Micro-dissolved fabrication of robust Superhydrophilic and Underwater Superoleophobic membranes based on cotton fabrics for oil/water separation

Jing Song
Southwest University
Qiuyu Yu
Southwest University
Xinyue Liang
Southwest University
Qin Rao
Southwest University
Peng Wang
Southwest University
Ming Lu
Southwest University
Hang Xiao (xhswu2018@swu.edu.cn)
Southwest University

Research Article

Keywords: Cotton fabric, Micro-dissolution, Oily wastewater treatment, Superhydrophilic, Underwater superoleophobic

Posted Date: May 3rd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1509553/v1

Abstract

The superhydrophilic and underwater superoleophobic membranes based on textile possessed excellent separation efficiency and anti-oil fouling property, but the poor stability caused by nanoparticles (NPs) shedding had severely limited the practical application in oily wastewater treatment. In this paper, a feasible method to prepare the robust membranes based on cotton fabric (CF) decorated with TiO 2 NPs and citric acid (CA) using micro-dissolution method was reported. The CF were slightly dissolved in a NaOH/urea solution at low temperature, allowing the incorporation of the TiO 2 NPs into the superficial layers of the fabrics. Then, the vacuum filtration process facilitated the TiO 2 NPs uniformly deposition on the CF surface. In the subsequent coagulation process, the TiO 2 NPs were firmly anchored on the fabric surface. Then, the esterification reaction between CA and cotton was carried out to impart the fabric with superior hydrophilic properties. The prepared membranes were characterized by Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), X-ray diffraction (XRD) and thermogravimetric analysis (TG). Additionally, the separation efficiency and stability of membranes were systematically evaluated. The results of SEM indicated that the TiO 2 NPs were uniformly anchored on the membrane surface. The prepared membranes could not only separate traditional oil/water mixture but also treat complicated oil-in-water (O/W) emulsion with excellent separation efficiency. What's more, the membranes could withstand various harsh condition and repeated use. Therefore, the prepared TiO 2 /CA decorated membranes have the potential to be used in the practical oily wastewater treatment.

1. Introduction

In recent years, membrane separation technology for the wastewater treatment had aroused the widespread interest in the academia and industry (Xue et al. 2011). Various available materials, such as metal mesh (Chen et al. 2020), filter paper (Wang et al. 2010), fabric (Sun et al. 2020), were applied to design mechanically flexible membranes with energy saving, simple operation, and environmentally friendly properties (Zhang et al. 2020). Current membranes with superhydrophilicity and superoleophilicity were recognized as the promising materials in oily water treatment, because of their water-removing and oil-removing properties, respectively. As for super-oleophilic membranes, bottlenecks still remained including oil fouling and low permeation flux in the practical application (Yuan et al. 2020). In contrast, superhydrophilic membranes could overcome the problems above due to its special wettability features. In many cases, the superhydrophilic surface made them in-air hydrophilic and underwater oleophobic (Wang et al. 2020), which was determined by the micro/nanostructure roughness structure and hydrophilic substances. The synergistic effect of the hierarchical structure and hydrophilic materials featured the membranes with high flux, superior separation efficiency and gravity-driven properties. Although these membranes possessed satisfactory performance, most of them could not be used in harsh conditions, which would limit the practical application of membranes (Gao et al. 2014). Therefore, the robust and stable superhydrophilic and underwater superoleophobic membranes for the separation of oily wastewater were highly desired.

Inspired by the micro/nanostructure of the fish scale and lotus leaf surface (Ge et al. 2018), various NPs were applied to construct a hierarchically structured layer on the surface of membranes by using spraying, dip coating, or in situ depositing method (Tian et al. 2014). However, the particles became unstable when exposed to high temperature and corrosive conditions due to the lack of strong bond between particles and membrane surface. Given the importance of hierarchical structure, numerous efforts had been made to improve adhesion of particle on membrane surface. Among these outstanding researches, the application of binder was one of most effective ways to enhance the anchoring stability. Dopamine, which could self-polymerize and adhere on various substrates surface, had been used to directly graft TiO_2 NPs on the PVDF membrane surface (Shi et al. 2016). To further improve adhesion between inorganic NPs and substrate, two commercial silane coupling agents (TTOP-12, KH550) were applied during the pretreatment process. The prepared membrane exhibited excellent stability even under harsh conditions, such as mechanical abrasion, high temperature, corrosion and UV radiation (Gao et al. 2018). Lin and coworkers prepared a robust waterborne super-hydrophobic coating by using inorganic binder (aluminum orthophosphate) to enhance the interfacial binding between the coating and the substrate (Lin et al. 2020). The coating exhibited excellent abrasion resistance due to the formation of phosphate networks. In addition, some researchers also reported facile methods to obtain membranes with excellent mechanical stability by using various high molecular materials as binders. However, the presence of the binder may have negative effect on separation performance of membranes due to the clogging of hole in the membranes. What's more, the using of binder will increase the cost of preparation process and may cause damages to the environment (Liu et al. 2012).

