## 1. INTRODUCTION

With the advancement of industrialization, many heavy metal ions are discharged into the environment. Water pollution caused by the toxic heavy metal ions is a serious environmental problem. Various techniques, such as chemical precipitation, ion exchange, membrane separation, and adsorption, have been committed to the removal of the metal ions in wastewater. At present, the adsorption method is considered to be an effective and economic one because of its relative simplicity, high efficiency, and recyclability.

The amount and accessibility of functional sites are crucial for an ideal adsorbent for metal ion removal from water. For a common solid material, only the functional sites on the surface can interact with the metal ions in the water. Hydrogels are polymeric materials in a three-dimensional network structure with high water retention and a stretched molecular structure. The functional groups in their network structures, such as carboxyl (−COOH), hydroxyl (−OH), and amine (−NH2), can provide the necessary chelating sites for the heavy metal ions. Moreover, the molecular chains are highly stretched in the captured water, which ensures an excellent accessibility of functional sites by the metal ions. A highly open cellular structure endows the P(AANa-co-HEMA) gel with high transport rates as a promising adsorbent. Adsorption properties were investigated by three isotherm models and two kinetic models. X-ray photoelectron spectroscopy analysis proved a chelating interaction between −COO− and metal ions. The adsorption capacity reached 630 mg·g−1 for Pb2+ under 303 K and a 400 μg·mL−1 initial concentration. The results show that the as-prepared PolyHIPE-based P(AANa-co-HEMA) gel possesses an open cellular structure, high adsorption capacity, and high selectivity for Pb2+.

In this work, a porous hydrogel-based adsorbent for metal ions was prepared through the copolymerization of acrylic acid and 2-hydroxyethyl methacrylate using a high internal phase emulsion (HIPE) method. Stretched molecular chains in the hydrogel ensure the excellent accessibility of functional sites by the metal ions. A highly open cellular structure endows the P(AANa-co-HEMA) gel with high transport rates as a promising adsorbent. Adsorption properties were investigated by three isotherm models and two kinetic models. X-ray photoelectron spectroscopy analysis proved a chelating interaction between −COO− and metal ions. The adsorption capacity reached 630 mg·g−1 for Pb2+ under 303 K and a 400 μg·mL−1 initial concentration. The results show that the as-prepared PolyHIPE-based P(AANa-co-HEMA) gel possesses an open cellular structure, high adsorption capacity, and high selectivity for Pb2+.

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Herein, a hydrophilic hydrogel with an open cellular PolyHIPE structure was prepared through polymerizing an oil-in-water (O/W) HIPE with an aqueous solution of acrylic acid and 2-hydroxyethyl methacrylate as the continuous phase. A PolyHIPE with a hydrophilic skeleton presents advantages in terms of accessibility of functional groups and high transport rates. The metal ions can be transported into the inner part of the hydrogel skeleton and interact freely with the functional sites. The effects of monomer content, internal phase ratio, oil phase composition, and acrylic acid content on the pore emulsions in which the internal phase has a volume fraction greater than 74% with a maximum up to 99%. Polymerizing the continuous phase will produce an open cellular porous structure with the interconnecting windows on the wall. Yang et al. synthesized an interconnected macroporous foam by templating an oil-in-water HIPE solely stabilized by lignin particles. They exhibited an excellent adsorption capacity for Cu(II) ions in aqueous solutions. Liu and Wang prepared chitosan scaffolds with hierarchical macroporous structures for recyclable adsorption of Cu(II) ions by templating from Pickering HIPEs for the first time. Wang et al. prepared a series of magnetic hydroxypropyl cellulose-g-acrylic porous spheres via O/W Pickering high internal phase emulsion (HIPE)-integrated precipitation polymerization. They had good adsorption capacity for Cu2+ and Cd2+ ions.

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structure were investigated. In addition, we also investigated the adsorption capacity of the obtained P(AANa-co-HEMA) gel for metal ions.

