Formulation of Lignin Based Surfactant Using Extracted Lignin from Ultrasound-Assisted Technique for Enhanced Oil Recovery

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Abstract

Surfactant are some of the most expensive chemicals used in Enhanced Oil Recovery (EOR). Thus, the reason of developing lignin based surfactant system for EOR is to lower the cost as it does not tie to the price of crude oil compare to other petroleum based surfactants. Besides, lignin could be extracted from oil palm waste that is available abundantly in Malaysia. The aim of this study is to determine the amount of lignin compound extracted from the oil palm Empty Fruit Bunch (EFB) by using ultrasound-assisted technique, to determine formulations of lignin based surfactant for EOR applications, and to determine the oil recovery performance of lignin based surfactant through surfactant flooding. The results of the study showed that the extraction of lignin using ultrasound-assisted technique enhanced the extraction amount of lignin, though it did not alter the lignin composition and structure, compared to traditional pulping process. The formulation of lignin based surfactant at 2 % total active surfactant showed good stability phase behavior and interfacial tension. The oil recovery from displacement test also showed significant results where the best formulation lignin based surfactant able to recover 11% of Oil Originally In Place (OOIP) after waterflooding, and is comparable to commercial surfactant.

Keywords
extracted lignin, ultrasound, surfactant, surfactant flooding, enhanced oil recovery

1. Introduction

According to U.S. Energy Information Administration, EIA (2016), Malaysia held proven oil reserves of 4.0 billion barrels as of January 2014, the fourth highest reserves in Asia Pacific after China, India and Vietnam. Malaysia is Southeast Asia's second largest oil producer after Indonesia. Petroleum and other liquids production (including crude oil, condensate, natural gas liquids, biofuels and refinery processing gains) in 2013 was nearly 670,000 barrels per day (bbl/d), hovering around the same level since 2011, down from the country's peak production of 844,000 bbl/d in 2003. The oil production has experienced overall declines as a result of maturing fields.

The alternative ways to increase oil production can be done by finding new fields or using new technology for mature fields. Deepwater activities are expected to play a prominent role in the development of Malaysia's oil and gas sector in the future. Petronas expects the deep-water sector to contribute 25 to 30 % of Malaysia's oil and gas production over the next five years. However, finding and extracting oil in green fields involves a colossal capital outlay. In 2013, Petronas reported plans to spend more than USD 61 billion over five years in Malaysia's oil and natural gas sector to boost oil and natural gas production and offset the current declines from ageing fields (EIA, 2016). Due to this

expensive cost, the alternative ways will be the interest of researchers in order to increase the oil production economically. Enhanced oil recovery (EOR) techniques are at present is a good choice to further improving oil recovery in matured exploration and producing areas in Malaysia.

Surfactant use for EOR is not a recent development in petroleum field. However, the cost of the surfactants has been the main reason for the limited use in the EOR processes. One problem with many surfactants is their high cost of manufacture and the raw material.

DeBons and Whittington (1991) in their study reported that one of the major reasons for developing lignin based surfactant systems for EOR was to lower the cost of chemicals. As a comparison, lignin amines are not tied to the price of crude oil, and have been relatively constant in price. Meanwhile, on the other hand, petroleum sulfonate surfactants showed a major increases and swings in the prices as the crude oil prices has varied. Therefore, it has been the main interest of many researchers as not only to develop efficient surfactants, but also to come out with the most economic surfactants. Their much lower cost means that they can be used economically at lower crude oil prices too.

According to Malaysian Palm Oil Board (2016), Malaysia has produced 104 million tonnes metric of oil palm fresh fruit bunches in 2015 making it the largest oil palm producer in the world. This is an incremental of 47 million tonnes metric production over the past 11 years. In 2004, Malaysia only produced 57 million tonnes metric of oil palm. The planted area also had doubled, with 3.9 million hectares in 2004, to 5.64 million hectares in 2015. For each tone of crude palm oil (CPO) produced from fresh fruit bunches, the following residues, which can all be used for the manufacture of biofuels, bioenergy and bioproducts, become available: around 6 tonnes of waste palm fronds, 1 tonne of palm trunks, 5 tonnes of empty fruit bunches (EFB), 1 tonne of press fiber (from the mesocarp of the fruit), half a tonne of palm kernel endocarp, 250 kg of palm kernel press cake, and 100 tonnes of palm oil mill effluent (POME) (Mekhilef et al., 2011). In short, a palm plantation has the potential to yield a very large amount of biomass that can be used to produce renewable products. Hence, Malaysia has the capacity of supplying raw material for lignin extraction from these plantation waste materials.

Several techniques can be applied to extract lignin from waste materials. Ibrahim & Azian (2005), Ibrahim, Nadiah & Azian (2006), Ibrahim, Yusof & Hashim (2007), Alriols et al. (2008), Harsono et al. (2016), Tan et al. (2009), Pan et al. (2006), Fu et al. (2010), Sun et al. (2005) utilized a universal method where the wood pulp from agriculture materials is cooked with sodium hydroxide (or other types of base) at high temperature. Once the black liquor has formed, the lignin is extracted using acid precipitation method. The precipitated lignin was then filtered and dried in an oven to get in powder-like shape.

