Desalination and Water Treatment
www.deswater.com

doi:10.5004/dwt.2017.20909

82 (2017) 170–178
July

Sustainable use of autoclaved aerated concrete waste to remove low concentration of Cd (II) ions in wastewater

Yuan Zhang, Lixuan Zeng*, Yuan Kang, Jiwen Luo, Weijie Li, Qiuyun Zhang

School of Chemistry and Environment, South China Normal University, No378, Waihuanxi Rd, Guangzhou 510006, China, Tel. +86 20 15521044429, email: 1257557278@qq.com (Y. Zhang), Tel. +86 20 13640221972, email: zenglx@scnu.edu.cn (L. Zeng), Tel. +86 20 18802007448, email: 519125292@qq.com (Y. Kang), Tel.+86 2015986331172, email: Holdit@126.com (J. Luo), Tel. +86 20 13560004628, email: 61869106@qq.com (W. Li), Tel. +86 20 13924100425, email: hnsdhks@163.com (Q. Zhang)

Received 18 November 2016; Accepted 11 May 2017

ABSTRACT

As an industrial byproduct, autoclaved aerated concrete waste (AACW) was used as an efficient and economic adsorbent for Cd (II) removal in wastewater. The structure and physical properties of AACW were characterized by XRF, SEM, XRD and its adsorption properties for removal of 3 mg/L Cd (II) under different conditions were also investigated. The results showed that the removal rate of AACW for Cd (II) has attained 97% after 90 min when the initial dosage of AACW was 10 g/L. The adsorption process was fitted to Langmuir model and pseudo-second-order kinetic model. Physisorption and chemisorption were both observed during the process. Besides, AACW possesses comprehensive removal effects for other heavy metal ions in industrial wastewater. The adsorption of Cd (II) ion was affected by other metal ions and different ions in the solution showed different inhibitory effects. Taken together, the AACW recycled from the construction process could serve as a promising adsorbent for toxic metals remediation from aqueous solution.

Keywords: Autoclaved aerated concrete; Industrial wastes; Cd (II); Adsorption; Chemisorption

1. Introduction

As one of the most toxic heavy metals, Cadmium (Cd) has attracted increasing attention of environmentalists for its irreversible impact on both human health and natural environment [1]. It is listed as the sixth most poisonous substance jeopardizing human health and being bio-accumulated in organism body such as bone, liver and kidneys [2]. Cd enters into the water from various industrial activities such as smelting, cadmium–nickel batteries, metal plating, mining, pigments and alloy industries [3,4]. Cd (II) is defined as the first category of hazardous waste pollutants in the Integrated Wastewater Discharge Standard of China (GB 8978-1996) with maximum acceptable emission concentration of 0.1 mg/L. And the drinking water guideline value recommended by World Health Organization as well as the permissible limit for Cd (II) in drinking water in China is 0.005 mg/L [5]. Exposure to low amounts of cadmium may cause disorders such as heart disease, cancer and diabetes [6]. The concentration of Cd (II) in wastewater and the most contaminated leachates may reach up to 3 mg/L [7]. However, previous studies focused on the removal of high concentrations of Cd (10–500 mg/L), so research on remediation the toxic metal at low concentrations is necessary, as presented in this paper.

Given pervasive cadmium contamination and the low industrial wastewater emission standards (0.1 mg/L), there is considerable interest in the development of techniques to remove cadmium from contaminated water before it reaches drinking water sources. Among various methods for removing Cd (II) and other heavy metals from aqueous solution, adsorption process has attracted much attention due to its economy and high efficiency [2]. Therefore, a large number of alternative non-conventional low-cost materials including natural materials and waste products from the industrial sector have been tested as adsorbent for the removal of heavy metals [8–10]. Meanwhile, there is upsurge of interest to exploit applicable adsorbents from various industrial wastes, e.g. fly ash, red mud and differ-

---

*Corresponding author.

1944-3994 / 1944-3986

ent types of slag [11–14] for the recovery of Cd (II) from aqueous solution and industrial effluents, which enable the reduction of adsorbent costs and help resolving problems in industrial waste utilization [15].

Autoclaved aerated concrete (AAC, Fig. 1a), a light weight and highly porous wall material owning national standard for preparation, has been invented in Sweden in 1923 and now becomes a worldwide attractive building material [16,17]. Abundant solid waste residues (Fig.1b, 1c) are unavoidably generated in the process of production of AAC [18], hence how to utilize or reuse this kind of industrial by-product has become a significant issue in recent years. To date, several studies have focused on that AACW could serve as an adsorbent or filter medium to purify the wastewater containing phosphate or oil products [15,18–23]. However, to our knowledge, little research has been conducted on the utilization of AACW for remediation of heavy metals from aqueous solutions. In fact, in addition to its wide availability, strong acid neutralization and coagulation-sedimentation ability, the excellent adsorption and cation exchange capacity of AACW has made it a potential adsorbent for the removal of heavy metals.

In the present experiment, we explore the viability of AACW as a novel economical adsorbent for the treatment of low concentration (3 mg/L) of Cd (II) ions in aqueous solution. The optimal adsorption conditions were investigated under varying experimental conditions, such as adsorbent dosage, solution pH, contact time, and initial concentration. And the kinetics and equilibrium data of the adsorption process were studied to quantify the adsorptive capacity. Cd (II) removal mechanism of AACW was also discussed. Moreover, the removal efficiency for other heavy metals by AACW and competitive adsorption of Cd (II) with Zn (II), Cu (II) and Ni (II) ions in mixed metals solution were proposed here.