Thus, it is necessary to investigate a feasible way to prepare membranes under the condition of maintaining their separation properties and also reducing the harm to the environment. According to the previous researches (Cai and Zhang 2005; Lu et al. 2016), CF could be partly dissolved in the NaOH/Urea (7 wt%/12 wt%) mixture solution at -12 ℃. In the NaOH/Urea aqueous solution, the cellulose macromolecules were interrupted by NaOH hydrates and Urea hydrates, which could destroy the hydrogen-bond networks of macromolecules at low temperature. In additional, the extent of dissolution could be controlled by adjust the experimental parameters. When the dissolved cellulose was introduced into Na_2SO_4(5 wt%)/H_2SO_4(5 wt%) coagulation bath, the dissolved superficial layers could work like glue to adhere on the surface of fabrics. Inspired by these meaningful results, various nanoparticles such as TiO_2 (Fan et al. 2016), Fe_3O_4 (Zhao et al. 2020) and carboxylated multiwall carbon nanotubes (Li et al. 2016) were embedded on the cotton fabrics surface to prepare functional materials using micro-dissolution method. The as-prepared composites exhibited satisfactory stability even after 2h washing.

In the paper, we prepared superhydrophilic and underwater superoleophobic membranes based on CF using the micro-dissolution method. Firstly, in order to achieve roughness structure, the CF was micro-dissolved in NaOH/ Urea mixture solution. Then, the TiO_2 NPs were directly assembled on the fabric surface by using vacuum filtration method. Owing to the self-glue of dissolved cotton fabric in the coagulation bath, the TiO_2 NPs were firmly anchored on the fabric surface. To further improve the hydrophilic properties of membrane, CF were modified with CA containing three carboxylic groups

through esterification reaction. Finally, the CA/TiO_2 decorated membranes were applied for separating various oil/water mixture and O/W emulsions. The water flux, oil rejection ratio, stability and recyclability of prepared fabrics membranes were systematically evaluated.

2. Experimental

2.1. Materials

Urea, sodium hydroxide, CA and sodium hypophosphite were purchased from Sinopharm Chemical Reagent Co., Ltd. (China). Titanium dioxide (40 nm) was supplied by Aladdin Reagent Co., Ltd. (China). Chloroform, isooctane, n-hexane, xylene and soybean oil were obtained from Taixin Chemical Reagent Co., Ltd. (China). Sodium dodecyl sulfate (SDS), dodecylphenol polyoxyethylene ether (OP-10), hexadecyl trimethyl ammonium bromide (CTAB) were purchased from Aladdin Co., Ltd. (China). CF (130 g/m^2) were bought from local market. All the chemicals were used as received without further purification.

2.2. Preparation of superhydrophilic and underwater superolephobic CA/TiO_2 decorated membranes

The superhydrophilic and underwater superolephobic CA/TiO_2 decorated membranes were prepared using micro-dissolution method. Firstly, the cotton fabric was immersed in 100 mL 7 wt% NaOH/14 wt% urea aqueous solution for 2 h at temperature of -12 ℃. The mixed solution containing 0.02g TiO_2, 7 wt% NaOH/14 wt% urea was ultrasonicated for 45 min to obtain a well-dispersed TiO_2 solution. Then, the mixed solution containing TiO_2 passed through the cotton fabric by vacuum filtration. Subsequently, the coagulation process of micro-dissolved cotton fabrics was carried out in the coagulation bath containing 5% wt H_2SO_4/ 5 wt% Na_2SO_4 for 30 min. After that, the cotton fabrics were dipped into 5 wt% CA/ 5 wt% SHP solution and nipped with a padder (MU3C5T, China) to obtain 80% pickup. Finally, as-prepared CA/TiO_2 decorated membranes were obtained by drying in oven at 80 ℃ and curing at 180 ℃ for 2 min.