However, this technique could be enhanced by using ultrasound-assisted technique. Nazir et al. (2013), Fahma et al. (2010), Mason et al. (2011), Yunus et al. (2010), Garcia et al. (2011) has shown that lignin could be extracted under alkaline conditions using ultrasound without significant changes in lignin composition and structure. This enhancement technique also supported by Rodrigues and Pinto (2007). The results of their study indicate that high amount of phenolics can be extracted from coconut shell by ultrasound assisted extraction technology, and that the extraction time was the most significant parameter for the process.

In petroleum area, only small number of research has been done to study the effectiveness of lignin-based surfactant development from waste material in surfactant flooding. Seng et al. (2006) has been trying to develop chemicals for EOR by using oil palm wastes as the raw material. In their experiment, the pyrolysis oil from oil palm shell contained high percentage of phenol and its derivatives more than 50 %. The extraction technique using alkaline solution was able to extract the phenol fraction and yielded average of 25 wt.%. The surfactant produced from pyrolysis oil resulted in additional oil recovery from 8 to 14 % of OOIP. However, no formulation nor quality of the surfactant is reported in the study.

Suryo and Murachman (2001) described that Sodium Lignosulfonate (SLS), which is produced as a result of sulfonation of lignin formed from the waste pulp industries and hydrolysis of oil palm husk, had potential to be used in EOR. They used the surfactant in the form of microemulsions during the chemical process experiment. However, they did not describe the method to produce nor the quality of the surfactant in their works.

Other recent studies try to prove the performance of lignin based surfactant in EOR. However, the lignin used in their study is not extracted from waste materials. Sun et al. (2017) and Chen et al. (2016) has shown that lignin based

surfactant were effective to lower the IFT between brine and crude oil. Nevertheless, no displacement test in porous media has been carried out to test its performance.

Therefore, the emphasis in this study is to show the results of lignin extraction from waste materials by using ultrasound-assisted technique; the best formulation of lignin based surfactant; and its performance in IFT measurement and displacement test in porous media. The performance of lignin based surfactant were compared with commercial surfactant.

2. Experimental description

The experiment was divided into two parts. First part was the extraction of the lignin compound from the oil palm empty fruit bunch (EFB) and the development of this locally extracted lignin into a new surfactant. Second part was using the new developed surfactant for oil displacement test in order to know the efficiency of this surfactant in recovering the oil.

The procedures of experiment were consisted of the extraction of lignin compound, characterization of extracted lignin compound, development of purified lignin compound into new surfactant, and analysis of produced surfactant until surfactant flooding experiment.

2.1 Extraction of lignin compound

The raw material used here is the empty fruit bunch (EFB) of the oil palm. The samples are grinded and sieved to a particle size of 1 – 2 mm. It is then dried in an oven for 3 hours at 100 °C prior to extraction process.

The EFB is pulped in a 1000 ml beaker unit with 20 % sodium hydroxide (NaOH) for 3 hours at a cooking temperature of 65 °C, with cooking liquor to EFB ratio of 8:1. An open rectangular ultrasonic cleaner bath (40 kHz, 240 V) is used to carry out the extractions.

The lignin is then precipitated from the concentrated black liquor by acidifying it to pH 2 using 20 % (v/v) sulfuric acid (H_2SO_4). The precipitated lignin is then filtered and washed with pH 2 water, which is prepared using the same acid in the earlier step. The lignin is then dried in an oven at 55 °C for 24 hours prior to further analysis.

2.2 Characterization of extracted lignin compound

Perkin Elmer Spectrum One Fourier Transform Infra-Red (FTIR) spectrophotometer is used to characterize the lignin compound produced from oil palm parts through the use of infra-red (IR) light. Each chemical substance absorbs IR energy differently. This test can detect even the smallest amounts of differences between the purified lignin from various parts of oil palm and the standard lignin.

2.3 Development of lignin based surfactant blends

The combination of water soluble lignin and water soluble anionic and non-ionic surfactants with an oil soluble organic amine is novel for use in enhanced oil recovery. The amines employed are generally fatty amines which are very insoluble in water and tend to precipitate when water is added. However, under the proper conditions, the amines can be dissolved in water which contains a surfactant.

Purified lignin from previous experiment that is almost identical to standard lignin is used in developing the lignin based surfactant. Further description of the procedure in developing the surfactant blends can be referred to Kieke (1999).

2.4 Analysis of produced surfactant

Once lignin amine surfactant blends have achieved the stability phase, the blends were sent for interfacial tension measurement. The interfacial tensions of different blends are measured using a KRUSS tensiometer at room temperature.

2.5 Oil displacement test

The effectiveness of the newly developed surfactant is tested through micro displacement using artificial porous medium. Figure 1 shows the schematic diagram of the oil displacement apparatus.