2. Materials and Methods

2.1. Preparation of materials

Autoclaved aerated concrete waste (AACW) used in this study was obtained from a building materials factory in Guangzhou, China. The material was ground and sieved to pass through 100 mesh sieve (0.15 mm), then dried at 105±0.5°C for 4 h and cooled to ambient temperature in a desiccator. The appearance of the fresh AACW is shown in Fig.1 and the main ingredients or the significant components are presented in Table 1.

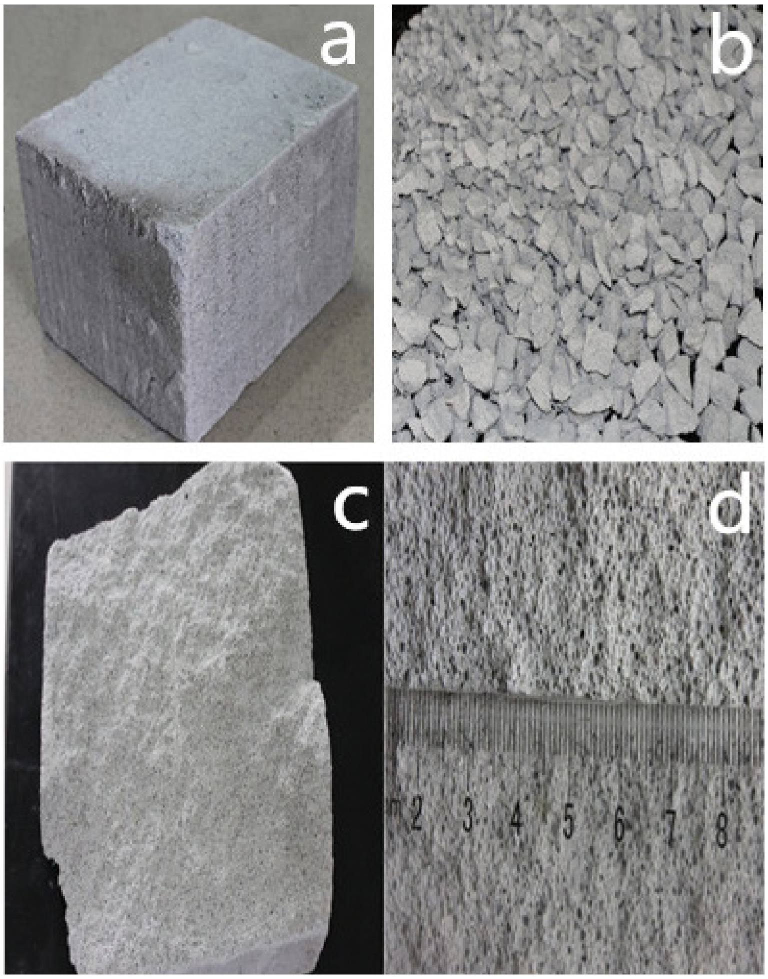

Fig. 1. Visual images of fresh AAC (a) and AACW (b, c, d).

Table 1
The chemical composition of AAC

Compound	wt (%)
SiO_2	48.11
CaO	28.59
Al_2O_3	8.25
Fe_2O_3	5.39
MgO	0.74
K_2O	0.72
SO_3	0.67
Na_2O	0.19

2.2. Preparation of solutions

All the chemicals used in this study were in the analytical grade and were used without further purification. Cd (II), Cu (II), Pb (II), Ni (II) and Zn (II) stock solution were prepared by dissolving an accurate quantity of their nitrate salt in deionized water, and other desired concentrations were prepared from the stock solution (1000 mg/L) by dilution, respectively. The pH of the solution was adjusted using 0.1 M HCl or 0.1 M NaOH. All laboratory wares used for analytical determination were cleaned first by trace metal grade nitric acid, followed by repeated rinsing with deionized water and oven-dried before each experiment.

2.3. Characterization, test method and instruments

The chemical composition of AACW was obtained by X-ray Fluorescence (XRF) (PW2404, PHILIPS Company). The X-ray diffraction patterns (XRD) of the samples before and after adsorption were measured on D8 advance X-ray diffractometer (Bruker, Germany) with Cu Kα radiation in the diffraction angle (2θ) range of 10–70°. Surface morphology of the adsorbent was determined by scanning electron microscope (SEM) (Zeiss Ultra 55, German). And the specific surface areas of the samples were determined from the N_2 sorption isotherms at –196°C by applying the Brunauer, Emmett and Teller (BET) method [25] using a surface area analyzer (ASAP2020, Micromeritics, USA).

In adsorption batch experiments, the conical flasks were shaken at room temperature (25°C) at 200 rpm using on a model HZQ-X100 thermo-stated shaker (Suzhou, China). After equilibration, the samples were centrifuged using a low speed centrifuge (KDC-40, Zonkia, China). Finally, the concentration of metal ions was measured by atomic absorption spectrophotometer (TAS-990, Persee, China).

In order to determine the pH of AACW, the samples were placed in deionized water with a solid to liquid ratio 1:100 (1 g material and 100 mL of deionised water) at room temperature (25°C) and agitated by the thermo-stated shaker at 200 rpm for 24 h. The final pH values of the adsorbent in water were determined.

