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Relationship between bulk foam stability, surfactant formulation and oil displacement efficiency in porous media

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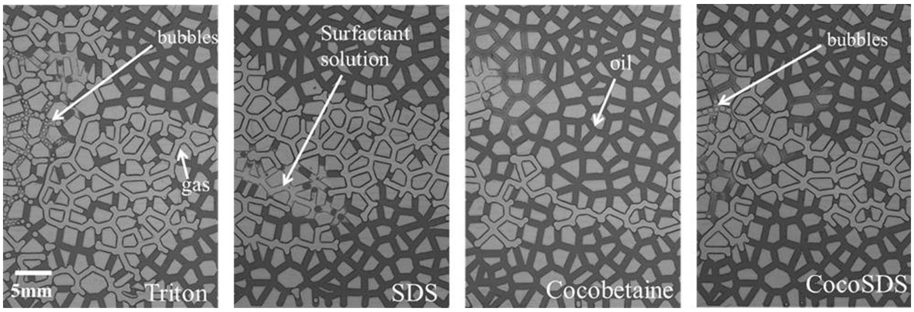
HIGHLIGHTS

- Oil displacement by foam was investigated in a 3D printed porous medium.
- Oil displacement by foam is strongly influenced by the surfactant formulation.
- No correlation between bulk foam stability and displacement efficiency was observed.
- Stability of foam at bulk scale does not determine its effectiveness in porous media.

GRAPHICAL ABSTRACT



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ABSTRACT

Success of foam as a displacing fluid in porous media depends on longevity of foams in the presence of non-aqueous phase liquids such as hydrocarbons. The stability of foam at bulk scale has been used in many cases to screen potential surfactants for core flooding studies. Although this method may aid in determining the foamability and stability of a surfactant, no reliable correlation has been found to exist between bulk foam stability and performance in porous media. We have conducted a comprehensive series of experiments to examine and compare the stability of selected surfactant foams at bulk scale and during oil displacement in porous media. The oil displacement was investigated in a micromodel manufactured by 3D printing technology. Our results demonstrated that oil displacement efficiency by foam is strongly influenced by the surfactant formulation. More importantly, no meaningful correlation between the bulk foam stability and the oil displacement efficiency of the corresponding foams in porous media was observed. Our pore-scale investigation shows that the stability or instability of foam at bulk scale does not necessarily determine its effectiveness in porous media. Hence, performing displacement tests as presented in our study may give more insights into the potential performance of foams.

1. Introduction

The application of foam in porous media is relevant to many processes such as enhanced oil recovery (EOR) [1–3], soil remediation [4,5] and CO_2 sequestration [6] due to its high effective viscosity and effective mobility control in porous media [7–11]. The high viscosity and fluid diversion ability of foam offers great potential to resolve some of the major challenges associated with gas

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injection in porous media such as gravity segregation, viscous fingering and selective flooding in heterogeneous systems [12–14]. These remarkable properties are attributed to the relatively low mobility of foam (defined as the ratio of the permeability and viscosity) in porous media [15,16]. During foam flow, a fraction of the gas is trapped in the porous medium which essentially reduces the flow paths available for the flowing gas. The result of this is a decrease in the gas relative permeability [7,9,17–19]. In addition, the presence of surfactant in foam can contribute to oil displacement by reducing the interfacial tension (hence capillary forces) helping to facilitate displacement.

A major concern with the application of foam as a displacing fluid in porous media is the stability of foam in the presence of hydrocarbons (hereafter referred as “oil”). The destructive effect of oil on foam stability has been observed in many experimental studies, both at bulk scale and in porous media [11,20–24]. Mechanisms by which oil destroys foam have been explained in terms of the surface interactions between oil and foam films. Classically, these interfacial processes and mechanisms have been described by the entry (E), spreading (S) and the bridging (B) coefficients given mathematically by:

$$E_{o/w} = \sigma_{wg} + \sigma_{ow} - \sigma_{og} \tag{1}$$

$$S_{o/w} = \sigma_{wg} - \sigma_{ow} - \sigma_{og} \tag{2}$$

$$B_{o/w} = \sigma_{wg}^2 + \sigma_{ow}^2 - \sigma_{og}^2 \tag{3}$$

where σ_{wg} is the surface tension of the surfactant solution, σ_{ow} is the interfacial tension between the oil and surfactant solution and σ_{og} the surface tension of the oil.