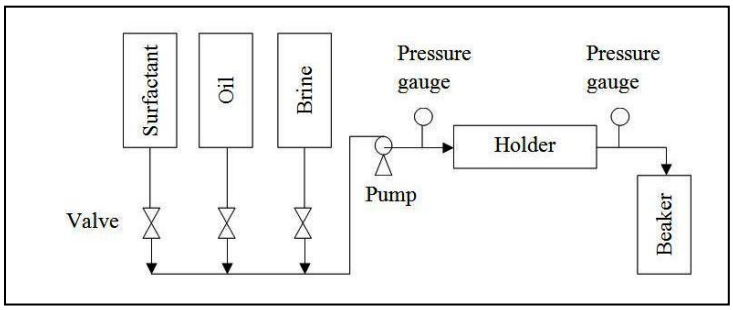

Figure 1. Experimental apparatus for oil displacement test

Brine and paraffin are used as the aqueous and oleic phases in the experiments. Brine salinity is 10,000 ppm of sodium chloride (NaCl) solution. Sand pack flooding is conducted at room temperature. Sand pack holder of 2.5 cm in diameter and length of 30 cm are used. For each test, 150 – 250 µm of clean glass beads are packed. The glass beads are used only once for each run. The assembly with the glass beads would represent an unconsolidated sandstone model. The porosity of the porous media were between 37 to 42 %. Meanwhile, the permeability were between 3.7 to 4.3 Darcy (D).

The displacement tests were conducted horizontally. The procedure is as follows: initially the porous media is injected with brine until it is 100 % saturated. Then, to represent oil migration, oil is injected until minimum water saturation or irreducible water saturation, Swir reach 20 %. Porous media is aged for 24 hours. Porous media is flooded by same brine until residual oil saturation, Sor is achieved around 20 %. This flood is designed to represent the secondary recovery by means of water flooding. The oil remaining in the reservoir after the water flooding is then subjected to injection of surfactant from purified lignin at different level of surfactant blends concentration from empty fruit bunch of oil palm – for the enhanced oil recovery displacement.

3. Results and discussion

3.1 Lignin compound extraction

During the extraction process, some materials were floating when EFB was mixed with sodium hydroxide. As the extraction process was carried out, the liquid changed to dark brown or even black. This behavior is due to the dissolution of lignin and other components. The reason that the color is darker than the raw material is that the sodium hydroxide causes some of the lignin molecules to change into a form that absorbs light in the visible spectrum. These molecules are called “chromophores” (Browning, 1963).

When the pulping process was completed, the pulp was separated from the black liquor. The black liquor produced in this pulping process has a pH of 13.5 at temperature of 23 °C. The black liquor is then acidified with 20 % v/v sulfuric acid until it reaches pH 2.0. During the reaction, the black liquor turned into dark brown color and produced dark brown precipitation. After the acidification, the precipitated lignin was separated from the liquor by using filter pump and the precipitated lignin was thoroughly washed with acidified water to remove any impurity. The precipitated lignin was then dried in an oven for 24 hours. The average lignin content for every sample prepared were 24 wt.% of the EFB (dried weight), with standard deviation of 3.33 % of these samples or in other measurement is 4.754 g from every 200-ml black liquor produced using ultrasound-assisted pulping technique.

Ibrahim & Azian (2005) stated that optimum yield of lignin is 3.016 g from every 200-ml black liquor (15 wt.%) produced using traditional pulping process of oil palm empty fruit bunch, without ultrasound-assisted technique. Alriols et al. (2008) in their study of agricultural palm oil tree residues as raw material for cellulose, lignin and hemicelluloses production, found out that soda lignin composition in EFB extracted using traditional soda pulping process (NaOH 15 wt.%, 180 °C, 90 min and liquid/solid ratio of 6:1) is 18.0 wt.%. Obviously, the extraction of lignin in this report showed a higher value if using ultrasound-assisted pulping technique during the extraction process.

3.2 Extracted lignin compound characterization

The lignin compound produced from the EFB was then characterized by using Perkin Elmer Spectrum One Fourier Transform Infra-Red (FTIR) spectrophotometer through the use of infra-red (IR) light. Figure 2 showed the infrared spectra of lignin fractions obtained from the black liquor of oil palm EFB and standard Kraft lignin (purchased from Sigma-Aldrich, CAS Number 8068-05-1). The FTIR spectra of lignin fractions obtained from black liquor of EFB appeared to be rather similar with standard Kraft lignin which showed the typical lignin spectra. Basically, the lignin structure does not change dramatically during the pulping process.