2.4. Experimental designs

Screening experiments were conducted to investigate the adsorption of Cd (II) ions by AACW. All sorption experiments were carried out in 250 mL conical flasks, in which an appropriate amount of adsorbent and 50 mL of Cd (II) ions solution were added. The mixture was next stirred at 200 rpm using on a thermo-stated shaker at 25°C. In order to determine the optimum dosage, different dosages were added into 50 mL of $Cd(NO_3)^2$ solution (pH 6.0) with an initial Cd concentration of 3 mg/L. To evaluate the pH effect, measurements were performed with the initial pH of the solution ranging from 1 to 11 within 2h. For adsorption kinetic study, 10 g/L of AACW were placing in a conical flask containing Cd (II) ion solution at pH 6.0 for predetermined intervals of time. A series of cadmium solution, ranging among 1–35 mg/L, were prepared to determine the equilibrium isotherms following the addition of 10 g/L AACW within 90 min.

Subsequently, the removal efficiency for Cd (II) and other heavy metals by AACW was performed at the same initial concentrations of 10 mg/L for each element including Cd (II), Cu (II), Pb (II), Ni (II) and Zn (II). The whole flasks were shaken continuously for 2 h to attain the equilibrium state. Besides, the change on Cd (II) ions uptake when exposed in binary solute and hybrid metal ions system was tested with constant metal concentration of 10 mg/L respectively.

After adsorption, all solution samples were primarily centrifuged and the supernatant was taken with a syringe and filtered through 0.45 μm filter membrane for analysis. The quantity of metal ions presenting in the filtrate was measured by atomic absorption spectrophotometer. All the experiments were performed in triplicate to ensure accuracy.

2.5. Calculation of removal percentage and adsorption capacity

The removal rate (A %), the amount of heavy metal ions adsorbed per unit mass of adsorbent at time t (Q_t, mg/g), and the amount of metal ions adsorbed per unit mass of adsorbent at equilibrium (Q_e, mg/g), were calculated from the following equations:

$$\mathrm{A}\% = \frac{C_0 - C_e}{C_0} \times 100 \tag{1}$$

$$Q_t = \frac{C_0 - C_t}{m_s} \times V \tag{2}$$

$$Q_e = \frac{C_0 - C_e}{m_s} \times V \tag{3}$$

where C_0 and C_e (mg/L) are the initial and the final concentrations of heavy metal ions in solution respectively, C_t (mg/L) is the concentration at time t. V is the volume of the solution (L) and m_s is the mass of adsorbent powder used (g).

2.6. Sorption isotherm models

Two models including Langmuir and Freundlich were applied to analyze the data. The Langmuir isotherm (Fig. 2, inset) model is based on the equation of

$$\frac{C_e}{Q_e} = \frac{1}{bQ_m} + \frac{C_e}{Q_m} \tag{4}$$

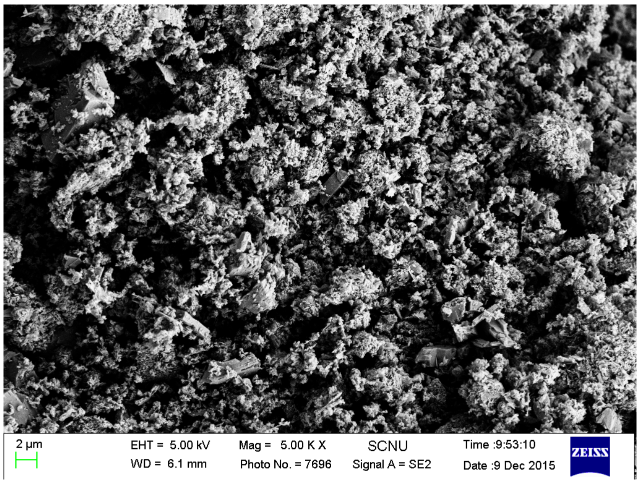

Fig. 2. SEM photograph of fresh AACW powder.

where b (L/mg) is the Langmuir parameter related to energy of adsorption. The linear plot of C_e/Q_e vs C_e gives the intercept and slope corresponding to $1/(Q_m b)$ and $1/Q_m$, respectively, from which both Q_m and b are derived.

The R_L value is a dimensionless parameter to express the essential characteristics of the Langmuir isotherm, which is defined as:

$$R_L = \frac{1}{1 + bC_0} \tag{5}$$

where b is the Langmuir constant and the C_0 is the initial concentration of Cd (II) ions. The value of R_L indicates the type of the isotherm to be either unfavorable ($R_L > 1$), linear ($R_L = 1$), favorable ($0 < R_L < 1$) or irreversible ($R_L = 0$) [4,5].

The Freundlich isotherm is analyzed based on the following equation:

$$\log Q_e = \log k + \frac{1}{n}\log C_e \tag{6}$$

where k [(mg/g)(L/g)$^{1/n}$] and n are Freundlich constants, indicating the sorption capacity and sorption intensity respectively. The plot of log Q_e against log C_e gives the intercept and slope corresponding to log k and n respectively, from which both K and n are obtained.

2.7. Kinetic models

The adsorption kinetic mechanism was evaluated using two conventional models, namely the pseudo-first-order and the pseudo-second-order equations [24]. The pseudo first-order equation is shown as:

$$\log\left(Q_e - Q_t\right) = \log Q_e - k_1 t \tag{7}$$

where k_1 (g/mg min) is the rate constant of the pseudo-first-order sorption, which can be calculated by plotting log $(Q_e - Q_t)$ versus t.

