Screening the synergy of sodium dodecylbenzenesulfonate and carboxymethyl cellulose for surfactant-polymer flooding

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ABSTRACT

Carboxymethyl cellulose (CMC) has emerged in oil and gas industries as a superior substitution to the conventional HPAM and xanthan gum (XG) for high viscosity polymer flooding application. In this study, the combined effect of conventional surfactant, sodium dodecylbenzenesulfonate (SDBS) and CMC for potential surfactant-polymer (SP) flooding in enhanced oil recovery (EOR) has been investigated. Thereafter, SDBS − CMC interaction and the functional groups present in CMC were appropriately identified. The presence of various C−O bonds signifies the existence of carboxymethyl group which greatly influence the rheological properties of CMC solution. The behaviour of SDBS−CMC was characterized by their viscosity, shear rate, solubilization, wettability, and surface tension. Tertiary flooding utilizing SDBS-CMC was performed and compared to commercial SDBS-XG SP flooding. The results indicate several SDBS-CMC combinations are favourable for EOR application. Solution viscosity shows direct relationship with CMC concentrations. Consequently, at any given SDBS concentrations, significant increment was observed at 0.3 wt% and above. However, the trend displayed inconclusive relation to SDBS fractions. Majority of the SDBS-CMC combinations generate Winsor III emulsions particularly at CMC of 0.2 and 0.3 wt%, while Type II were observed in few combinations. Increasing CMC concentrations increased the contact angle, while gradual reductions were observed with SDBS concentrations. The gradual reduction in surface tension was highly influenced by the addition of CMC rather than SDBS. A novel combination of 0.3 wt% SDBS and 0.4 wt% CMC possessed an encouraging criterion in term of viscosity, solubilization, and surface tension reduction for EOR application. Flooding experiment from several SDBS-CMC combinations proved to recover additional oil ranging 16.4—20.2% of oil initially in place (OIIP). The trend in incremental oil recovery is similar to that of when utilising SDBS-XG.

1. Introduction

Polymers, be it synthetic or bio-based (biopolymer), have been widely studied for enhanced oil recovery (EOR) application (Needham and Doe, 1987). The extend of its dependency in EOR application highly rely on the chemical chains and their physical entanglement (Taylor and Nasr-El-Din, 1995). Hydrolysed polyacrylamide (HPAM) is commonly used in polymer flooding due to the inexpensive handling cost, relatively resistant to bacterial attack, high solubility in water, and available in large scale (Sheng

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et al., 2015; Gbadamosi et al., 2019a, 2019b). Despite these advantages, HPAM tend to degrade faster under harsh reservoir conditions, restricting its injection into oilfield reservoir (Wei et al., 2014; Jang et al., 2015; AlZahid et al., 2016; Ghoumrassi-Barr and Aliouche, 2016; Agi et al., 2019, 2020). Instead, more HPAM need to be injected to meet the goals, consequently increasing the operating cost. In contrast, biopolymer demonstrates excellent behaviour in such condition (Jang et al., 2015; AlZahid et al., 2016). Xanthan gum (XG) on the other hand is preferable as it is rigid and stable at elevated temperature and pressure condition (Pu et al., 2018).

Progressively, biopolymers have been extensively integrated in oil and gas field (Gastone et al., 2014; Leonhardt et al., 2014; Wei et al., 2014; Jang et al., 2015). Cellulose, which is major constituent in most biopolymer have excellent viscoelastic behaviour and chemical stability, showing a promising characteristic as a substitution to HPAM in EOR application (Li et al., 2017). Carboxymethyl cellulose (CMC) in particular, has governed a huge attention by many researchers as it is abundance, non-toxic, biodegradable, and inexpensive thickening agent. High molecular weight CMC shows great solubility, viscosities and stable in seawater (Falk and Norton, 1976). It has been widely used in drilling (Sagitov et al., 2017), fracturing (Hua et al., 2016; Ming et al., 2016), production (Verret et al., 2000), and EOR (Wei et al., 2017; Pandey et al., 2018). CMC is an anionic polysaccharide possessing both hydrophilic and hydrophobic fractions which promote emulsifying and stabilizing behaviour in emulsion system (Mirhosseini et al., 2008).

Surfactants on the other hand are frequently being injected or generated in-situ (in reservoir) following waterflooding to loose-up oil-water interfacial tension (IFT), rendering the fluids displaceable and moveable in micro pore condition (Al Adasani and Bai, 2011). A thriving result in surfactant flooding was proven achievable by controlling injected banks propagation (Mattax et al., 1983). Thus, proper injection schemes of surfactant and polymer solution have undoubtedly been beneficial in improving oil recovery (Cai et al., 2019; Klimenko et al., 2020; Southwick et al., 2020). Polymer act as chased water viscosifier; improving the oil-water displacement efficiency by diverting injected water into poor or unswept area in the reservoir (Bera et al., 2014; Izadi et al., 2018). The process can be further improved by adding surfactant to alter the rock surface wettability, loosen up the immobilized oil on the rock (Huang et al., 2019). Field implementations show that SP combination can recover as high as 20% of oil initially in place (OIIP) (Abidin et al., 2012; Lu et al., 2015). However, major drawback such as scaling problem in production well, difficulty in handling produced liquid, and severe emulsion production, might lead to high operating cost (Zhu et al., 2013).

