

SHALE OIL RECOVERY FROM OIL SHALE SLUDGE USING SOLVENT EXTRACTION AND SURFACTANT WASHING

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Abstract. Shale oil recovery from oil shale sludge can reclaim secondary energy source and has drawn widespread attention in recent years. In this study, three oil recovery approaches, namely surfactant washing, solvent extraction, and the combination of the two procedures, were investigated to compare their oil removal capacities. Results showed that optimum conditions for surfactant washing were as follows: stirring rate 250 rpm, reaction temperature 80 °C, liquid-to-solid mass ratio 7:1, duration 30 min and surfactant solution concentration 6g/L. In case of solvent extraction, ethanol achieved the highest extraction yield, 89.53%, and petroleum ether (PE) performed with the shortest extraction time. Solvent extraction was more promising than surfactant washing in removing oil components. In the combined process, surfactant sodium dodecyl sulfate (SDS) washing and different solvent extractions contributed to each other's oil removal capacity. GC-MS analysis showed that the extracted oil mainly contained saturates and 1-alkenes in the range of C₁₁–C₃₄, and that the previous surfactant washing could enhance the leaching of light hydrocarbons from oil shale sludge when using methyl ethyl ketone (MEK) and dichloromethane (DCM) extractions. The extracted oils could be recovered through distillation, which needed a hermetic apparatus to prevent the loss of oil components.

Keywords: oil shale sludge, surfactant washing, solvent extraction, GC-MS analysis, oil recovery.

1. Introduction

Oil shale sludge is a by-product produced in the retorting process of oil shale, which is a kind of natural sedimentary rock containing solid organic matter called kerogen, and one of alternative energy sources in modern oil

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crisis. Formation of oil shale sludge mainly occurs in the retorting process in which a large amount of shale dust contained in the retorting gas and vapor is absorbed by fine shale oil mist to generate a sort of oleophilic substance, which then goes through a violent agitation to transform into colloidal semi-solid material, i.e. oil shale sludge [1, 2]. Oily sludge is a kind of hazardous waste whose quantities generated are enormous and need to be disposed of [3]. Due to its adverse nature, many treatment methods have been developed for oil recovery from oily sludge and sludge disposal, including solvent extraction, stabilization/solidification [4, 5], surfactant washing [6–9], freeze/thaw treatment [10], pyrolysis [11, 12] and oxidation treatment [13, 14].

Compared with other treatment methods, oil recovery from refinery oily sludge washed by a surfactant solution has been reported to be less costly, less complicated and relatively efficient. However, since the distinction between physical and chemical properties of refinery oily sludge and oil shale sludge is likely to make the availability of both for surfactant washing different, the application of the latter technique to oil shale sludge needs to be investigated in more detail to determine its suitability and efficiency.

Solvent extraction has been proven a promising treatment method for the recovery of organic compounds from oil shale. But there are few cases reporting the application of this potential, efficient and clean method to the recovery of shale oil, hereinafter referred to as the “oil”, from oil shale sludge. Abouelnasr and Zubaidy [15] achieved oil recoveries of 30% and 32% from refinery oily sludge using methyl ethyl ketone (MEK) and liquid petroleum gas condensate (LPGC), respectively. A variety of organic substances, including aliphatic hydrocarbons, aromatic hydrocarbons and heteroatom-containing compounds, can be extracted from oil shale under certain conditions [16–18]. Because of physical and chemical similarities between oil in oil shale sludge and oil generated from oil shale retorting, solvent extraction can be considered as an exploratory trial for oil recovery from oil shale sludge.

The combination of alternative oil separation and recovery methods may be more effective than any individual method alone, which has been proven by Zhang and Li [10]. With regard to this, first the surfactant washing alone and the solvent extraction alone were conducted in this study, to determine optimum process conditions and residual oil rate for surfactant washing, and the best-performing organic solvent for solvent extraction. Then the combined surfactant washing and solvent extraction treatment was carried out for comparison with the former two approaches in terms of removal oil rate, and to investigate the interaction between the two. Finally, the compositions of extracted oils from individual extractions and combined processes were analyzed by gas chromatography-mass spectrometry (GC-MS).

2. Methodology

2.1. Sample source

The oil shale sludge sample investigated in this study was obtained from a major on-duty shale oil refinery located in Huadian City, Jilin Province, China. The oil shale sludge is a black, sticky and slightly emulsified solid, which is odorous and releases a small amount of moisture and oil on the surface after a long period of storage. The characteristics of oil shale sludge were investigated through some standardized fundamental experiments, including proximate analysis, ultimate analysis, and Fischer-Schrader assay. The results are given in Table 1.

Table 1. Characteristics of oil shale sludge sample

Proximate analysis, air dried, wt%	
Moisture, wt%	8.42
Ash, wt%	43.18
Volatile, wt%	40.80
Fixed carbon, wt%	7.6
Ultimate analysis, air dried, wt%	
C, wt%	36.259
H, wt%	5.302
N, wt%	1.003
S, wt%	0.738
O, wt%	5.098
Fischer-Schrader assay, air dried, wt%	
Oil content, wt%	40.54
Solid, wt%	49.33
Moisture, wt%	9.91
Non-condensable gas, wt%	0.22

2.2. Reagents

Surfactant is a kind of organic compound that is amphiphilic, containing a hydrophobic tail and a hydrophilic tail. In the case where water is mixed with oil, the surfactants diffuse in water when the hydrophobic tails extend out of the bulk water phase, into the oil phase, and the hydrophilic tails remain in the water phase. This makes surfactant molecules absorb at the interfaces between oil and water and lower the surface tension. Thus the mobility of petroleum hydrocarbon compounds (PHCs) is enhanced. As a result, the diffusion of oil into the surfactant solution is facilitated. The process is shown in Figure 1.