The pseudo-second-order equation can be written as:

$$\frac{t}{Q_t} = \frac{1}{k_2 {Q_e}^2} + \frac{t}{Q_e} \tag{8}$$

where k_2 (g/mg min) is the rate constant of pseudo-second-order adsorption. The values of $1/(k_2 Q_e)^2$ and $1/Q_e$ are derived experimentally from the intercept and slope of the linear plots of t/Q_t versus t.

3. Results and discussion

3.1. Physicochemical characterization of AACW

Since the adsorption process from the liquid phase to the solid phase is influenced by the intrinsic characteristics of the adsorbent, the physicochemical structure of AACW need to be investigated for proper interpretation of Cd (II) remediation from aqueous solution.

The chemical compositions of the AACW detected by the XRF are listed in Table 1. The main chemical compositions of the material consist of SiO_2 and CaO, other oxide composition found in the AACW are Al_2O_3, Fe_2O_3 and MgO and so on.

The SEM micrographs of AACW powder is shown in Fig. 2. SEM observations reveal its surface textures. It shows that AACW mainly contains some pieces of irregular shape particles and porous network structure. These properties should facilitate the diffusion of the Cd(II) ions to the surface of adsorbent. Although Fig. 1 and Fig. 2 both indicate the porous structure of the AACW, a low specific surface area (11.56 m^2/g) was determined by BET analysis. Even lower surface areas for similar materials have been observed earlier [3,8].

The X-ray diffraction (XRD) patterns of AACW are demonstrated in Fig. 3. The main diffraction peaks of the adsorbent are attributed to quartz (SiO_2), tobermorite ($Ca_5Si_6O_{16}(OH)_2{\cdot}4H_2O$), anhydrite ($CaSO_4$), and limestone ($CaCO_3$). In contrast to the XRD pattern of AACW after adsorption, this result shows that $CdCO_3$ (23.20°, 31.86°, 36.13°, 43.38°) was formed after adsorption of 100 mg/L Cd (II), which may indicate that the ion exchange reaction happened between Ca (II) released from AACW and Cd (II) ion in solution.

The AACW is an alkaline material which can release OH^- ions after hydration reaction. The final solution pH was close to 9.0 when 1 g of sample was placed in 100 mL deionised water. It indicated that the adsorbent showed strong acid neutralization capacity as used in wastewater especially acid mine drainage.

3.2. Effect of adsorbent dosage

The effect of the AACW dosage on the removal of Cd (II) is shown in Fig. 4. The removal rate A% increased with an increasing dosage of AACW from 6 g/L to 10 g/L, this tendency results from the availability of larger surface area and more adsorption sites. While the A% remained the same level when adsorbent dosage ranged from 10 g/L to 18 g/L. And at adsorbent dosage >10 g/L, the removal percentage of Cd (II) do not enhance obviously as the surface metal ions concentration and the solution metal ions con-

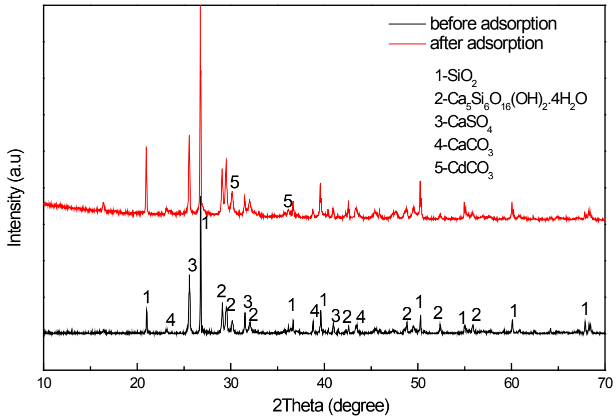

Fig. 3. XRD patterns of AACW before and after adsorption of Cd (II) ions under condition with Cd (II) initial concentration = 3 mg/L, pH 6.0, AACW 10.0 g/L, *t* = 90 min and *T* = 25°C.

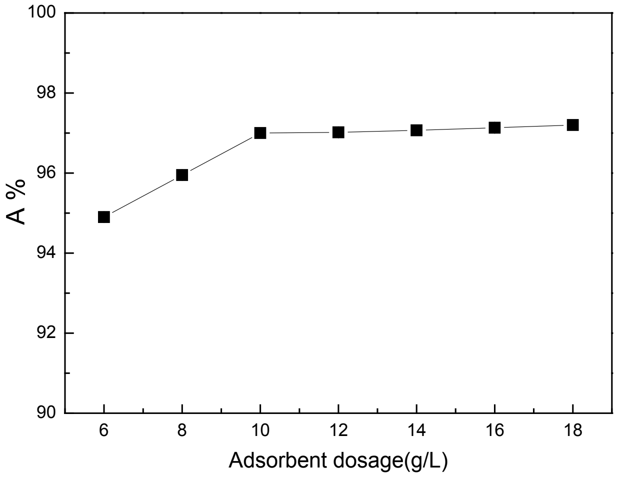

Fig. 4. Effect of adsorbent dose on the removal of Cd (II) ions by AACW under condition with Cd (II) initial concentration = 3 mg/L, pH 6.0, AACW 0.3~2.0 g/L, *t* = 2 h and *T* = 25°C.

centration come to equilibrium with each other [25], besides that, these high amounts of adsorbent had more sorption sites which could not be saturated through the adsorption reaction when the total concentration of Cd(II) ions in the solution remained fixed [26]. As the gain in the removal of Cd(II) using AACW doses higher than 10 g/L did not increase substantially, concurrently the effluent concentration of Cd (II) meet the industrial wastewater emission standards (0.1 mg/L), hence the dose was decided to apply for all future experiments.