For oil to destabilize a bubble, it must first invade the gas-liquid interface [22,25,26]. This criterion is satisfied when $E > 0$. Upon oil droplet entry into the foam film, it may spread on the surface of the film if $S > 0$. Oil spreading will force liquid (surfactant solution) out of the film into the Plateau borders (the junction where three films intersect) causing the film to thin and eventually collapse [27]. Alternatively, oil may form a lens at the gas-liquid interface and destabilize the bubble if it penetrates the film. This occurs when $S < 0$ and $B \geq 0$ (bridging mechanism) [22,28]. While the entering and spreading coefficients could determine the thermodynamic feasibility droplet entry for a given oil-surfactant system [29,30], many studies have shown that this method of assessment is inaccurate and falls short of predicting the stability of foam for a given surfactant-oil system [30–33]. Manlowe and Radke [30] observed that foam stability in porous media is governed by the strength of the so-called ‘pseudoemulsion film’ that formed between oil and foam. According to their visualization study, oil could only spread on gas-liquid interface after the rupturing of this film.

Many experimental studies have revealed that, in the presence of hydrocarbons, foams generated by different surfactants behave distinctly [2,5,33,34,42,43]. Consequently the choice of foaming agent for displacement in porous media is crucial to the success of the process. The bulk foam stability test has been used in many cases as the ‘litmus test’ to screen surfactants for core flooding [2,29,32,33,35] investigations. For example, Andrianov et al. [2] found that a mixture of Alpha olefin sulfonate (AOS) and fluorochemical provided the best stability in the presence of oil out of five other surfactants (including SDS and AOS) among the surfactants investigated. This surfactant combination was then selected for their core flooding study.

Although the bulk foam test is a quick method of determining the foamability and stability of surfactants as opposed to time-consuming core-flooding experiments, studies have shown no reliable correlation between bulk foam stability and foam performance in porous media in the presence of oil [42,43]. Jones et al. [43] recently studied the correlation between foam stability at bulk scale and porous media using their so-called ‘small core-flood set-up’. By analysing the apparent viscosity of foams made by different surfactants, they observed a relationship between the bulk foam stability and foam strength (apparent viscosity) in porous media in the absence of oil, however no correlation was observed when the porous medium was saturated with oil.

To shed more light on this subject, we conducted a comprehensive series of experiments to study the stability of foam made by four different surfactants at bulk scale (see Table 1). The oil displacement performance of the same surfactants was investigated in a 2D porous medium manufactured by a high resolution 3D printer (Fig. 1). This paper provides a direct visualisation of the influence of surfactant formulation on foam stability during oil displacement in porous media which could be a more insightful approach to determining the potential effectiveness of a given surfactant in porous media.

2. Experimental considerations

2.1. Design and fabrication of porous media

The porous medium was designed with ‘Grasshopper’, a plugin for Rhinoceros 3D software package. The pore network was created from a Voronoi diagram [36] which was constructed from a random configuration points in a 2D domain by tessellating the space into random polygons. The Voronoi polygons were then constructed around each point with the condition that every point inside a polygon was closer to its Poisson point than those of the neighbouring polygons [36]. The pore throat size was randomly distributed in the network using a normal distribution (see Fig. A1) of sizes ranging from 0.8 to 1.0 mm. The depth of the porous medium was 0.5 mm (half the maximum pore size) and constant throughout the entire model. The dimensions of pore network were 110 mm by 50 mm. The model was then printed with an acrylic based polymer using a state-of-the-art Polyjet 3D printer (Objet 30 pro, Stratasys). The image of the printed model is shown in Fig. 1a. The top of the model was sealed completely with a borosilicate glass plate and firmly fixed in a Plexiglas frame with clamps. Two fittings were attached at both ends of the model to enable injection of fluid into and out of the cell. The model was oil-wet and had porosity and permeability of 50.1% and 6.3D, respectively.

2.2. Materials

To compare the influence of surfactant formulation on the stability of foam in the bulk scale and oil recovery efficiency in porous media, four surfactants were employed, namely: Cocamidopropyl betaine (Cocobetaine) (The Soap Kitchen, UK); Sodium dodecyl sulphate (SDS) (Sigma, UK), Triton X100 (Sigma, UK) and a 1:1 mixture of Cocobetaine and SDS which we have called CocoSDS hereafter. Surfactant solutions of 2% concentration (active content)

Table 1
Properties of surfactant solutions used in our study. The interfacial tensions listed here are the interfacial tensions between the surfactant solutions and Isopar V measured with a spinning drop tensiometer. The viscosities of the surfactants were measured by a rheometer.

