the role of the lignin acidity number on its efficiency.

2. MATERIALS AND METHODS

2.1. Materials. **2.1.1. Quartz and Clay Minerals.** Reservoir minerals quartz-sand, kaolinite, illite, and montmorillonite were used in the study. Quartz was collected from Teluk Ramunia in Johor Bahru, Malaysia. The quartz samples were subsequently washed and air-dried for 24 h. Next, the air-dried sample was dried at 105 °C for 24 h in an oven. Illite was acquired from Kuala Rompin, Pahang, Malaysia and used as received. Kaolinite and montmorillonite were purchased from Sigma-Aldrich (USA). The surface area of the samples was determined by the BET (Brunauer–Emmett–Teller) method using a Micrometrics surface analyzer (model: Micrometrics AccuSorb 2100E, USA). Furthermore, powder X-ray diffraction (XRD) equipment from Smart Lab, Rigaku (USA), scanning electron microscopy (SEM), and an electron-dispersive X-ray (EDX) model S0433N-Hitachi were conducted to characterize the proportion of any minerals present in the samples. In this study, the SEM–EDX analyses were employed to determine compositions and morphologies of the different clay minerals.

2.1.2. Chemicals. The anionic surfactants used were dioctyl sulfosuccinate sodium salt (or bis(2-ethylhexyl)) and sulfosuccinate sodium salt (Aerosol-OT). The Aerosol-OT (96% purity) was acquired from Acros Organics BVBA (Geel, Belgium). The Aerosol-OT has the chemical formula $C_{20}H_{37}NaO_7S$ and molecular weight $M_w = 444.55$ g/mol. The sacrificial agent used was alkali lignin, which was bought from Sigma-Aldrich (USA). The product was supplied as a brown powder with 95% purity and molecular weight $M_w = 10,000$ g/mol. The chemical structures for the surfactant and the sacrificial agent were presented previously by Baczkowski et al. in 2001 and Lebo Jr. et al. in 2002, respectively.^{36,37}

2.1.3. Chemical Preparation. The solution of brine was primed in standard volumetric flasks ($V = 1000$ mL) by adding 35 g of sodium chloride (NaCl). Next, aqueous solutions of the surfactant were prepared with different concentrations between 0.001 and 5 wt %. The same procedure was used to prepare the lignin solutions with a concentration of 2 wt %. The pH of lignin was modified using NaOH.

2.2. Static Adsorption Test. For this test, precisely 60 mL of the surfactant at different concentrations was mixed with 10 g of the quartz-sand/clay mineral at different compositions. The percentage of clay minerals was varied between 2 and 10 wt %. The samples were then sealed in cylindrical bottles and stirred using a magnetic plate for 16 h. Next, the solution was filtered and measured for surface tension using a du Noüy ring tensiometer. The detailed procedure is presented in our previous work.³⁸ The amount of Aerosol-OT adsorbed to the adsorbents is equal to the difference between the pure Aerosol-OT Critical Micelle Concentration (CMC) and the CMC after equilibrium with adsorbents

$$\Gamma = CMC_{\text{pure}} - CMC_{\text{eq}} \left(\frac{V}{W} \right) \quad (1)$$

where Γ represents the amount of adsorbed material (g/kg), CMC_p is the surfactant pure CMC (g/L), CMC_{eq} stands for the surfactant equilibrium CMC (g/L), V is the volume of the surfactant solution (L), and W is the mass of the dry adsorbents (kg). All experiments were repeated three times, and the average value was used and detected from the inflection point of surface tension vs concentration curves.

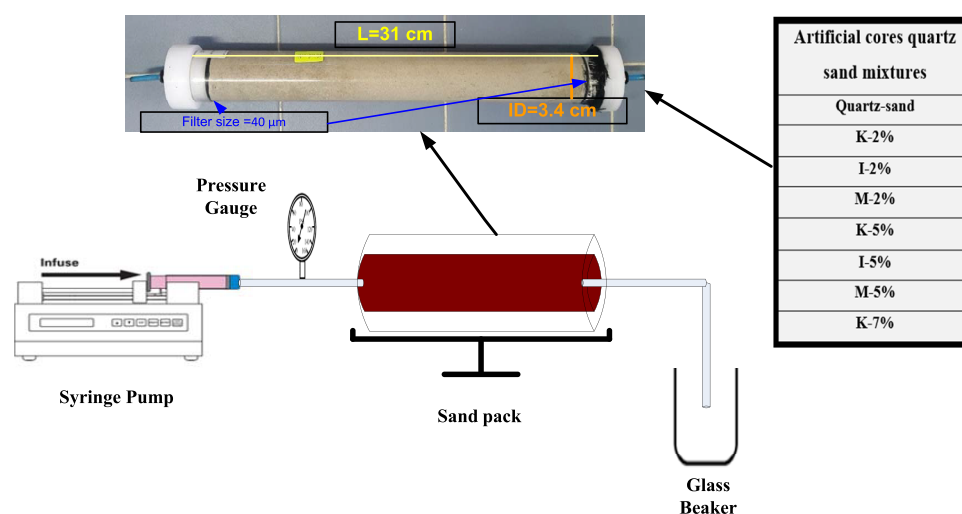


Figure 1. Experimental setup for sand pack flooding.