Earlier studies show sodium dodecylbenzenesulfonate (SDBS) has high ability to favourably enhanced the rheological behaviour of injected fluid for SP flooding (Zhou et al., 2003; Abdelfatah et al., 2020). Hence, this experimental work was conducted to investigate the effectiveness of SDBS surfactant alongside CMC biopolymer derives from palm oil empty fruit bunch (POEFB) for potential EOR application. The combinations were characterized by several criteria; solubilization, contact angle, surface tension, and rheological behaviour. Consequently, displacement procedures were performed to evaluate the amount of recoverable oil using SP combination.

2. Materials and methods

2.1. Materials

CMC derived from POEFB was supplied by Waris Nove Sdn. Bhd. Anionic SDBS surfactant, $C_{18}H_{29}SO_3Na$, is a white powdery compound with molecular weight of 348.48 g/mol was utilized in this study. XG used has a molecular weight and viscosity of 90000 g/mol and 1200 mPa.s, respectively. Paraffin oil possesses a maximum dynamic viscosity and density of 230 mPa.s and 0.89 g/mL (at 20 °C), respectively, was used for the experiments. Sodium chloride (NaCl) with 99.5% purity was used in the preparation of the brine solution. Brine and paraffin were dyed green and red, respectively, to distinguish the fluids in solubilization study. Except for CMC, other materials were obtained from Sigma Aldrich (Malaysia) Sdn. Bhd.

2.2. Methods

2.2.1. Sample preparation

SDBS solutions at 0.1, 0.3, 0.5, 0.7, and 0.9 wt% concentrations were prepared by dissolving them in 15000 ppm brine, separately. CMC was tested at various concentrations of 0.1, 0.2, 0.3, 0.4, and 0.5 wt%. CMC at respective concentrations were dissolved in SDBS solutions using magnetic stirrer at 70 rpm until a homogeneous solutions were obtained and no agglomeration was observed (Felix et al., 2015). The solutions were then sealed and stored at room condition for further used.

2.2.2. Fourier transform infrared spectrophotometer (FTIR) analysis

The FTIR spectra of CMC was used to analyse the presence of oxygen-binding functional groups using PerkinElmer. The potassium bromide (KBr) FTIR method was used in this study. The dry sample was mixed with KBr before placing in the sample holder. The sample was then pressed into a disc before analysis. The FTIR spectra was performed within the wave ranges of 400—4000 cm^{-1}.

2.2.3. Rheological study

Solution viscosity was measured by using Anton Paar Electronic MCR 301 Rheometer. The steady shear data were obtained at a shear rate ranges of 0—100 s^{-1} at ambient condition. All measurements were performed three times for precise measurement (Deng et al., 2002).

2.2.4. Emulsion stability and solubilization study

For all samples, 5 ml CMC-SDBS solution was added into 5 ml oil and mixed vigorously for 1 h using magnetic stirrer. The samples were then immediately transferred into a graduated cylinder and sealed. Volume of initial emulsion generated, excess oil and excess solution were recorded. Samples were allowed to settle and stored at room condition. Fraction of emulsion were observed and recorded at regular basis (Zhang et al., 2010; Arshad et al., 2018).

2.2.5. Contact angle and surface tension measurements

Contact angle and surface tension measurements were performed by using VCA-3000 Contact Angle Goniometer. The sessile drop technique was used to measure angles of contact at different conditions of wettability. Sandstone cores from onshore Bintulu, Sarawak, with flat surface (1 cm thick x 5 cm diameter) were used to measure the contact angles (Hosseinzade Khanamiri et al., 2016). Wettability assessment of the sandstone core at several combinations of CMC-SDBS was performed by estimating the contact angles.

2.2.6. Oil displacement study

Oil recovery experiment was conducted by performing displacement test in sandpack holder dimension of 1 inch diameter x 1 ft long. The experimental setup is shown in Fig. 1. Waterflooding was performed at 0.5 ml/min of injection until the oil is uneconomical enough to be proceeded (Fu et al., 2016). Then, several combinations of CMC-SDBS slug ratio were injected at 0.5 ml/min
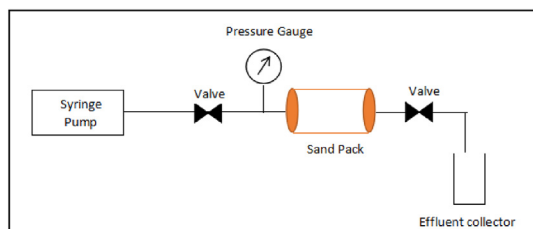
Fig. 1. Experimental setup for oil recovery procedures.

in parallel into the sandpack (Jang and Chon, 2014). Then, the sandpack was flooded with 1 PV chased water, also at 0.5 ml/min (Kumari et al., 2019).