Surfactant	Active content (%)	Interfacial tension (mN/m)	Viscosity (Pa s)
Triton X100	100.0	0.40	8.14×10^{-4}
SDS	85.5	0.50	9.35×10^{-4}
Cocobetaine	30.7	0.38	8.19×10^{-4}
CocoSDS	–	0.13	0.35

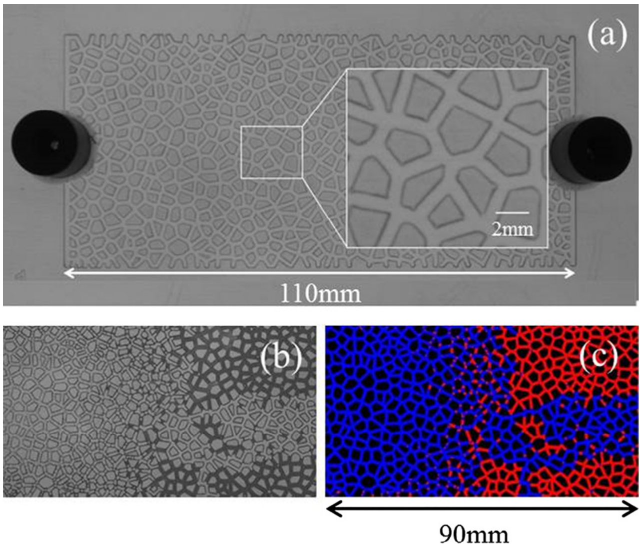

Fig. 1. (a) Top view of the printed porous medium used to study oil displacement by foam. (b) A typical gray-scale image recorded by the camera (c) the segmented image with black, red and blue corresponding to the solid grains, oil and foam/gas respectively.

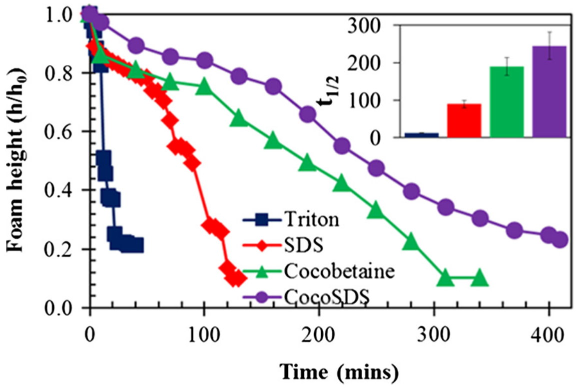

Fig. 2. Stability of foams generated by Triton X100, SDS, Cocobetaine and CocoSDS in the presence of Isopar V. The inset shows the average half-life of foam influenced by the type of surfactant (indicated by the legend). The error bars represent the standard deviations for three rounds of experiments conducted for each surfactant.

were prepared with 0.5 M NaCl (Sigma, UK) in deionised water (18 MΩ/cm). The properties of the surfactants are displayed in Table 1. Isopar V (Brentagg, UK) (with the viscosity of 10.84 Pa·s, density of 0.82 g/cm^3 and boiling point of 270 °C) was used as the oil phase.

2.3. Bulk foam stability experiment

Foam stability in the bulk-scale was studied in a chromatograph column following the same method explained in Osei-Bonsu et al. [33]. The column was initially filled with 100 ml of surfactant solution and 5 ml of Isopar V. By the use of a mass flow controller (Bronkhorst, UK), pure air was injected from the bottom of the column at a constant volumetric flux of 100 ml/min to create foam of a fixed volume. A computer controlled camera was used to capture the evolution of foam height at well-defined time intervals after gas sparging was terminated. More detail about the bulk foam stability experiments and analysis can be found in Osei-Bonsu et al. [33].