Surfactants are usually sorted into two types – ionic and non-ionic, based on whether charges are present or not in polar head groups. The ionic surfactants are further classified into anionic surfactants carrying negative charges and cationic surfactants carrying positive charges. An anionic surfactant sodium dodecyl sulfate (SDS) and a non-ionic surfactant OP-10 were used in the present work.

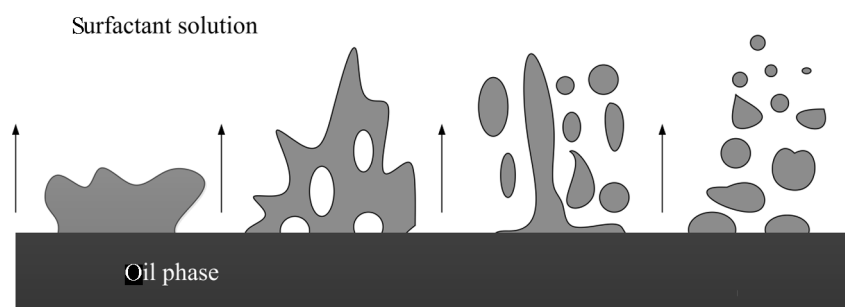


Fig. 1. Mechanism of separation of oil from oil shale sludge by surfactant washing.

For solvent extraction, methyl ethyl ketone (MEK), petroleum ether (PE), dichloromethane (DCM) and ethanol were used in this work.

2.3. Apparatus and procedure

2.3.1. Surfactant washing

A 50 g sample of oil shale sludge was placed into a 1000 ml beaker which was thereafter loaded with an eluent (surfactant solution or hot water) at a specified liquid-to-solid mass ratio. The beaker was then put into an HH-2 digital thermostatic water bath and heated from below the pre-set temperature at which the beaker was inserted into a stirrer (TA-2 programmed coagulating stirrer). After the stirring duration and stirring rate had been input in the control panel, the stirrer was started to wash the sludge inside the beaker. After sludge-washing, the stirrer was lifted, the supernate was decanted after 30 min of settling, and the residue was then weighed and transferred into a dry oven to be dried at 105 °C for 4 h. After having been completely dried, the residue was weighed again and placed into a muffle furnace to be heated at 600 °C for 1 h. Finally the mass of heated residue in the muffle furnace was weighed. Based on the procedure described above, the residual oil rate can be calculated using the following equation:

$$R = 1 - \frac{M_3}{M_1} - \frac{M_1 - M_2}{M_1} = \frac{M_2 - M_3}{M_1}, \quad (1)$$

where R is the residual oil rate, wt%; M_1 is the mass of sludge after washing; M_2 is the mass of dried sludge; and M_3 is the mass of heated residue in the muffle furnace.

2.3.2. Solvent extraction for shale oil recovery

A separate aliquot of oil shale sludge, 2000 g, together with a tray, was placed into the dry oven and dried at a temperature of 105 °C for 4 h, to provide a moisture-free sample source available for the supply of samples for further experiments.

13 g samples of dried sludge were added to 200 ml of different solvents, including methyl ethyl ketone (MEK), petroleum ether (PE), dichloromethane (DCM) and ethanol. The whole extraction process was carried out in a Soxhlet extraction apparatus placed in a fume hood to ensure that the hazardous solvent vapors were drained. Each sample was extracted for 36 h so that the organic components could be extracted to the greatest extent. Upon the completion of the extraction procedure, the raffinate was distilled using a makeshift distillation apparatus. The solvent was recovered as distillate until no solvent droplet was observed, and the remaining liquid in the still pot was considered as recovered oil whose mass was determined by subtracting the mass of the still pot from the mass of the pot with the remaining liquid. The remaining semi-solid from extraction was dried in a dry oven at 70 °C for 24 h to remove any solvent, and then the remaining solid without the solvent was weighed.

2.3.3. Combined surfactant washing and solvent extraction treatment

Four sludge samples of 13 g were subjected to surfactant OP-10 washing first, and then another four samples of the same mass were washed by surfactant SDS. All the samples were taken from the moisture-free sample source and washed by surfactant solutions of optimum concentration in optimum washing conditions. The specific procedure was the same as that for surfactant washing alone.

The former four samples having gone through OP-10 washing were extracted by solvents MEK, PE, DCM and ethanol, respectively. Then the latter four washed by SDS were also extracted by the above four solvents, respectively. The procedure for this part was the same as that for solvent extraction alone. Finally, these eight batches of remaining solids having gone through the combined treatment process were all moisture- and solvent-free.

2.3.4. Scanning electron microscopy (SEM) and GC-MS analysis

Sludge samples before and after surfactant washing and solvent extraction were characterized by the JEOL-JSM-6510LV scanning electron microscope (SEM; USA) operating at an accelerating voltage of 20 kV [19]. The compositions of oils recovered from solvent extraction alone and the combined process were determined by GC-MS analysis, which was conducted on Shimadzu GC-MS-2010-Plus mass spectrometer (Japan). The compounds were identified using the NIST05 mass spectral library [20]. All the extracted oils were diluted to the same concentration before analysis [21].

3. Results and discussion

3.1. Determination of optimum washing conditions

The sludge sample was subjected to hot-water washing first to determine optimum washing conditions. In this study, all the factors were investigated in turn using a single factor experiment [22].

Figure 2 shows that the residual oil rate reached a minimum corresponding to a stirring rate of 250 rpm. Appropriate stirring could intensify oil desorption from solid particles, and hence facilitate the separation of moisture, solid and oil phases. But over-intensified stirring may result in the formation of an oil-in-water emulsion, thus affecting the washing effect.

Figure 3 shows that the residual oil rate was minimal at the reaction temperature of 80 °C. The oil, solid and water phases could not be layered at a low temperature, but the viscosity of oil decreased with increasing temperature, thus leading to a reinforced detachment of oil from solid particles and evidently layering oil, solid and water phases.

Figure 4 shows that the residual oil rate was minimum at the liquid-to-solid mass ratio of 7:1. While insufficient addition of water could not afford the separation of oil from solid, excessive addition of it resulted in large amounts of reagents and involved extra cost.

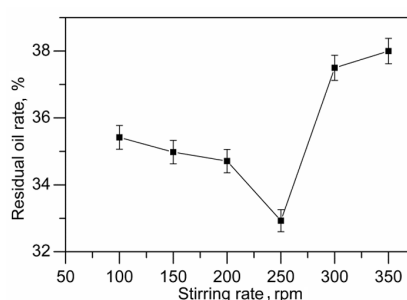


Fig. 2. Stirring rate versus residual oil rate.

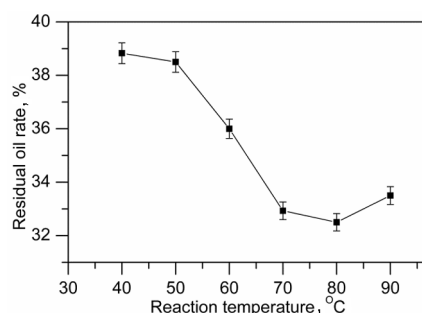


Fig. 3. Reaction temperature versus residual oil rate.

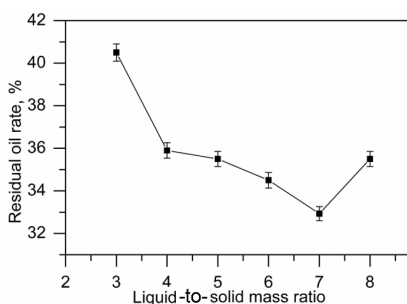


Fig. 4. Liquid-to-solid mass ratio versus residual oil rate.

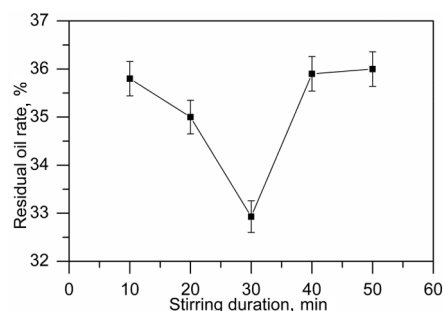


Fig. 5. Stirring duration versus residual oil rate.

Figure 5 shows that the washing effect was best at 30 minutes. The washing effect could be affected by either an insufficient process duration resulting in a non-uniform dispersion of sludge into the water phase, or a prolonged one causing an intensified emulsion of sludge.

Therefore, optimum washing conditions used in further experiments were: stirring rate 250 rpm, reaction temperature 80 °C, liquid-to-solid mass ratio 7:1 and duration 30 min.

3.2. Surfactant washing

The surfactant washing was conducted in optimum conditions with the surfactant solution concentration changed to determine its optimum. The effect of surfactant solution concentration on residual oil rate is shown in Figure 6.

From Figure 6 it can be seen that as the surfactant solution concentration increased, the residual oil rate dropped, reaching a minimum at the solution concentration of 6g/L. Thereafter no decrease but a significant increase in residual oil rate was observed as the surfactant solution concentration increased. This is because the critical micelle concentration (CMC) at which the surface tension of the surfactant solution is the lowest, was approached in terms of variation in solution concentration. A further increase of surfactant solution concentration would not decrease but increase residual oil rate, due to the formation of large amounts of micelles. For both SDS and OP-10 the residual oil rate was the lowest at the solution concentration of 6g/L.

In general, surfactant washing is not efficient enough, in view of the fact that the lowest residual oil rate achieved was 29.60%, and the highest reduction in oil content was only 26.99%. So it is suggested that a further treatment of the residue should be carried out to remove more oil.

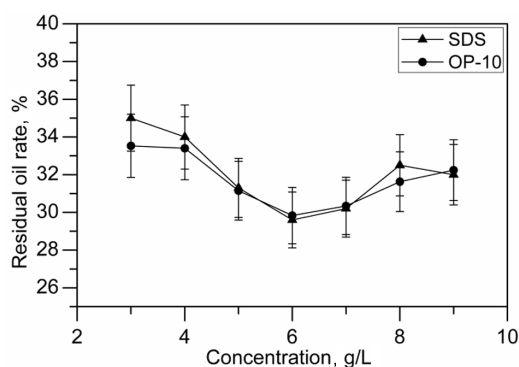


Fig. 6. Surfactant solution concentration versus residual oil rate in optimum washing conditions.

3.3. Shale oil recovery through extraction process

For comparison with surfactant washing, the extraction process using organic solvent was conducted to determine its oil recovery as well as extraction yield. Experimental measurements are given in Table 2.

Table 2. Experimental measurements for different solvents

Solvent	Material used in extraction		Material recovered		Material recovered		
	Sludge, g	Solvent, ml	Shale oil, g	Solid, g	Oil recovered, %	Solid remaining, %	Loss of sludge, %
MEK	13	200	2.83	8.63	21.77	66.38	11.85
PE	13	200	4.06	8.03	31.23	61.77	7.00
DCM	13	200	3.84	8.61	29.54	66.23	4.23
Ethanol	13	200	4.17	7.81	32.08	60.07	7.85

Oil recovery for each solvent is defined as the ratio of the mass of recovered oil to the mass of oil shale sludge measured as 13 g. This value was lowest for MEK and highest for ethanol, resulting from the fact that the higher solvent boiling point would cause a higher loss of oil components in the extraction process, which vaporize at a temperature lower or approximately equal to the solvent boiling point. Sludge loss is given by the ratio of the difference between the mass of sludge and the combined mass of recovered oil and remaining solid to the mass of sludge. Solvent MEK of the highest boiling point was associated with the highest sludge loss, 11.85%, probably contributed to by the highest loss of oil components.

The extraction yield is calculated using the following equation:

$$R_{ey} = \frac{(M_s - M_{rs}) \times (1 - R_m)}{M_s \times R_{oc}}, \quad (2)$$

where R_{ey} is extraction yield, wt%; M_s is the mass of sludge, 13 g; M_{rs} is the mass of remaining solid; R_{oc} is the oil content determined by Fischer assay; and R_m is the moisture content of original sample source and can be estimated from the following equation:

$$R_m = \frac{M_{oss} - M_{ss}}{M_{oss}}, \quad (3)$$

where M_{oss} is the mass of original sample source; and M_{ss} is the mass of sample source without moisture. In the present work, the value of R_m is 0.1.

Replacing variables in Equation (2) with the value of the variable R_{oc} in Table 1 and values of other variables in Table 2 leads to the results described in Figure 7.

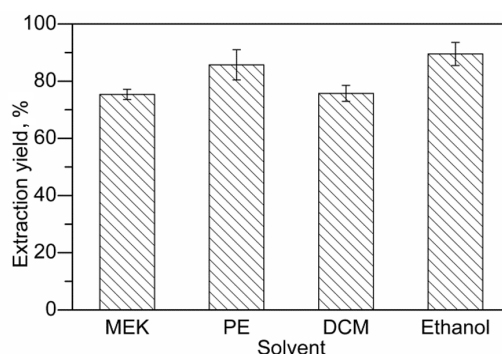


Fig. 7. Extraction yields for different solvents.

The residual oil rate for the extraction process is given by the following equation:

$$R_{ro} = R_{oc} - \frac{(M_s - M_{rs}) \times (1 - R_m)}{M_s}, \quad (4)$$

where R_{ro} (wt. %) is the residual oil rate for solvent extraction converted to the basis of original sample source.

Replacing variables in Equation (4) with values as described before leads to the results described in Figure 8. For comparison, residual oil rates for surfactants OP-10 and SDS of optimum concentrations in optimum washing conditions are also included.

Figure 7 displays the extraction yields for solvents MEK, PE, DCM and ethanol. Ethanol achieved the highest extraction yield, 89.53%, followed by PE with 85.73% and DCM with 75.73%. MEK performed worst in extracting oil components from sludge, its extraction yield being 75.38%, which is not in line with the result previously reported by Abouelnasr and Zubaidy [15]. As shown in Table 2, the mass of recovered oil is proportional to the extraction yield, but the sludge loss (wt%) is poorly related to it. As oil components vaporize in the distillation process, it needs to be carried out in a hermetic system to avoid sludge loss and promote oil recovery.

Figure 8 presents the residual oil rates converted to the basis of original sample source for different solvents, surfactants OP-10 and SDS included. From delineation of Figure 8, solvent extraction could significantly lower residual oil rates, as compared with surfactant washing. Ethanol achieved the lowest residual oil rate, only 4.61%, which is much smaller than those for SDS and OP-10. Lower residual oil rates indicated that more oils were removed during the treatments. Considering this, solvent extraction is a more promising method than surfactant washing in terms of oil removal.

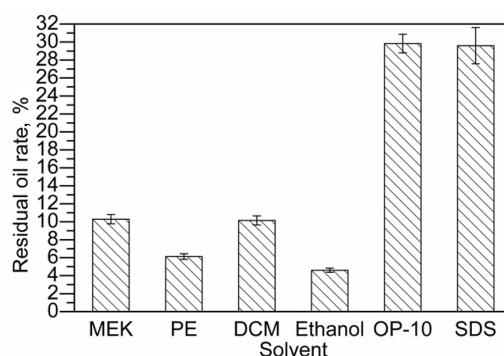


Fig. 8. Residual oil rates converted to the basis of original sample source, for different solvents plus OP-10 and SDS.

3.4. Effect of process duration on extraction yield

Batches of sludge samples of the same mass were extracted by each solvent with the extraction duration changed and other conditions maintained, to investigate the effect of duration on extraction yield. The results are given in Figure 9.

Figure 9 presents the variation in extraction yield for each solvent as the process continues. Solvent PE was associated with the shortest process time, 8 h, during which the extraction approached a thermodynamic equilibrium. The process durations for DCM and MEK to achieve approximate thermodynamic equilibriums were longer, 12 and 20 h, respectively. Ethanol had no evident turning point at which the extraction process reached a thermodynamic equilibrium. In case of PE, DCM and MEK, increase in extraction yield leveled off after the respective turning points, while for ethanol it kept increasing steadily. So, ethanol turned out to be the solvent affording the highest extraction yield. It was common for the above four solvents that the increasing rate in extraction yield decreased as the process continued.

Overall, solvent PE completed the extraction with the shortest time, while ethanol, with the longest one.

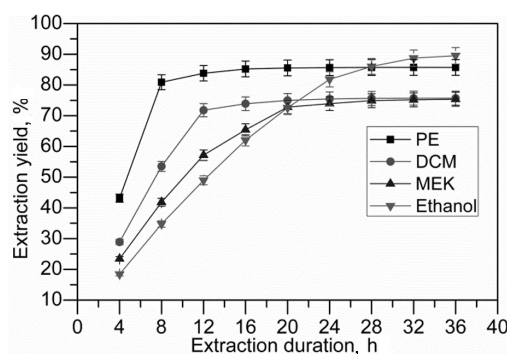


Fig. 9. Effect of process duration on extraction yield.

3.5. Combined surfactant washing and solvent extraction

Removal oil rate was used for comparisons between solvent extraction, surfactant washing and the combination of the two methods. In surfactant washing, only optimum washing conditions and solution concentration were used.

The removal oil rate for the combined treatment method is estimated by the following equation:

$$R_{ror}^{com} = \frac{(M_{bsw} - M_{frs}) \times (1 - R_m)}{M_{bsw}}, \quad (5)$$

where R_{ror}^{com} (wt%) is the removal oil rate for the combined process; M_{bsw} is the mass of sludge before surfactant washing, 13 g; and M_{frs} is the mass of final solid remaining after the combined process.

The removal oil rate for solvent extraction alone is given by the following equation:

$$R_{ror}^{sea} = R_{ey} \times R_{oc}, \quad (6)$$

where R_{ror}^{sea} (wt%) is the removal oil rate for solvent extraction alone; R_{ey} is the extraction yield described in Equation (2); and R_{oc} is the oil content determined by Fischer assay.

The removal oil rate for surfactant washing alone is calculated by the following equation:

$$R_{ror}^{sura} = R_{oc} - R, \quad (7)$$

where R_{ror}^{sura} (wt%) is the removal oil rate for surfactant washing alone; and R is the residual oil rate for surfactant washing described in Equation (1).

Replacing variables in Equations (5), (6), and (7) with relevant experimental measurements and values gives the results shown in Figures 10 and 11.

Figure 10 presents the comparison between OP-10 washing alone, solvent extraction alone and the combination of the two methods, in terms of removal oil rate. Different solvent extraction processes coupled with the OP-10 washing procedure produced different oil removal effects. The combination of OP-10 washing and DCM extraction achieved a removal oil rate of 34.18%, which was higher than that for DCM extraction alone, 30.39%, and that for OP-10 washing alone, 10.71%. Among the four combination types, OP-10 washing coupled with MEK extraction process afforded the highest removal oil rate, 38.86%. However, the removal oil rate for the combination of OP-10 washing and PE extraction was 33% and for the combination of OP-10 washing and ethanol extraction 34.61%, being lower than that for PE extraction alone, 34.41%, and for ethanol extraction alone, 35.93%, respectively. This indicates that OP-10 washing is selective when combined with different solvent extraction processes, in terms of oil removal, which makes the respective combinations not promising enough to be used for this purpose.

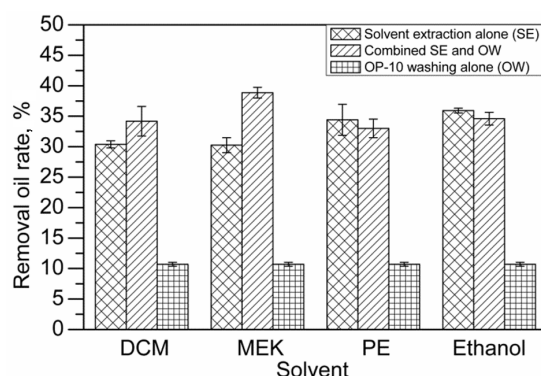


Fig. 10. Comparison between OP-10 washing, solvent extraction, and the combined process.

Figure 11 delineates the removal oil rates for SDS washing alone, different individual solvent extraction processes alone and combinations of the two treatment methods. Unlike OP-10 washing, SDS washing process combined with different solvent extractions displayed generally higher removal oil rates than those for both SDS washing and solvent extraction separately. The combined DCM extraction and SDS washing achieved a removal oil rate of 38.72%, which was higher than that for DCM extraction alone, 30.39%, and that for SDS washing alone, 10.94%, and was also the highest among these four types of combinations. The oil removal can also be estimated from the ratio of removal oil rate to the oil content determined by Fischer assay, while the value for the combined DCM extraction and SDS washing was 95.51%. In general, the combination of SDS washing and solvent extraction is more promising in terms of oil removal.

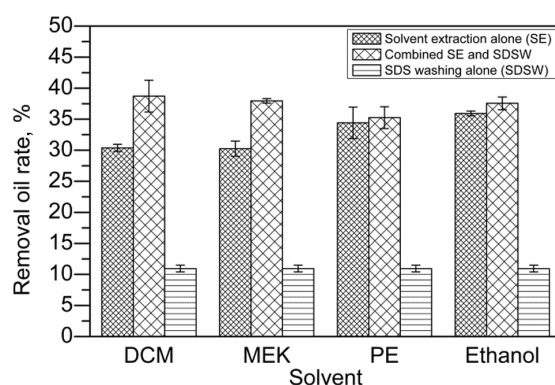


Fig. 11. Comparison between SDS washing, solvent extraction and the combined process.

3.6. SEM and GC-MS analyses

The morphological changes of sludge samples corresponding to different stages in the combined treatment are shown in Figure 12. Since the combination of SDS washing and different solvent extractions performed more satisfactorily than the combinations of OP-10 washing and these same extractions, in terms of oil removal, only the sample having gone through SDS washing and DCM extraction was used in SEM analysis. As seen in Figure 12, original sludge (a) basically resembles dry sludge (b), except that the former is characterized by a sticky large block and the latter is a bit dispersed due to moisture evaporation. Sludge washed by surfactant SDS (c) evidences further dispersed particles with irregular boundaries and variable sizes, forming a network-like structure with much more micropores. This increases the contact area between sludge and organic solvents in the extraction process following surfactant washing, thus more oils are removed in the combined process than in an individual treatment. The solid remaining upon DCM extraction (d) displays a fully scattered structure, probably as a

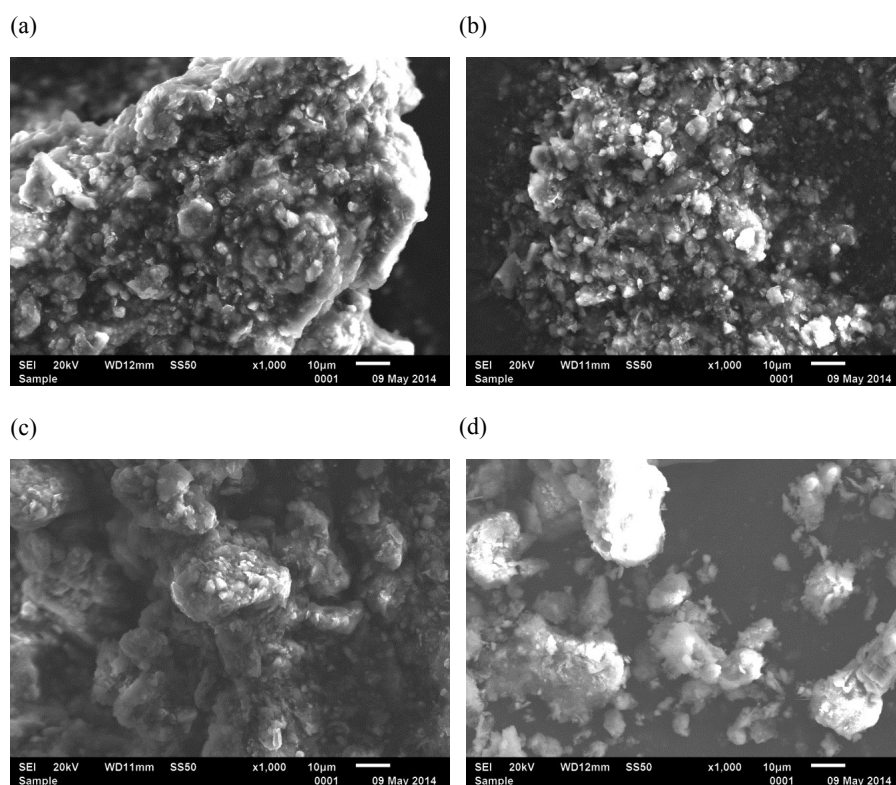


Fig. 12. SEM images (at 1000x magnification) of (a) original sludge; (b) dry sludge; (c) sludge upon SDS washing; (d) solid remaining upon DCM extraction.

result of pore formation upon detachment of organic matter from solid particles and the following solvent evaporation. The combinations of SDS washing and other solvent extractions followed the same mechanism.

Figures 13 and 14 present the GC profiles of extracts from solvent extractions alone and combined solvent extraction and surfactant washing processes. It can be seen from these figures that since the samples investigated in the present work were obtained from the same sample source, compounds corresponding to the same residence times were basically the same.

Among the twelve samples investigated, the extracted oils from extractions alone and combined processes mainly contained aliphatics, including long-chain n-alkanes and 1-alkenes, and a small amount of aromatics, alcohol, phenol and pyrrolidinone. A semi-quantitative study was made using the percentage of area of chromatographic peaks, to determine the fraction distribution of hydrocarbons in the oil. From Figure 13 it can be seen that PE extract was associated with more light hydrocarbons, unlike extracts from PE extractions upon SDS washing and OP-10 washing, respectively. In addition, tetratriacontane was absent from extracts because of surfactant washing. However, the combination of MEK extraction and surfactant washing displayed the opposite effect. More light hydrocarbons were observed in MEK extracts upon SDS washing and OP-10 washing, respectively, than in MEK extracts alone, while MEK alone performed in extracting heavy hydrocarbons better than combined processes.

From Figure 14 it is clear that after surfactants washing, both light and heavy hydrocarbons were decreased in ethanol extracts, while intermediate hydrocarbons were not significantly affected. Light hydrocarbons increased in DCM extracts following surfactants washing, but pyrrolidinone was removed through washing processes. Like other extractions, surfactants washing had no effect on intermediate hydrocarbons in DCM extracts.

For comparisons between DCM, MEK, PE and ethanol, Figures 13 and 14 show that the main peaks of MEK and DCM extracts shift to the right of GC profiles, unlike those of ethanol and PE extracts. This indicates that MEK and DCM extracted more heavy hydrocarbons than PE and ethanol in extraction processes.

In general, extracts from all the twelve samples contain long-chain aliphatics mainly in the range of C_{11} – C_{34} . Other compounds, such as aromatics, alcohol, phenol and pyrrolidinone, are present in either trace amounts or as entrained impurities. Thus they hardly affect the main compounds of extracts and are not considered as such.

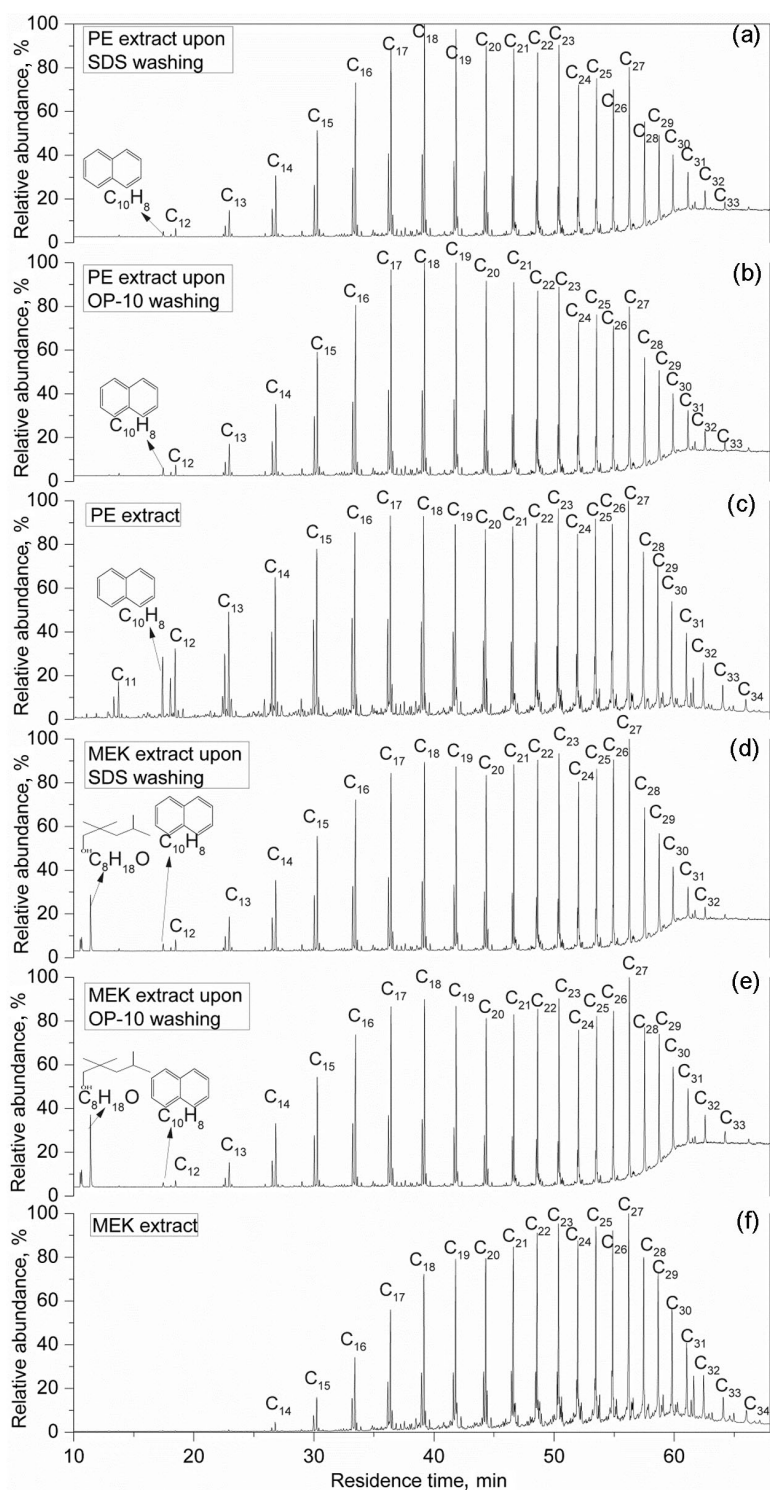


Fig. 13. Total ion chromatograms of MEK and PE extracts.

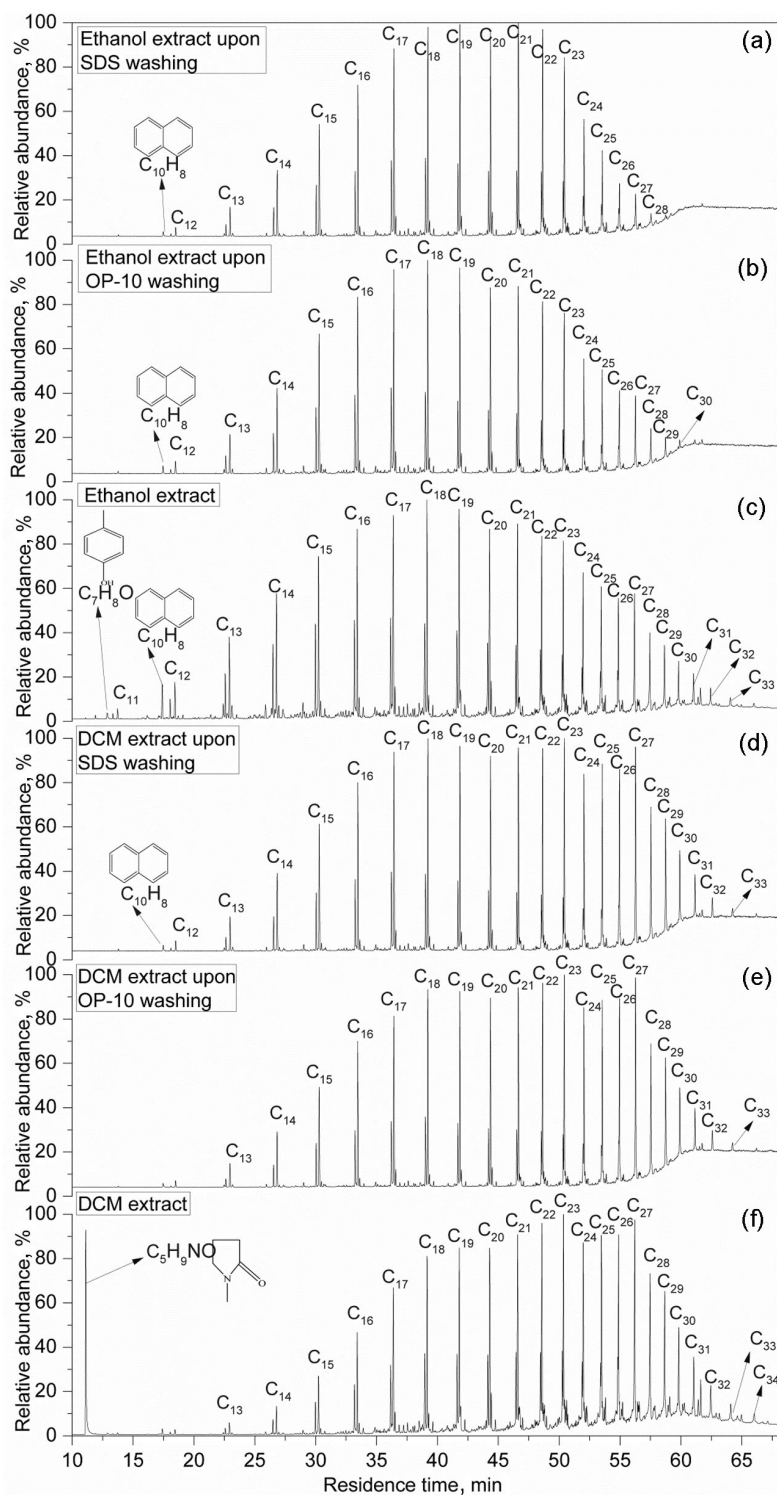


Fig. 14. Total ion chromatograms of DCM and ethanol extracts.

4. Conclusions

This study considers oil recovery from oil shale sludge. Three approaches, namely surfactant washing alone, solvent extraction alone and the combination of the two methods, were investigated to compare their oil removal capacities. A single factor experiment was used to determine optimum washing conditions, in which surfactants SDS and OP-10 removed respectively 26.99% and 26.42% of oil from oil shale sludge at the solution concentration of 6g/L. By solvent extraction more oil could be removed than by surfactant washing, while with 89.53% of oil removed from oil shale sludge ethanol was the best-performing solvent of the above four solvents. Surfactant SDS washing combined with different solvent extractions exhibited higher oil removal capacity than any relevant individual method alone, while surfactant OP-10 was selective for oil removal from oil shale sludge in combination with different solvent extractions. The mechanism behind this phenomenon was that through SDS washing, the area of contact between oil shale sludge and solvent was increased, which facilitated the extraction process. The extracted oil could be recovered through distillation which needed a hermetic system to keep from oil loss. Through GC-MS analysis, the extracted oils were detected to contain mainly long-chain n-alkanes (saturates) and 1-alkenes ranging from C₁₁ to C₃₄. After OP-10 and SDS washings, more light hydrocarbons were observed in MEK and DCM extracts than in these extracts without previous surfactant washing. This indicated that surfactant washing enhanced the leaching of light hydrocarbons from oil shale sludge using MEK and DCM extractions. Comparison showed MEK and DCM to be more suitable for extracting heavy hydrocarbons than PE and ethanol. The extracted oils were mainly straight-chain hydrocarbons with a high heating value and low viscosity. Thus the extracted oils would be more suitable to be used for industrial purposes if they underwent certain processes to break long-chain structures.

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