3. Results and discussion

3.1. FTIR analysis

Fig. 2 illustrates the FTIR spectra of CMC. The stretch band between 3390 to 3152 cm^{-1} suggesting the presence of free O−H resulting from both inter- and intra-molecular of hydrogen bonds in CMC molecules. This adsorption band was found at a slightly broader range, between 3500 to 3200 cm^{-1}, in previous studies (Abraham et al., 2011; Muhamad Parid et al., 2017). From 2906 to 2790 cm^{-1} the vibration resulted from C−H stretch of aliphatic group which usually exist in cellulose, hemicellulose, and lignin (Hebeish et al., 2014; Qin et al., 2016). Significant characteristic peaks were observed between 1482 to 880 cm^{-1}. The strong absorption peak at 1482 cm^{-1} correspond to O−CH$_3$ in methoxyl-O-CH$_3$ compounds (Yang et al., 2007). It is worth to point out that the absorbance indicating the existence of amorphous crystalline structure in cellulose is suggested to be within this range (Kamal Bahrin et al., 2012). The weak bands at 1300 and 1196 cm^{-1} are attribute to C−H bend and C−O−C stretch, respectively (Liu and Kim, 2017). The C−H bands are characteristic of aliphatic carbon, methylene, and methyl group (Jamari and Howse, 2012). The C−O−C stretching, C−O covalent bond, and C−OH linkage are highly possible to be associated to the vibration of esters, phenols, and aliphatic alcohols exist in cellulose and lignin components in raw POEFB stalk fibres (Parida et al., 2006; Yang et al., 2007; Sevilla and Fuertes, 2009). Absorption band between 917 to 881 cm^{-1} is the results of C−O stretching which indicates the characteristic of β-glycosidic that binds the glucose units within the cellulose

(Azubuike and Okhamafe, 2012; Jamari and Howse, 2012; Qin et al., 2016; Hedayati et al., 2020). The presence of carboxymethyl groups from various C−O stretching and bending has a strong influenced on the rheological properties of CMC solution, making it favourable for EOR application (Pu et al., 2018; Zhao et al., 2003).

3.2. Solution viscosity and shear rate

Solution viscosity showed an increment in both CMC and SDBS concentrations. Fig. 3 presents the viscosity measured at various CMC and SDBS concentrations. Adding 0.1 wt% CMC showed no significant effects on solution viscosity. Up to 0.3 wt% of CMC a gradual viscosity increment was observed for all SDBS concentrations. The trend shows an abrupt change from 0.4 wt% CMC concentrations onwards. This behaviour is predictable since the increase of CMC molecules might cause aggregates formation within bulk liquid, and thus, increasing the viscosity (Szabo, 1979; Wang et al., 2010). For 0.3 wt% SDBS concentration, increasing CMC to 0.5 wt% shows significant viscosity enhancement. The result however indicates a reduction in viscosity as SDBS concentration increased to 0.5 and 0.7 wt%. At higher concentration, hydrophobic microdomains from the solubilized surfactant molecules was presumed to dominate the solutions, disrupting the supposedly entangled cross-linkages network of SP intermolecular forces, and gradually decreasing solution viscosity (Zhou et al., 2003). Consequently, viscosity of SP solutions may become independent of SDBS concentrations. A significant change in fluid viscosity was observed at higher CMC concentrations, 0.5 wt%, and the highest viscosity recorded was at 0.3 wt% SDBS. This favourable outcome is somewhat encouraging as least amount of both SDBS and CMC are required to obtained optimum viscosity. From the physical data provided by manufacturer, degree of substitution (DS) for CMC was 0.81, indicating the excellent thickening properties (Wahyuni et al., 2019). Solubility, emulsibility, acid and salt tolerance, and stability were also highly affected by DS; the higher the DS the better the performance, which is desirable in EOR application (Pu et al., 2018). Viscosity of the polymer/biopolymer solution was found to be crucial factor during targeted injection procedures. Previously, biopolymer showed excellent viscosity at 0.075 wt% concentration compared to that of synthetic polymer, at 0.2 wt% (AlZahid et al., 2016).

Fig. 4 illustrates the trend of viscosity change with shear rates. Viscosity reduces gradually with shear rates signifying shear thinning behaviour (Pal, 2000; Zhou et al., 2003), and the deformation of CMC molecules (Dolz et al., 1991). Chemically, CMC possesses
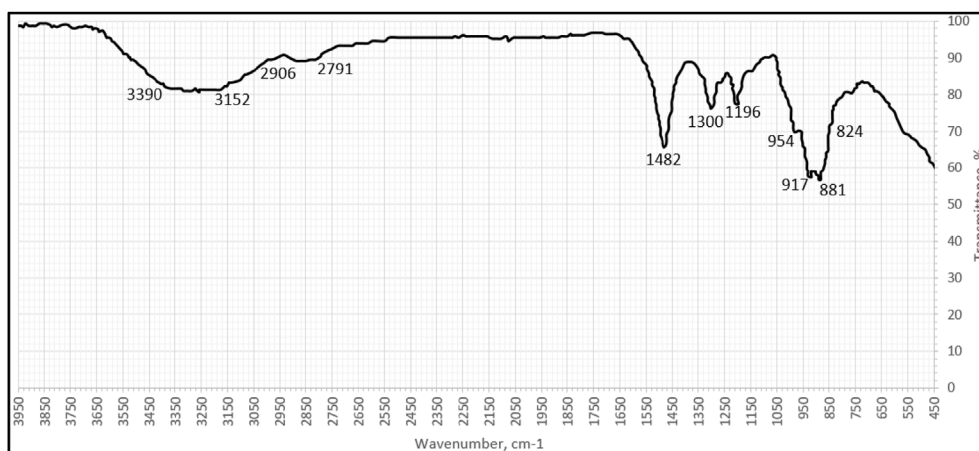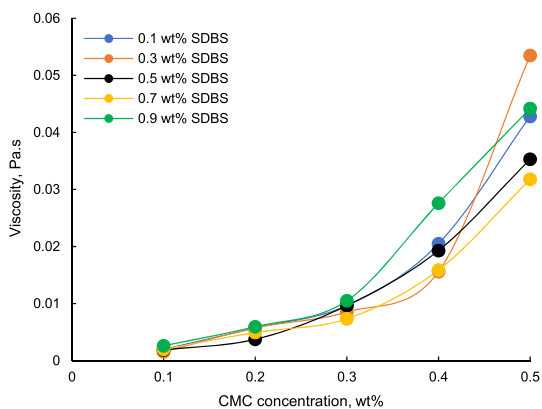

Fig. 2. FTIR analysis of CMC.

Fig. 3. Viscosity vs CMC concentration at various SDBS fractions.

irregular internal order of molecular chains that creates a high resistance against flow (Ghannam and Esmail, 1997). Thus, when subjecting to high shear stress CMC molecules disentangled, stretched, and realigned; enable them to lapse each other freely, and further reduced the viscosity (Ghannam and Esmail, 1997). For all concentrations, a slight hump was observed around 4–6 rpm (Fig. 3), where the viscosity increased slightly suggesting the molecules structure recovery condition before it further deform at higher shear rates (Nakai et al., 1993). Minimum polymer viscosity and shear rate required for desirable injectivity was previously identified to be in a range of 0.3–0.4 wt% and 6–7 rpm, which consistent with the results from previous study by Katz Marquez (2019). This observation however, might varies depending on the type of SP/biopolymer-copolymer used for the application, as some studies observed the favourable injectable concentrations to be much lower (AlZahid et al., 2016). Regardless, low apparent viscosity due to the increase in shear rates was found to be desirable for injection in porous media (Mahboob et al., 2022).

3.3. Emulsion stability and solubilization

Height of emulsions generated, and its classification are presented in Tables 1 and 2 and presented in Fig. 5 (a - d). Emulsion phase is highly desired compared to that of surfactant or polymer solution slug alone in chemical flooding as lower surfactant adsorption and IFT are obtainable (Bera et al., 2014). The ability of these combinations to generate emulsion base on its volume were determined. This analysis is consistent with indexing the parameter (emulsification index, S_{ei}) that is, the greater the value, the better the emulsification performance (Zhu et al., 2013). From our
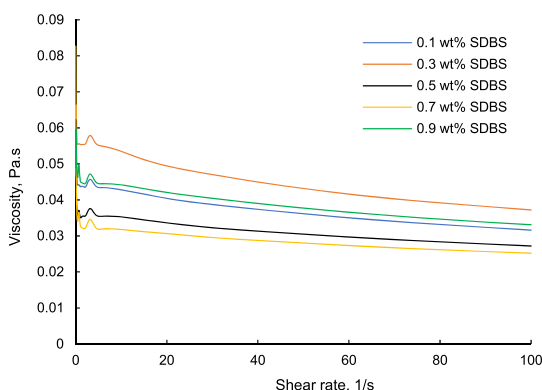

Fig. 4. Viscosity vs shear rate at 0.5 wt% CMC.

observation, SDBS-CMC combinations able to emulsify oil-brine solution to certain extent, typically at intermediate CMC concentrations (0.2–0.3 wt%). These emulsions are stable up to few months (typically more than 4 months of observation period) upon characterization process. From 0.1- 0.3 wt% CMC, emulsions generated are Type III bicontinuous phase, showing remain of both excess oil and water, concurrently (Winsor, 1948). Type III emulsion are usually characterized as possessing ultralow IFT behaviour which leads to excellent tertiary oil recovery (Abdelfatah et al., 2020). This middle-phase emulsion was bicontinuously existed due to the intervention of surfactant layer, that is the presence of SDBS (Huh, 1979). It was highly speculated that the middle phase may composed of both oil/water and water/oil emulsion (Miller and Neogi, 1980); the existence of actual molecules of oil, surfactant and water molecules (Shah et al., 1976); and mostly embodied with alternating lamellar layers of oil and brine (Shinoda and Friberg, 1975). The high stability emulsion was generated up to certain concentrations as a result of electrostatic repulsion due to the presence of water-soluble CMC in the emulsion (Kika et al., 2007; Mahboob et al., 2022). Owing to the feasible CMC structure, their molecules strongly adsorbed on the emulsion droplets surface, consequently hindering the aggregation, flocculation and coalescing (Mirhosseini et al., 2008). It is deemed that the adsorbed CMC molecules reduced the oil-water IFT, rendering emulsification process and further, their stability.