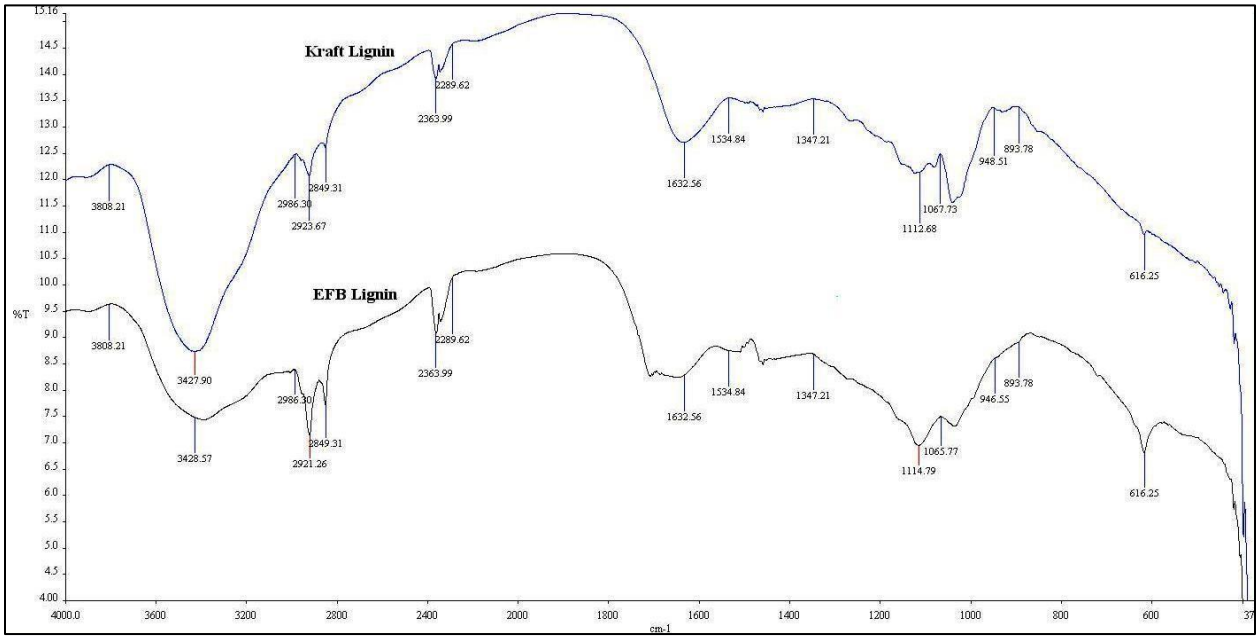

Figure 2. Infrared spectra of lignin fractions obtained from the EFB lignin and Kraft lignin of industry type

From the FTIR test, the results showed that the unbounded or free hydroxyl group of alcohols and phenols lie strongly in the 3,650 – 3,580 cm^{-1} region. From Figure 2, the characteristic of O-H group or phenolic compound for Kraft lignin is located at 3,428 cm^{-1} while for EFB lignin is located at 3,429 cm^{-1}.

The band 1,347 cm^{-1} is due to the bending of vibration in phenolic O-H and normally this bending vibration occurs in the general region of 1,420 – 1,330 cm^{-1}. The stretching vibrations assigned to the C-S linkage occur in the region 700 – 600 cm^{-1}. From the figure, the strong and sharp band at 616 cm^{-1} is only present in the spectrum of lignin precipitated from sulfuric acid.

Moreover, the band at 1,113 cm^{-1} (Kraft lignin) and 1,115 cm^{-1} (EFB lignin) indicates the ether stretching. In the spectra of aliphatic ethers, the most characteristics absorption is in the 1,150 – 1,085 cm^{-1} region because of the asymmetrical C-O-C stretching. This band usually occurs near 1,125 cm^{-1}.

C-H stretching vibrations occur in the 3,000 – 2,840 cm^{-1} and for methylene occur in the band 1,470 – 1,400 cm^{-1}. The positions of the C-H stretching vibrations are among the most stable in the spectrum. From Figure 2, the band at 2,921 cm^{-1} and 1,460 cm^{-1} (EFB lignin) are assigned to C-H stretching and methyl or methylene group respectively.

Moreover, C=C stretching in conjugate aromatic occur in the 1,020 – 1,608 cm^{-1} and from the Figure 2, it is clear that the band 1,042 cm^{-1} is the characteristics of aromatic. This result also showed that broad medium band at 1,633 cm^{-1} is due to conjugated carbonyl stretching. The absorption of carbonyl group occurs in between 1,750 – 1,000 cm^{-1} region.

The FTIR results showed that the solid fraction extracted from black liquor was lignin. Although, the lignin purification was not 100 %, there is no difference of lignin extracted using ultrasound-assisted technique with the

conventional method of extraction. The ultrasound does not alter the functional group of the extracted lignin and it is proven from the FTIR analysis.

3.3 Development of lignin based surfactant blends

The procedure to developed lignin based surfactant blends is by combining the amine and the lignin and to add brine which has been preheated to a temperature above the melting point of the amine. In the case of Octadecyl Amine, a temperature of about 60 to 70 °C is adequate. The combination of lignin, amine and brine is stirred at about 65 °C for about one hour. The water-soluble surfactant, such as Sodium Dodecyl Sulfate (SDS) is then added directly into the warm, brine solution. After an additional 1 to 5 hours of stirring at about 65 °C, the solution is allowed to cool. Figure 3 and Figure 4 showed the surfactant blends composition for each sample prepared.