2. EXPERIMENTAL SECTION

2.1. Materials. Poly(ethylene glycol)-block-poly(propylene glycol)-block-poly(ethylene glycol) (F68) and 2-hydroxyethyl methacrylate (HEMA, 97%) were purchased from Adamas-beta (Shanghai, China). N,N,N′,N′-Tetramethylethylenediamine (TEMED, 99%), acrylic acid (AA, 99%), Pb(NO3)2 (99%), and NaOH were purchased from Xiya Reagent (Chengdu, China). N,N′-Methylene bisacrylamide (MBAA, 99%) was purchased from Shanghai Yuanye Bio-Technology Co., Ltd. (Shanghai, China). Toluene (TL, 99.5%), (NH4)2S2O8 (APS, 98%), cyclohexane (CYH, 99%), acetone, and ethanol (absolute) were purchased from Chengdu Kelon Chemical Reagent (Chengdu, China).

2.2. Preparation of the P(AA-co-HEMA) Gel. In a typical polymerization reaction, AA and HEMA were charged into a 150 mL beaker along with H2O, the cross-linker MBAA (18 wt% based on the total mass of AA and HEMA), and F68 (15 wt% based on the water phase) and stirred at 400 rpm for 10 min. Then, a mixture of cyclohexane and toluene was added dropwise under stirring. Once all the oil phases were added, the initiator APS (2 wt% monomer, dissolved in 1 mL of water) was added, and the mixture was then stirred at 3000 rpm for 8 min using a homogenizer. Next, the catalyst TEMED (20 µL) was added, and stirring was continued for 2 min to obtain a viscous milky O/W HIPE. The emulsion was then transferred to a glass test tube and polymerized in a 50 °C water bath for 10 h. The obtained monolith was cut into small pieces and purified by Soxhlet extraction with ethanol. The internal structure and morphology were determined on a FEI-Verios G4 scanning electron microscope (SEM). Pore properties were determined on an AutoPore IV 9500 mercury porosimeter. The backbone component of the P(AA-co-HEMA) gel was determined on a TENSOR 27 infrared spectrometer. Each element’s information was determined by X-ray photoelectron spectroscopy (XPS; Kratos, AXIS Ultra DLD). The zero charge point of the adsorbent was determined by the method in refs 14 and 15.

2.3. Adsorption Experiments. The P(AA-co-HEMA) gel was changed to the P(AANa-co-HEMA) gel by NaOH solution (0.1 M) before the adsorption experiment. The adsorption experiments were carried out by a batch method. In a constant temperature oscillator, 50 mL of Pb2+ solution was brought into contact with 20 mg of the adsorbent for 3 h. The residual Pb2+ in the solution was traced using atomic adsorption spectroscopy (AAS). The adsorption capacity Qe was calculated by eq 1.

\[
Q_e = \frac{(C_0 - C_e)V}{m}
\]

where \(C_0\) and \(C_e\) are the Pb2+ concentration in the solution before and after the adsorption process, respectively, \(V\) is the volume of the Pb2+ solution, and \(m\) is the mass of the P(AANa-co-HEMA) gel used (g).

2.4. Regeneration Experiment. After the adsorption, the P(AANa-co-HEMA) gel adsorbent was regenerated through a desorption procedure. First, the adsorbent was desorbed in 50 mL of HCl solution (0.1 M) for 2 h at 303 K, and the desorption procedure was repeated three times. Second, the desorbed adsorbent was soaked with NaOH (0.1 M) to change the P(AA-co-HEMA) gel to P(AANa-co-HEMA) gel. Third, the P(AANa-co-HEMA) gel was washed with deionized water.

3. RESULTS AND DISCUSSION

3.1. Pore Structure of P(AA-co-HEMA) Gel. By polymerizing the continuous phase of the HIPE, an open cellular PolyHIPE structure was prepared extensively, especially for a hydrophobic skeleton. Herein, an oil-in-water (O/W) HIPE was employed to achieve a hydrophilic hydrogel where the molecular chains were in a status of fully stretching. To obtain a PolyHIPE-based P(AA-co-HEMA) gel with high interconnectivity, the effects of the monomer content, internal phase ratio, oil phase composition, and acrylic acid content on the pore structure were investigated (Figure 1 and Figures S1–S3). Typical open cellular PolyHIPE structures prepared with different AA contents are presented and summarized in Table 1.

