**Synthesis, characterization and adsorption of Pb(Ⅱ), Cd(Ⅱ) and Cu(Ⅱ) by red mud/polyacrylic acid/sodium carboxymethyl cellulose hydrogel**

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**Text S1.** RMAAC physical performance tests.

The N2 adsorption/desorption method (BET, 3H-2000PS4) was employed to determine the specific surface area and average pore size of RMAAC. The hydrogels (3 × 3 cm²) were dried in an oven at 105 °C until they reached a constant weight to determine their moisture content. The dried hydrogels were then immersed in deionized water, filtered, and transferred to a constant-temperature shaker (25 °C, 50 rpm) for 24 hours. After removal from the shaker, the hydrogels were dried again at 105 °C to evaluate their water solubility.

Based on the measurement techniques described, the specific surface area and average pore size of RMAAC were found to be 0.4091 m²/g and 24.15 μm, respectively. The porosity was measured at 90.13%, while the moisture content was 42.16% and the water solubility was 85.34%. The thickness of the hydrogels was 739.67 mm.

**Text S2.** Formulas and methods used in batch adsorption experiments.

The adsorption capacity (equation 1) and removal rate (equation 2) were calculated were calculated as follows:

In the given expression, Q represents the equilibrium adsorption of RMAAC per unit mass (mg/g), denotes the removal rate of heavy metals by RMAAC (%), is the initial mass concentration of the solution before adsorption (mg/L), while is the equilibrium mass concentration of the solution after adsorption (mg/L), On the other hand, is the dosage of RMAAC (g) and is the volume of solution (mL).

The adsorption characteristics of RMAAC were further investigated by fitting the adsorption isothermal experimental data with Langmuir (equation 3), Freundlich (equation 4), and Temkin (equation 5) modelling equations, respectively, with the following equations:

In the expression provided, is the theoretical saturated adsorption capacity (mg/g), is the theoretical saturated adsorption capacity (mg/g), is Langmuir constant, while and n represent Freundlich constant. Additionally, is the concentration of heavy metal ions at adsorption equilibrium (mg/L), is the equilibrium association constant and is the coefficient related to adsorption heat.

In order to better describe the adsorption process of heavy metals by RMAAC, quasi-first-order kinetics (equation 6), quasi-second-order kinetics (equation 7) and in-particle diffusion model (equation 8) were used to fit the adsorption data of Pb(Ⅱ), Cd(Ⅱ) and Cu(Ⅱ) respectively. The formula is as follows:

In the given expression, is the adsorption time (min), is the adsorption amount at time t (mg/g), is the pseudo-first-order kinetic adsorption rate constant (min-1), is the pseudo-second-order kinetic adsorption rate constant (g/(mg·min)), is the intra-particle diffusion constant (mg/(g·min1/2)) and is the intercept.

The method for determining the point of zero charge (pHpzc) of hydrogels is as follows: Prepare 50 mL of a 0.1 mol/L NaCl solution and adjust the pH to between 2 and 12 using a 0.1 mol/L HCl/NaOH solution. Add 0.1 g of RMAAC to the solutions with different pH levels and incubate at 298 K while oscillating at 150 r/min for 24 hours. After this period, measure the pH value of the remaining solution. Plot the initial pH values on the horizontal axes and the pH differences before and after the experiment on the vertical axis. The pH corresponding to the intersection point where the pH difference equals zero indicates the pHpzc of RMAAC.

**Text S3.** Characterization methods.

The concentrations of Pb(Ⅱ), Cd(Ⅱ), and Cu(Ⅱ) in the solution were measured using an AA-6300 atomic absorption meter (Shimadzu Company, Japan). The crystallization state of RMAAC before and after adsorption of three heavy metals was analyzed by Bruker D8 advance X-ray diffractometer (XRD, Bruker Company, Germany). Surface characteristic functional groups were determined using Nicoet460 Fourier infrared spectrometer (FTIR, Hitachi, Japan), and surface characteristics and main element composition were determined using Regulus8100 field emission scanning electron microscope (SEM-EDS, Hitachi, Japan). The Escalab 250Xi X-ray photoelectron spectroscopy analyzer (XPS, Thermo Scientific, USA) was used for electron spectroscopy analysis.