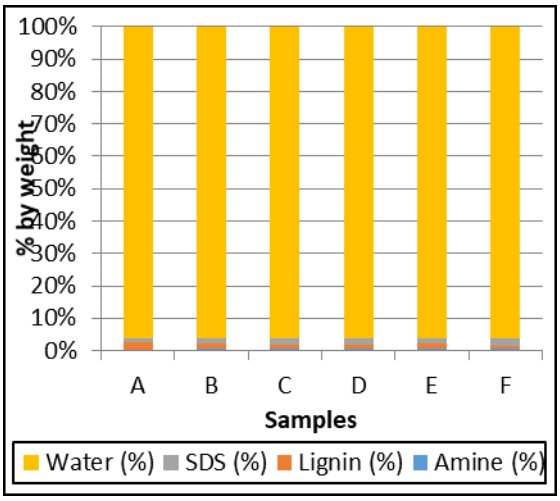

Figure 3. The surfactant blends composition consisted of water, lignin, SDS, and amine

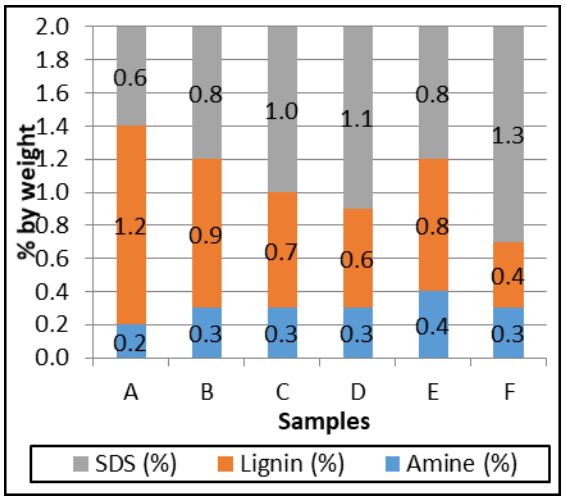

Figure 4. The surfactant blends composition consisted of lignin, SSDS

The blend was prepared at a level of 2 % total active surfactant. After 24 hours, some of the blends showed precipitation and instability phase. From Figure 5, samples A, B and C showed severe precipitation. Meanwhile, samples D, E and F showed little or no precipitation. For the displacement tests, it was decided to use only three samples, i.e. sample D, E and F as these samples showed little precipitation and thus will not cause plugging inside the sand-pore.

When the ratio and total concentration of lignin, water-soluble sulfonate (Sodium Dodecyl Sulfate, SDS) and amine are correct, a stable solution were formed. Generally, too much amine (higher than 20 % by volume of the mixture) or too little water-soluble sulfonate (lower than 20 % of the mixture) will formed precipitation in the surfactant within 24 hours. The stable solutions usually remain as a single phase indefinitely once they have remained stable for 24 hours. While phase stability is preferred, blends which are phase unstable can be used in enhanced oil recovery systems (Kieke, 1999).

3.4 Analysis of produced surfactant

After the lignin amine surfactant blends were cooled down and had been left for 24 hours, the blends were sent for interfacial tension (IFT) measurement between the blends itself with paraffin oil (as substitution for crude oil). The IFT of different blends were measured using KRUSS tensiometer at room temperature. From Figure 6, the IFT measured in laboratory have large discrepancies compare to those IFT values found in Kieke (1999). The main reason for these discrepancies lied on the apparatus to measure the IFT. In this report, a Kruss Tensiometer with measuring range of 0 to 90 mN/m was used. Meanwhile in Kieke (1999), the researcher was using University of Texas Spinning Drop Interfacial Tensiometer with ability to measure IFT up to 0.001 mN/m.

However, the IFT measured in the laboratory showed the same trend as the IFT from Kieke (1999). Sample B illustrated the highest IFT value while sample F demonstrated the lowest IFT value among these six samples both in laboratory measurement and Kieke (1999).