In the O/W HIPE, the monomer was dissolved in water and polymerized into a hydrogel skeleton of PolyHIPE. We started the experiment with AA as solely the monomer to achieve a high density of functional groups for heavy metals. The prepared PAA gel presented a large portion of closed voids (Figure 1A1). We speculate that this is ascribed to the poor stability of the emulsion caused by the high polarity of AA. Targeted on the polarity, HEMA was copolymerized, and a highly interconnecting P(AA-co-HEMA) gel was achieved, as shown in Figure 1 and summarized in Table 1. The content of AA has a significant effect on the pore structure. As the \(V_{AA}/V_{HEMA}\) decreased from 3:1 to 1:3, the porosity of the P(AA-co-HEMA) gel increased from 62.4 to 84.7%, and the P(AA-co-HEMA) gel contained abundant windows and a highly open cellular structure.

3.2. Characterization of Adsorbent Materials. FTIR (Fourier transform infrared spectroscopy) and XPS were used to confirm the successful preparation of the P(AANa-co-HEMA) gel. Figure 2 shows the FTIR spectra of P(AA-co-HEMA) and P(AANa-co-HEMA) gels. For the P(AA-co-HEMA) gel, special peaks around 3400 cm⁻¹, 1719 cm⁻¹, and 1719 cm⁻¹ are attributed to νO-H (including alcoholic hydroxyl groups and carboxyhydroxy groups of HEMA) and νC=O, respectively. In the P(AANa-co-HEMA) gel, two new peaks
appear at 1565 and 1400 cm\(^{-1}\). They are assigned to the asymmetric and symmetric stretching vibrations of the carboxylate anion \(\text{–COO}^-\), respectively.\(^{16,17}\) XPS was performed to determine the chemical composition of the adsorbent surface. The C 1s, N 1s, and O 1s peaks were detected at 284, 397, and 531 eV, respectively, in the P(AA-co-HEMA) gel XPS spectra (Figure 3a). In Figure 3b, a new peak attributed to Na 1s appears at 1069 eV.

### 3.3. Adsorption of the Metal Ion by P(AANa-co-HEMA) Gel

#### 3.3.1. Adsorption Mechanism

We employed the original P(AA-co-HEMA) gel as an adsorbent for Pb\(^{2+}\) and found that the P(AA-co-HEMA) gel had almost zero adsorption capacity for Pb\(^{2+}\). After being treated with NaOH, the P(AA-co-HEMA) gel transformed into the P(AANa-co-HEMA) gel and presented good adsorption performance. These results indicated that the adsorption originated from the \(\text{–COO}^-\) group of P(AANa-co-HEMA).

In order to further explore the mechanism of adsorption, this study used X-ray photoelectron spectroscopy to analyze the hydrogel before and after adsorption. The high-resolution XPS spectra of the P(AANa-co-HEMA) gel and P(AANa-co-HEMA) gel –Pb\(^{2+}\) for C 1s, O 1s, and Pb 4f are presented in Figure 4. Three group peaks of the P(AANa-co-HEMA) gel and P(AANa-co-HEMA) gel –Pb\(^{2+}\) in Figure 4a are attributed to the C–C, C–N, and C=O binding energies of C 1s, respectively. Obviously, all the binding energies of C 1s increased slightly after adsorption of Pb\(^{2+}\) due to the reaction between the adjacent N or O atoms and Pb\(^{2+}\). Two group peaks of the P(AANa-co-HEMA) gel and P(AANa-co-HEMA) gel –Pb\(^{2+}\) in Figure 4b are attributed to the C=O and C–O binding energies of O 1s, respectively. It can be seen that the binding energy of C–O significantly increased from 530.19 to 533.11 eV after adsorption of Pb\(^{2+}\), which indicates that there is a strong combination between the absorbent \(\text{–COO}^-\) and Pb\(^{2+}\). Therefore, it was speculated that the reaction between \(\text{–COO}^-\) and Pb\(^{2+}\) was via chelation.\(^{15,18,19}\)

#### 3.3.2. Effect of the Solution pH

The pH plays an important role in the adsorption behavior because the pH can have an effect not only on the surface charge density of the adsorbent but also on the existing form of the adsorbate.\(^{20–22}\) As shown in Figure 5, the adsorption of Pb\(^{2+}\) shows a great pH-dependent property. The adsorption capacity \(Q_e\) increases remarkably with the increase in pH from 2 to 4 then retains a high \(Q_e\) at pH 4–6. The pH value at zero point charge (pH\(_{\text{PZC}}\)) of the P(AANa-co-HEMA) hydrogel is about 8.86 (Figure S4). At pH < pH\(_{\text{PZC}}\), the adsorbent is highly positively charged, and the electrostatic repulsion counts against the adsorption of positive metal ions.\(^{23,24}\) As the pH increases, the protonation reaction \((\text{–COO}^- + \text{H}^+ \rightarrow \text{–COOH})\) decreases, leading to an increase in \(Q_e\). When pH increases to 5, Pb\(^{2+}\) becomes a priority over H\(^+\) when competing for the adsorption site \((\text{–COO}^-)\), and the \(Q_e\) reached a maximum. At pH > pH\(_{\text{PZC}}\), the adsorbent becomes deprotonated, which promotes the adsorption of heavy metal ions. However, at this pH condition, Pb\(^{2+}\) forms hydroxide precipitates. According to the solubility product constant of Pb(OH)\(_2\) (4.8 × 10\(^{-20}\)), the pH value beginning to form hydroxide precipitates was calculated to be 5.8.\(^{19}\)

#### 3.3.3. Adsorption Capacity and Regeneration of the Material

Adsorption capacities of P(AANa-co-HEMA) gel A1, A2, A3, and A4 are presented in Table 1. The pore parameters of P(AA-co-HEMA) gel prepared with different AA contents are also listed in Table 1. The V\(_{\text{TL}}\)/V\(_{\text{CYH}}\) ratio in the internal phase is 75 for all the gels, and the \(V_{\text{AA}}/V_{\text{HEMA}}\) monomer (%) is 4:0, 3:1, 2:2, and 1:3 for samples A1, A2, A3, and A4, respectively.

![Figure 2. FTIR spectra of the (a) P(AA-co-HEMA) and (b) P(AANa-co-HEMA) gel.](image)

![Figure 3. XPS spectra of the (a) P(AA-co-HEMA) and (b) P(AANa-co-HEMA) gel.](image)

Table 1. Pore Parameters of P(AA-co-HEMA) Gel Prepared with Different AA Contents

| sample | \(V_{\text{AA}}/V_{\text{HEMA}}\) monomer (%) | internal phase (%) | \(V_{\text{TL}}/V_{\text{CYH}}\) | porosity (%) | pore diameter (nm) | pore area (m\(^2\)·g\(^{-1}\)) |
|--------|--------------------------------|-------------------|-----------------|-------------|-----------------|-------------------|
| A1     | 4:0                           | 32                | 75              | 2:2         | "               | "                 |
| A2     | 3:1                           | 32                | 75              | 2:2         | 62.4            | 7575              | 1.33              |
| A3     | 2:2                           | 32                | 75              | 2:2         | 75.5            | 4098              | 4.81              |
| A4     | 1:3                           | 32                | 75              | 2:2         | 84.7            | 1124              | 17.00              |

\(^{a}\)Large portion of closed voids.
A2, A3, and A4 were investigated under 303 K and different Pb\(^{2+}\) initial concentrations. The results are shown in Figure 6.

Under 200 \(\mu g \cdot mL^{-1}\) of Pb\(^{2+}\) concentration, \(Q_e\) increased from 130 to 480 mg \(g^{-1}\) as the AA content increased from 25\% (A4) to 100\% (A1). Under 400 \(\mu g \cdot mL^{-1}\) Pb\(^{2+}\), the \(Q_e\) of the A2 hydrogel reached 527 mg \(g^{-1}\), and the maximum adsorption capacity reached 630 mg \(g^{-1}\) for the A1 hydrogel. Our results reveal that the as-prepared hydrogel has relatively larger adsorption capacities than similar hydrogel adsorbents published previously (Table 2).

Regeneration of the adsorbent has an important significance for the application of the adsorbent. The adsorption efficiency of the P(AANa-co-HEMA) gel at different cycle times is shown in Figure 7. After five times adsorption–desorption processes, adsorption of Pb\(^{2+}\) by the P(AANa-co-HEMA) gel preserves more than 95\% of the initial adsorption amount, indicating that the as-prepared porous hydrogel is a high-performance recyclable adsorbent for metal ions.

### Isothermal Adsorption

The adsorption isotherms of the prepared absorbent at three different temperatures are represented in Figure 8. The initial ion concentration provides the necessary driving force to overcome mass transfer resistance until the maximum adsorption capacity is reached.\(^{30}\) As a result, the adsorption capacity increased significantly during the initial stage until the adsorption is almost at equilibrium. The \(Q_e\) increases from 481 mg \(g^{-1}\) at 293 K to 606 mg \(g^{-1}\) at 313 K, indicating that the adsorption is an endothermic process.

Three isotherm adsorption models were employed to fit the adsorption process (Figure S7). The calculated parameters and correlation coefficients are listed in Table 3. A higher \(R^2\) for the Freundlich equation indicates a multilayer adsorption model rather than a monolayer model.\(^{31,32}\) This is consistent with our hypothesis that the metal ion can intrude into the stretched molecular chains.

### Adsorption Kinetics

The porous structure of the P(AANa-co-HEMA) gel can diminish the diffusion limitation during the adsorption, shortening the adsorption time to reach adsorption equilibrium. As shown in Figure 9, the P(AANa-co-HEMA) gel adsorbs Pb\(^{2+}\) rapidly in 45 min and reaches equilibrium in 1 h. Pseudo-first-order and pseudo-second-order models were used to fit the experimental data, as described by the following equations

\[
\log(Q_e - Q_t) = \log Q_e - \frac{k_1 t}{2.303}
\]

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\]
\[ t = \frac{1}{Q_t} + \frac{1}{Q_e t} \]  

(3)

where \( Q_t \) and \( Q_e \) are the adsorption amounts (mg \cdot g\(^{-1}\)) at equilibrium and time \( t \), respectively, and \( k_f \) (min\(^{-1}\)) and \( k_s \) (g/(mg \cdot min)) are primary and secondary constants, respectively.

The fitting curves are presented in Figure 9, and the calculated parameters are listed in Table 4. A higher correlation coefficient shows that the pseudo-second-order model can be used for the whole adsorption process. This result indicates that the adsorption rate of Pb\(^{2+}\) by the P(AANa-co-HEMA) gel is controlled by chemical processes.\(^{33,34} \)

3.3.6. Selective Adsorption. The selectivity of adsorbents for heavy metals has an important impact in practical industrial applications. Highly selective adsorbents are suitable for wastewater treatment with a single heavy metal ion, while low selectivity is more effective for treating wastewater containing multiple heavy metal ions. In a constant temperature oscillator, 50 mL of a mixed solution containing 50 \( \mu \)g \cdot mL\(^{-1}\) Pb\(^{2+}\), Cu\(^{2+}\), and Zn\(^{2+}\) was brought into contact with 20 mg of the adsorbent for 3 h. The results of selective adsorption of the P(AANa-co-HEMA) gel on the same concentration of three metal-ion-mixed solutions are shown in Figure 10. Under 50 \( \mu \)g \cdot mL\(^{-1}\) of ions, the adsorption ratios of Pb\(^{2+}\), Cu\(^{2+}\), and Zn\(^{2+}\) by the P(AANa-co-HEMA) gel were 93.7, 77.7, and 52.3\%, respectively. Under a higher concentration of the metal ion mixture, a similar tendency of the adsorption ratio was achieved (Pb\(^{2+}\) > Cu\(^{2+}\) > Zn\(^{2+}\)). From the results of adsorption of a single heavy metal ion, the P(AANa-co-HEMA) gel can achieve a nearly 100% adsorption rate for Pb\(^{2+}\). The adsorption ratio for Pb\(^{2+}\) in these solutions was greater than 90\% in 3 h.

Table 2. Comparison of Metal Ion Adsorption among Different Hydrogel Adsorbents

| hydrogel adsorbents         | metal ion | \( Q_e \) (mg \cdot g\(^{-1}\)) | references          |
|-----------------------------|----------|--------------------------------|---------------------|
| P(AMPS-co-IA)               | Pb\(^{2+}\) | 360                            | Çavuş et al. (2009)\(^{25} \) |
| m-chitosan/PVA/CCNFs        | Pb\(^{2+}\) | 171                            | Zhou et al. (2014)\(^{26} \) |
| m-chitosan/PVA              | Pb\(^{2+}\) | 117                            | Zhou et al. (2014)\(^{26} \) |
| Gg-cl-P(AAm-co-AN)          | Pb\(^{2+}\), Cu\(^{2+}\) | 385, 204                        | Mittal et al. (2015)\(^{27} \) |
| P(AANa-co-AM)/GO            | Pb\(^{2+}\), Cd\(^{2+}\) | 452, 196                        | He et al. (2016)\(^{35} \) |
| CTS-g-PAA                   | Cu\(^{2+}\), Pb\(^{2+}\) | 300, 600                        | Zhu et al. (2016)\(^{36} \) |
| Jute/PAA                    | Cd\(^{2+}\), Pb\(^{2+}\) | 401, 542                        | Zhou et al. (2017)\(^{37} \) |
| CMC/PAM composite hydrogel  | Pb\(^{2+}\), Cd\(^{2+}\) | 312, 256                        | Godiya et al. (2019)\(^{38} \) |