2.3. Characterization

The morphologies of treated CF were observed by a SEM analyzer (Quanta-250, FEI, USA). The chemical compositions and elemental compositions were analyzed by a FTIR (Alpha, Brooke Germany) and an elemental dispersive spectrometry (EDS, Ametek, USA), respectively. The crystal structures of cotton fabrics were measured by XRD (TD-3500, China) using Cu $K\alpha_1$ radiation (λ=0.15406 nm) at 30 kV and 20 mA. Additionally, the angle was from 5° to 60° in steps of 0.02°. The thermostability of samples were studied by a TG analyzer (TG 209, Netzsch, Germany) with a heating rate of 10 ℃/min. The water contact angle (WCA) and underwater oil contact angle (UOCA) were evaluated by a contact angle meter (OCA200, dataphysics, Germany) using 4 μL of water or oil. The obtained values were the average measurement of five random regions of the membranes. To comprehensively evaluate the oil adhesion properties, the oil droplet (chloroform) was pressed on the surface of samples by external force, and then was lifted. The droplet size of O/W emulsion was measured by nanometer particle size meter (Zetasizer Lab, Malvern Panalytical, UK).

2.4. Oil/water separation experiments

The CA/TiO_2 decorated membranes were firstly wetted with 10 g/L NaOH solution for 30 min at 50 ℃ and then fixed on a filter element with a diameter of 2.5 cm, which was placed between two glass tubes. The oil/water mixture was prepared by mixing oil (xylene, n-hexane and soybean oil) with water at volume ratio of 1:1 to obtain 200 mL solution. Then the mixture solution was poured into the upper tube, and the water rapidly passed through the fabric while the oil was restrained. Moreover, series of O/W emulsions were prepared by mixing oil (hexane, petroleum ether, trichloromethane) and water in the ratio of 1:100 v/v and shearing under a speed of 12000 rpm for 15 s, the concentration of surfactant (SDS, OP-10, CTAB) was 0.2 g/L. The emulsions were stable for serval hours before they were used for separation. What's more, all the separation was carried out under gravity. The oil/water separation efficiency defined as oil rejection coefficient (R) and water flux (F) were calculated according to the Eq. (1) and Eq. (2), respectively.

$$R = V_1/V_0 \times 100\% \quad (1)$$

$$F = V/(S \cdot t) \quad (2)$$

where V_0 and V_1 were the volume of water before and after oil/water separation, respectively. V was the volume of passed solution through the prepared fabric and S was effective separation area of membrane. Additionally, t represented the passing time of separation.

2.5. Stability of membranes

To assess the durability of membranes, the chemical, mechanical and thermal performance were investigated according to the previous studies. The anti-corrosion properties of prepared membranes were characterized by soaking in a series of pH=1-14 solutions at 25 ℃ for 2 h. As for the evaluation of anti-abrasion properties, the modified side of membranes were pressed on a sandpaper (1200 mesh) under a weight of 100 g and moved straightly for 20 cm. To assess the temperature stability, the prepared membranes were immersed in 100 mL aqueous solute at various temperature ranged from 20 ℃ to 100 ℃. Above tests were monitored by measuring the water flux, oil rejection coefficient and UOCA before and after treatment.

3. Results

3.1. Structural characterization

The preparation process of TiO_2/CA decorated membranes consisted of three steps. In the first step, the CF slightly dissolved in urea/ NaOH solution could sever as a loading platform. In the second step, the TiO_2 particles were distributed on the fabric surface by vacuum filtration. Then, the re-coagulate process in the Na_2SO_4/ H_2SO_4 aqueous solution facilitated the immobilization of NPs on the surface of CF. In the

third step, the CA was grafted on cotton fabric by esterification reaction to construct superhydrophilic coating on membrane surface. Compared to the CF, a new absorption peak at 1760 cm^{-1} could be clearly observed in the CA/TiO_2/CF (Fig. 1a), indicating that CA was successfully grafted on the CF. During the separation process, the negatively charged cotton fabrics were activated by alkali treatment, leading to absorb abundant water due to the hydration effect of sodion presented in -COONa groups. Additionally, the TG analysis of samples after modification were conducted under nitrogen atmosphere with a heating rate of 10 ℃/min. As shown in Fig. 1b, in the first stage, the two TG curves were similar and the weight lost was around 5% in the temperature ranged from 50 ℃ to 100 ℃, which was ascribed to the dehydration of fiber (Zhou et al. 2019). The onset degradation temperature of second stage, namely the degradation of cellulose, decreased from 378 ℃ to 362 ℃ after the introduction of CA, which was attributed to that the presence of organic acid facilitated the destruction of the polymer chains of cellulose during the heating process. Furthermore, the char yield of CA/TiO_2/CF at 600 ℃ could reach 21%, which was much higher than that of CF (1.2%), indicating that the TiO_2 nanoparticles was firmly embedded on the surface of cellulose. The crystal structure of samples was investigated by XRD analysis. For the CF, the appearance of peaks at approximately 14.8º, 16.5º, 22.8º, and 34.1º were assigned to the (1 -1 0), (1 1 0), (0 0 2) and (0 4 0) crystal faces of cellulose, respectively. The locations of these peaks for TiO_2/CF and CA/TiO_2/CF did not change distinctly, implying that micro-dissolution process and esterification process had no crucial effect on the fabrics. Moreover, five new peaks at 25.11º, 37.74º, 47.92º, 53.87º and 54.86º were detected for TiO_2/CF and CA/TiO_2/CF (Fig. 1c), which were corresponded to the (1 0 1), (0 0 4), (2 0 0), (1 0 5) and (2 1 1) crystal faces of anatase TiO_2. The appearance of the typical TiO_2 peaks demonstrated that the TiO_2 particles were anchored on the surface of CF. The surface morphologies aftertreatment were visualized by SEM. From Fig. 2a, it was clear that CF had relatively clean and smooth surface. After micro-dissolution process, the surface of TiO_2/CF was distinctly rough and the TiO_2 particles were trapped in the ravine along the length of the fiber. Vacuum filtration method was applied to construct uniform TiO_2 NPs coating on the substrate fabric with a tunable deposition amount. With further increase the amount of TiO_2 (Fig. 2d), the surface of CA/TiO_2/CF became coarser, indicating that the TiO_2 particles were uniformly distributed on the surface of cotton fabrics. Form the EDS results (Fig. 1d), a certain amount of Ti from the surface of the TiO_2/CF and CA/TiO_2/CF can be clearly verified while only C and O emerge on the surface of CF, which also confirmed that TiO_2 particles were successfully anchored on the fabric surface.

3.2. Surface wettability analysis

The surface wettability was essential to the permeation property of the membranes. The CF coated with TiO_2 NPs and CA were compared to investigate effect of deposition materials on the permeation of water droplet through the membrane. For the CF decorated with TiO_2 NPs, the WCA decreased instantly to 0º in 105 ms (Fig. 3b), indicating the presence of TiO_2 nanoparticles notably enhanced the hydrophilic property of CF. More superior results were also observed for the membranes coated with TiO_2 NPs and CA (Fig. 3c). The difference in the water spread on the surface of membranes originated from the synergistic

effect of NPs and hydrophilic materials (Zhang et al. 2014) On one hand, the hydrophilic layer with numerous anionic groups gave rise to proper water wettability, ensuring the water droplets quickly spreading on the membrane surfaces (Wu et al. 2018). On the other hand, the presence of TiO_2 NPs endowed the membrane surface with hierarchical structure, resulting in further improving hydrophilic feature of membranes. As a consequence, the water spreading speed of membrane decorated with TiO_2 NPs and CA was much faster than pristine CF, providing a chance that water droplets rapidly permeated through membranes.

The occurrence of membrane fouling by oil was one of the most difficult problems during the oily wastewater separation process. This problem could be handled by lowering the oil adhesion on the membrane surface. To evaluate the underwater oleophobicity of as-prepared membranes, we used n-hexane, octane, xylene, 1,2-dichloroethane and chloroform to test the UOCA, as shown in Fig. 4. The UOCAs of CA/TiO_2/CF reached to 150º, revealing that the membranes displayed underwater super-oleophobic properties. As the oil droplets contacted the membrane surface, the hydrophilic materials and hierarchical structure hindered the spread of oil droplets on the surface. As a result, the shape of oil droplets maintained an almost sphere, leading to the reduction in the contact area between oil and membrane and the enhancement in the antifouling property of membrane. Further work demonstrated the underwater-oil adhesion property of the prepared membranes. As depicted in Fig. 5c, the oil droplets could be easily lifted from the surface of TiO_2/CA/CF and kept the initial shape even after being compressed. It was difficult to lift the oil droplets from surface of the CF (Fig. 5a) and TiO_2/CF (Fig. 5b). As a consequence, the above results indicated that the TiO_2/CA/CF have the potential to exhibit outstanding superhydrophilic and underwater superoleophobic properties, which benefited to prevent the occurrence of membrane fouling by oils.

3.3. Oil/water separation of the membranes

The separation properties of prepared membranes under gravity condition were deeply evaluated in terms of water flux and oil rejection ratio. In the separation process, three types of oil/water mixture (soybean oil/water, n-hexane oil/water, xylene oil/water) were used. At the beginning of separation process, the fabric membranes were wetted with water and then fixed on a glass funnel. The purpose for the wetting of fabric membrane was to expel air bubbles from membrane and ensure the feasibility of the separation (Yang et al. 2016). As showed in Fig. 6a, the oil rejection rate exhibited by membranes was exceeded 97%. When the oily water was poured into the upper container, water rapidly passed through the membranes, while the oil remained over the membrane surface, as depicted in Fig. 6b. The presence of TiO_2 NPs and CA promoted the separation of oil/water mixture with water flux of 1201 L/m^2h, which was approximately twice for the CF membrane with water flux of 646.4 L/m^2h.The excellent separation performance of prepared fabric membrane could be attribute to the synergistic effect of presence of hierarchical structure and hydrophilic material, which made the water spread quickly on the membrane surface.

Furthermore, a series of O/W emulsions containing n-hexane, petroleum ether and chloroform were prepared to evaluate the universality of membranes decorated by CA/TiO_2, concerning the separation of different oils with diverse density in large-scale application. Fig. 8a showed that a muddy emulsion became transparent after filtration by gravity. From the optical microscope images, there was no emulsion droplets in the filtrate, while a large number of emulsion droplets presented in the original mixture. It was interesting to observe that the highest water flux was for that emulsion prepared with SDS (negative charge), while the CTAB-stabilized emulsion (positive charge) displayed the lowest water flux (Fig. 8b). This phenomenon was attributed to the charge-screening effect (An et al. 2018). During the separation process, the electrostatic repulsion between same charges hindered the approach of emulsion droplets to membrane surface, which facilitated the water penetration through the membrane. On the contrary, electrostatic attraction between positive charge presented in CTAB and negative charge presented in CA accelerated the deemulsification on the surface of membrane, leading to occupation of membrane surface by oils or emulsion droplets, thus obstructing the penetration of water droplets. The mechanism of deemulsification was briefly depicted in Fig. 7. Therefore, the charged CA coating was beneficial to promote an effective separation for the O/W emulsion with similar charge features.

Taking the oil density into consideration, the light oil (n-hexane, petroleum ether) exhibited more superior separation flux than that of heavy oil (chloroform). This behavior was ascribed to that the oil droplets of chloroform after deemulsification tended to go down and aggregate on the membrane surface because of its high density, leading to a low separation flux (Hu et al. 2015).

To study the effect of emulsion size on water flux, three types of oils stabilized by CTAB was selected to evaluate the separation performance. The measured average size was 5620, 685 and 435 nm for petroleum ether, n-hexane and chloroform emulsions, respectively. It was clearly seen that the larger the droplets were, the faster was the separation (Fig. 8d). The reason for the higher separation flux of petroleum ether could be explained as follows. As the emulsion droplets were aggregated on the membrane surface by electrostatic attraction (Wang et al. 2016), the existence of interspace between the bigger emulsion droplets facilitated the water to penetrate through membranes, resulting in improving the separation flux. The above results indicated that the CA/TiO_2 decorated membrane could separate both conventional oil/water mixture and complicated emulsion, thus exhibiting great potential for application in practical oily wastewater separation.

3.4. Stability of CA/TiO_2 coated membrane

Although detail measurement results revealed that the wettability and separation performance of prepared membranes were outstanding, but still there were lots of technical challenges in application stability of membrane that must be overcome before those products could be applied in the practical oily wastewater treatment (Li et al. 2016). Therefore, the mechanical abrasion stability and corrosion resistance of prepared fabric membrane in harsh condition was worth to pay attention. In order to evaluate the anti-abrasion stability of as-prepared membranes, the modified side of membranes were pressed on a sandpaper under a weight of 100 g and moved straightly for 20 cm. As exhibited in Fig. 9a,