3.3. Effect of pH

The pH of the adsorption system strongly influences the adsorption process as it affects the surface charge of the adsorbent and the degree of ionization and speciation of the metal contaminant [27]. Experiments were conducted over a pH ranging from 1 to 11 to study the effect of pH on Cd (II) adsorption by AACW (Fig. 5). In strong acid solution (pH between 1 and 3), only a slight amount of Cd (II) could be removed, and then the removal efficiency increased when pH value up to 3, after which the rate remained stable. Out of overall consideration, the raw water pH 6.0 was employed for further study, avoiding the hydroxide precipitation of Cd at pH value upon 9.36.

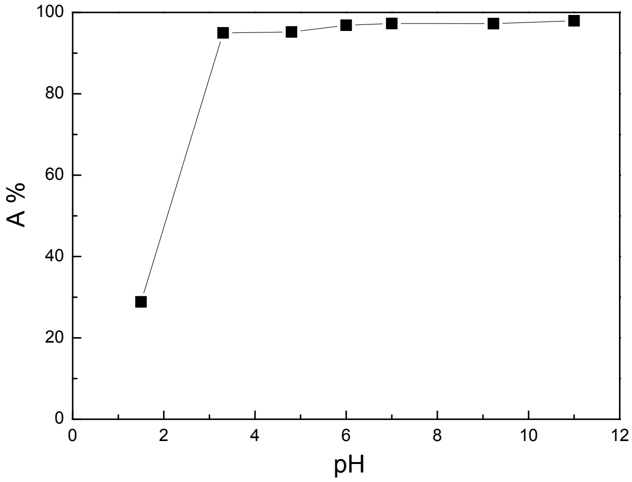

Fig. 5. Effect of pH on the removal of Cd (II) ions by AACW under condition with Cd (II) initial concentration = 3 mg/L, pH 1.0~11.0, AACW 10.0 g/L, *t* = 2 h and *T* = 25°C.

Under strong acid solution, the hydrated surface of AACW is protonated with a reaction (9) and therefore acquired positive charge.

$$\mathrm{Sur-OH}+H^{+}\rightarrow \mathrm{Sur-OH_2^{+}} \tag{9}$$

where Sur stands for the surface sites of the AACW, and the Sur – OH represents a surface hydroxyl group.

Leading to the released OH^- ions (reaction 10) and increase in pH, the hydrated surface of AACW is deprotonated with reaction (11), thereby obtained a negative charge.

$$\mathrm{Sur}+H_2\mathrm{O}\xrightarrow{H^{+}}\mathrm{Sur-OH^{+}}+OH^{-} \tag{10}$$

$$\mathrm{Sur-OH}+OH^{-}\rightarrow \mathrm{Sur}-O^{-}+H_2O \tag{11}$$

Therefore, low pH values are unfavorable for the adsorption process: on the one hand, there would be a competition between protons and Cd (II) ions for the adsorptive sites; on the other hand, electrostatic repulsion takes place between the cationic metal ions and the positively charged surface of the adsorbent in low pH. With an increase in pH, the degree of protonation on surface hydroxyl group of the adsorbent decreased and the adsorption process is more favorable, resulting in an increase in removal efficiency. Similar theories have also been proposed by other researchers for the metal adsorption [3,5,28]. Regarding the $\mathrm{pH_{pzc}}$ of AACW is 5.75, in solution having pH value lower than $\mathrm{pH_{pzc}}$ of AACW, the surface hydroxyl sites could be protonated and positively charged while it was negative at a pH above the $\mathrm{pH_{pzc}}$ [5,28]. However, in this study, the removal of Cd (II) ions was observed in solutions having pH values less than pH_{pzc} of AACW, therefore, the adsorption process on AACW surface would occur via non-electrostatic interaction. Furthermore, the alkalinity nature of the adsorbent makes it a good neutralizing agent with the pH of the effluent water keeping 7–8 in these series of tests, which means that the adsorbent can also act as a pH buffer for the heavy metal removal from acidic wastewater stream.

3.4. Effects of contact time and adsorption kinetics

The results in Fig. 6 show that process of removal Cd (II) was rapid at the beginning and about 90 % of total Cd (II) was removed within 5 min. Thereafter, the removal rate increased slowly before the adsorption equilibrium time of 90 min, and then the removal rate remained constant. Thus, as stated above, the contact time was set to 90 min in the following experiments, which was considered as sufficient for the remediation of Cd (II) ions to meet the industrial wastewater emission standards.

The kinetic parameters for Cd (II) adsorbed by AACW were calculated using the pseudo-first-order and pseudo-second-order equations. The R^2 value for the second-order kinetic model is 0.9999, indicating that the system under study is more appropriately described by the pseudo-second-order model (Fig. 7), which exhibits the following characters: (1) Cd (II) ions were adsorbed onto the adsorbent surface via chemical interaction, (2) the adsorption followed a monolayer regime on the adsorbent surface, (3) the rate of adsorption occurred rapidly at the initial step of adsorption. Similar trends of Cd (II) ions adsorption from aqueous solutions have been reported by other adsorbents [24,28].