Some SDBS-CMC formulations observed induced Winsor Type II emulsion, profoundly at 0.4 and 0.5 wt% CMC, while few others produced no emulsion, leaving the oil − brine in two separate phases. Maximum volume of emulsion was generated at 0.7 wt% SDBS − 0.5 wt% CMC. Type II emulsion significantly leave excess water phase as evidently photographed in Fig. 5(d). Few of these water-in-oil (w/o) emulsions produced were turbid in appearance rather than transparent solution, most particularly at higher CMC concentrations (0.4–0.5 wt%), with much cloudier were observed as surfactant concentration increases (Fig. 5(c) and (d)). Emulsion stability is highly influenced by its turbidity in which highly reflected by the droplet sizes and solution concentrations (Reddy and Fogler, 1981). Abdelfatah et al. (2020) in his recent study discovered the cloudy nature of emulsion suggested the larger emulsion droplets (more than 100 nm sizes) being generated. Contrary, the transparent emulsions was found as a result of tiny droplet size being generated (Shah et al., 1976). Regardless, one shouldn't simply term the transparent emulsion generated as 'microemulsion', unless microscopic measurement is performed to obtain the exact droplet sizes. Defining microemulsion as; being transparent, possess high stability, achieve optimum or lowest IFT; seem vague and uncertain as concluded previously (Shah et al., 1976; Reddy and Fogler, 1981; Abdelfatah et al., 2020).

Overall observation of SDBS-CMC emulsions photographed describe uncertain trend in which highly presumed to be affected by interfacial activities. Though the surface tension reductions are insignificant, the increased in contact angles (Fig. 6) indicates water-wet behaviour which is preferable in EOR application. From our observation, SDBS-CMC emulsions remained stable for few months.

3.4. Influence of CMC-SDBS interaction on wettability alteration

Fig. 6 shows the relationship between contact angle change with SDBS and CMC concentrations. Increased in SDBS concentrations clearly resulted in contact angle reduction. Addition of CMC however demonstrates remarkable increment in contact angle. This indicates that SDBS has a pronounced effect on contact angle than CMC existence. The lowest point recorded was at 0.9 wt% SDBS − 0.1 wt% CMC with angle of 7.42°. Meanwhile, the highest angle

Table 1
Emulsion height generated in the presence of SDBS and CMC.

Emulsion height, cm		SDBS Concentrations, wt%				
		0.1	0.3	0.5	0.7	0.9
CMC concentrations, wt%	**0.1**	None	0.1	0.1	0.8	0.2
	0.2	2.8	0.1	3.0	3.1	0.5
	0.3	0.1	2.9	0.5	0.5	0.85
	0.4	2.1	4.4	None	4.1	0.6
	0.5	None	0.4	None	4.5	2.1

Table 2
Characterization of emulsion.

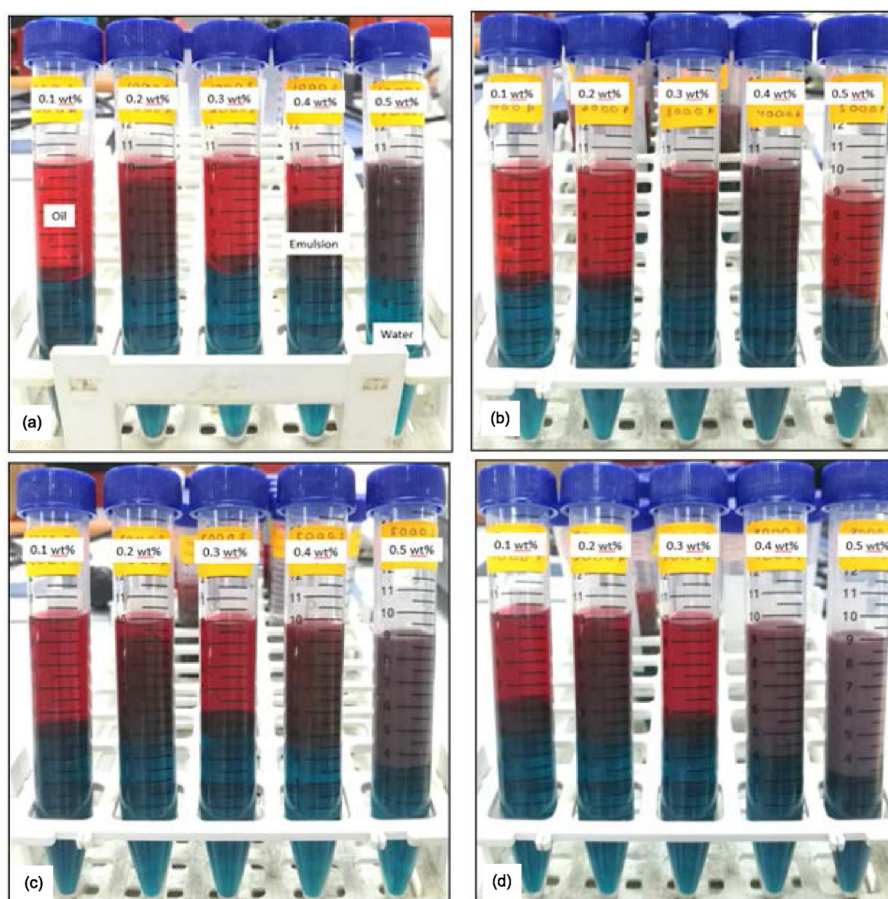| Winsor Category		SDBS Concentrations, wt%				
		0.1	0.3	0.5	0.7	0.9
CMC concentrations, wt%	**0.1**	—	III	III	III	III
	0.2	III	III	III	III	III
	0.3	III	III	III	III	III
	0.4	III	II	—	II	III
	0.5	—	III	—	II	III