the separation flux and oil rejection ration of membranes changed slightly after 20 cycles friction, suggesting that the membranes possessed satisfying mechanical stability, which was attribute to the strong adhesion between TiO_2 NPs and membrane surface (Yu et al. 2018). During the preparing process, the TiO_2 particles were tightly anchored on the fiber surface due to the self-glue effect of CF in the coagulation bath. In addition, the CA was grafted on fabric through covalent bond. The corrosion resistance of fabric membranes was investigated by soaking the membranes in the different acid or alkali solutions for 2 h under room temperature. The separation flux and rejection ratio of each membrane was shown in Fig. 9b. It was observed that there were negligible variations in the flux with the pH more than 8. Further decrease of pH value (pH<7) could lead to the slight decline in the water flux, which was ascribed to the protonation of carboxyl group, resulting in reducing the affinity of membrane surface to water. What's more, the separation performance of fabric membrane under high temperature condition was also assessed, as shown in Fig. 9c. Apparently, the separation flux increased with increasing the temperature, and oil rejection ratio still remained above 98%. The improvement in separation flux of fabric membrane at high temperature may be attributed to the decrease of fabric pore size due to the swelling of fiber. With decrease pore size of the fabrics, the water-holding properties decreased, leading to facilitate the water penetrate through the membrane (Zheng et al. 2015).

In practical application, the clogging of membrane caused by oil pollution was always occurred, resulting in the decline in the separation performance. Therefore, the reusability of prepared fabric membrane was one of important factor to determine the separation performance of membrane. The oil/water mixture separation experiments were carried out for ten cycles. As could be seen from Fig. 9d, although the water flux slightly decreased with increasing the number of separation cycle, the separation flux kept above 1059 L/m^2h, and the oil rejection ratio kept above 97%. Additionally, the UOCA of fabrics membranes still kept above 146° after 10 cycles of separation. From the results above, it could be concluded that the CA/TiO_2 decorated membrane exhibited superior stability for long-term usage.

4. Conclusion

In this study, an efficient and versatile method was proposed to prepared a robust superhydrophilic and underwater superoleophobic membranes decorated with TiO_2 NPs and CA, which could effectively separate oily wastewater by gravity. Nanoparticle-stacked surface roughness, along with retention of abundant hydrophilic groups conferred the membranes with excellent superhydrophilicity. The characterization results revealed that the TiO_2 NPs were uniformly distributed on the surface of fabric by using vacuum filtration. More importantly than high efficiency oily wastewater separation, the TiO_2/CA decorated membranes exhibited excellent application stability after even applied in harsh conditions. This success in fabricating membranes based on CF for oily wastewater treatment suggested that the surface micro-dissolution method was benefited for immobilizing the NPs on the surface of fabrics. In view of the separation efficiency and application stability, the membranes based on cotton fabrics could be used as commercial membranes and display the potential of its application on an industrial scale.

Declarations

Acknowledgement

This research was supported by the Natural Science Foundation Project of Chongqing (grant number: cstc2020jcyj-msxmX0437), Chongqing Innovation and Entrepreneurship Training Program for College Students (grant number: S202110635152) Southwest University Innovation and Entrepreneurship Training Program for College Students (grant number: X202110635335).

Statements and Declarations

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

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Figures

Figure 1

(a) FTIR spectra of cotton fabric and TiO_2/CA decorated CF (TiO_2/CA/CF), (b) TG and DTG analysis of CF and TiO_2/CA/CF under nitrogen condition, (c) XRD spectra of CF, TiO_2 decorated CF (TiO_2/ CF) and TiO_2/CA/CF, (d) EDS analysis of TiO_2/CA/CF

Figure 2

The SEM images of (a) CF, (b) CF coated with 0.02 g/L TiO_2, (c) TiO_2/CA/CF, (d) CF coated with CA and 0.1g/L TiO_2

Figure 3

The surface wettability of the (a) CF, (b) TiO_2/ CF, (c) TiO_2/CA/CF

Figure 4

The UOCA of various oils on the membrane surface

Figure 5

The underwater-oil adhesion property of (a) CF, (b) TiO_2/ CF, (c) TiO_2/CA/CF

Figure 6

The oil/water mixture separation performance of membranes. (a) the water flux and oil

Figure 7

The mechanism of deemulsification

Figure 8

O/W emulsion separation performance of membranes. (a) Image of O/W emulsion before and after separation, (b) the water flux of separation, (c) the oil rejection ratio of separation, (d) the average size of emulsion droplets stabilized by various surfactants

Figure 9

The excellent durability characteristics of the membranes. (a) abrasion-resistant stability of membranes, (b) corrosion resistant stability of membranes, (c) high temperature stability of membranes, (d)

reusability of membranes

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