Table 3. Parameters of Langmuir, Freundlich, and D–R Isotherm Adsorption Models

| \( T \) (K) | \( Q_m \) (mg \cdot g\(^{-1}\)) | \( K_L \) (L \cdot mg\(^{-1}\)) | \( R^2 \) | \( 1/n \) | \( K_F \) ((mg \cdot g\(^{-1}\) \cdot (L \cdot mg\(^{-1}\))\(^{1/n}\)) | \( R^2 \) | \( Q_m \) (mg \cdot g\(^{-1}\)) | \( E \) (kJ \cdot mol\(^{-1}\)) | \( R^2 \) |
|------------|--------------------------------|-------------------------------|--------|--------|---------------------------------|---------|--------------------------------|-----------------|--------|
| 293        | 505                            | 0.0528                         | 0.988  | 87.4   | 0.318                           | 0.996   | 917                             | 13.8            | 0.981  |
| 303        | 552                            | 0.0682                         | 0.988  | 110    | 0.297                           | 0.995   | 948                             | 15.0            | 0.983  |
| 313        | 617                            | 0.122                          | 0.989  | 168    | 0.247                           | 0.997   | 1025                            | 16.8            | 0.988  |

Table 4. Parameters Fitted from Pseudo-First-Order and Pseudo-Second-Order Models

| temperature | \( Q_e \) (mg \cdot g\(^{-1}\)) | \( k_f \) (min\(^{-1}\)) | \( R^2 \) | \( Q_e \) (mg \cdot g\(^{-1}\)) | \( k_s \) (g/(mg \cdot min)) | \( R^2 \) |
|-------------|--------------------------------|-----------------|--------|--------------------------------|-----------------|--------|
| 303 K       | 548                            | 0.0526          | 0.945  | 437                            | 1.19 \times 10\(^{-4}\) | 0.994  |
of Pb\(^{2+}\) by the P(AANa-co-HEMA) gel was slightly affected in competitive adsorption experiments in binary metal ion systems. The adsorption capacity of the P(AANa-co-HEMA) gel for different heavy metals is mainly due to the difference in the binding ability of functional groups to heavy metal ions. The experimental results show that the adsorbent can efficiently treat wastewater containing Pb\(^{2+}\).

4. CONCLUSIONS

In this study, an open cellular PolyHIPE hydrogel was prepared by polymerizing HIPE with acrylic acid and 2-hydroxyethyl methacrylate as monomers. SEM images confirm that the as-prepared porous hydrogel monolith shows a good open cellular framework structure, and the pore structure can be adjusted by changing the polymerization parameters, such as acrylic acid content, monomer content, internal phase ratio, and oil phase composition. This open cellular hydrogel presents faster adsorption kinetics and a high adsorption capacity for Pb\(^{2+}\) and has potential to be a highly effective adsorbent for the enrichment of metal ions from the aqueous solution.
Table S1: pore parameters of the P(AA-co-HEMA) gel prepared under different monomer contents; Figure S1: SEM images of the P(AA-co-HEMA) gel prepared under different monomer contents; Table S2: pore parameters of the P(AA-co-HEMA) gel prepared under different internal phase ratios; Figure S2: SEM images of the P(AA-co-HEMA) gel prepared under different internal phase ratios; Table S3: pore parameters of the P(AA-co-HEMA) gel prepared under different oil phase compositions; Figure S3: SEM image of the P(AA-co-HEMA) gel composed of different oil phases; Figure S4: zero point charge of P(AA-co-HEMA) at different pH solutions; Figure S5: photograph of the adsorbent before (left) and after (right) water absorption; Table S4: ESR of hydrogels with different AA contents; Figure S6: compressive nominal stress—strain curves with compressive strain; Figure S7: Langmuir, Freundlich, and Dubinin—Radushkevich isotherm adsorption models; and Table S8: parameters of Langmuir, Freundlich and D–R isotherm adsorption models (PDF).

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Notes
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