**Table S1**

Response surface design experiment results.

| Factor | MBA % | KPS % | SCMC % | YPb(mg/g) | YCd(mg/g) | YCu(mg/g) |
| --- | --- | --- | --- | --- | --- | --- |
| 1 | 0.15 | 0.2 | 1.5 | 381.7 | 169.8 | 195.8 |
| 2 | 0.15 | 0.15 | 0.5 | 343.2 | 137.2 | 187.2 |
| 3 | 0.15 | 0.2 | 1.5 | 376.2 | 160.7 | 196.1 |
| 4 | 0.15 | 0.25 | 2.5 | 303.3 | 128.2 | 184.7 |
| 5 | 0.2 | 0.15 | 1.5 | 374.2 | 161.7 | 189.7 |
| 6 | 0.15 | 0.25 | 0.5 | 326.6 | 131.3 | 185.7 |
| 7 | 0.2 | 0.2 | 2.5 | 363.4 | 161.5 | 189.4 |
| 8 | 0.1 | 0.15 | 1.5 | 390.9 | 153.3 | 193.7 |
| 9 | 0.1 | 0.2 | 0.5 | 371.3 | 138.7 | 187.8 |
| 10 | 0.1 | 0.25 | 1.5 | 402.4 | 148 | 191.2 |
| 11 | 0.2 | 0.2 | 0.5 | 377.1 | 136.4 | 192.4 |
| 12 | 0.2 | 0.25 | 1.5 | 420.07 | 158 | 192.5 |
| 13 | 0.15 | 0.2 | 1.5 | 379.3 | 153.9 | 193.9 |
| 14 | 0.15 | 0.2 | 1.5 | 380.8 | 162.8 | 194.4 |
| 15 | 0.1 | 0.2 | 2.5 | 343.7 | 153.2 | 189.1 |
| 16 | 0.15 | 0.2 | 1.5 | 351.5 | 162.1 | 195.2 |
| 17 | 0.15 | 0.15 | 2.5 | 301.1 | 150.1 | 185.7 |

**Table S2**

Analysis of YPb model variance.

| Source | Quadratic sum | Degree of freedom | Mean square | F-value | P-value | Significance |
| --- | --- | --- | --- | --- | --- | --- |
| Model | 15253.98 | 9 | 1694.89 | 8.26 | 0.0055 | significant |
| A (MBA) | 87.58 | 1 | 87.58 | 0.43 | 0.5344 |  |
| B (KPS) | 230.8 | 1 | 230.8 | 1.12 | 0.3241 |  |
| C (SCMC) | 1423.11 | 1 | 1423.11 | 6.94 | 0.0337 |  |
| AB | 295.32 | 1 | 295.32 | 1.44 | 0.2693 |  |
| AC | 48.3 | 1 | 48.3 | 0.24 | 0.6424 |  |
| BC | 88.36 | 1 | 88.36 | 0.43 | 0.5327 |  |
| A2 | 4912.93 | 1 | 4912.93 | 23.94 | 0.0018 |  |
| B2 | 524.99 | 1 | 524.99 | 2.56 | 0.1537 |  |
| C2 | 8219.81 | 1 | 8219.81 | 40.06 | 0.0004 |  |
| residual | 1436.34 | 7 | 205.19 |  |  |  |
| Missing items | 791.68 | 3 | 263.89 | 1.64 | 0.3153 | not significant |
| error | 644.66 | 4 | 161.17 |  |  |  |
| total deviation | 16690.33 | 16 |  |  |  |  |

**Table S3**

Analysis of YCd model variance.

| Source | Quadratic sum | Degree of freedom | Mean square | F-value | P-value | Significance |
| --- | --- | --- | --- | --- | --- | --- |
| Model | 214.53 | 9 | 23.84 | 14.25 | 0.001 | significant |
| A (MBA) | 0.6 | 1 | 3.9 | 0.97 | 0.5665 |  |
| B (KPS) | 0.6 | 1 | 0.6 | 0.36 | 0.5665 |  |
| C (SCMC) | 2.2 | 1 | 2.2 | 1.32 | 0.2886 |  |
| AB | 7.02 | 1 | 7.02 | 4.2 | 0.0796 |  |
| AC | 4.62 | 1 | 4.62 | 2.76 | 0.1404 |  |
| BC | 0.062 | 1 | 0.062 | 0.037 | 0.8522 |  |
| A2 | 0.31 | 1 | 0.31 | 0.19 | 0.6785 |  |
| B2 | 53.89 | 1 | 53.89 | 32.22 | 0.0008 |  |
| C2 | 135.72 | 1 | 135.72 | 81.15 | < 0.0001 |  |
| residual | 11.71 | 7 | 1.67 |  |  |  |
| Missing items | 8.28 | 3 | 2.76 | 3.22 | 0.1441 | not significant |
| error | 3.43 | 4 | 0.86 |  |  |  |
| total deviation | 226.24 | 16 |  |  |  |  |

**Table S4**

Analysis of YCu model variance.

| Source | Quadratic sum | Degree of freedom | Mean square | F-value | P-value | Significance |
| --- | --- | --- | --- | --- | --- | --- |
| Model | 2171.79 | 9 | 241.31 | 5.57 | 0.0169 | significant |
| A (MBA) | 74.42 | 1 | 74.42 | 1.72 | 0.2312 |  |
| B (KPS) | 169.28 | 1 | 169.28 | 3.91 | 0.0885 |  |
| C (SCMC) | 305.04 | 1 | 305.04 | 7.04 | 0.0327 |  |
| AB | 0.64 | 1 | 0.64 | 0.015 | 0.9067 |  |
| AC | 28.09 | 1 | 28.09 | 0.65 | 0.4471 |  |
| BC | 64 | 1 | 64 | 1.48 | 0.2635 |  |
| A2 | 18.04 | 1 | 18.04 | 0.42 | 0.5392 |  |
| B2 | 317.23 | 1 | 317.23 | 7.33 | 0.0303 |  |
| C2 | 1143.54 | 1 | 1143.54 | 26.41 | 0.0013 |  |
| residual | 303.1 | 7 | 43.3 |  |  |  |
| Missing items | 174.41 | 3 | 58.14 | 1.81 | 0.2855 | not significant |
| error | 128.69 | 4 | 32.17 |  |  |  |
| total deviation | 2474.89 | 16 |  |  |  |  |

**Table S5**

Effect of RM addition amount on adsorption effect.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| RM ratio（%） | Pb removal rate（%） | Cd removal rate（%） | Cu removal rate（%） | Form |
| 0 | 93.22 | 90.43 | 87.52 | No red mud was added |
| 0.5 | 95.47 | 94.50 | 90.56 | Evenly distributed of red mud |
| 1 | 86.64 | 85.37 | 82.5 | Small accumulation of red mud |
| 2 | 78.46 | 77.21 | 71.04 | Obvious accumulation of red mud |

**Table S6**

Isotherm fitting parameters.

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Pollutants | Temperature  (K) | Langmuir | | | Freundlich | | | Temkin | | |
| *Q*m  /(mg/g) | *K*L  /(L/mg) | *R*2 | *K*F  /(mg1-n﹒Ln/g) | 1/n | *R*2 | A | B | *R*2 |
| Pb(Ⅱ) | 298 | 730.16 | 0.0219 | 0.977 | 74.84 | 0.362 | 0.752 | 156.5 | 0.19 | 0.849 |
| 308 | 708.39 | 0.0272 | 0.980 | 89.41 | 0.328 | 0.703 | 146.5 | 0.24 | 0.801 |
| 318 | 719.15 | 0.0828 | 0.988 | 94.36 | 0.320 | 0.673 | 148.7 | 0.24 | 0.791 |
| Cd(Ⅱ) | 298 | 292.71 | 0.1527 | 0.902 | 72.77 | 0.270 | 0.726 | 54.9 | 0.70 | 0.883 |
| 308 | 293.86 | 0.0663 | 0.951 | 51.57 | 0.324 | 0.799 | 55.8 | 0.82 | 0.919 |
| 318 | 295.25 | 0.0499 | 0.918 | 46.13 | 0.339 | 0.781 | 52.4 | 1.80 | 0.851 |
| Cu(Ⅱ) | 298 | 215.37 | 0.0867 | 0.942 | 45.20 | 0.284 | 0.809 | 37.8 | 1.24 | 0.910 |
| 308 | 222.38 | 0.094 | 0.941 | 49.17 | 0.279 | 0.792 | 39.1 | 1.30 | 0.902 |
| 318 | 233.48 | 0.067 | 0.941 | 42.95 | 0.314 | 0.836 | 42.1 | 1.01 | 0.927 |

**Table S7**

Kinetic fitting parameters.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| heavy metal | Pseudo-first-order  dynamics model | | | Pseudo-second-order dynamics model | | | Intra particle  diffusion model | | | | | |
| *q*e /(mg·g-1) | *k*1  /min-1 | *R*2 | *q*e  /(mg·g-1) | *k*2  /min-1 | *R*2 | *k*d1  /(mg·m-1·min-0.5) | *C*1 | *R*2 | *k*d2  /(mg·m-1·min-0.5) | *C*2 | *R*2 |
| Pb(II) | 477.65 | 0.0176 | 0.886 | 522.73 | 0.0033 | 0.964 | 54.734 | 129.14 | 0.973 | 0.069 | 465.17 | 0.737 |
| Cd(II) | 190.84 | 0.0178 | 0.938 | 209.02 | 0.0022 | 0.990 | 18.068 | 22.297 | 0.975 | 0.751 | 169.21 | 0.607 |
| Cu(II) | 196.18 | 0.0191 | 0.959 | 213.95 | 0.0025 | 0.998 | 18.280 | 16.109 | 0.976 | 0.668 | 117.65 | 0.715 |