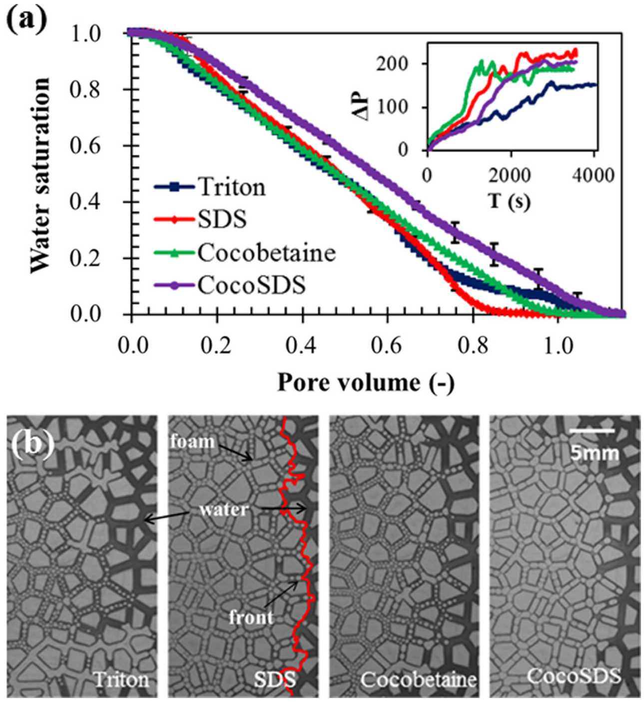

Fig. 3. (a) Evolution of water saturation during displacement by foams made by Triton X100, SDS, Cocobetaine and CocoSDS. The inset shows the evolution of the pressure drop (mbar) during the course of water displacement. (b) Typical examples of foam-water distribution during water displacement by foams generated from different surfactants (indicated on each image). In all cases, the images illustrate the phase distribution close to the inlet of the micromodel after 200 s from the onset of the experiment. The red line represents the interface between the foam and the water being displaced. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.4. Porous media experiment

Prior to foam injection, the model was saturated fully with either water or oil. This was achieved by placing the model vertically and by applying pressure at the outlet to eliminate gas trapping in the model. The gas and the surfactant solution were injected simultaneously through a foam generator (built in-house with a sintered disc) to create foam. The flow rate of the gas phase (pure air) was regulated by a mass flow controller (EL – Flow, Bronkhorst, UK) while the surfactant solution was controlled by a syringe pump (PHD Ultra, Harvard Apparatus, USA). The foam emerging from the generator was injected directly into the saturated model via a plastic tube (internal diameter of 0.5 mm). The foam flow rate (sum of the flowrate of the gas and surfactant which was 5 ml/h and 0.88 ml/hr, respectively) and quality (85%) were maintained constant. This foam quality is in the low quality regime [1] A pressure sensor was connected to the inlet of the model to measure the evolution of the pressure drop during the displacement. All experiments were conducted at room temperature and pressure. Two sets of experiments were conducted in this study: Firstly, we investigated the performance of the surfactant foams in a water saturated porous medium (i.e. the model was fully saturated with water and then foam was injected continuously to displace the water). Secondly, the dynamics and the recovery performance of the same surfactant foams were studied in the porous medium saturated with oil.

2.5. Image acquisition and processing

A monochromic camera (Teledyne Dalsa Genie) controlled automatically by a computer was mounted above the model to capture

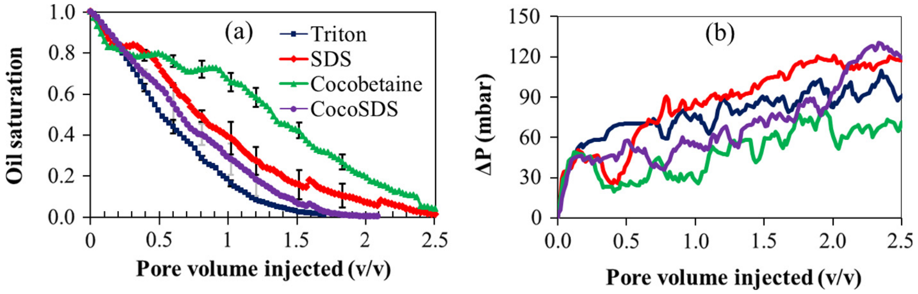

Fig. 4. (a) Evolution of oil saturation in porous media as a function of pore volume of foam injected for Triton X100, SDS, Cocobetaine and CocoSDS. The error bars represent the standard deviation of three studies conducted for each surfactant, (b) evolution of pressure drop (ΔP) during oil displacement.