3.5. Effects of initial concentration and adsorption isotherms

The effect of initial concentration on the adsorption of Cd (II) ions by AACW was investigated with varying solution concentrations (1, 3, 5, 7, 15, 20, 25, 35 mg/L) using 0.5 g adsorbent dose (Fig. 8) after 90 min of contact time. With increasing concentration of solution, Q_e increased, while A % decreased. At lower initial concentration, the surface area and the availability of adsorption sites were relatively high, and the Cd (II) ions were easily adsorbed and removed. At higher initial concentration, the total available adsorption sites are limited, thus resulting in a decrease in removal rate. The increased Q_e at higher initial concentration can be attributed to enhanced driving force.

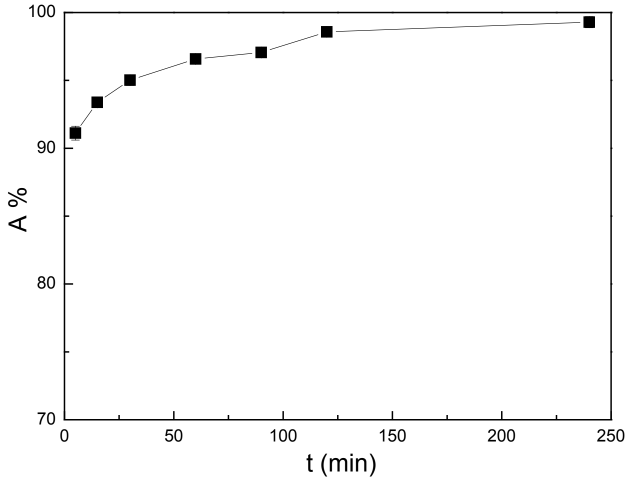

Fig. 6. Effect of the contact time on the removal of Cd (II) ions by AACW under condition with Cd (II) initial concentration = 3 mg/L, pH 6.0, AACW 10.0 g/L, t = 0~240 min and T = 25°C.

The parameters calculated from the Langmuir and Freundlich isotherm models are listed in Table 2. The Langmuir

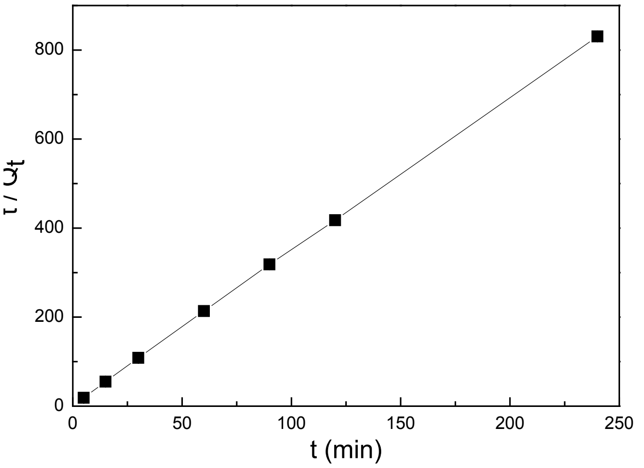

Fig. 7. Pseudo-second-order kinetic model for adsorption of Cd (II) ions on AACW.

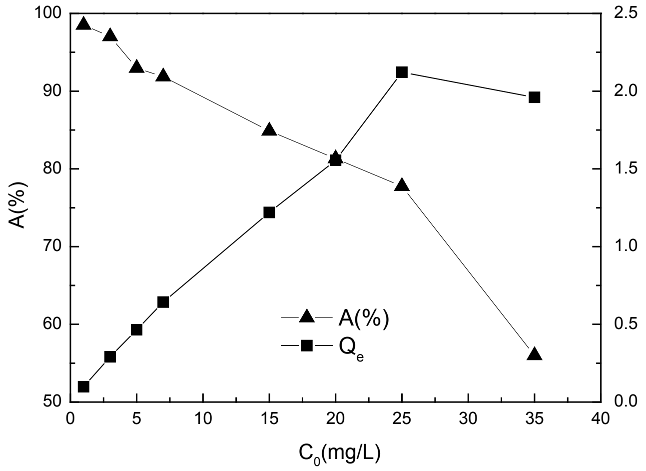

Fig. 8. Effect of initial concentration on the removal and adsorption of Cd (II) ions by AACW under condition with Cd (II) initial concentration = 1~35 mg/L, pH 6.0, AACW 10.0 g/L, t = 90 min and T = 25°C.

Table 2
Langmuir and Freundlich parameters for adsorption of Cd (II) ions on AACW

Freundlich model			Langmuir model		
k	$1/n$	R^2	Q_m	b	R^2
0.7839	0.4561	0.962	2.07	1.07	0.9835

model is more likely applicable due to the higher correlation coefficient (R^2 = 0.9835), indicating the applicability of monolayer coverage of cadmium on AACW surface. Besides, the values of R_L obtained for the present adsorbent is 0.24, suggesting that a favorable adsorption took place in the process studied.

Meanwhile, Table 3 lists a comparison of maximum monolayer adsorption capacity of Cd (II) on some low-cost adsorbents [12,29–33]. The maximum adsorption capacity of AACW is higher than most adsorbents presented in the list. Furthermore, the more promising feature of AACW is the strong acid neutralization capacity which can expand its environmental applications compared with other adsorbents.

