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# Achieving Practical Venue Recycle of Waste Oil-Based Drilling Fluids with Vacuum Distillation Technology

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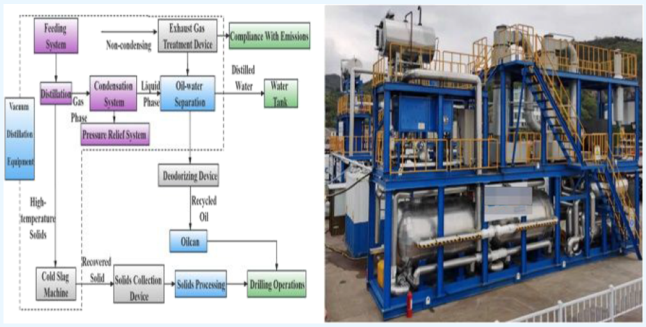
**ABSTRACT:** Drilling fluids are essential operating additives for extracting oil and shale gas. Thus, their pollution control and recycling utilization are significant to petrochemical development. Vacuum distillation technology was used in this research to handle waste oil-based drilling fluids and achieve reutilization. Briefly, recycled oil and recovered solids can be obtained from waste oil-based drilling fluids whose density is 1.24−1.37 g/cm$^3$ by vacuum distillation under the condition of an external heat transfer oil temperature of 270 ± 5 °C and a reaction pressure below 5 × 10$^3$ Pa. Meanwhile, recycled oil has excellent apparent viscosity (AV, 21 mPa·s) and plastic viscosity (PV, 14 mPa·s), which could be used as a substitute for 3# white oil. Furthermore, PF-ECOSEAL prepared by recycled solids exhibited better rheological properties (27.5 mPa·s AV, 18.5 mPa·s PV, and 9 Pa yield point) and plugging performance (32 mL $V_0$, 1.90 mL/min$^{1/2}$ $V_{sf}$) than drilling fluids prepared with the conventional plugging agent PF-LPF. Our work confirmed that vacuum distillation is a valid technology in innocuity treatment and resource utilization of drilling fluids and has great value in industrial applications.




## 1. INTRODUCTION

Oil-based drilling fluids are widely used in drilling operations of the highly difficult oil−gas pool due to their excellent advantages including high-temperature resistance, salt and calcium contamination resistance, reusability, etc.[1−3] However, the harmful microsolid phase in the drilling fluid oil system increases continually after long-term use and then leads to worse performance. Waste oil-based drilling fluids contain lots of mineral oils, phenolic compounds, and other toxic substances, which are extremely harmful to the soil and groundwater. Therefore, the environmental legislation of all countries in the world prohibits their direct emission.[4,5] It is of far-reaching significance for oil and gas extraction to study the harmless disposal technology of waste oil-based drilling fluids and reuse them under the condition of retaining active ingredients.

In the past few decades, several treatment methods for waste oil-based drilling fluids have been developed, such as thermal desorption, solvent extraction, sealed landfill, bioremediation, etc.[6,7] However, utilization of any of these methods has some limitations. Thermal desorption needs higher energy consumption to maintain temperature, and the obtained regeneration oil has poor quality.[8] Furthermore, the reagent residues of solvent extraction and chemical demulsification would affect the property of regeneration oil, and some residues in the solid phase have not been removed.[9] Sealed landfill has the risk of pollutant leakage. Bioremediation needs a long repair time and a large area, and the living conditions of microorganisms are harsh.[10] Aiming at the problems of high cost, secondary pollution risk, and low regenerated oil rates by the current treatment technology, drilling operators are seeking a more economical, effective, and environment-friendly alternative technology for recycling waste oil-based drilling fluids.

Vacuum distillation is a novel terminal disposal technology with less pollution, lower cost, and broader adaptability, which is widely applied to organic purification, protein concentration, high-salt wastewater treatment, etc.[11−14] Therefore, vacuum distillation technology has huge potential for the separation and purification of substances. Yan et al.[15] purified the purification petroleum refinery wastewater successfully with vacuum distillation technology, achieving well COD removal and low effluent salinity (65 $\mu$S cm$^{-1}$). Shao et al.[16] obtained novel solid fuel (bio-coal) by using vacuum distillation technology, which can be further replaced by conventional coal. Vacuum distillation technology can also be utilized in the petrochemical industry for the rapid solid−liquid separation of waste oil-based drilling fluids at low temperatures and for

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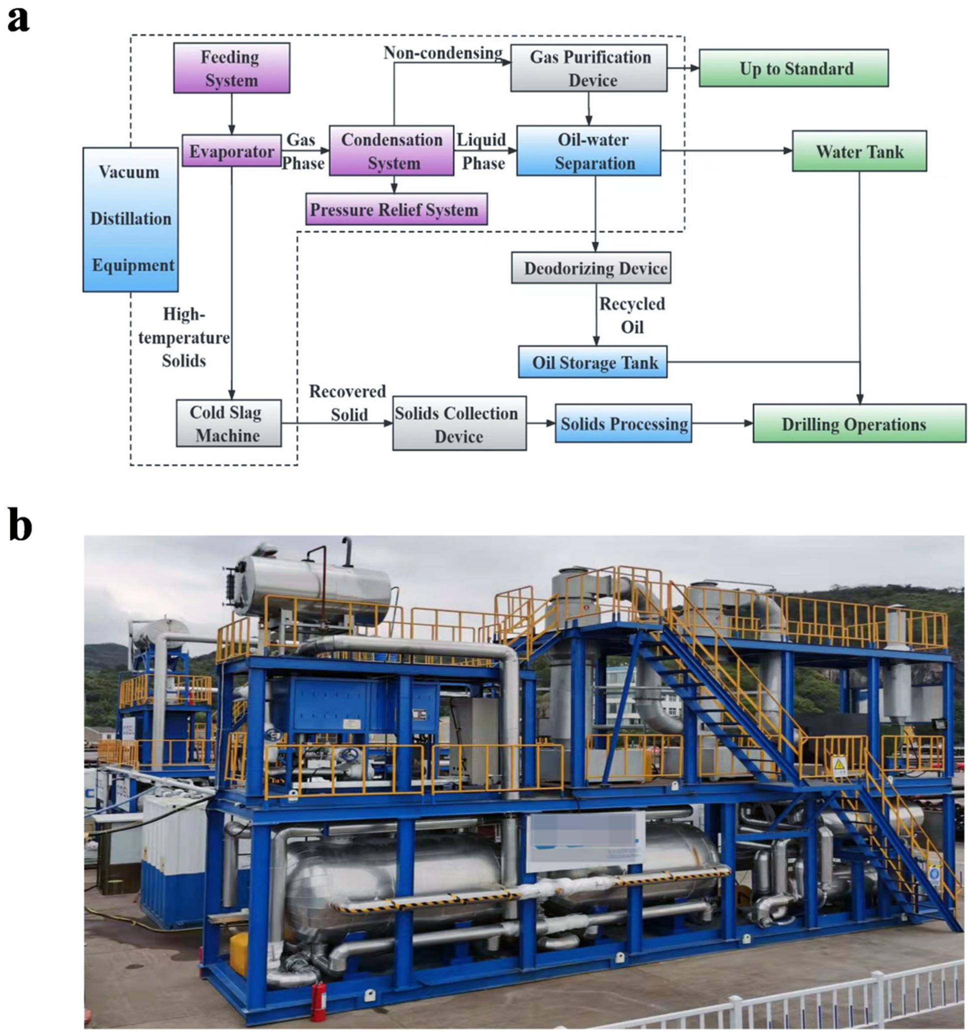


**Figure 1.** (a) Technical route and (b) production site of waste oil-based drilling fluid regeneration.

inhibiting the formation of secondary pollutants, which can improve the performance of distillate oil effectively. As such, vacuum distillation is considered as a promising treatment technology for waste oil-based drilling fluids.

Previously, it was reported that oil sludge and oil-based drilling cuttings can be treated by incineration, pyrolysis, and low-temperature distillation. Sankaran et al.[17] applied fluidized bed incineration to treat three different oil sludges conducted in the fluid-bed incinerator system showing that more than 98% combustion efficiency and 99% incineration efficiencies were achieved for all three types of oil sludge wastes. Delgado et al.[18] applied a low-temperature distillation technique to desorb oil contained in drill cuttings from oil-based drilling fluids and have proven to recover mineral oil from the drilling mud. Then, there was no report about the vacuum distillation of oil-based drilling fluids, and most of the vacuum distillation technology still stayed in the laboratory stage.

This paper considers the overall Chinese offshore oil drilling process and develops resourceful technologies that are tailored to the application of drilling operations (vacuum distillation technology). It is characterized by the solid−liquid separation of waste drilling fluids according to the requirements, ensuring that the separated liquid phase (mainly oil) can be used for the preparation of drilling fluids and recovered solids can be recycled. The performance of recycled oil was evaluated systematically in this paper, which met the demand of use. In addition, the solid phase was used in the manufacture of water-based drilling fluids and has been applied in the laboratory and field, which met the requirements of use. The whole set of processes has resourced all the waste drilling fluids and realized the recycling process of drilling fluids, which protects the environment and generates better economic benefits at the same time. The technology was then applied to 2000 $m^3$ industrial productions, tracking the regeneration of waste oil-based drilling fluids. This study provides an industrial demonstration and realistic basis for the resource treatment and high-value reuse of oil-based drilling fluids.

## 2. MATERIALS AND METHODS

**2.1. Materials and Instruments.** The density of the waste oil-based drilling fluid is 1.32 g $cm^{-3}$. The oil-based drilling fluid was prepared with 3# white oil and the recycled oil was obtained from waste oil-based drilling fluids through vacuum distillation. The samples used in this article were all obtained from China Oilfield Services Limited (COSL). NaOH, $Na_2CO_3$, NaCl, and KCl were obtained from Tianjin Fuyu Fine Chemical Co., Ltd. (Tianjin, China).

A gas chromatograph−mass spectrometer (7890B-5977B, Agilent, USA); headspace gas chromatography−mass spectrometry (HSGCMS, GC6890-5975I MS, Agilent, USA); a

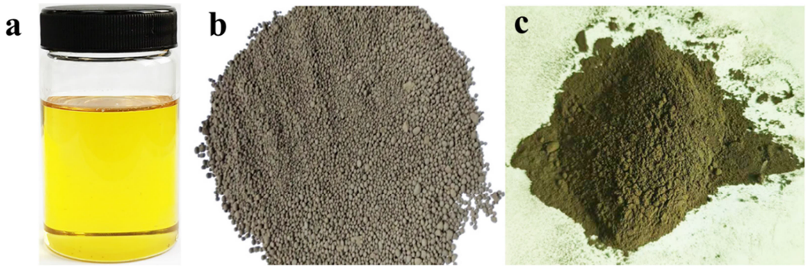

**Figure 2.** Products of vacuum distillation: (a) recycled oil, (b) recovered solid, and (c) PF-ECOSEAL.

Karl Fischer moisture tester (Mettler Toledo V20S, USA); a Fourier variable infrared spectrometer (iS5, Nicolet, USA); pyrolysis gas chromatography/mass spectrometry (PYGCMS, EGA/PY-3030 D, Thermo, USA); energy-dispersive X-ray spectrometry (EDS, Apreo C, Scientific TMUltraDry EDS, Thermo Scientific, USA); X-ray fluorescence spectrometry (XRF, S8 TIGER II, Germany); an X-ray diffractometer (D/MAX-2500); a digital densitometer (Beijing Institute of Exploration Engineering, WT-YMS, China); a full automatic flash point tester (Shandong Zhonghui Instrument Co., Ltd., China); a high-temperature and high-pressure filter press (Ofite OFI170-00-4, Germany); and vacuum distillation equipment (COSL, China) were used for the experiments.

**2.2. Regenerative Process of Waste Oil-Based Drilling Fluids.** As shown in Figure 1, the 2 $m^3$ waste oil-based drilling fluid with a density of 1.32 $g/cm^3$ was added into vacuum distillation equipment, and the vacuum pump was started and pumped to a vacuum degree of 99% (reaction pressure is $5 \times 10^3$ Pa). At the same time, the equipment was heated with a constant temperature heat transfer oil of 270 ± 5 °C, and the condensation system was cooled with cooling water at a temperature of 15 ± 2 °C. After the 12 h reaction, separation, and deodorization, the residual gas was discharged after the exhaust gas treatment system and the solid phase and liquid phase at the bottom of the tower were collected.

The liquid phase included regenerated oil (Figure 2a) and distilled water and the liquid phase was used for testing the properties and drilling fluid preparation to verify whether the recycled oil meets the use standard for drilling operations.

The solids were recovered by a cooling slag machine (Figure 2b) and further used as raw materials to manufacture plugging agents (named PF-ECOSEAL, Figure 2c). PF-ECOSEAL can be used as an additive for water-based drilling fluids. The solid phase was tested for the experimental performance of drilling fluid preparation and plugging experiments to verify the availability of the solid phase.

## 3. RESULTS AND DISCUSSION

**3.1. Characteristics of Recycled Oil.** *3.1.1. Physicochemical Properties of Recycled Oil.* The physicochemical properties of recycled oil and 3# white oil are shown in Table 1. It can be seen that the density of recycled oil is 0.81 g $cm^{-3}$, which is the same as 3# white oil. The kinematic viscosity, flash point, and pour point are 2.70 $mm^2$ $s^{-1}$, 126.2 °C, and −31.5 °C, respectively, which are lower than the values of 3# white oil. Thus, the above physicochemical properties of recycled oil and 3# white oil are similar. They both have good security and low-temperature fluidity, which can satisfy the desired requirements. This indicates that vacuum distillation has a low impact on base oil, which is a reliable isolating method. The relative errors of the properties of recycled oil and white oil are calculated, and the relative errors of density, flash points, and pour points are all less than 5%. Compared with kinematic viscosity data, it is known that the kinematic viscosity of recycled oil is small and the fluidity is good, and the kinematic viscosity of recycled oil is reduced by 10.5% compared with white oil. Therefore, from the analysis of properties, it is known that there is little difference between recycled oil and white oil, and the fluidity is due to white oil.

**Table 1. Comparison in Performance of Recycled Oil and 3# White Oil**

| physicochemical property | density ($g/cm^3$) | kinematic viscosity ($mm^2/s$) | flash point (°C) | pour point (°C) |
|---|---|---|---|---|
| recycled oil | 0.81 | 2.70 | 126.2 | −31.5 |
| 3# white oil | 0.81 | 3.02 | 131.2 | −32.6 |

*3.1.2. Analysis of Recycled Oil Components.* Gas chromatography−mass spectrometry (GCMS) was used for the composition analysis of 3# white oil and recycled oil, and the experimental results are shown in Figure 3. The composition of 3# white oil is a C12−C25 long-chain alkane, while recycled oil is a C10−C25 long-chain alkane, both of which are mainly cycloalkanes and isoparaffin.[19−21]

A detailed analysis of specific components of recycled oil and 3# white oil is shown in Figure 4 and Table S1, indicating that recycled oil had minor changes after vacuum distillation. The component of 3# white oil is mainly districted in C12−C17, while that of recycled oil is mainly districted in C11−C19, both of which are primarily cycloalkanes and isoparaffin.[22−24] Compared to 3# white oil, carbon chains of recycled oil have a broader distribution, with a small number of components detected in C11 and the content of C17−C20 is higher, and aromatic hydrocarbons are not detected in either. In addition, the content of high molecular weight hydrocarbons (>C25) in recycled oil has slightly declined. This is because macromolecular hydrocarbons will be broken down into small molecular hydrocarbons in the heating process.[25−27] Moreover, the two components with the highest content in 3# white oil and recycled oil are C14 and C15, which have similarities in major constituents. Additionally, 3# white oil was not large-scale cracked as a base oil during the vacuum distillation process, so the setting temperature, time, and other parameters of hypobaric treatment equipment are reasonable. Combined with the component analysis and the above comparative analysis of the properties of recycled oil and white oil, it can be seen that there is little difference in the components and properties between recycled oil and white oil, and the fluidity of recycled oil is also better than white oil. In order to further explore whether recycled oil can be used as a substitute for white oil, we further conduct drilling fluid preparation experiments to verify its reusability.


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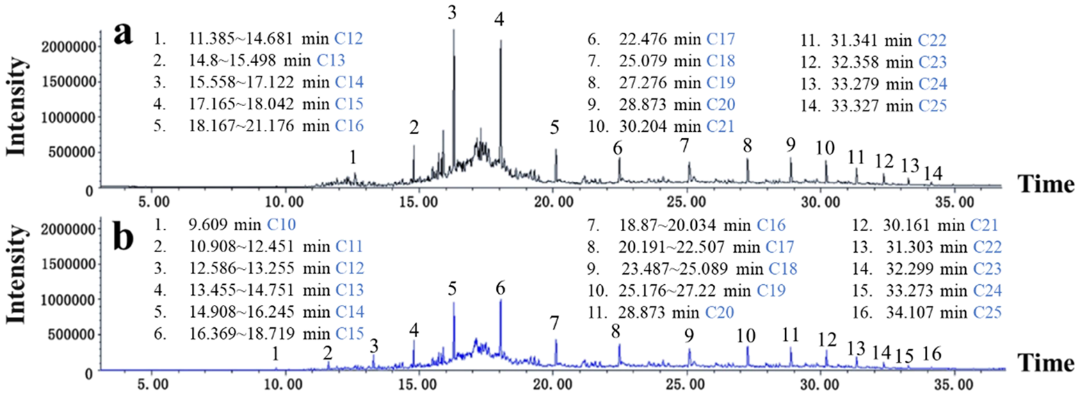


**Figure 3.** GCMS comparative analysis of (a) 3# white oil and (b) recycled oil.

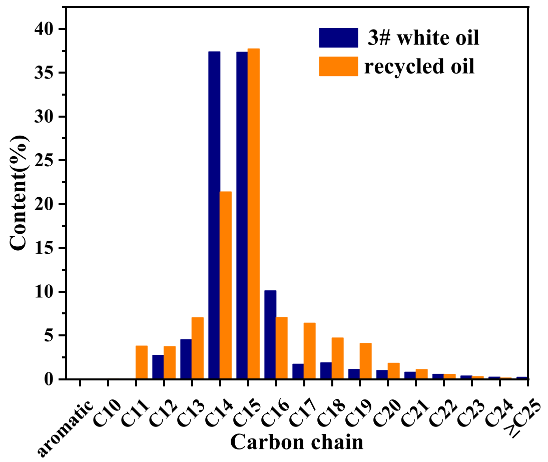


**Figure 4.** Carbon chain distribution of 3# white oil and recycled oil.

*3.1.3. Performance of Drilling Fluids Prepared by Recycled Oil.* The performance of the prepared drilling fluids by using recycled oil as the base oil was evaluated. According to the formula in Table S2, the drilling fluid was prepared using recycled oil and 3# white oil, respectively, and the performance comparison is shown in Table 2. The apparent viscosity (AV), plastic viscosity (PV), and yield point (YP) of drilling fluids prepared by recycled oil are similar to those prepared by 3# white oil, which can meet the desired requirements. However, it should be noted that the demulsification voltage of drilling fluids prepared by recycled oil is 731 V, which is lower than the 766 V of white oil drilling fluids, indicating that emulsion stability decreases slightly.[28,29] This may be due to some materials that are conducive to improving the emulsification of the drilling fluid are decomposed at high temperatures during the vacuum distillation process.[30,31] These materials mainly include the primary emulsifier PF-MOEMUL and co-emulsifier PF-MOCOAT, which both contain amide compounds. The decomposition of these materials at high temperatures could cause the amide-based compounds to follow the gas phase into the back end. However, the amide compounds can improve the emulsifying property of the drilling fluid.

Infrared spectra were further used to compare and analyze the components of recycled oil and 3# white oil. As can be seen from Figure 5, compared with 3# white oil, the infrared characteristic absorption peak of recycled oil is mainly different from that of 3422.12, 1653.40, and 1010.27 $cm^{-1}$. Generally, it is the O−H or N−H stretching vibration zone at 3750−3000 $cm^{-1}$, and no moisture is detected in the two samples, so it is not likely that the characteristic absorption peak at 3422 $cm^{-1}$ is of (−OH). Generally, the compounds containing $-NH_2$ groups have absorption peaks near the frequencies of 3500−3100 and 1650 $cm^{-1}$, while the infrared characteristic peaks of the amide group (−CONH−) generally appear at 3100, 1680, 1500, and 1200 $cm^{-1}$. Analysis of compounds indicated that returned oil might contain amide groups (due to a lot of amide compounds being used in the drilling fluid material). Therefore, we predicted that some drilling fluid material might enter into the hot desorption oil with the gas phase in the process of thermal desorption. After centrifugation, a small amount of amide groups were still present in the recycled oil. We calculate the relative errors of drilling fluid performance indexes prepared by recycled oil and white oil. Based on white

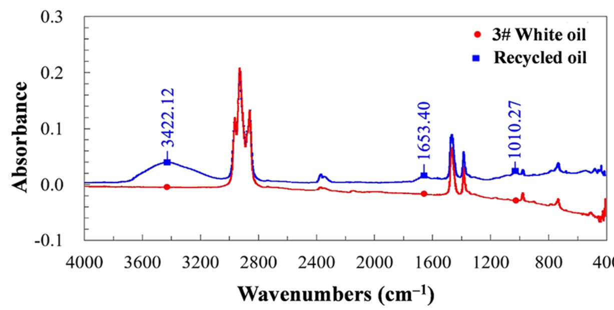


**Figure 5.** Fourier transform infrared (FTIR) spectrum analysis of recycled oil and 3# white oil.

**Table 2. Performance Comparison of Drilling Fluids Prepared by Recycled Oil and 3# White Oil**[a]

| sample | AV (mPa·s) | PV (mPa·s) | YP (Pa) | Φ600 | Φ300 | Φ200 | Φ100 | Φ6 | Φ3 | demulsification voltage (V) | 120 °C HTHP (mL) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| recycled oil | 21 | 14 | 6.7 | 42 | 28 | 22 | 15 | 5 | 4 | 731 | 6.4 |
| 3# white oil | 20 | 13.5 | 6.2 | 40 | 26.5 | 21 | 14.5 | 4.5 | 4 | 766 | 4 |

[a]Formula: AV = Φ600/2; PV = Φ600−Φ300; YP = 0.48 × (Φ300 − PV); where AV is apparent viscosity in millipascal second (mPa·s); PV is plastic viscosity in millipascal second (mPa·s); and YP is the yield point in pascal (Pa).


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oil, the relative errors of AV, PV, and demulsification voltage of recycled oil are less than 5% and YP is less than 10%, indicating that there is little difference in performance between them. In addition, the 120 °C high temperature and high pressure (HTHP) water loss property of the recycled oil drilling fluids is better than that of the 3# white oil drilling fluids, which indicates that the highly resistant material conducive to improving filtration performance enters the recycled oil with the gas phase in the process of vacuum distillation.[32] To sum up, the recycled oil recovered from the waste oil-based drilling fluid can replace the standard 3# white oil in performance, thus realizing the rational utilization of waste resources.

**3.2. Characteristic of Recovered Solids.** *3.2.1. Morphology and Element Analysis of Recycled Solids.* FE-SEM was used to observe the surface morphology and microstructure of the materials. As shown in Figure 6a, the sample was directly

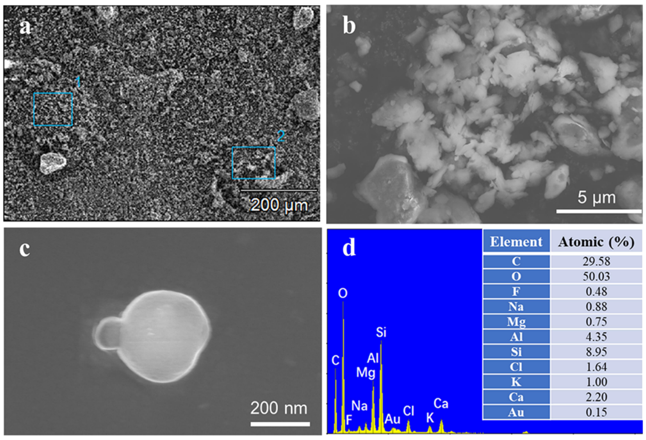


**Figure 6.** (a−c) SEM images and (d) corresponding EDS image of recovered solids.

applied to the conductive adhesive and the presentation was transparent. In addition, the recovered solids appeared irregularly diamond-shaped with relatively aggregated. For the convenience of observation, the material was dissolved in anhydrous ethanol for ultrasonic dispersion (Figure 6b,c), indicating that the material is spherical after dispersion, with a smooth surface and no hole structure. Moreover, the element composition of recovered solids was detected by SEM-EDS as shown in Figure 6d. The results exhibited that the solids mainly contain C (29.58%), O (50.03%), Si (8.95%), and Al (4.35%) elements, indicating that the materials were mainly carbon-based and silicon-based components.[33,34]

FTIR spectroscopy is a common method for characterizing and identifying chemical species, which can be used to study the structure and chemical bonds of molecules. As shown in Figure 7, two FTIR spectra had higher match degrees, indicating that recovered solids were mainly clay materials.[35] Specifically, the band at around 3442 $cm^{-1}$ was due to the adsorbed water on the surface of the solid. The weak band at 2924 and 2853 $cm^{-1}$ corresponded to the C−H stretching vibrations of some organic compounds. Si−O symmetric and asymmetric bending vibrations occurred at about 694 and 1031 $cm^{-1}$, respectively. Moreover, the broad absorption band around 469 $cm^{-1}$ was due to Si−O−Si bending vibration. The small band observed at 532 $cm^{-1}$ was assignable to the presence of Al−O−Si in kaolinite.

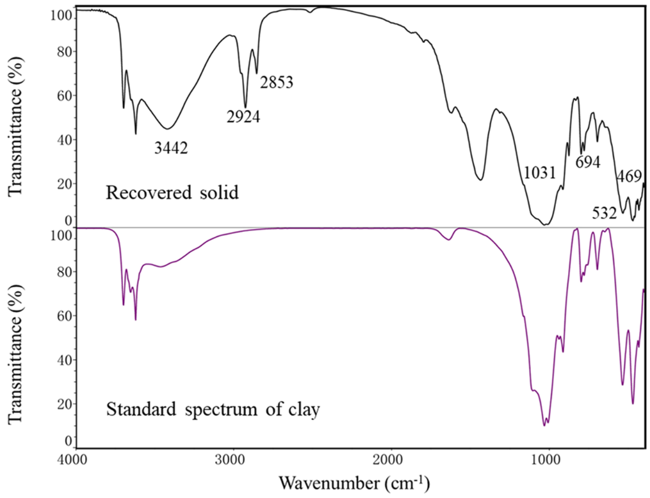


**Figure 7.** FTIR spectra analysis of the recovered solid.

XRF is a multielemental, sensitive, and nondestructive method that can quickly and accurately analyze most elements in the material. Through the analysis of XRF, it could be observed that the solid mainly contains Si, Al, Cl, C, and other elements. Table 3 shows the characterization components of several elements in the solid, among which the content of $SiO_2$ (40.3%), $Al_2O_3$ (13.3%), and CaO (12.4%) was high. This result further proved that the material was mainly composed of $SiO_2$, $CaCO_3$, and aluminosilicate, which was conducive to reducing the cost and protecting the environment.

**Table 3. Concentration Ranges (wt %) of Recovered Solids**

| component | content (mass%) | intensity (kcps) |
|---|---|---|
| $SiO_2$ | 40.3 | 40.0 |
| $Al_2O_3$ | 13.3 | 18.8 |
| CaO | 12.4 | 26.9 |
| Cl | 6.2 | 29.6 |
| $SO_3$ | 6.0 | 8.5 |
| $Fe_2O_3$ | 4.4 | 10.3 |
| MgO | 2.1 | 0.6 |

The crystal structures of both dry and wet samples were further detected by X-ray diffraction (XRD) as shown in Figure 8. There are two distinct peaks at 26.6° and 42.5° appeared in both samples, which were attributed to the (101) and (200) plane of $SiO_2$ (PDF#46-1045). The peaks at 25.9°, 29.4°, and 31.7° are corresponded to the (200), (104), and (200) planes

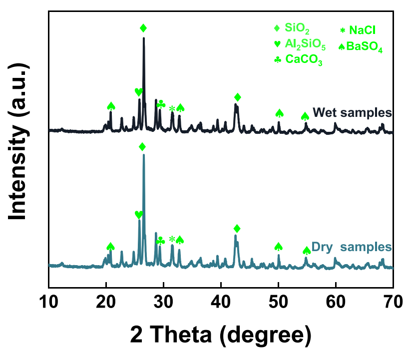


**Figure 8.** XRD characterization of wet and dry solid materials.


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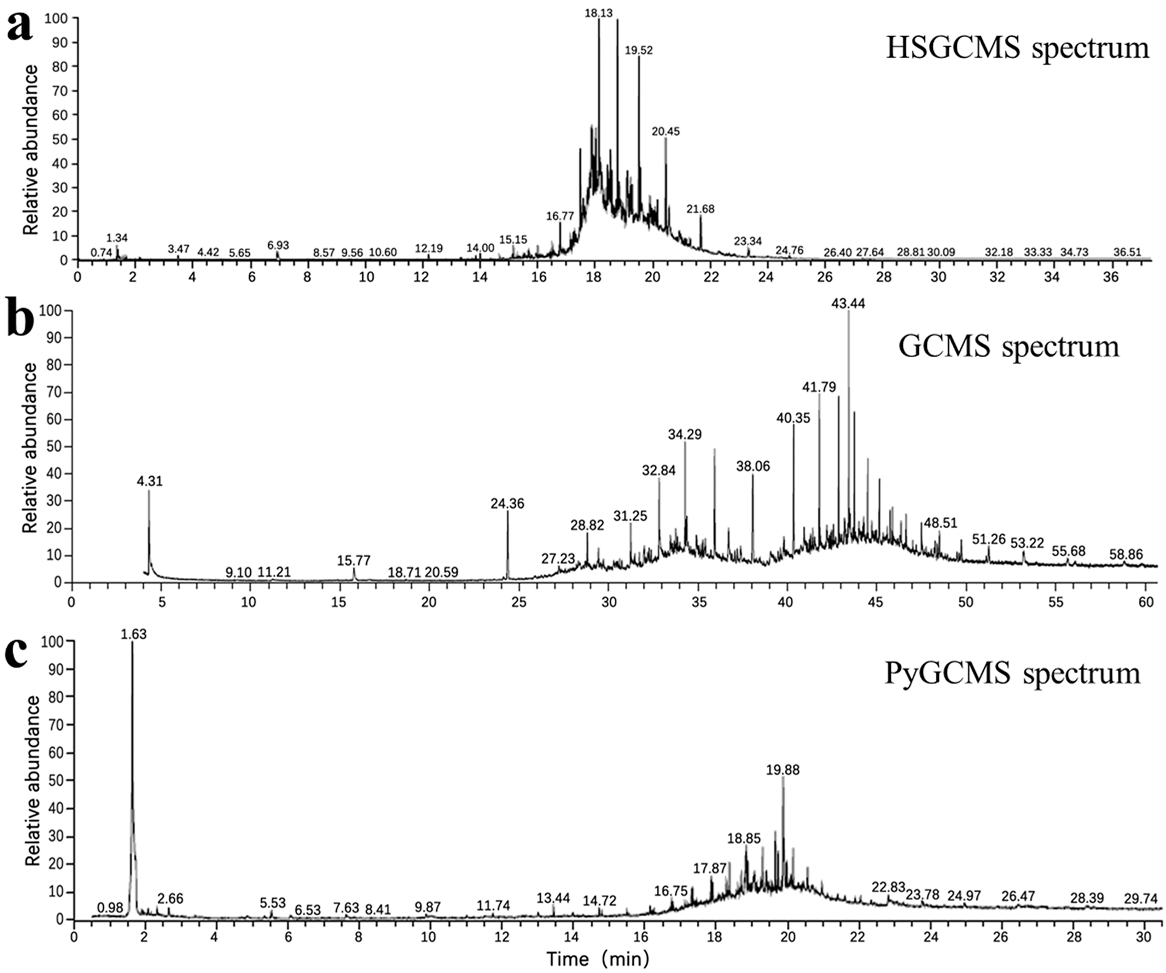


**Figure 9.** (a) HSGCMS analysis of recovered solids; (b) GCMS of recovered solids; and (c) PYGCMS analysis of recovered solids.

of $Al_2SiO_5$ (PDF#99-0068), $CaCO_3$ (PDF#05-0586), and NaCl (PDF#99-0059), respectively. In addition, $BaSO_4$ (PDF#99-0016) is observed at the peak at 20.5° (011), 32.1° (202), 51.0° (004), and 54.8° (421), respectively. According to XRD analysis, the samples mainly contain silica, sodium chloride, calcium carbonate, aluminum silicate, and other substances.

*3.2.2. Composition Analysis of Recovered Solids.* The composition and properties of recovered solids were detected by HSGCMS, GCMS, and PYGCMS. The results are shown in Figure 9 and Table S5. According to the PYGCMS spectrum analysis, as shown in Figure 7c, the dried samples may contain 7-isoprop-1-menaphthalene, 3,7,11-trimethyldodecanol, tetradecanoic acid, pentadecane, 1-methylphene, methyl dehydroabietic acid, 2,7-dimethylphene, 2,3,5-trimethylphene, cetamide ethanol, 4,4′-diisopropyl phenylbiphenyl, 1,2,3,4-tetrahydro-6-(1 ethylbenzene)-naphthalene, naphthalene, *n*-oleylpyrrolidone, 1-methyl-4-*p*-methylene naphthalene, 8-isopropyl-1,3-dimethyl anthracene, hexadecane, hexadecanic acid, and other substances. There are 5-methyl-4-hendecene, tridecane, 2-hexyldecanol, tetradecane, 3,7,11-trimethyldodecanol, 4-ethyltetradecane, 3-methylpentadecane, 3-methylhexadecane, 4-methylhexadecane, heptadecane, 2-methylheptadecane, octadecane, 4-methylheptadecane, 2-methyloctadecane, nonadecane, heneicosane, 2-methyltetracosane, heptacosane, 2,6,10,14-tetramethylhexadecane, *tert*-hexadecanethiol, etc.

The remains include normal and isomeric alkanes, polycyclic aromatic hydrocarbons, alcohols, lipids, other oxygen-containing compounds, and a little moisture. Normal and isomeric alkanes have excellent lubrication in water-based drilling fluids.[36,37] Polycyclic aromatic hydrocarbons are the predominant composition of asphalt colloid, which can make water-based drilling fluids have a significant plugging effect.[38] These substances are the basis of the recycling and productization of recovered solids. Based on the composition and properties, the recovered solids are prepared into particles by mechanical grinding and used as the primary raw material of the water-based drilling fluid plugging agent (PF-ECOSEAL).

**3.3. Performance of Drilling Fluids Prepared by PF-ECOSEAL.** Water-based drilling fluids are prepared according to the formula shown in Table S3. The one without the addition of the plugging agent is called PF-0, the drilling fluid with the addition of a conventional plugging agent is called PF-LPF, and the addition of recovered solids is called PF-ECOSEAL. Rheology and plugging properties of the three drilling fluids need to be tested, thus assessing the performance of PF-ECOSEAL.

Rheological properties of drilling fluids directly affect wellbore purification, downhole safety, and mechanical drilling speed.[39,40] Therefore, the rheological property of drilling fluids is very important. According to the rheological experimental results (Figure 10a and Table S6), the changes of adding PF-ECOSEAL compared to the conventional blocking agent PF-


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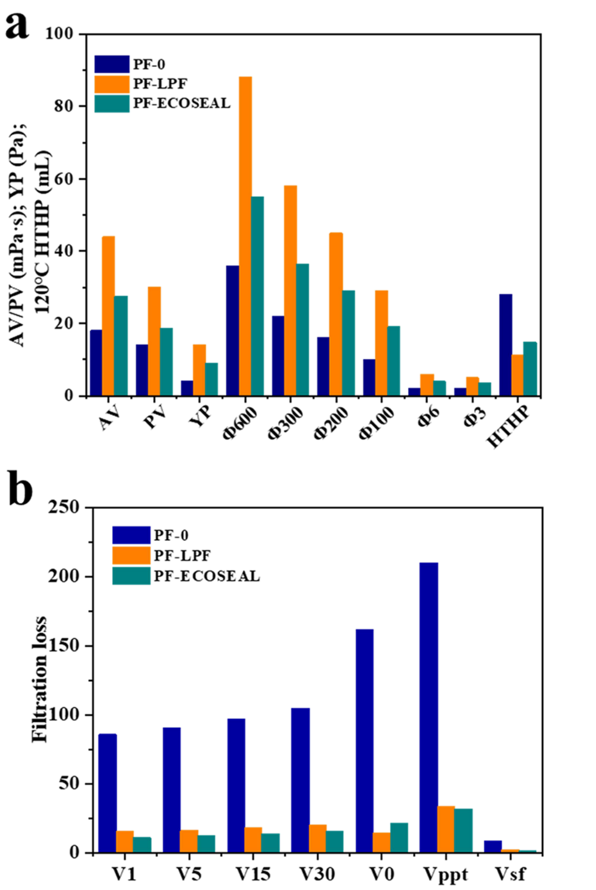


Figure 10. Comparison of (a) rheological properties and (b) plugging performance.

LPF are shown as follows: AV decreases by 22.7%, from 33.75 to 27.5 mPa·s; PV decreases by 45.9%, from 27 to 18.5 mPa·s; and YP increases by 33.3%, from 6.75 to 9 Pa. The small AV and PV and large YP are not only beneficial to control the rheological property but ensure sufficient suspended sand carrying capacity.[41−43] The results showed that PF-ECOSEAL has better rheological properties than drilling fluids prepared with the conventional plugging agent PF-LPF, which can satisfy the desired drilling fluid requirements.

The plugging function of drilling fluids has a significant meaning on the stability of the shaft wall. The plugging function can be improved on the whole scale by adding some compound plugging agents when using water-based drilling fluids, which is conducive to ensuring the stability of the shaft wall.[44] The HTHP filtration loss of PF-ECOSEAL with recovered solids as a plugging agent is significantly lower than without a plugging agent (PF-0), which indicates that the addition of recovered solids can improve the HTHP performance of drilling fluids and play a better role in reservoir protection (Figure 10b). Detailed plugging test data are listed in Table S4. Compared with the conventional plugging agent PF-LPF, PF-ECOSEAL shows a better effect on fluid loss. With the addition of PF-ECOSEAL and PF-LPF drilling fluids, the leakage plugging of PPT filtration is significantly reduced. Moreover, the thickness of the mud cake can be compared intuitively from Figure S1, in which the filter cake formed by plugging fluids containing PF-ECOSEAL was more compact. The result shows that PF-ECOSEAL and PF-LPF have effectively improved the plugging performance of the drilling fluid system, and PF-ECOSEAL has a better effect on improving the plugging property. In summary, PF-ECOSEAL has excellent performance and is a suitable water-based drilling fluid material.

### 3.4. Results of Industrial Application and the Benefits Generated.

At present, the company has established industrial application facilities. In 2021, 2000 cubic meter of drilling fluid was treated and 1200 cubic meter of base oil was recovered, with an economic value of about 1.12 million dollars. At the same time, the storage cost of waste drilling fluids was saved by 0.54 million dollars, and the direct treatment cost was 0.29 million dollars, which has excellent economic value. The plugging agent made of recycled solids has been applied in drilling in the Bohai Sea. At present, two wells have been used, which will be gradually popularized and used in the later period and will still produce good economic value.

## 4. CONCLUSIONS

In this research, vacuum distillation was used to dispose of waste-based drilling fluids at the condition of $5 \times 10^3$ Pa and an external heat transfer oil temperature of 270 ± 5 °C. The AV and PV of the recycled oil was 21 and 14 mPa·s, respectively. Demulsification voltage could reach 731 V, which fully met the required standards. In addition, the recovered solids were used as raw materials to prepare the plugging agent PF-ECOSEAL, which was a necessary additive of water-based drilling fluids. It showed a smaller AV (22.7% decrease), smaller PV (45.9% decrease), and larger YP (33.3% increase) than the conventional blocking agent PF-LPF, corresponding to better rheological properties. Furthermore, the leakage plugging experiment indicated that the $V_{ppt}$ and $V_{sf}$ of PF-ECOSEAL were 32 mL and 1.90 mL $min^{-1/2}$, respectively. They were both lower than the drilling fluid system including PF-LPF, demonstrating that PF-ECOSEAL has a better plugging performance. This article proved vacuum distillation is an effective technology for transforming waste-based drilling fluids into recycled oil and recovered solids, which provides an engineering example for its practical application.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.3c00967.

Carbon chain distribution of 3# white oil and recycled oil (Table S4); composition of recycled solids (Table S5); experimental data of rheological properties (Table S6); experimental data of the leakage plugging (Table S7); and comparison of mud cake morphology with different plugging agents (Figure S1) (PDF)

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### Author Contributions

S.M. carried out the conceptualization, methodology, formal analysis, investigation, and writing of the original draft, review, and editing; G.Z. contributed in the methodology, supervision, and resources; C.S. investigation and resources; Q.D. did the investigation and writing—review and editing; and T.J. carried out the supervision.

### Notes

The authors declare no competing financial interest.

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