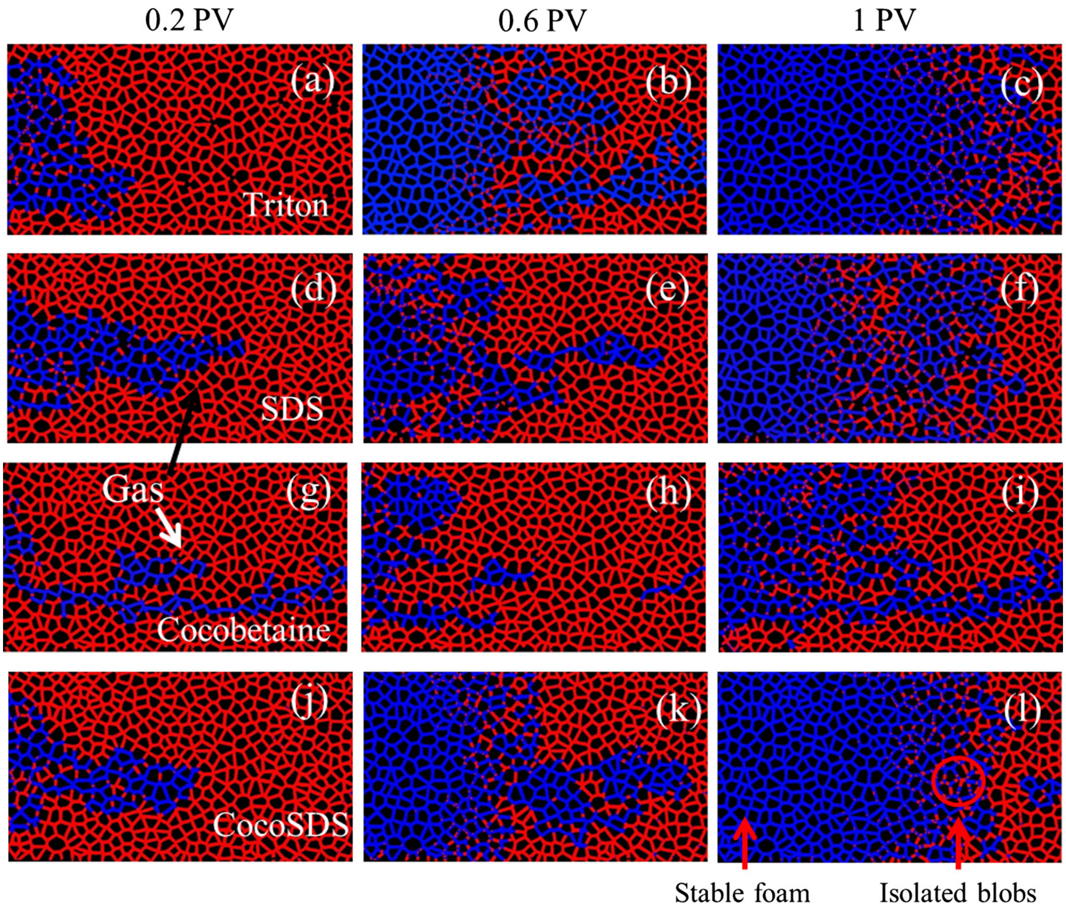

Fig. 5. Phase distribution and displacement patterns of Triton X100 (a–c), SDS (d–f), Cocobetaine (g–f) and CocoSDS (j–l): blue, red, and black correspond to foam, oil and solid grains respectively. Finger-like patterns are due to the low viscosity ratio between gas and the oil. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the displacement of oil by foam at regular time intervals. A light box was placed under the model to enhance and ensure homogenous illumination. The resolution of the output images was 2560 × 2048 pixels, with 8 bit gray levels providing the spatial magnification of 0.04 mm per pixel. The oil phase was dyed (Oil red) in order to enhance the contrast between the foam and oil in the pore network. A code was developed in MATLAB to quantify the distribution of phases and the oil recovery efficiency as influenced by the surfactant formulation (see Osei-Bonsu et al. [1] and Shokri et al. [23] for details about the image processing algorithm). Fig. 1(b and c) illustrates a typical example of the recorded image by the camera and the resulting segmented image which was used for the image quantification.

3. Results and discussion

3.1. Bulk foam stability

To assess the stability of the foams at bulk scale in the presence of oil, the normalized height of the foam in the column was plotted as a function of time. The normalized height was defined as the height of the foam at any given time h, divided by the height h_0 at the onset of the experiment. Fig. 2 displays the time evolution of the foam height in the presence of Isopar V for the four surfactants under investigation. The slope of the curves represents the rate of foam height decay. According to Fig. 2, CocoSDS is the most stable in the presence of Isopar V as it demonstrated the lowest

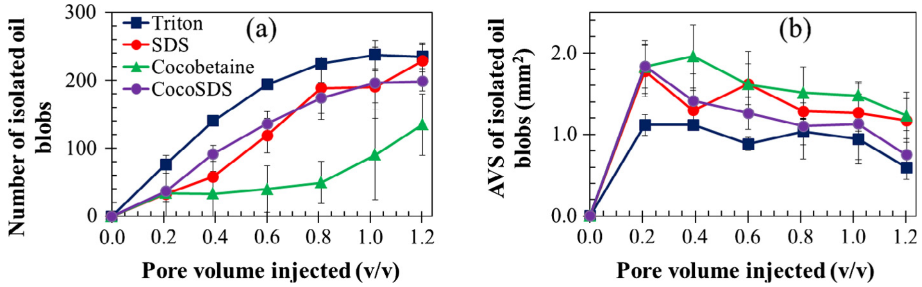

Fig. 6. (a) Number of isolated oil blobs (b) average size (AVS) of the isolated oil blobs as a function of pore volume of foam injected. The error bars represent the standard deviations of three different displacement experiments conducted for each surfactant. Fig A1. Pore throat size (diameter) distribution of the pore network manufactured by the 3D printer. Pore sizes were randomly distributed in the porous medium using a random generator function in Grasshopper software in the software package used to create pore the network.