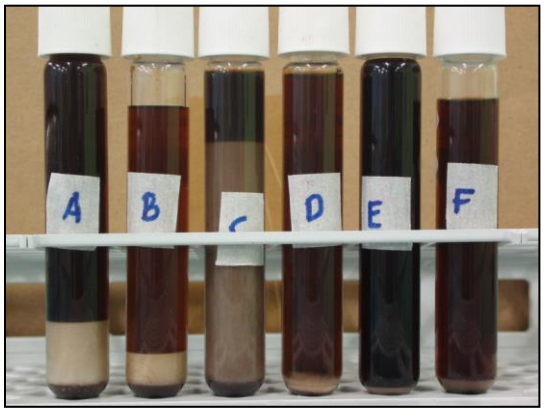

Figure 5. The stability phase of surfactant blends after 24 hours

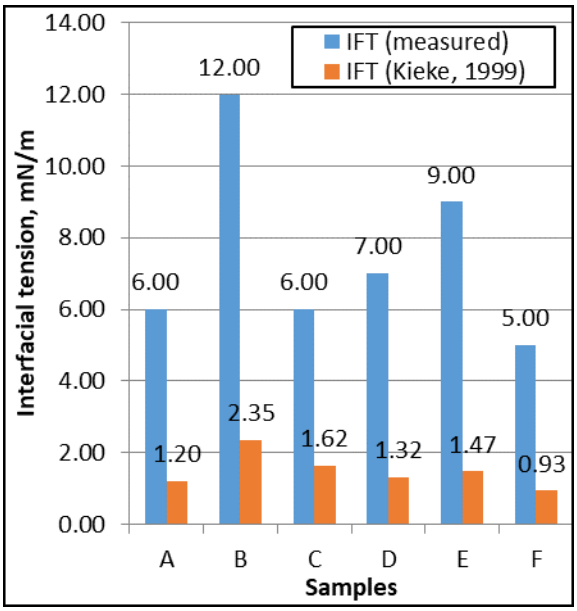

Figure 6. IFT of the surfactant blends from lab measurements and Kieke (1999)

3.5 Oil displacement test

Four displacement tests were carried out by using three different samples of surfactant blends and one using surfactant SDS alone as a controlled experiment. The composition of the surfactant blends are given in Figure 3 and Figure 4 previously. All the experiments were carried out at ambient temperature.

The oil recovery by volume of surfactant injected was plotted in Figure 7. It could be seen from the plot that sample containing SDS only yielded the highest recovery (17.39 % of OOIP) followed by sample F (11.11 % of OOIP), sample D (6.52 % of OOIP) and sample E (6.25 % of OOIP) at the end of flooding.

The oil recovery by water flooding and the additional recovery due to tertiary surfactant flooding are shown in the Figure 8. The graph was plotted in terms of the recovery of oil original in place (OOIP).

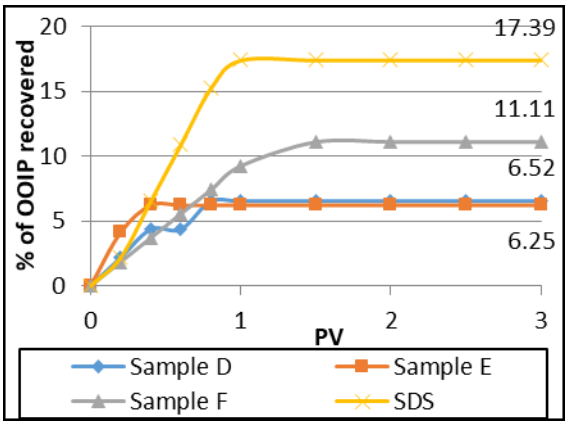

Figure 7. Oil recoveries versus volume of surfactant injected

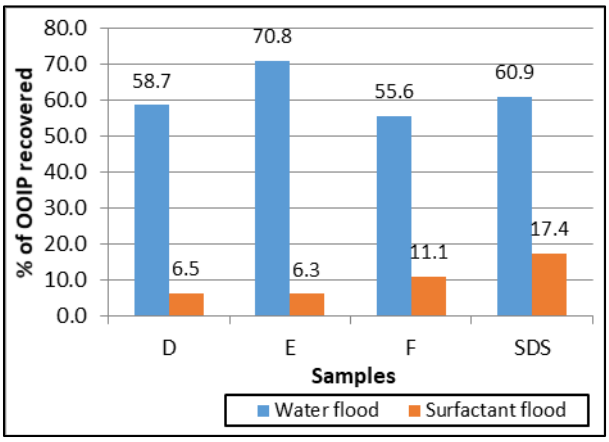

Figure 8. Oil recoveries due to water flooding and subsequent surfactant flooding

All samples produced an average of 60% recovery factor of water flooding, indicating a good quality of packing and the base line was identical prior to the surfactant flooding. On the other hand, the highest surfactant flooding recovery was obtained in the sample containing SDS only, which was 17.4 %. Obviously, the performance of the surfactant

flooding depends on the surfactant blends. There was no relation of the previous water flood history on the surfactant recovery.

For evaluation of the additional recovery due to surfactant flooding, the percentage of original oil in place recovered was plotted in Figure 9. The highest recovery was obtained in controlled experiment by using SDS alone, which has recovery of 17.4 % of OOIP. The lowest recovery was from sample E which yielded 6.25 % of OOIP. It is not surprisingly to know that sample E, which had highest IFT (9.0 mN/m) between paraffin and surfactant resulted in lowest tertiary recovery (6.25 % of OOIP). On the contrary, sample containing only SDS, which had the lowest IFT (2.0 mN/m), resulted in highest tertiary recovery (17.4 % of OOIP). Obviously, the lower the IFT a surfactant have, the higher recovery of OOIP it could achieve. In general, all lignin surfactant blends which have good properties as the commercial surfactant will gives better recoveries.

Figure 10 and Figure 11 showed the photos of the sand pack model before and after water flooding followed by surfactant flooding. The red-dye-oil was injected into the sand pack as shown in Figure 10. As shown in Figure 11, the surfactant flooding gave good displacement performance in this study. The red-dye-oil in the sand pack was displaced by the injected surfactant. The surfactant containing only SDS yielded the best performance. However, the other surfactant blends also exhibit the good performance in oil displacement test, and therefore it is a good candidate for enhanced oil recovery.