2.3. Sand Pack Preparation. The artificial sand pack was selected due to the flexibility of changing the percentage of quartz and clay minerals as required. In addition, it permits the comparative study of the experimental results.^{11,39} The porous media holder used in this experiment was a PVC tube with an inner diameter (ID) of 3.4 cm with a length of 31 cm, as seen in Figure 2. Sand packs were prepared by mixing the desired percentage of the clay mineral with sand in isothermal conditions using a control mortar mixer (model: 65-L5 at 500 rpm) to ensure a homogeneous mixture. During each test, the grains were slowly loaded and pushed into the holder. Next, a specially designed screw was used to homogeneously compact the column while simultaneously shaking the holder. A vacuum pump was used for full extraction of water from the bottom of the pipe and collected in the extraction bottle. The movement of the fine grains was constrained using a 40 μm micron filter to block both ends. All the sand packs were aged for 30 days in the sun before further use, as described in the work of Amirianshoja et al.¹¹ The porosity and permeability were measured as provided in our previous work.²⁵

2.4. Dynamic Adsorption Test Procedure. The sand pack flooding test was conducted horizontally at ambient temperature, as seen in Figure 1. The surfactant eluted from the sand pack was accumulated in a collector beaker after which the surfactant concentration (wt %) was measured in each test. The steps of collecting the samples were based on the injected pore volume. To determine the surfactant concentration, a UV-vis spectrophotometer (model 6305) was used in the procedure. The surfactant solution at the CMC concentration was used to find the appropriate wavelength, which gives the highest peak. Several surfactant concentrations were used to generate the calibration curve. The main examination is the recorded absorbance, and it was compared to the calibration curve to verify the new concentration after adsorption. It is worth noting that UV-vis was calibrated using DIW each time the cuvette was used. Further details can be found in the work of Abbas et al.³⁸ The method is in line with changes in the concentration that occurs during the adsorption.⁴⁰

In the second stage, the efficiency of the alkali lignin in reducing the surfactant adsorption was determined. For this purpose, a few steps were developed: The entire experiment was run at a constant injection rate of 2 mL/min at room

temperature. Three stock solutions were prepared at pH values of 7, 9, and 11. The experimental runs were conducted using the alkali lignin preflush ahead of the surfactant flooding with a concentration of 1.5 wt % as found in preliminary studies and supported by earlier findings.^{33,41}

After the preflush flooding of the cores, a preselected shut-off time of 4 h was allowed for each sand pack to ensure that maximum adsorption occurred. On resuming the experiment, the alkali lignin in the sand packs was completely washed off by injecting two pore volumes (2 PV) of brine. Next, the surfactant was injected, and last, the surfactant adsorption before and after the alkali-lignin preflush was compared to determine the flood efficiency and measure the concentration losses.

3. RESULTS AND DISCUSSION

3.1. Mineral Characterization. The clay mineral used in this experiment was tested with different methods. Figure 2 shows the SEM-EDX spectra, and Figure 3 shows the result obtained from XRD.

The SEM micrographs recorded at 300 μm reveal sub-angular to sub-rounded sparse particles of well-sorted quartz. The particle sizes range from 250 to 90 μm , indicating a fine texture. However, for kaolinite and poorly crystallized kaolinite particles, the particle sizes range from 10 to 40 μm , indicating a very fine texture. The big plates of kaolinite particles are composed of even smaller platelets of thin anhedral aggregates and plates of illite particles. The particle sizes range from 0.5 to 5 μm , indicating a very fine texture. In addition, the micrographs show the typical aggregates of clay minerals and the individual platelets of illitic clays. For the thin montmorillonite plates, the particle sizes range from 5 to 10 μm , indicating a very fine texture. The micrographs show the typical aggregates of clay minerals and the individual platelets of montmorillonite clays.

The XRD result for sand-quartz shows the highest peak at 2 theta = 26.7, indicating that sand contains pure quartz with 100% composition. Table 1 summarizes the characterization and identification results from different sources. Zeta potential measurements of surface charge under neutral conditions (pH = 7) were -36.6 mV for kaolinite, -27 mV for montmorillonite, -36.7 for sand-quartz, and -34 mV for illite. The zeta