Fig. 5. Oil — brine system in the presence of (a) 0.1, (b) 0.3, (c) 0.5 and (d) 0.7 wt% SDBS at various CMC concentrations.

(27.01°) was observed at 0.1 wt% SDBS — 0.5 wt% CMC combination. The decline in contact angle from 27.01° to 7.42° indicates the ability of SDBS - CMC to alter sandstone wettability more preferably water-wet. Regardless, the SP combinations tested are still within a desirable water — wet condition (Hendraningrat et al., 2013; AlSofi et al., 2020).

3.5. Impact of CMC concentration on surface tension of SDBS

Surface tension reduction in the presence of CMC is presented in Fig. 7. Significant reduction was observed with the addition of CMC. The trend however proves that adding more SDBS steadily increased the surface tension instead of the contrary, with the measurement reached the value of that pure brine. Thus, it is
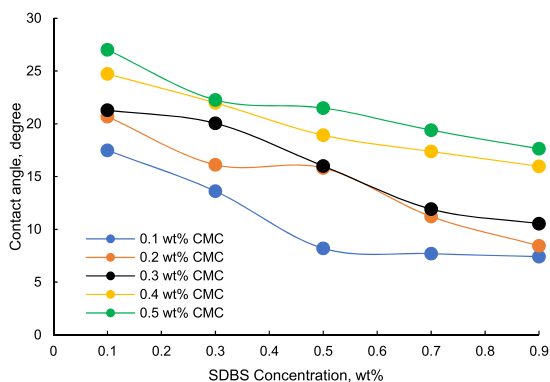
Fig. 6. Contact angle vs SDBS concentration at various CMC concentrations.
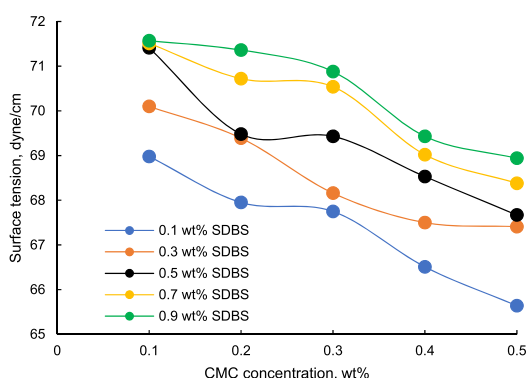

Fig. 7. Surface tension trends as a function of CMC concentration at various SDBS fractions.

evidence that adding CMC has potentially activated the interfacial activities. Interfacial tension, IFT, on the other hand, has a huge influenced on emulsification which further enhance sweep and displacement efficiency (Wang et al., 2010). This confirmed the formation of emulsions although several combinations show no emulsion generation. However, it is apparent that surface tension values somehow show almost negligible effect based on the reduction trend. The lowest surface tension achieved was only at 65 dyne/cm which is still considerably high. It is highly convincing that CMC does contribute to surface tension reduction and emulsion generation. CMC was categorized as polymeric surfactant (Ghannam and Esmail, 1997; Manglik et al., 2001), hence, the addition of this material does facilitate the oil-water interfacial activities. For an emulsion system, ultralow IFT can be achieved by generating middle phase (Type III) emulsion (Bera et al., 2014). This condition somewhat uncertain in our findings. Lowest surface tension for every SDBS concentrations tested does not directly

resulted in the generation of Type III emulsions. In some cases, no emulsion was observed or yielded (Table 2). With regards to emulsion stability, surface tension was found to be crucial parameter in our flooding experiment. The suggested combinations for Experiment 1 and 3 (Table 3), have preferable low/optimum surface tension and emulsion stability criteria for this application, similar to that being examined earlier (Abdelfatah et al., 2020). Surface tension measurement, however, is highly affected by water salinity (Zhang et al., 2009; Bera et al., 2014; Mavaddat et al., 2015). Thus, the pronounced effect of salt ions and concentrations on this trend should further be investigated.

3.6. Displacement test results

From characterization, several optimum conditions of SDBS-CMC concentrations were chosen to be tested for SP EOR. These combinations, however, did not comply with the desired condition; highest viscosity and fraction of emulsion produced, and lowest surface tension and contact angle. Rather, the combinations were chosen to cater for as much favourable parameters involved as possible.

Table 3 tabulates the displacement test results of SDBS − CMC SP flooding. Sandpack porosity (Ø), and permeability (k), were estimated to be 38% and 72.14 Darcy, respectively. Average connate water (Sw_i), and residual oil saturations (So_r) were calculated to be 0.186 and 0.438, respectively. Oil recovered shows significant increment via the assistance of CMC, ranging from 14 − 20%. Result indicates that at fix SDBS concentration of 0.3 wt%, highest increment of 19.84% was observed at lowest CMC concentration, 0.3 wt%. This suggest that, adding more CMC in the system will unnecessarily increase the recoverable oil. This behaviour might be due to the increase in viscosity of the displacement fluid which might have improved the oil mobility (Cohen and Christ, 1986; Sheng et al., 2015), and this is consistent with the previous studies where HPAM solution perform well at concentration above 0.2 wt% (Wang et al., 2000; Yang et al., 2004; Felix et al., 2015). At fix CMC concentration, 0.2 wt%, additional oil being recovered increases with SDBS concentrations. Fig. 8 shows the percentage oil recovered using SDBS − CMC combinations.

Furthermore, the influencing parameters (solution viscosity, surface tension, contact angle, and emulsification) were correlated with incremental oil recovery as shown in Table 3. The selected SDBS − CMC combinations implemented in tertiary recovery significantly yield additional oil being produced, approximately within the range of 16–20%. Highest viscosity recorded during screening process (at 0.3% SDBS- 0.5% CMC) resulting in 19.19% of OIIP. Also, it might be due to the in-situ emulsion generation during the displacement that had a huge impact on additional oil recovery compared to that of surface tension reduction and viscosity effect. Nonetheless, previous studies shows that the IFT reduction permits spontaneous emulsion generation in porous media which in turned enable the oil displacement (Pottmann, 1974; Lake, 1989; Bera et al., 2014). The outcome of this study is consistent with that obtained by

Table 3
SDBS − CMC tertiary recovery results.

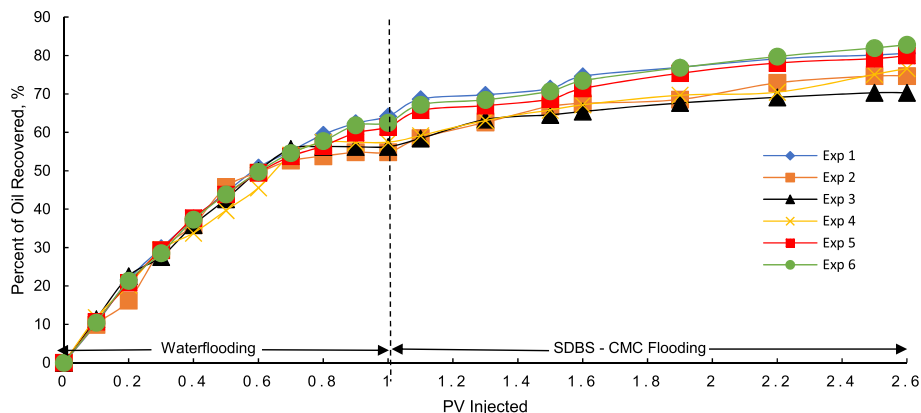| Exp	SDBS conc. (wt%)	CMC conc. (wt%)	Secondary recovery (%)	Increment oil recovered (%)	Total oil recovered (%	Possible influencing Parameters
1	0.1	0.2	64.17	16.42	80.59	Emulsion, surface tension
2	0.3	0.3	54.84	19.84	74.68	Emulsion
3	0.3	0.4	56.25	14.06	70.31	Emulsion, surface tension
4	0.3	0.5	57.42	19.19	76.61	Viscosity
5	0.5	0.2	61.43	18.57	80.00	Emulsion, Wettability
6	0.7	0.2	62.50	20.31	82.81	Emulsion, Wettability

Fig. 8. Percentage of oil recovered for secondary and SDBS - CMC flooding.

Table 4
SDBS − XG tertiary recovery results.

Exp.	SDBS conc. (wt%)	XG conc. (wt%)	Secondary recovery (%)	Increment oil recovered (%)	Total oil recovered (%)
7	0.3	0.3	56.34	18.31	74.65
8	0.7	0.2	63.08	18.45	81.53
9	0.9	0.2	58.11	19.57	80.79

Falk as the increment oil recovered does not simply proportional with solution viscosity (1976). Emulsion generation in SP flooding is critical in dissolving and solubilizing reservoir oil, enable them to be displaced more easily (Shindy et al., 1997).

3.7. Comparison to xanthan gum performance

As comparison, displacement test was being performed by using SDBS and 0.2 and 0.3 wt% XG (Table 4). Compared to SDBS − CMC combination, SDBS − XG at the same tested concentrations results in slightly lower oil recovery. Previous studies suggested that more oil can be recovered at low XG concentration (Saleh et al., 2014; Jang et al., 2015). Fig. 9 shows the comparison of SDBS − CMC and SDBS − XG emulsions system being generated at specified concentrations. Clear evidence of emulsion phases was observed in CMC system compared to XG. Graphical representations of oil recovery percentage in SDBS − XG flooding is plotted in Fig. 10 with incremental oil recovery between 18 − 19%. The insignificant different in oil recovery percentage was believed to be owing to the

rheological behaviour of aqueous XG and CMC, respectively, which were discovered to be slightly similar (Westra, 1989). Aqueous XG possesses strong pseudoplastic characteristics, enabling the viscosity to be sustained over period of times, even at low concentration and increasing shear rates (Nor Hayati et al., 2016). Furthermore, the congested branches of XG offer outstanding viscosifying effect over wide range of flow conditions to satisfy oil recovery process (Casas et al., 2000; AlZahid et al., 2016). CMC on the other hand, exhibits shear thinning Newtonian fluid behaviour as discussed in section 3.2, which favourably act as mobility control agent and emulsion stabilizers for this oil displacement process (Ghannam and Esmail, 1997).

4. Conclusions

Based on the experimental results, the following conclusions were reached.

(a) SDBS − CMC shows a promising result as additives for potential EOR application.
(b) Combination of lower SDBS − intermediate CMC concentrations is preferable for maximum viscosity performance.
(c) High emulsions were generated and stable at 0.3−0.5 wt% SDBS and 0.2−0.5 wt% CMC.
(d) Sandstone exhibit water−wet and strongly water−wet formation when subjected to SDBS − CMC formulation at various concentration tested.
(e) Surface tension shows insignificant reduction at every combination tested.
(f) SP flooding indicates significant oil increment, between 14 − 20%, when displaced with SDBS − CMC.
(g) At fix SDBS concentration, lowest CMC concentration results in highest additional oil recovery.
(h) At fix CMC concentration however, high SDBS concentration is required to obtain high oil recovery.
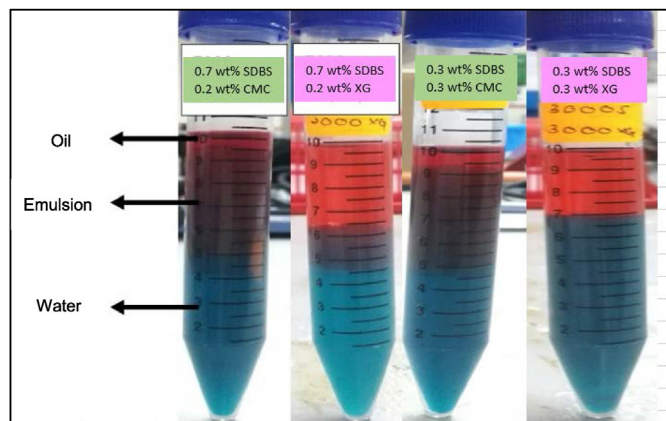(i) Compared to XG, emulsion system in the presence of CMC shows high volume being generated.

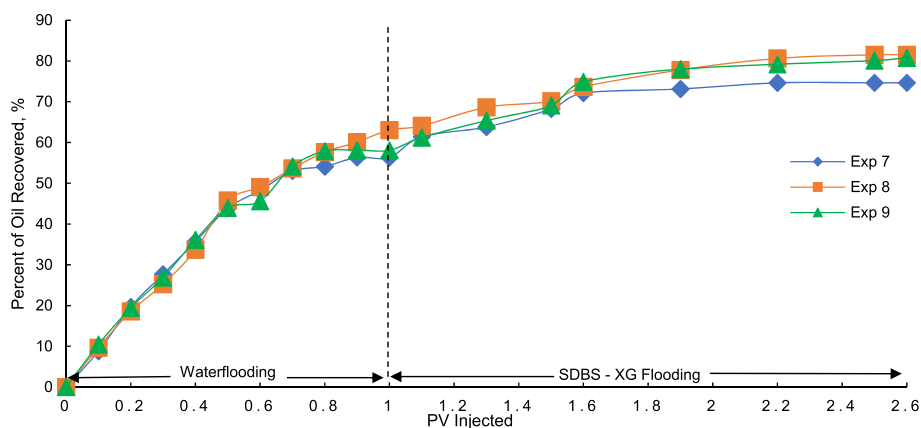**Fig. 9.** SDBS − CMC and SDBS − XG phase behaviour evaluation.

Fig. 10. Percentage of oil recovered during SDBS − XG flooding.

(j) Oil recovered by SDBS − CMC reveals the potential of this combination to be used in EOR application as the trend in oil produced was similar to that of SDBS − XG combination.

(k) Possible influencing parameters that are responsible for oil recovery increment was presumed to be influenced by several factors, optimum viscosity, surface tension reduction, improvement of wetting surface, and primarily emulsion generation.

This preliminary study was performed on the basis of gathering the idea, knowledge, ability, and feasibility of these materials, SDBS − CMC combinations, to be used in tertiary recovery. Hence, details investigation should be conducted as to understand their behaviour and to cater their applicability at reservoir condition. As the parameters involve varies broadly and integrated interchangeably, studying their properties is deemed necessary. Characterizing SDBS − CMC in term of their emulsification (solubilization parameter, ternary diagram, emulsion droplet sizes, etc), zeta potential, adsorption on rock surface, injectability, slug and injection scheme, and etc. are critical for EOR application. The effect of concentration, salinity, temperature, pressure, and other flooding conditions should also be further investigated thoroughly.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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