Figure 12 showed the phase behavior of each component in after the surfactant flooding. The black-color-liquid, settling at the bottom of centrifuge tube is the surfactant blend. Meanwhile, the red-color-liquid, at the top of the mixture, is the red-dye-oil. Interestingly, some of the oil that coming out of the sand pack during the surfactant flooding is in the form of emulsion This could be proved by the milky-white-substance formed in the middle of surfactant blends and red-dyed-oil, as it is coming out from the sand pack during surfactant flooding process.

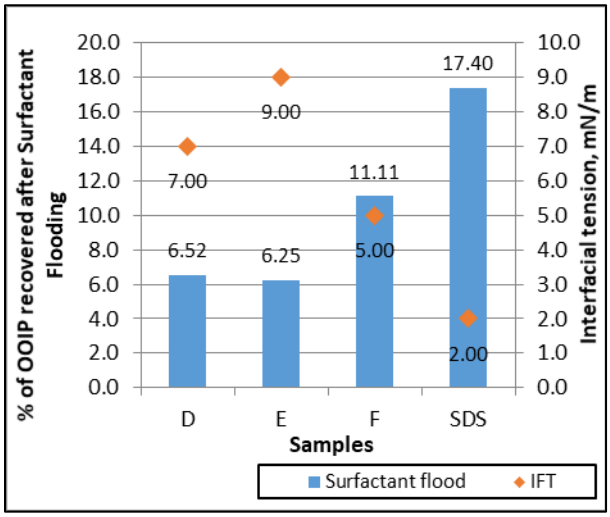

Figure 9. The surfactant flooding recovery and IFT for each samples

Figure 10. The sand pack saturated with red-dye-oil before flooding

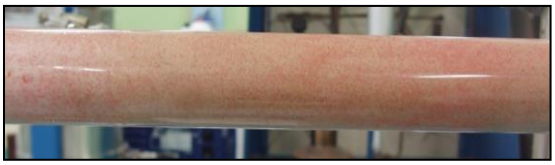

Figure 11. The sand pack after water flooding succeeded by surfactant flooding

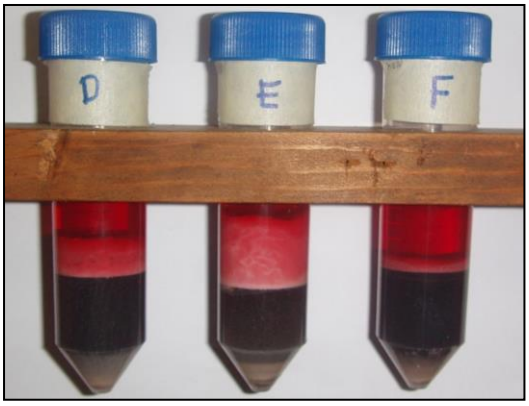

Figure 12. Phase behaviour of oil and surfactant recovered after flooding

4. Conclusions

The extraction of lignin using ultrasound-assisted technique does not alter the lignin composition and structure. This finding agrees with other researches by Nazir et al. (2013), Fahma et al. (2010), Mason et al. (2011), Yunus et al. (2010), Garcia et al. (2011). In addition, ultrasound-assisted technique enhanced the extraction amount of lignin compared with traditional pulping process (Ibrahim & Azian, 2005) and is supported by similar finding from Alriols et al. (2008), Nazir et al. (2013), Mason et al. (2011), Garcia et al. (2011). The formulation of lignin based surfactant at 2 % total active surfactant showed good stability phase behavior and IFT. The oil recovery from displacement test also showed significant results where the best formulation lignin based surfactant able to recover 11% of OOIP after waterflooding, and is comparable to commercial surfactant SDS.

References

Alriols, M. G., Tejado, A., Blanco, M. A., Mondragon, I., and Labidi, J., Agricultural palm oil tree residues as raw material for cellulose, lignin and hemicelluloses production by ethylene glycol pulping process, *Chemical Engineering Journal*, vol. 148, no. 1, pp. 106-114, 2009.

Browing, B. L., *The Chemistry of Wood*, The Institute of Paper Chemistry, Wisconsin, 1963.

Chen, S., Shen, S., Yan, X., Mi, J., Wang, G., Zhang, J., and Zhou, Y., Synthesis of surfactants from alkali lignin for enhanced oil recovery, *Journal of Dispersion Science and Technology*, vol. 37, no. 11, pp. 1574-1580, 2016.

DeBons, F. E., and Whittington, L. E., A novel lignin based surfactant system for the Salem unit, *SPE Annual Technical Conference and Exhibition*, Dallas, Texas, October 6 – 9, 1991.

Fahma, F., Iwamoto, S., Hori, N., Iwata, T., and Takemura, A., Isolation, preparation and characterization of nanofibers from oil palm empty-fruit-bunch (OPEFB), *Cellulose*, vol. 17, no. 5, pp. 977-985, 2010.