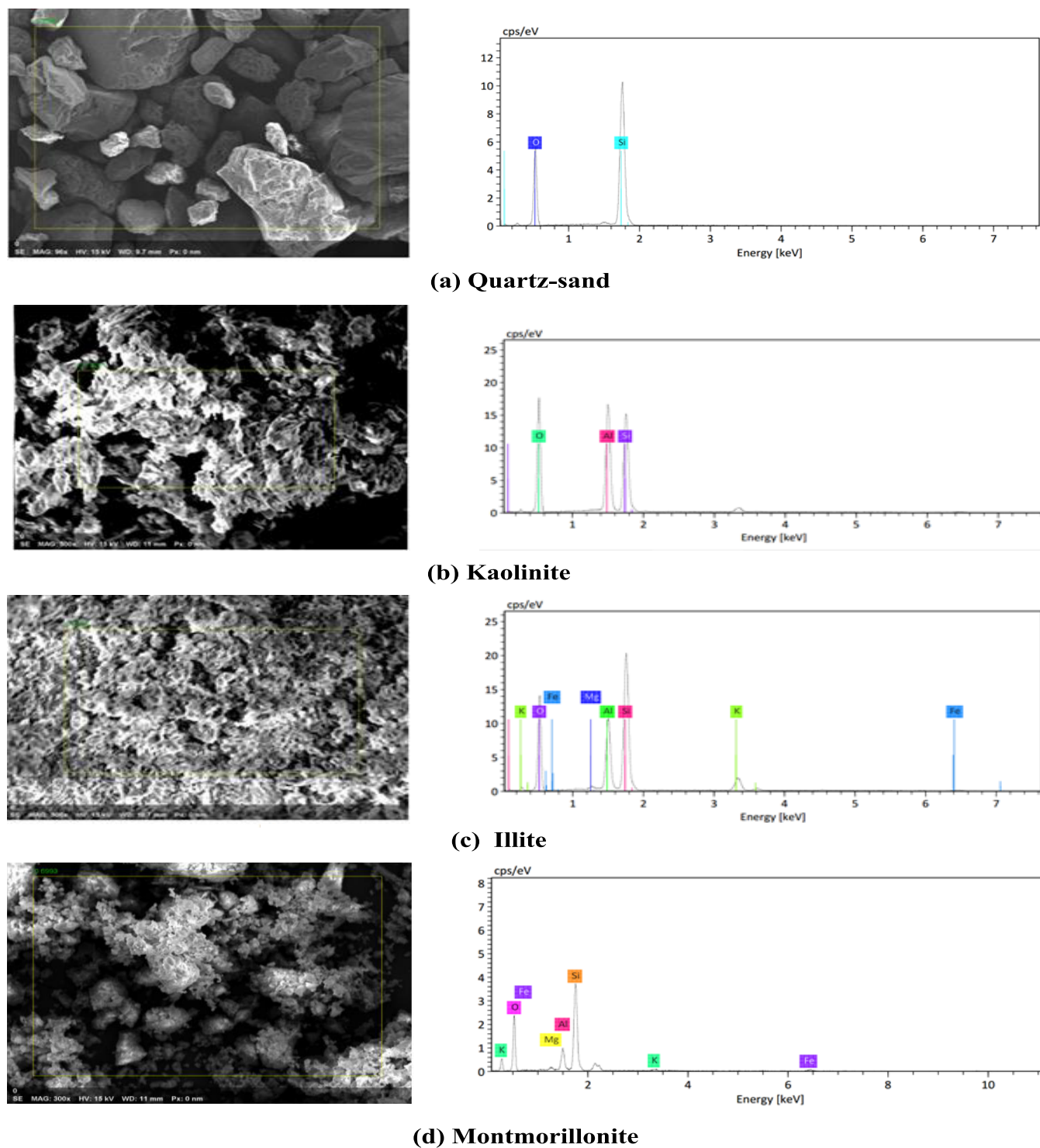


Figure 2. SEM–EDX for (a) quartz-sand, (b) kaolinite, (c) illite, and (d) montmorillonite.

potential measurement shows that increasing the pH resulted in increasing the negative value for all minerals.

3.2. Static Adsorption Test. Since clay mineral distribution is not identical in all locations in the reservoirs, there is a need to understand the quantification range of the adsorption that might occur. Understanding the adsorption range based on reservoir mineralogical characteristics can help us delineate the implementation location. Accordingly, this study's selected percentages were based on several fields previously evaluated in the literature.⁴² The main objective is

to ease the comparison of the results. The presence of the clay mineral as a fraction of the rock in the reservoir system requires sensitive measurement to avoid the overestimation of adsorption. Figure 4 shows surface tensions versus concentrations of Aerosol-OT before and after equilibration with quartz-sand/kaolinite, quartz-sand/illite, and quartz-sand/montmorillonite. The percentage ranges selected were 2, 5, 7, and 10% for the clay minerals. According to the result trend in Figure 5, it is clear that there is an increase in surface tension, especially at the low surfactant concentrations. The

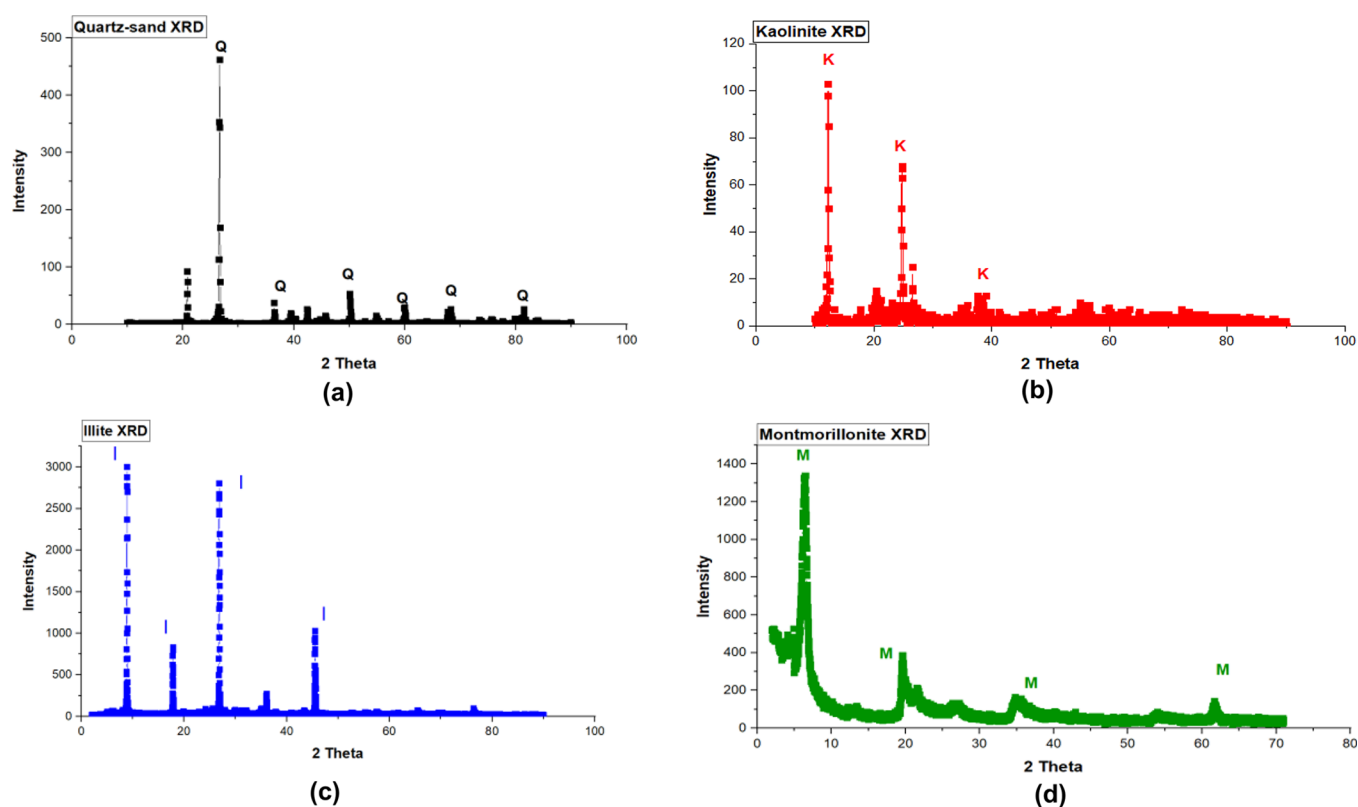


Figure 3. XRD spectra for (a) quartz-sand, (b) kaolinite, (c) illite, and (d) montmorillonite.

Table 1. Summary of Mineral Characteristics

mineral	quartz (%)	kaolinite (%)	illite (%)	montmorillonite (%)	traces	BET m ² /g	CEC meq/100 g
quartz	100.0					2.9	4.0
kaolinite	11.2	88.8				10.0	8.5
montmorillonite				100		21.6	76.0
illite	22.0		78		Fe	258	27.9

changes of surface tension reflected on shifting in the CMC. However, by looking at the surface tension at the stabilization points, they were very close to the surface tension of the pure surfactants. Note that, at 10% of kaolinite, the surface tension was slightly higher. As CMC is detected by the intersection between the stabilization points and the deviated line, the CMC results differed from the pure surfactant solution. Also, from the observation, the increase in clay percentage increased the CMC values for all clay minerals compared to the pure quartz. This indicates that increasing the surface area of the solid content impacted the surfactant tendency to complete the aggregation on low concentrations. For each clay mineral used, increasing the clay mineral percentage increased the CMC. This in fact brings attention to the interaction of the surfactant and the clay mineral surfaces. For instance, the anionic surfactants show a high tendency to aggregate on clay mineral surfaces by establishing different bonds. The surfactant adsorbs by the hydrophobic effect in illite and montmorillonite and forms an electrostatic interaction in the presence of kaolinite.

The relation of CMC and adsorption is shown in eq 1. The obtained adsorption is presented in Figure 5. As observed, the adsorption of Aerosol-OT on kaolinite is the highest. Increasing the clay minerals increased the adsorption of surfactants. Moreover, the adsorption on illite and montmorillonite cannot be ignored. The Aerosol-OT adsorption rank

follows the order of kaolinite > illite > montmorillonite > quartz-sand.

The surfactant adsorption on the surfaces of quartz-sand is related to the surfactant's ability to spread over the surface of quartz due to van der Waals forces.^{43,44} Another reason could be the long chains of Aerosol-OT, which trigger the hydrophobic bond onto the quartz-sand surface. A similar mechanism for the long hydrocarbon chain was reported by Gale and Sandvik in 1973. For kaolinite, the general mechanisms found are the electrostatic mechanism, ion exchange, and metal-activated, surface, and bulk precipitation. The kaolinite mineral has been found to be dissolved and transformed, hence contributing to adsorption.⁹ The significant adsorption of Aerosol-OT on kaolinite can be attributed to the coexistence of both positive- and negative-charged sites on kaolinite surfaces.^{45,46} As the Aerosol-OT has a long hydrocarbon tail, these results indicated the possibility of adsorption on both negative and positive surfaces. In previous studies, the ability of anionic surfactant adsorption was related to the zeta potential of kaolinite in the presence of anionic surfactants. It was found that the zeta potential of kaolinite became less negative in the presence of anionic surfactants even at a low pH. This was not found highly significant for quartz.⁴⁷ Similar to the case of quartz-sand, it is also believed that the adsorption of Aerosol-OT on illite and montmor-

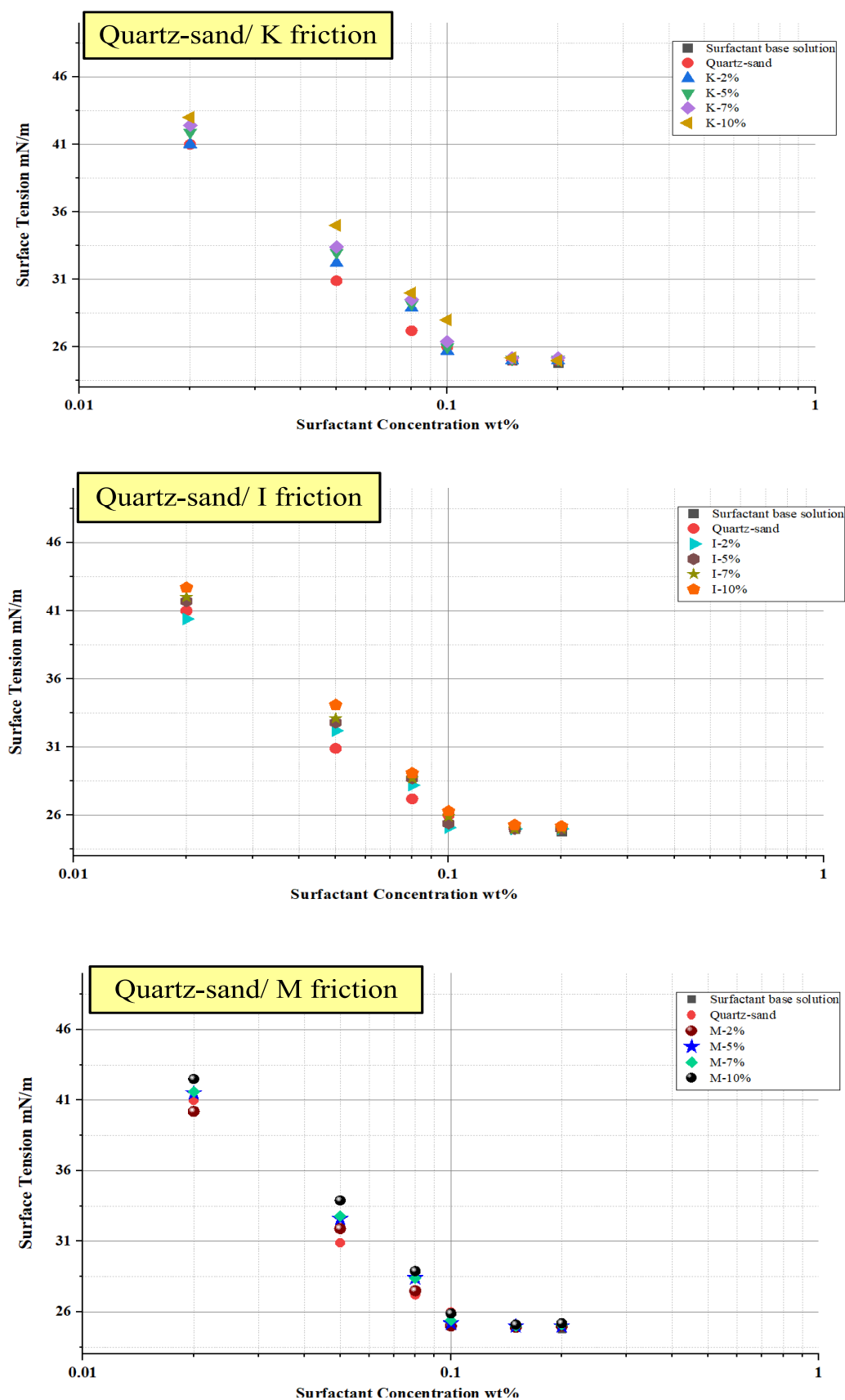


Figure 4. Surface tension of Aerosol-OT/35,000 ppm NaCl and different clay mineral frictions.

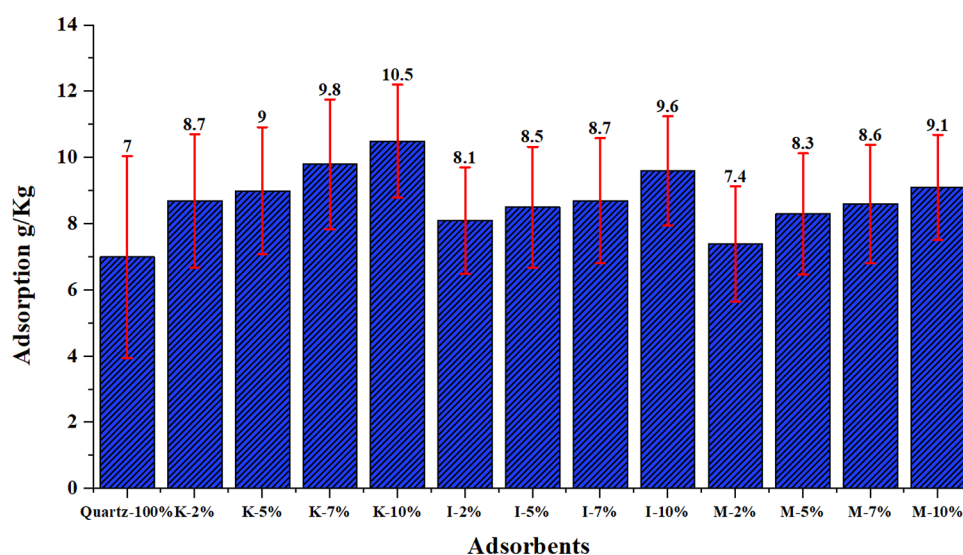


Figure 5. Adsorption in different clay mineral contents.

Table 2. Properties of the Sand Pack

sand pack	quartz-sand	K-2%	I-2%	M-2%	K-5%	I-5%	M-5%	K-7%
average porosity (%)	38.5	32.6	30.7	29.8	23.8	24.5	22.2	20.9
average permeability (D)	1.96	0.93	0.88	0.83	0.52	0.45	0.4	0.39

illinite is due to its versatile long carbon chains. Typically, the Aerosol-OT chains enhance their hydrophobic nature, which mitigates adsorption.

Furthermore, the experiment was conducted in a high NaCl concentration, which also contributed to the adsorption. NaCl is believed to form a hydrogen bond between the head and water molecules, which consequently increases the micellar size.²⁹ The free hydrated surfactants are more likely to be adsorbed onto the adsorbent's surface. Additionally, NaCl tends to compress the electronic double layer, which eases the surfactant's approach to the surface.⁴⁸ Some reports have indicated that NaCl generates a deflocculated system in an electrical double layer, which increases the exchange of ions. The deflocculated system can be generated at any given negatively charged surface in the presence of hydrosphere particles with a cation of an intermediate size such as Na⁺. Consequently, the forces of repulsion produced an unstable condition. The deflocculated system may increase the adsorption.^{45,49,50}

3.3. Effect of Clay Mineral Percentage on Aerosol-OT Dynamic Adsorption. The dynamic flooding experiment was performed using sand packs containing different percentages of the clay mineral. The average values for each property of the sand packs are listed in Table 2.

To assess Aerosol-OT adsorption during the dynamic flow, the reduction of the initial surfactant concentration was measured. The study applied flow rate is 2 mL/min because the low rate allows better interaction within the porous media and follows darcy flow for laminar flow. The relationship between Aerosol-OT concentration in each PV and clay mineral percentage is presented in Figure 7. In practical terms, Figure 7 demonstrates the required surfactant quantity to reach its full potential and overcome the effect of porous media. Overcoming the losses is considered vital for the project's profitability (Abbas et al.).

The baseline of the study is the quartz-sand, which is used as a standard point. It was observed that half of the effluent was significantly reduced after the first injected concentration of the surfactant. This is in good agreement with a previous study explored that confirms the Aerosol-OT behavior on different quartz surfaces.⁴⁴

In the presence of different clay mineral contents, the surfactant concentration response varies according to the type of clay mineral. The surfactant concentration decreased with increasing the clay mineral content. The result also showed a significant surfactant concentration reduction in kaolinite presence compared to the other clay minerals. Consequently, the entire result is attributed to Aerosol-OT adsorption on the clay mineral.⁵¹

Moreover, the results in Figure 6 confirm the role of increasing the clay mineral in increasing the surfactant losses. The number of PV injections required increased compared to the quartz-sand pack. The PV depends on the type of clay mineral in the mixture, which was similar to the previous findings in the static conditions observed.^{9,11,52} The highest PV injected was in the sand packs containing 7% kaolinite. The results of illite and montmorillonite were also very similar at 2%, which reflects that there is no significant difference between them at a low content. The impact of the clay mineral type affects both of the total losses and PV in the dynamic conditions, which follows a similar trend to the static batch test for the anionic surfactants.^{14,53}

Considering the adsorption in each sand pack, the total adsorption depends on the solid content in each sand pack. Figure 7 elucidates the adsorption and the percentile of adsorption compared to the quartz-sand pack. Generally, the adsorbed amount of surfactant during the dynamic flow is greater than the literature's static adsorption data.^{13,38,54,55} The high adsorbent content caused high adsorption during the dynamic flow experiments.²¹

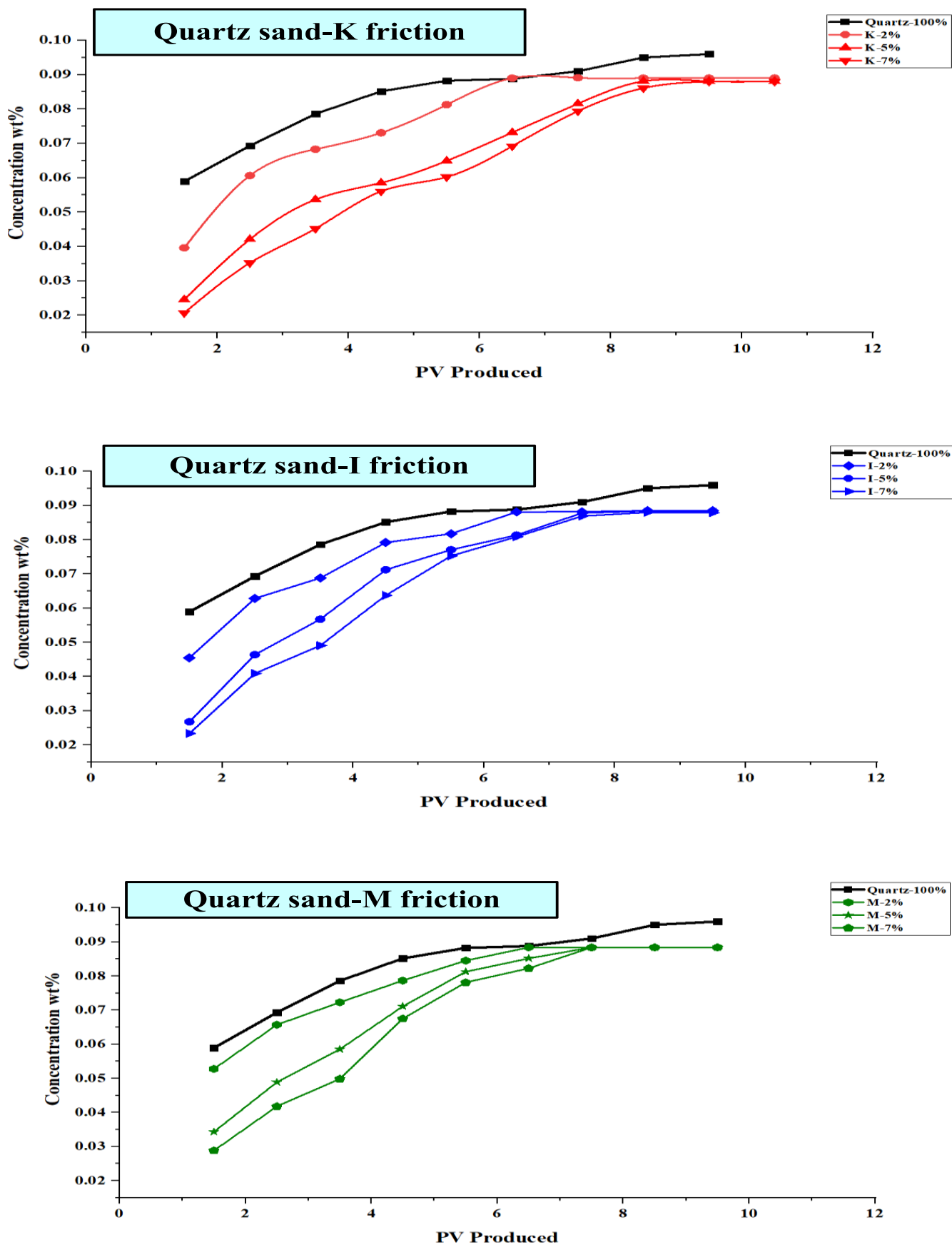


Figure 6. Aerosol-OT concentration in the effluent samples based on pore volume (PV).

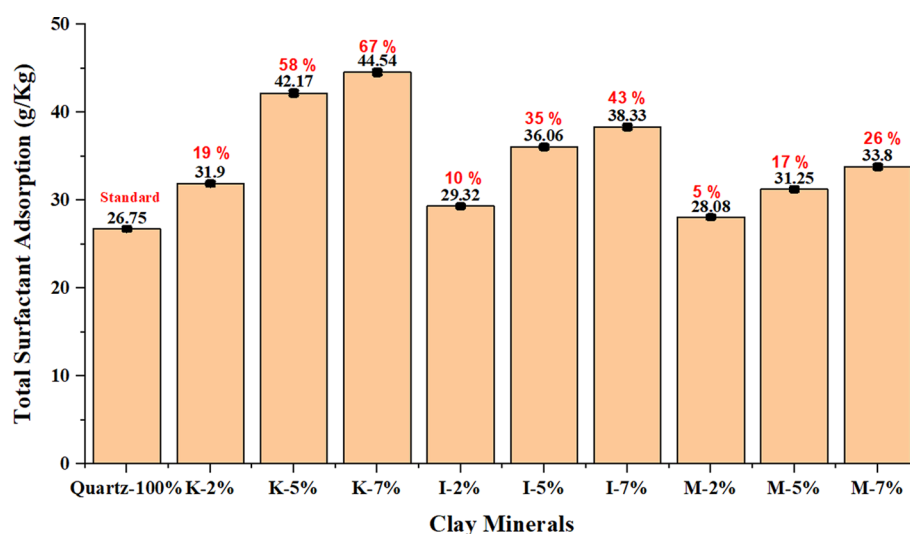


Figure 7. Aerosol-OT adsorption as a function of clay mineral percentage in the sand pack.

Table 3. Surfactant Adsorption after Lignin Preflush with Different pH

sand packs	quartz	K-2%	K-5%	K-7%	I-2%	I-5%	M-2%	M-5%
adsorption in g/kg								
no preflush	5.52	6.76	8.24	8.51	6.34	8.21	5.50	7.30
pH 7	3.49	3.89	5.02	7.17	3.87	5.06	3.75	5.58
pH 9	3.46	3.70	4.34	5.16	3.65	4.75	3.51	5.15
pH 11	2.91	3.08	3.39	3.71	3.20	3.33	3.01	3.19

3.4. Effect of Alkali Lignin as a Sacrificial Agent on Aerosol-OT Adsorption. The purpose of lignin is to reduce Aerosol-OT adsorption. The result of the surfactant adsorption after the flow was compared to the adsorption obtained without lignin. Each pH resulted in different adsorption quantities, as observed in Table 3.