rate of foam decay and the longest foam life time while Triton X100 is the least stable. The order of foam stability is as follows: CocoSDS > Cocobetaine > SDS > Triton X100. The inset in Fig. 2 shows the half – decay time (also known as the half – life defined as the time taken for the foam to reach half its initial height) for the foams which follow the trend above. The foam half – decay time for CocoSDS was approximately twenty times the half-life of Triton X100. The foam stability at bulk scale is mainly controlled by two main processes [37]: 1) Drainage of liquid out of the foam network by the influence of gravity which results in film thinning and 2) coalescence of bubbles which is accelerated by the presence of oil. These two processes depend on several factors that relate closely to the physiochemical properties of the surfactant as well as the oil. A few possible reasons for the observed trend in foam stability and behaviour have been discussed extensively in Osei-Bonsu et al. [33] thus are not repeated here.

As mentioned previously, the information obtained from the bulk foam stability analysis such as the one presented in Fig. 2 have been generally used as an assessment criterion to select surfactants for core flooding experiments. In attempt to test the validity of this assessment criterion, water and oil displacement tests were carried out in a micromodel using the same surfactants studied at bulk scale (illustrated in Fig. 2).

3.2. Water displacement by foam in porous media

In order to evaluate accurately and understand the influence of oil on the foams generated by the selected surfactants, water displacement experiments (by foam) was first conducted. The purpose of these tests was to investigate the influence of the porous medium itself on the stability of foams made by the surfactants in the absence of the destabilising hydrocarbons. Results from this study revealed little dependence of the surfactant formulation on water recovery by foam. Fig. 3 shows quantitatively and qualitatively the water displacement by foams generated with Triton X100, SDS, Cocobetaine and CocoSDS. The water saturation (or equivalently, water recovery factor, which is 1 minus the water saturation) was defined as the ratio of the volume of water (number of black pixels) in the porous medium at any given time to the volume of water in the model at time t = 0 (initial water saturation of the model was 1 indicating that the model was saturated fully with water (i.e. initial number of black pixels). As foam was being injected into the model, the residing water saturation decreased until all water initially occupying the model was displaced, i.e. water saturation = 0). It was observed that, foam generated by all four surfactants displaced all the water from the porous medium after about 1.15 PV of foam had been injected. Up until about 0.6 PV of foam injection,, the amount of water recovered from the model was approximately the same for Triton X100, SDS and Cocobetaine but slightly lower for CocoSDS. The pressure drop across the model also showed little variation between the selected surfactants during first 500 seconds which is in agreement with the water saturation profiles. However, as illustrated in the inset of Fig. 3a, the pressure behaviour changed when all water had been displaced from the model and subsequently, different steady-state pressures were recorded for the investigated surfactants.

The steady-state pressure was used to calculate the apparent viscosity of the foams (generally used to determine foam strength [7,43]) using Darcy's law given by $\mu_{app} = \frac{k}{q}\frac{\Delta P}{L}$, where k is the permeability of the porous medium, L is the length, q is the Darcy velocity of foam (total of liquid and gas velocities), and ΔP is the steady-state pressure drop across the model (please see the inset in Fig. 3a). Fig. A2 (in the appendix) presents a comparison of the apparent viscosities of the foams at 85% foam quality used in our study. Triton X100 recorded the least apparent viscosity (0.013 Pa·s) of the four which is consistent with its low stability at bulk scale. The apparent viscosity of SDS, Cocobetaine and CocoSDS were almost the same (0.019, 0.017 and 0.017 Pa·s, respectively).

Fig. 3b shows the images of a region close to the inlet of the micromodel taken 200 s after foam injection commenced. Examination of the images reveals that the foams generated by all four surfactants were stable in the porous medium from the onset of foam injection. No widespread collapse of bubbles was observed here (compared to the case when oil was present in the porous medium as illustrated in the graphical abstract). In the case of Triton X100, some coalescence was observed initially at some parts of the interface between foam and water; however, this ceased as foam injection progressed. Furthermore, this coalescence did not seem to influence the displacement of water by the foam. It was also observed that (Fig. 3b), for the same foam quality, bubble size generated in the porous medium was relatively smaller than the average pore throat size of the porous medium in the initial stage of foam injection except for the case of CocoSDS where most of bubbles were bigger and span the entire pore within which they were confined. The bigger bubbles observed during water displacement by CocoSDS foam was also observed during the bulk scale experiments [33]. This behaviour could be ascribed to the high viscosity of CocoSDS compared to the other surfactants [33]. The higher viscosity of CocoSDS (see Table 1) reduced the rate of bubble formation subsequently leading to the formation of bigger bubbles as seen in Fig. 3b.