Fu, D., Mazza, G., and Tamaki, Y., Lignin extraction from straw by ionic liquids and enzymatic hydrolysis of the cellulosic residues, *Journal of Agricultural and Food Chemistry*, vol. 58, no. 5, pp. 2915-2922, 2010.

Garcia, A., Alriols, M. G., Llano-Ponte, R., and Labidi, J., Ultrasound-assisted fractionation of the lignocellulosic material, *Bioresource Technology*, vol. 102, no. 10, pp. 6326-6330, 2011.

Harsono, H., Putra, A. S., Maryana, R., Rizaluddin, A. T., H'ng, Y. Y., Nakagawa-izumi, A., and Ohi, H., Preparation of dissolving pulp from oil palm empty fruit bunch by prehydrolysis soda-anthraquinone cooking method, *Journal of Wood Science*, vol. 62, no. 1, pp. 65-73, 2016.

Ibrahim, M. M., and Azian, H., Extracting soda lignin from the black liquor of oil palm empty fruit bunch, *Jurnal Teknologi*, vol.42, pp. 11-20, 2005.

Ibrahim, M. M., Nadiah, M. N., and Azian, H., Comparison studies between soda lignin and soda-anthraquinone lignin in terms of physic-chemical properties and structural features, *Journal of Applied Sciences*, vol. 6, no. 2, pp. 292-296, 2006.

Ibrahim, M. M., Yusof, N. M., and Hashim, A., Comparison studies on soda lignin and soda anthraquinone lignin, *The Malaysian Journal of Analytical Sciences*, vol. 11, no. 1, pp. 206-212, 2007.

Kieke, D. E., *U.S. Patent No. 5,911,276*, U.S. Patent and Trademark Office, Washington D.C., 1999.

Malaysian Palm Oil Board, Overview of the Malaysian Oil Palm Industry 2015, Available: http://bepi.mpob.gov.my/images/overview/Overview_of_Industry_2015.pdf, October 1, 2016.

Mason, T. J., Chemat, F., & Vinatoru, M., The extraction of natural products using ultrasound or microwaves, *Current Organic Chemistry*, vol. 15, no. 2, pp. 237-247, 2011.

Mekhilef, S., Saidur, R., Safari, A., and Mustaffa, W. E. S. B., Biomass energy in Malaysia: current state and prospects, *Renewable and Sustainable Energy Reviews*, vol. 15, no. 7, pp. 3360-3370, 2011.

Nazir, M. S., Wahjoedi, B. A., Yussof, A. W., and Abdullah, M. A., Eco-friendly extraction and characterization of cellulose from oil palm empty fruit bunches, *BioResources*, vol. 8, no. 2, pp. 2161-2172, 2013.

Pan, X., Kadla, J. F., Ehara, K., Gilkes, N., and Saddler, J. N., Organosolv ethanol lignin from hybrid poplar as a radical scavenger: relationship between lignin structure, extraction conditions, and antioxidant activity, *Journal of agricultural and food chemistry*, vol. 54, no. 16, pp. 5806-5813, 2006.

Rodrigues, S., and Pinto, G. A., Ultrasound extraction of phenolic compounds from coconut (Cocos nucifera) shell powder, *Journal of Food Engineering*, vol. 80, no. 3, pp. 869-872, 2007.

Seng, G. M., Awang, M., Yi, L., and Ani, F. N., Production of pyrolytic oil for enhanced oil recovery, *Proceedings of the 1st International Conference on Natural Resources Engineering & Technology*, Putrajaya, Malaysia, July 24 – 25, 2006.

Sun, H., Liu, Q., Chen, S., Yan, X., Dai, L., Zhou, Y., and Zhang, J., Study on synthesis and performance of lignin polyether sulfonate surfactants for enhanced oil recovery, *Journal of Dispersion Science and Technology*, vol. 38, no. 8, pp. 1124-1128, 2017.

Sun, X. F., Sun, R., Fowler, P., and Baird, M. S., Extraction and characterization of original lignin and hemicelluloses from wheat straw, *Journal of Agricultural and Food Chemistry*, vol. 53, no. 4, pp. 860-870, 2005.

Suryo, P., and Murachman, B., Development of non petroleum base chemicals for improving oil recovery in Indonesia, *SPE Asia Pacific Oil and Gas Conference and Exhibition*, Jakarta, Indonesia, April 17 – 19, 2001.

Tan, S. S., MacFarlane, D. R., Upfal, J., Edye, L. A., Doherty, W. O., Patti, A. F., and Scott, J. L., Extraction of lignin from lignocellulose at atmospheric pressure using alkylbenzenesulfonate ionic liquid, *Green Chemistry*, vol. 11, no. 3, pp. 339-345, 2009.

U.S. Energy Information Administration (EIA), Malaysia, Available: http://www.eia.gov., October 1, 2016.

Yunus, R., Salleh, S. F., Abdullah, N., and Biak, D. R. A., Effect of ultrasonic pre-treatment on low temperature acid hydrolysis of oil palm empty fruit bunch, *Bioresource Technology*, vol. 101, no. 24, pp. 9792-9796, 2010.

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