During the experiment, the flow of lignin was hampered by obstacles in the sand packs containing 7% illite or montmorillonite. The limitation of lignin flow may be related to the retention mechanism during the flow of polymeric solutions through porous media at low rates. Accordingly, the results of these sand packs have been excluded and considered as a limitation in lignin usage under dynamic conditions. However, the use of lignin was previously reported to be satisfactory in field scenarios due to the high injection pressure.⁵⁶

The reduction in Aerosol-OT adsorption with the change in the pH is a result of alkali lignin adsorption due to the polymeric property of the alkali lignin. Typically, the hydrogen bond is generated as a result of the interaction between the alkali lignin and the adsorbent containing clay minerals. As a result, the alkali lignin strongly bonds to the surface until it fully covers the entire surface area.^{57,58} In addition, the presence of sodium cation (Na^+) in the brine induces an electrostatic interaction between the alkali lignin and the adsorbent. This causes thickening of the adsorbed layer and deflocculation in the system. However, the increase in the pH causes an increase in the negative charge present around the adsorbed film, thereby preventing the injected surfactant from interacting with the surface. Consequently, the pH of the alkali lignin plays a role in decreasing the double-diffusive layer. These results confirm the effectiveness of using alkali lignin to reduce the Aerosol-OT adsorption in dynamic flow conditions in the presence of clay minerals. However, it is crucial to state that the alkali lignin does not reduce surfactant adsorption to

zero. The evidence we found shows that, at pH 9, the surfactant adsorption reduction is similar to pH 7 and not significant, except for K-5% and K-7%.

Generally, the molecular weight of alkali lignin prevents its flow in the internal surface area.⁴⁹ Overall, lignin covers the solid surface, thereby minimizing the loss of the surfactant. The alkali lignin covers the surface and establishes the hydrogen bond to prevent Aerosol-OT adsorption. However, the increase in the pH causes the phenol group in lignin to react and, for ionized salt, increases the negativity of the surface and prevents anionic surfactant adsorption, particularly at the pH above lignin phenolic acidity, which is 8.1.⁵⁹ Similar findings were observed on bentonite and natural clay.^{60,61} Furthermore, the high pH alters the surface, thereby increasing its negativity that reduces the surfactant adsorption. This mechanism was also observed under different alkaline preflush conditions.⁶² Likewise, the presence of NaCl enhances lignin adsorption.^{63,64} NaCl lowers the expansion of the electrostatic double layer, and thus, it decreases the thickness of the polymer-adsorbed layer. So, it provides ionic stabilization, and such conditions prevent the anionic surfactant from adsorption.

Despite the chemical justification given in the literature, the alkali lignin may have caused the plugging of the pore throat, which prevents the surfactant from flowing in the low pores containing clay content. Likewise, this may also be the reason that the surfactant adsorbed less by diverting the flow path to larger pores.⁶⁵ In comparison with other anionic surfactants, the reduction of anionic surfactant TRS adsorption on montmorillonite ranged from 46 to 56% by lignin derivatives.³⁰ The current study found that, at pH 11, the alkali lignin reduced the adsorption in a similar range for Aerosol-OT. The difference between the previous research and the present study is the application of dynamic flow. Furthermore, the analysis of alkali lignin on sand showed that the reduction in betaine

adsorption on sand is normally 40%,³³ which is in good agreement with the findings of this study.

4. CONCLUSIONS

This study has presented the role of clay minerals on Aerosol-OT dynamic adsorption and the possibility of minimizing the losses through lignin preflush. The evidence from this study indicates the following:

1. Aerosol-OT adsorption increased with increasing clay mineral percentage during the static test, where the highest adsorption was in the kaolinite samples.
2. The ability of Aerosol-OT to flow in a high clay content was good. This has enhanced the prospects of application in harsh conditions of low permeability and porosity.
3. Aerosol-OT concentration reduced drastically in the first produced PV, where the concentration reduced up to 60% of its initial conditions.
4. The number of PV required to overcome the adsorption in the continuous flooding is between 7 and 9 PV, although this depends on the mineral type, which was found to be less significant in low clay contents of 2%.
5. Aerosol-OT adsorbed on the clay mineral surface varies on the bases of the content and type of minerals, where the highest adsorption is up to 45 g/kg at 7% kaolinite.
6. The investigation of lignin as a sacrificial agent for Aerosol-OT at different mineral content showed limitation of its flow in 7% illite and 7% montmorillonite.
7. The difficulty of flooding the alkali lignin in low permeability and low porosity can be avoided by designing the location of the injector in zones with moderate porosity and permeability.
8. Lignin efficiency was dependent on the pH of the solution used, with the best effect observed at pH 11.
9. The adsorption reduction varies between 25 and 60%, which indicates that the previous generalization about the efficiency may be compromised in the case of Aerosol-OT or a clay mineral content of up to 2%.

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A.H.A. performed the conceptualization, methodology, data curation, and writing of the original draft. A.H.A., W.R.W.S., and P.P. performed the visualization and investigation. W.R.W.S. and M.Z.J. provided the supervision. W.R.W.S. provided the validation. P.P., M.Z.J., and B.B.N. reviewed and edited the draft.

Notes

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