3.3. Oil displacement by foam in porous media

Fig. 4 shows the oil recovery efficiency of the selected surfactant foams considered in our study. Similar to the previous section, the oil saturation at any given time was defined as the volume of oil remaining in the porous medium divided by the volume of oil in the model at time t = 0. The recovery efficiency is governed by the rate of oil displacement by foam (and the time taken to recover the oil fully). Pore volume injected (PV) is a dimensionless value given by the ratio of the total volume of foam injected at a given time to the total volume of the pores in the porous medium. The order of oil recovery efficiency according to the Fig. 4 is as follows: Triton X100 > CocoSDS > SDS and Cocobetaine. The order of oil recovery (i.e. number of pore volumes required to displace the oil in the model) is essentially a measure of the stability of the foams. When foam is unstable in the porous media, phase separation between the gas and liquid phase occurs leading to the formation of fingers by the gas phase which is undesirable in oil displacement in porous media [24,1]. Note that in the study of the bulk foam stability (Fig. 2), Triton X100 demonstrated extremely low stability in the presence of Isopar V while Cocobetaine showed relatively higher stability. However, when the foams were applied during oil displacement in the micromodel, Cocobetaine was the most unstable and demonstrated the lowest pressure drop due to excessive and prolonged period of bubble collapse in the presence of oil compared to Triton X100.

The outcome of the oil displacement investigations (Fig. 4) reveal no correlation between the foam stability of a surfactant at bulk scale and its stability and oil displacement efficiency in porous media [43]. The entry and spreading coefficient that are generally used to predict foam stability at bulk scale also failed to describe and predict the stability and efficiency of oil displacement by foam in porous media as observed in other studies [33,43]. Additionally, the apparent viscosities of the foams discussed in the previous section do not correlate with the oil recovery efficiencies of the surfactants under our experimental conditions [43]. One of the main reasons for this outcome is that, foams flowing in confined micro-pores behave differently from bulk foam under static conditions as the two processes are controlled by different physical processes [38]. In addition, the complexity of porous media geometry and topology may influence the interactions between the flowing foam and the oil. Our visualization study supports some of the previous studies that, the behaviour of bulk foams under static conditions is not representative of the processes occurring during foam flow in an oil saturated porous media. Hence, using bulk foam stability test as an assessment criterion for surfactant selection for further investigation in core flooding studies or any porous media application for that matter may be unreliable as a surfactant like Triton X100 could be disregarded based on its bulk scale performance [39,43].

The dynamics of foam flow in the oil saturated model was observed to be distinct from the previous scenario where the porous medium was filled with water. Fig. 5 provides a qualitative observation of oil displacement by foams generated by the surfactants as a function of pore volumes of foam injected. The bubbles experienced a catastrophic collapse immediately upon entering the pore network due to the presence of oil (see graphical abstract). Phase separation occurring as a result of bubble destabilization by oil resulted in finger-like patterns [1] in the micromodel due to the escaping of the gas phase from foam network and moving rapidly through the oil (this scenario is typified by Fig. 5g). This phenomenon was observed in all foams tested in our investigations. However, the time taken for stable foams to persist and propagate through the oil-saturated model (which is the key to the oil recovery efficiency) was different for all surfactants. Unlike the other three surfactants, the foam generated by Cocobetaine was unstable even after 1 PV of foam had been injected. This explains the significant difference in the oil recovery between Cocobetaine and Triton X100 (in which stable foams began to form just after 0.28 PV of foam injection).

Fig. 6 shows quantitatively the evolution of the isolated oil blobs as a function of pore volumes of foam injected. The number of the isolated oil blobs and their average sizes provide some insights about the stability and performance of the foams used as the displacing fluid. More fragmentation in the oil phase (the increase in the number of isolated blobs) indicates that early formation and propagation of stable foams and the permeation of a large portion of the porous medium [1]. The increase in fragmentation in the oil phase occurs as a consequence of bubbles forcing their way through multiple pore throats across the entire model. On the other hand, when the foam is less stable, the rate of bubble collapse is higher, causing the released gas to penetrate the oil phase creating fingering patterns. As a result of this, the injected fluid only contacts a smaller portion of the model leaving most of the oil phase connected and the isolated oil phases bigger. However, it must be stated that for extremely stable foam (i.e. where the influence of oil on bubble collapse is minimal), a stable foam front and uniform oil displacement is expected with little fragmentation (if any) in the oil phase [11].