3.6. Mechanisms of Cd (II) removal by AACW

In the experiment, chemical adsorption and physical adsorption certainly occurred at the same time during our adsorption experiment process.

The nature of the adsorbent dispersion presented in the SEM micrograph (Fig. 2) confirms the presence of micrometric-sized and irregular-shaped particles, which implying that AACW possess physical adsorption capacity for the heavy metal adsorption. Besides, this adsorbent also emerges unique advantage of coagulation-sedimentation ability to support Cd (II) removal.

Furthermore, ion exchange reaction may happen between the release of interlayer cations such as Ca (II) and Cd (II) in solution to form $CdCO_3$, as demonstrated in the XRD analysis above. On the other side, metal oxide and metal oxide hydrate particles in solution would favor the adsorption of Cd (II) ions depending on metal complexation between surface hydroxyl groups (–M–OH) on particulate matter interface and metal ions as follows:

$$\mathrm{M-OH} + Cd^{2+} \rightarrow M-OCd^{+} + H^{+}\left(M = Si, Ca, Al, Fe, etc.\right) \qquad (12)$$

$$2\mathrm{M-OH} + Cd^{2+} \rightarrow \left[M-O\right]2Cd^{+} + 2H^{+} \qquad (13)$$

$$M-OH + Cd^{2+} + H_2O \rightarrow M-OCdOH + 2H^{+} \qquad (14)$$

Table 3
Comparison of adsorption capacities of Cd (II) ions with some low-cost adsorbents.

Adsorbent	Q_m (mg/g)	Refs
AACW	2.07	This work
Areca waste	1.32	[25]
Kaolinite clay	0.88	[26]
Rice husk	0.89	[27] InD
Saw dust	0.29	[27] InD
Baggase fly ash	2.00	[11]
Pine bark char	0.34	[28]
Oak wood char	0.37	[28]
Coconut copra meal	1.84	[29]

3.7. Removal efficiency for other heavy metals by AACW

The batch screening studies were performed to assess the adsorption of other heavy metals by AACW. For capacity study, the solutions of 10 mg/L of Cu (II), Pb (II), Ni (II), Zn (II) and Cd (II) at raw water pH were used. Using adsorbent dose of 10 g/L, the percentage of removal was obtained after 2 h. As shown in Fig. 9, the removal efficiency was decreased in the order: Pb (II) > Cd (II) > Cu (II) > Zn (II) > Ni (II), implying that AACW as a new low-cost adsorbent expresses comprehensive removal ability for main toxic heavy metal in contaminated water and potential to be applied on actual complex wastewater.

3.8. Competitive adsorption of Cd (II) with Zn (II), Cu (II) and Ni (II) ions

Wastewaters, however, typically contain a mixture of metals may exhibit a different sorption pattern compared

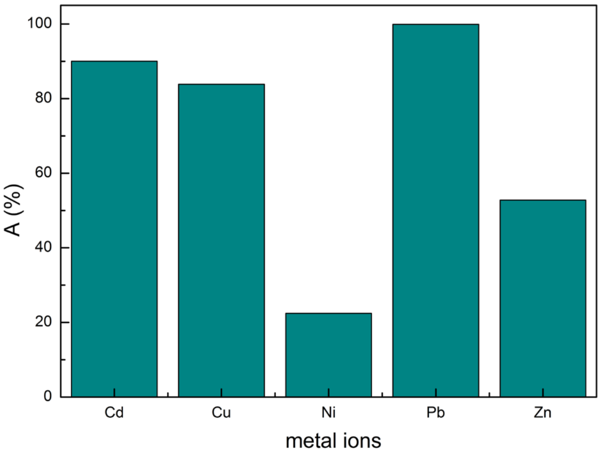

Fig. 9. Removal of different heavy metal ions using AACW under condition with initial concentration of each ion = 10 mg/L, pH 6.0, AACW 10.0 g/L, *t* = 90 min and *T* = 25°C.

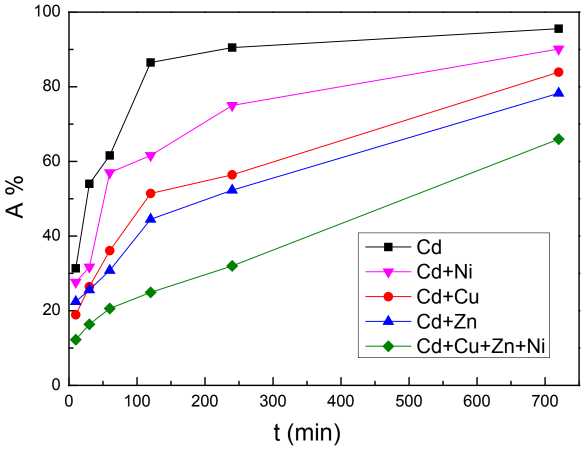

Fig. 10. Competitive adsorption of Cd (II) with Zn (II), Cu (II) and Ni (II) ions from binary and hybrid solute under condition with initial concentration of each ion = 10 mg/L, pH 6.0, AACW 10.0 g/L, *t* = 90 min and *T* = 25°C.

with single metal, resulting in a change on removal efficiency for Cd (II) ion by AACW. In this research, the Cd (II) removal efficiencies were determined when used in binary solute and hybrid metal ions system with constant initial concentration of 10 mg/L, respectively. It proved that Hybrid system emerges the biggest influence on Cd (II) removal effect. In the binary system: the strongest inhibitory effect was mainly attributed to Zn (II), followed by Cu (II) and Ni (II) ion. It indicated that adsorption of Cd (II) ion was reduced by the presence of other metal ions, which competes for the same available adsorption surface active sites onto the adsorbent [34].

4. Conclusions

This study represents the first attempt to establish the ability of AACW to adsorb Cd (II) of low concentration from solutions. The optimum conditions of sorption were as follows: a sorbent dose of 0.5 g in 50 mL of Cd (II), contact time of 90 min and pH 6. The adsorption process was found to follow pseudo-second-order kinetic model and Langmuir isotherm model. The mechanism of Cd (II) remediation by this by-product can be attributed to physisorption and chemisorption including ion exchange reaction as well as metal complexation. The cost-efficient and availability of AACW make it a potentially attractive adsorbent for eliminating Cd (II) and other heavy metals in aqueous solution. Additionally, the last but not least, the application will realize the resource utilization of large quantities of AAC residues resulting from the construction industry.

In the future, modifications and optimization of manufacturing conditions of AACW to enhance the adsorption capacity, in addition to strengthen its applicability at industrial scale need further studies.

Acknowledgment

Financial support from the Science and Technology Planning Project of Guangzhou city, Guangdong Province, China (Grant No. 201510010006) is gratefully acknowledged.

References

[1] G. Chen, G. Zeng, L. Tang, C. Du, X. Jiang, G. Huang, H. Liu, G. Shen, Cadmium removal from simulated wastewater to biomass byproduct of Lentinus edodes, Bioresour. Technol., 99 (2008) 7034–7040.

[2] D. Purkayastha, U. Mishra, S. Biswas, A comprehensive review on Cd(II) removal from aqueous solution, J. Water Proc. Eng., 2 (2014) 105–128.

[3] J. Duan, B. Su, Removal characteristics of Cd(II) from acidic aqueous solution by modified steel-making slag, Chem. Eng. J., 246 (2014) 160–167.

[4] P.A. Amoyaw, M. Williams, X.R. Bu, The fast removal of low concentration of cadmium(II) from aqueous media by chelating polymers with salicylaldehyde units, J. Hazard. Mater., 170 (2009) 22–26.

[5] F.Y. Wang, H. Wang, J.W. Ma, Adsorption of cadmium (II) ions from aqueous solution by a new low-cost adsorbent--bamboo charcoal, J. Hazard. Mater., 177 (2010) 300–306.

[6] H. Javadian, F. Ghorbani, H.-a. Tayebi, S.H. Asl, Study of the adsorption of Cd (II) from aqueous solution using zeolite-based geopolymer, synthesized from coal fly ash; kinetic, isotherm and thermodynamic studies, Arab. J. Chem., 8 (2015) 837–849.

[7] Y. Kalmykova, A.-M. Strömvall, B.-M. Steenari, Adsorption of Cd, Cu, Ni, Pb and Zn on Sphagnum peat from solutions with low metal concentrations, J. Hazard. Mater., 152 (2008) 885–891.

[8] E. Repo, J.K. Warchoł, L.J. Westholm, M. Sillanpää, Steel slag as a low-cost sorbent for metal removal in the presence of chelating agents, J. Ind. Eng. Chem., 27 (2015) 115–125.

[9] S.M. Shaheen, F.I. Eissa, K.M. Ghanem, H.M. Gamal El-Din, F.S. Al Anany, Heavy metals removal from aqueous solutions and wastewaters by using various byproducts, J. Environ. Manage., 128 (2013) 514–521.

[10] D. Sud, G. Mahajan, M.P. Kaur, Agricultural waste material as potential adsorbent for sequestering heavy metal ions from aqueous solutions - a review, Bioresour. Technol., 99 (2008) 6017–6027.

[11] C. Zhu, Z. Luan, Y. Wang, X. Shan, Removal of cadmium from aqueous solutions by adsorption on granular red mud (GRM), Sep. Purif. Technol., 57 (2007) 161–169.

[12] V.K. Gupta, C.K. Jain, I. Ali, M. Sharma, V.K. Saini, Removal of cadmium and nickel from wastewater using bagasse fly ash - a sugar industry waste, Water Res., 37 (2003) 4038–4044.

[13] A. Bhatnagar, V.J. Vilar, C.M. Botelho, R.A. Boaventura, A review of the use of red mud as adsorbent for the removal of toxic pollutants from water and wastewater, Environ. Technol., 32 (2011) 231–249.

[14] L. Remenárová, M. Pipíška, E. Florková, M. Horník, M. Rozložník, J. Augustín, Zeolites from coal fly ash as efficient sorbents for cadmium ions, Clean Technol. Environ., 16 (2014) 1551–1564.

[15] M. Sinica, G. Sezemanas, D. Mikulskis, M. Kligys, V. Česnauskas, Investigation of sorption properties in crushed autoclaved aerated concrete waste, J. Environ. Eng. Landsc., 20 (2012) 67–75.

[16] P. Walczak, J. Małolepszy, M. Reben, P. Szymański, K. Rzepa, Utilization of waste glass in autoclaved aerated concrete, Procedia Eng., 122 (2015) 302–309.

[17] M. Jerman, M. Keppert, J. Výborný, R. Černý, