

Phosphate Adsorption onto Granular-Acid-Activated-Neutralized Red Mud: Parameter Optimization, Kinetics, Isotherms, and Mechanism Analysis

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Abstract Powdered-acid-activated-neutralized red mud (Aan-RM), the chemico-physically modified product of red mud, was for the first time employed with hydroxypropyl methylcellulose and powdered straw as the main ingredients for granular Aan-RM production for phosphate removal. In order to better understand the phosphate adsorption characteristics of granular Aan-RM, the influence of operational parameters on the performance of granular Aan-RM and the possible adsorption mechanisms involved were investigated. The results demonstrated that the adsorbent dosage, adsorption temperature, and initial solution pH influenced the adsorption performance of granular Aan-RM significantly. The maximum phosphate adsorption capacity

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of granular Aan-RM reached 153.227 mg/g with the granular Aan-RM dosage of 3.0 g/L, adsorption temperature of 40 °C, and initial solution pH of 6.0. The whole adsorption process was well described by *n*th-order kinetic model and Langmuir–Freundlich isotherm. Meanwhile, X-ray photoelectron spectroscopy (XPS) analysis of P 2p peak on granular Aan-RM after phosphate adsorption demonstrated that 79.01 % of the phosphate was adsorbed through precipitation and ion exchange mechanisms with strong chemical bonds, and 20.99 % of the phosphate was adsorbed through surface deposition mechanism with weak chemical bonds.

Keywords Red mud · Granule · Phosphate adsorption · Precipitation · Surface deposition

1 Introduction

Phosphate is regarded as one of necessary nutrient elements to support the growth of biological organisms in aquatic environment (Yoon et al. 2014). However, extra phosphate in waters has promoted the growth of cyanobacteria as harmful algal blooms, which can not only seriously destroy the biodiversity but also threaten the drinking water safety (Paerl and Huisman 2008). Therefore, a great deal of effort has been devoted toward the development of various new techniques to reduce and control the concentration of phosphate in wastewater (Barca et al. 2012; Yao et al. 2011a; Hui et al. 2014; Sowmya and Meenakshi 2014).

Among these techniques, adsorption method is considered to be superior to other techniques for water reuse in terms of cost, simplicity of design, ease of operation, and insensitivity to toxic substances (Meshko et al. 2001, Liu et al. 2009). Various industrial solid wastes, agricultural by-products, and similar materials have been employed as adsorbents for phosphate removal (Selvi et al. 2001). Red mud, a solid waste from alumina production, has attracted great interest in recent years. Various attempts have been tried on the application of red mud adsorbent for aqueous pollutants, especially phosphate (Huang et al. 2008; Zhao et al. 2009; Castaldi et al. 2010). However, most materials used in these research studies are not suitable for commercial and industrial application, because the powder form of them often causes serious problems like pore clogging, pressure drop, and mass loss during operations. Thus, it is better to stabilize, fix, and granulate the powdered red mud for practical adsorption processes (Dou et al. 2013).

To date, only limited research studies have been performed on investigation and application of granulated red mud for phosphate removal and recovery (Zhao et al. 2012; Despland et al. 2011). In this research, powdered-acid-activated-neutralized red mud (Aan-RM), the chemico-physically modified product of red mud, was for the first time chosen as the main ingredient for novel adsorbent (granular Aan-RM) production for phosphate removal. Meanwhile, hydroxypropyl methylcellulose (HPMC) and powdered straw were applied as cementing agent and aperture producer, respectively. The aims of this study were to (1) assess the influence of different operational factors on phosphate adsorption onto granular Aan-RM, (2) use different kinetic and isotherm models to analyze the adsorption process, and (3) characterize the granular Aan-RM before and after phosphate adsorption to identify the main phosphate adsorption mechanisms.

2 Materials and Methods

2.1 Raw Material

processed (Milačič et al. 2012). The results of X-ray fluorescence analysis (S4 Exploere, Bruker, Germany) indicated that the red mud was primarily a mixture of Fe (47.39 %), Al (22.38 %), Na (12.76 %), Si (8.88 %), and Ti (7.33 %) oxides. HPMC was of analytical grade (Alfa Aesar, China). The sun-dried straws were from Hunan, China, and were milled into powders with an average diameter of 0.25 mm.

2.2 Preparation of Granular Aan-RM

Powdered Aan-RM, which was also described by the term "acid-activated Bauxsol" (Genç-Fuhrman et al. 2004, Despland et al. 2011), was prepared by the methods reported in Ye et al. (2014). Granular Aan-RM samples were produced by evenly mixing powdered Aan-RM, powdered straw, and HPMC, and then an appropriate amount of pure water was added to form a paste with the thickness of 2 mm. The paste was then cut into particles, which were naturally dried in the open air for 24 h. After that, they were sintered for a certain time.

According to the preliminary experiments, the optimal mass ratio of powdered AaN-RM, powdered straw, and HPMC was chosen as 71:22:7, and the optimal sintering temperature and sintering time were 225 °C and 30 min, respectively.

2.3 Characterization of Granular Aan-RM

The specific surface area and total pore volume of granular Aan-RM were determined by BET N₂ adsorption–desorption analysis using a surface area analyzer (ASAP 2020 V3.04 H, Micromeritics, USA). The surface morphology was analyzed with an electron dispersive X-ray analysis (OXFORD X-Max, Oxford Instruments, UK), which was coupled with an electronic detector (LEO 1530, LEO, Germany). The XRD pattern of granular Aan-RM was detected using an X-ray diffractometer (XRD-6000, Shimadzu, Japan) with Cu K α radiation at 40 kV and 30 mA. The XRD patterns were recorded in a 2θ range of 10° – 70° at a scan speed range of 0.02° /s.

2.4 Batch Adsorption Experiment

Many industrial wastewaters contain high concentration of phosphate. For instance, Sohsalam and Sirianuntapiboon (2008) found that the phosphorus concentration in molasses wastewater reached 225– 3038 mg/L. Mohana et al. (2009) showed that the phosphate concentration in distillery spent wash was about 740–2500 mg/L. Vymazal (2014) concluded that the phosphate concentration in olive oil mill wastewater was higher than 410 mg/L. Meanwhile, it is reported that the temperature of industrial wastewaters varied greatly, which even reached 70–80 °C (Pandey et al. 2003). In order to investigate the potential of granular Aan-RM for treating industrial wastewater with high phosphate concentration in a wide temperature range, the initial phosphate concentration and adsorption temperature were chosen as 500 mg/L and 20–70 °C, respectively.

A series of phosphate solutions (500 mg/L) with different pH (varying from 1.0 to 9.0) were prepared with 1 and 0.1 mol/L HCl or NaOH solution. The influences of dosage, initial solution pH, and adsorption temperature on the phosphate adsorption performance of granular Aan-RM were performed in beaker flasks. The beaker flasks were shaken at 100 r/min for 48 h with different granular Aan-RM dosages (varying from 1.0 to 6.0 g/L) and adsorption temperatures (varying from 20 to 70 °C). After equilibrium, the samples were centrifuged at 3000 r/min for 1 min and the supernatants were taken to analyze the phosphate concentration. The equilibrium time of 48 h was determined by the preliminary experiments.

Adsorption kinetic experiments were conducted in beaker flasks containing 500 mg/L phosphate solution with granular Aan-RM dose of 3 g/L. The flasks were shaken at 100 r/min. The samples were taken at predetermined time intervals, centrifuged, and analyzed for the residual phosphate concentration.

Adsorption isotherm experiments were conducted in beaker flasks containing different phosphate solutions (50, 150, 250, 500, 1000, 2000 mg/L) with a granular Aan-RM dose of 3 g/L. The flasks were shaken at 100 r/ min until reaching equilibrium. After equilibrium, samples were centrifuged and analyzed for the residual phosphate concentration.

All experiments were conducted in triplicate and the average values were used for data analysis. The phosphate concentration was determined via the spectrophotometric method DIN-EN-ISO-15681-1 with a QuikChem 8500 flow injection analysis system (Lachat Instruments, USA). The phosphate adsorbed by per unit of granular Aan-RM was calculated by Eq. (1):

$$q = \frac{(C_i - C_f) \cdot V}{m} \tag{1}$$

where $q \text{ (mg/g, as PO_4^{3^-})}$ is the phosphate adsorption capacity per unit of granular Aan-RM, $C_i \text{ (mg/L)}$ and $C_f \text{ (mg/L)}$ are the initial and final phosphate concentration, respectively, V (L) is the solution volume, and m (g) is the mass of sorbent.

Phosphate solution was prepared by potassium dihydrogen phosphate, which was of analytical grade (Merck, Germany). The adsorption temperature was controlled with a gyratory water bath shaker (model G76, New Brunswick Scientific, USA). The pH value of phosphate adsorption was measured with a multimeter (model Multiline P4, WTW, Germany).

2.5 Kinetics and Isotherms

The kinetics data were fitted using different models in order to elucidate the adsorption mechanism. In addition to the commonly used pseudo first-order and pseudo second-order models, Elovich model and Ritchie *n*th-order model were also used, and the governing equations are (Ma et al. 2009; Yahyaei et al. 2014; Yao et al. 2011b)

$$\frac{\mathrm{d}q_{\mathrm{t}}}{\mathrm{d}t} = k_1(q_{\mathrm{e}} - q_{\mathrm{t}}) \quad \text{Pseudo} \quad \text{first-order} \tag{2}$$

$$\frac{\mathrm{d}q_{\mathrm{t}}}{\mathrm{d}t} = \alpha \exp(-\beta q_{\mathrm{t}}) \quad \text{Elovich} \tag{3}$$

$$\frac{\mathrm{d}q_{\mathrm{t}}}{\mathrm{d}t} = k_2 (q_{\mathrm{e}} - q_{\mathrm{t}})^2 \quad \text{Pseudo} \quad \text{second-order} \quad (4)$$

$$\frac{\mathrm{d}q_{\mathrm{t}}}{\mathrm{d}t} = k_{\mathrm{n}}(q_{\mathrm{e}}-q_{\mathrm{t}})^{n} \qquad \text{Ritchie} \qquad n\text{th-order} \qquad (5)$$



Fig. 1 Photograph (a) and SEM (b) image of granular Aan-RM



Fig. 2 XRD pattern of granular Aan-RM

where $q_e (mg/g)$ and $q_t (mg/g)$ are the adsorption capacities of the sample at equilibrium and at time t (min), respectively; $k_1 (min^{-1})$, $k_2 (g/(mg \cdot min))$, and $k_n (g^{n-1}/(mg^{n-1} \cdot min))$ are the equilibrium rate constants for the pseudo first-order, the pseudo second-order, and *n*thorder kinetic models; and $\alpha (mg/(g \cdot min))$ and $\beta (g/mg)$ are the Elovich constants.

Three common types of isotherms, Langmuir isotherm, Freundlich isotherm, and Langmuir–Freundlich isotherm, were applied to describe the equilibrium adsorption. The governing equations are shown as Eqs. (6–8) (Yao et al. 2011b):

$$q_{\rm e} = \frac{K_l Q C_{\rm e}}{1 + K_l C_{\rm e}} \qquad \text{Langmuir} \tag{6}$$



Fig. 3 The influence of dosage on phosphate adsorption capacity of granular Aan-RM (initial phosphate concentration, 500 mg/L; initial solution pH, 7.0; adsorption temperature, 20 °C; agitation speed, 100 r/min)



Fig. 4 The influence of adsorption temperature on phosphate adsorption capacity of granular Aan-RM (initial phosphate concentration, 500 mg/L; Aan-RM dosage, 3 g/L; initial solution pH, 7.0; agitation speed, 100 r/min)

$$q_{\rm e} = K_{\rm f} C_{\rm e}^{\ n} \quad \text{Freundlich} \tag{7}$$

$$q_{\rm e} = \frac{K_{lf}QC_{\rm e}^{\ n}}{1 + K_{lf}C_{\rm e}^{\ n}} \qquad \text{Langmuir} \quad -\text{Freundlich} \quad (8)$$

where $C_{\rm e}$ (mg/L) is the equilibrium concentration of solution, $q_{\rm e}$ (mg/g) is the adsorption capacity of the sample at equilibrium, Q (mg/g) is the maximum adsorption capacity of sample, K_1 (L/mg) represents the Langmuir bonding term related to interaction energies,



Fig. 5 The influence of initial solution pH (pH_i) on phosphate adsorption capacity of granular Aan-RM and the solution pH after phosphate adsorption (pH_f) (initial phosphate concentration, 500 mg/L; Aan-RM dosage, 3 g/L; adsorption temperature, 40 °C; agitation speed, 100 r/min)



Fig. 6 Adsorption kinetics of phosphate adsorption onto granular Aan-RM (granular Aan-RM dosage, 3 g/L; initial concentration, 500 mg/L; initial solution pH, 6.0; adsorption temperature, 40 °C; agitation speed, 100 r/min)

 $K_{\rm f}(({\rm mg}^{(1-{\rm n})}\cdot{\rm L}^{\rm n})/{\rm g})$ is the Freundlich affinity coefficient, $K_{\rm lf}({\rm L}^{\rm n}/{\rm mg}^{\rm n})$ represents the Langmuir–Freundlich affinity parameter, and *n* (dimensionless) is the Freundlich linearity constant.

2.6 Adsorption Mechanism Analysis

Granular Aan-RM after phosphate adsorption was characterized for further mechanism analysis. The granular Aan-RM was collected from isotherm studies with an initial phosphate concentration of 500 mg/L, followed by rinsing with deionized water and drying at 50 °C. X-ray photoelectron spectroscopy (XPS) measurements were performed using an X-ray photoelectron spectrometer (Escalab 250Xi, Thermo Scientific, UK) equipped with Al K α radiation (1486.6 eV) to determine the elemental composition on the surface of granular Aan-RM.

3 Results and Discussion

3.1 Properties of Granular Aan-RM

Photograph of the granular Aan-RM is shown in Fig. 1a. The granules were 2 mm in length, 2 mm in width, and 1–2 mm in height. The corresponding SEM image is shown in Fig. 1b, which clearly reveals the rough and porous surface of granular Aan-RM. With BET N₂ adsorption–desorption analysis, it was found that the BET surface area and total pore volume of granular Aan-RM were 113.54 m²/g of 0.0287 cm²/g, respective-ly. Figure 2 shows X-ray diffraction patterns of granular Aan-RM. Granular Aan-RM had specific chemical composition diffraction peaks at different 2 θ (°), indicating the presence of FeOCl, gibbsite (Al(OH)₃), anatase (TiO₂), and quartz (SiO₂).

3.2 Influence of Operational Parameters on Phosphate Removal

According to the results from preliminary experiments, three main operational factors influencing the phosphate adsorption performance of granular Aan-RM were chosen: granular Aan-RM dosage, adsorption temperature, and initial solution pH.

3.2.1 The Influence of Granular Aan-RM Dosage

The influence of dosage of granular Aan-RM on phosphate adsorption capacity is shown in Fig. 3. When the dosage of granular Aan-RM was higher than 3.0 g/L, the phosphate adsorption capacity of granular Aan-RM decreased significantly. The increase of adsorbent dosage would increase the collision probability between different adsorbent particles, which would reduce the efficient utilization of functional groups on adsorbent surface, and then

 Table 1
 Calculated parameter values for adsorption kinetics for phosphate adsorption onto granular Aan-RM (granular Aan-RM dosage, 3 g/L; initial concentration, 500 mg/L; initial solution pH, 6.0; adsorption temperature, 40 °C; agitation speed, 100 r/min)

Models	Parameter 1	Parameter 2	Parameter 3	R^2
Pseudo first-order	$k_1 = 0.042 \ (\text{min}^{-1})$	$q_{\rm e}$ =113.037 (mg/g)		0.9345
Elovich	α =153.933 (mg/(g·min))	β =0.087 (g/mg)		0.9803
Pseudo second-order	$k_2 = 2.309 \text{E-4} (g/(\text{mg·min}))$	$q_e = 119.282 \text{ (mg/g)}$		0.9886
<i>n</i> th-order	$k_n = 3.268 \text{E-7} (\text{g}^{n-1} / (\text{mg}^{n-1} \cdot \text{min}))$	$q_e = 122.439 \text{ (mg/g)}$	<i>n</i> =3.422	0.9997



Fig. 7 Comparison of different isotherm models for phosphate adsorption onto granular Aan-RM (granular Aan-RM dosage, 3 g/L; initial phosphate concentrations for isotherms, 50, 150, 250, 500, 1000, and 2000 mg/L; initial solution pH, 6.0; adsorption temperature, 40 °C; agitation speed, 100 r/min)

influence the phosphate adsorption capacity (Babatunde et al. 2008). Therefore, adsorbent dosage of 3.0 g/L was chosen for the following experiments.

3.2.2 The Influence of Adsorption Temperature

As shown in Fig. 4, the phosphate adsorption capacity of granular Aan-RM first increased with the increase of adsorption temperature and then decreased. The maximum phosphate adsorption capacity reached 84.56 mg/ g with the adsorption temperature of 40 °C. The influence of adsorption temperature on the performances of various adsorbents was different. Schreiber et al. (2005) demonstrated that increasing the temperature from 5 to 35 °C had a positive effect on dissolved organic matter adsorption onto activated carbon. Angove et al. (1998) also found that the adsorption of Cd(II) and Co(II) onto goethite increased as the temperature was increased from 10 and 70 °C. However, Riebe et al. (2005)

 Table 2
 Calculated parameter values for adsorption isotherms for phosphate adsorption onto granular Aan-RM (granular Aan-RM dosage, 3 g/L; initial phosphate concentrations for isotherms, 50,

illustrated that with equilibrium temperatures of 20– 60 °C, the iodide adsorption performance of organoclay minerals decreased slightly with increasing temperature. This phenomenon could be explained by the thermodynamic and entropic effects of different adsorption processes (Schreiber et al. 2005). In this research, the phosphate adsorption capacity of granular Aan-RM decreased after adsorption temperature was higher than 40 °C. This might be because the stability of granular Aan-RM was influenced by the higher temperature, which would further result in the decrease of phosphate adsorption capacity. A similar result was reported by Liu et al. (2007). Therefore, the optimal adsorption temperature was 40 °C.

3.2.3 The Influence of Initial Solution pH

The influence of pH variation on granular Aan-RM performance was investigated, and the results are shown in Fig. 5. With the increase of pH, the phosphate adsorption capacity of granular Aan-RM first increased and then decreased. The highest phosphate adsorption capacity of 120.68 mg/g was observed when pH value was 6.0. A similar behavior was also reported for the adsorption of anionic species from aqueous solution on other red mud adsorbents (Pradhan et al. 1999; Liu et al. 2007; Genç-Fuhrman et al. 2004). At relatively low pH, the competition adsorption between OH⁻ and phosphate was not strong. So the neutralization of negatively charged phosphate with the positively charged metal species on the surface of granular Aan-RM such as ferrum and aluminum species could be promoted. However, if pH was too low, the phosphate adsorption performance would be restricted because phosphoric acid (H₃PO₄) was the main existence form, which was not as active as $H_2PO_4^-$ and HPO_4^{2-} in chemical adsorption (Kim et al. 2002). Therefore, the optimal initial solution pH was 6.0.

150, 250, 500, 1000, and 2000 mg/L; initial solution pH, 6.0; adsorption temperature, 40 $^{\circ}\mathrm{C}$; agitation speed, 100 r/min)

Models	Parameter 1	Parameter 2	Parameter 3	R^2
Langmuir Freundlich	$K_{\rm I}$ =0.015 (L/mg) $K_{\rm r}$ =25.329 ((mg ⁽¹⁻ⁿ⁾ .1 ⁿ)/g)	Q = 162.687 (mg/g) n = 0.258		0.9824
Langmuir-Freundlich	$K_{\rm f}$ =0.003 (L ⁿ /mg ⁿ)	Q = 153.227 (mg/g)	s=1.439	0.8752

The relationship between the initial solution pH (pH_i) and the solution pH after phosphate adsorption (pH_f) is also shown in Fig. 5. A higher phosphate adsorption capacity agreed with a higher difference between pH_i and pH_f. As shown in Fig. 1, FeOCl and Al(OH)₃ were the effective chemical compositions of granular Aan-RM for phosphate removal. Therefore, the possible mechanisms for the relationship between pH_i and pH_f were as Eqs. (9–11). The release of hydrogen ions after the phosphate adsorption reactions resulted in the pH change:

$$FeOCl \rightarrow FeO^+ + Cl \tag{9}$$

$$FeO^{+} + HPO_{4}^{2^{-}}/H_{2}PO_{4}^{-} \rightarrow [FeO-PO_{4}]_{adsorption species} + H^{+}$$
(10)

$$Al(OH)_{3} + HPO_{4}^{2-}/H_{2}PO_{4}^{-} \rightarrow [Al(OH)_{3} - PO_{4}]_{adsorption species} + H^{+}$$
(11)

3.3 Kinetics and Isotherm

Kinetics data for phosphate adsorption onto granular Aan-RM are shown in Fig. 6. It is found that the phosphate adsorption took place with two interconnected processes: a rapid initial adsorption process, which took place within 720 min, followed by a slow adsorption process. This behavior was similar to the finding reported by Luengo et al. (2007), who proposed the fast process as the direct binding between the oxoanions in aqueous solution and the functional groups on adsorbent surface. However, there was no consensus regarding the reaction in slow process, which might be controlled with several possible mechanisms such as intraparticle diffusion or diffusion into pores (Grossl et al. 1997; Zhang & Stanforth 2005).

The pseudo first-order, pseudo second-order, and *n*th-order model can describe the kinetics of solidsolution system based on mononuclear, binuclear, and n-nuclear adsorption. The Elovich model is an empirical equation considering the contribution of desorption (Gerente et al. 2007). The related kinetics parameters are summarized in Table 1. It was found that the pseudo second-order model and *n*th-order model (n=3.422) better fitted the kinetic data than pseudo first-order model and Elovich model with R^2 exceeding 0.9850. The results demonstrated that polynuclear adsorption including binuclear adsorption existed, suggesting that



Fig. 8 XPS spectra of survey before phosphate adsorption (a), after phosphate adsorption (b), and P 2p (c) region for granular Aan-RM after phosphate adsorption

the phosphate adsorption onto granular Aan-RM could be controlled by multiple mechanisms.

 Table 3
 Proportion of different

 phosphate species reacted with
 the functional groups on the surface of granular Aan-RM

Binding energy	Phosphate species	Functional groups	Proportion
135.2 eV	$H_2PO_4^-$	FeO ⁺ /Al(OH) ₃	19.23 %
134.2 eV	HPO_4^{2-}	FeO ⁺ /Al(OH) ₃	59.78 %
133.4 eV	H_3PO_4 analog	[FeO-PO4] _{adsorption} species/ [Al(OH)3-PO4] _{adsorption} species	20.99 %

The maximum phosphate adsorption capacity of granular Aan-RM obtained from isotherm study was greater than 150 mg/g, indicating that granular Aan-RM could be used as an effective phosphate adsorbent (Fig. 7). Calculated parameter values of adsorption isotherms for phosphate adsorption onto granular Aan-RM are shown in Table 2. The Langmuir–Freundlich model matched the experimental data better than Langmuir model and Freundlich model, suggesting that the interaction between phosphate adsorbed and granular Aan-RM could be affected by both the Langmuir and Freundlich processes. These results are consistent with the kinetics study results that the phosphate adsorption onto granular Aan-RM could be governed by multiple mechanisms.

3.4 Adsorption Mechanism

As shown in Fig. 8a, iron (Fe), aluminum (Al), oxygen (O), silicon (Si), and carbon (C) were detected on the surface of granular Aan-RM before phosphate adsorption. After phosphate adsorption, phosphorus (P) appeared on the spectrum (Fig. 8b), which demonstrated that phosphate was successfully adsorbed onto the surface of granular Aan-RM.

XPS spectra of P 2p region for granular Aan-RM after phosphate adsorption are shown in Fig. 8c. The binding energies of the P 2p peak represented three kinds of phosphorus ions in the solution. Phosphate could react with FeO⁺ and Al(OH)₃ by the precipitation and ion exchange mechanisms (Barbaux et al. 1992). The formed phosphate complexes including [FeO-PO₄]_{adsorption} species and [Al(OH)₃-PO₄]_{adsorption} species could also adsorb additional H₃PO₄ analog by hydrogen bonding (Vanderkooi 1983). The proportion of different phosphate species reacted with the functional groups on the surface of granular Aan-RM is shown in Table 3 (Barbaux et al. 1992; Yao et al. 2013). As shown in Table 3, 79.01 % of the phosphate was adsorbed onto granular Aan-RM through the precipitation and ion exchange mechanisms with strong chemical bonds, and 20.99 % of the phosphate was adsorbed through the surface deposition mechanism with weak chemical bonds.

4 Conclusion

- The adsorbent dosage, adsorption temperature, and initial solution pH could influence the adsorption performance of granular Aan-RM significantly. The optimal granular Aan-RM dosage, adsorption temperature, and initial solution pH were 3.0 g/L, 40 °C, and 6.0, respectively.
- The kinetics and isotherm studies showed that the phosphate adsorption process was well described by Ritchie *n*th-order kinetic model and Langmuir–Freundlich isotherm, which demonstrated that the phosphate adsorption onto granular Aan-RM could be governed by multiple mechanisms.
- XPS analysis of P 2p peak on granular Aan-RM after phosphate adsorption demonstrated that 79.01 % of the phosphate was adsorbed onto granular Aan-RM through the precipitation and ion exchange mechanisms with strong chemical bonds, and 20.99 % of the phosphate was adsorbed through the surface deposition mechanism with weak chemical bonds.

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