Our results revealed smaller blobs and a higher rate of fragmentation in the oil phase during displacement by foam made by Triton X100 due to the propagation of more stable foams in the presence of oil in the model. On the other hand, the blobs formed during injection of foam made by Cocobetaine into the model were larger and the number of the isolated blobs increased slower compared to the foam made by Triton X100 (after the same amount of injected pore volume of foam).

4. Conclusions

A comprehensive series of experiments have been conducted to investigate the relationship between the information obtained from bulk-scale foam stability analysis and the efficiency of foam displacing fluid in porous media for selected surfactants. No meaningful relationship was observed between the two studies. This is due to the difference in the physics controlling foam behaviour and stability at bulk-scale and porous media. In the static bulk foam experiment where the foam is mixed with the oil, foam stability is primarily governed by the rate of liquid drainage from the Plateau border and the rate of coalescence of bubbles which is accelerated by the invasion of oil droplets into lamella. However, bubbles of the foam flowing in porous media saturated by oil are subjected to different forces and mechanisms which influence the foam behaviour. The bubbles are confined in geometries (pores) whose sizes are in the order of the size of the bubbles. This means that each bubble is influenced by the interaction with the pore wall. Such interactions are absent in the bulk-scale foam test. Also, the continuous injection and regeneration of bubbles during gas and surfactant flow within porous media lowers the effect of liquid film drainage on foam behaviour (while it is an important feature at the bulk scale). However, it must be noted that, if the pore throat size were much larger than the average bubble size, foam might tend to exhibit the bulk behaviour.

Additionally, as observed in our study, the apparent viscosity of a surfactant foam in a porous medium may not be a reliable indicator of the potential performance of foam in the presence of oil as the steady state pressure drop is obtained after most of the oil in the porous medium has been displaced. Our previous study showed instability of foam in the presence of oil increases as the foam quality increases (though increasing foam quality increases the apparent viscosity) [1]. Consequently, a displacement study as the one conducted here may provide more insights into the potential performance of a given surfactant for further displacement applications.

Apart from the effects of the complex geometry of the porous media on foam-oil interaction, properties such as wettability of the medium can also affect the effectiveness of a given surfactant foam [40,41]. The adsorption of surfactant molecules onto the walls of the matrix which depends on the chemical properties of the surfactant can alter the wettability of the surface which in turn could modify oil interaction with foam [24]. Elucidating the influence upon foam displacement of the particular material constituting the porous media is an avenue for further work.

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Appendix A

The pore throat size distribution of porous media (Fig. A1) and apparent viscosities of the foams at 85% foam quality (Fig. A2).

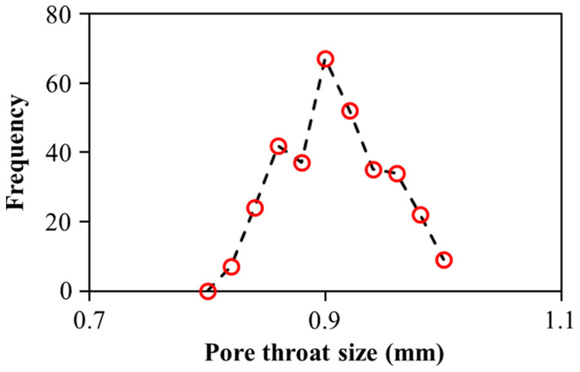

Fig. A1. Pore throat size (diameter) distribution of the pore network manufactured by the 3D printer. Pore sizes were randomly distributed in the porous medium using a random generator function in Grasshopper software in the software package used to create pore the network.

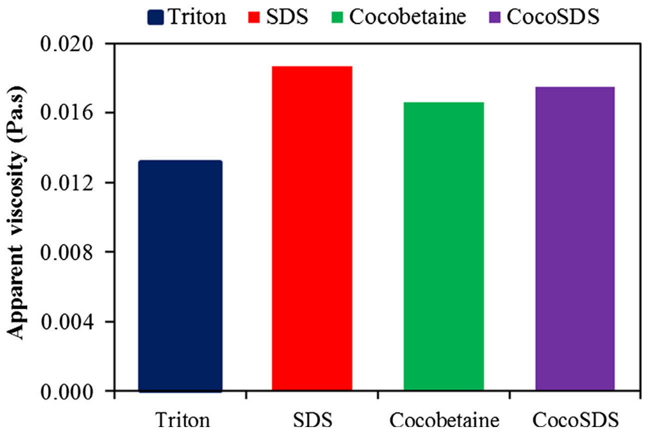

Fig. A2. The influence of surfactant formulation on the apparent viscosity of foam in the micromodel.

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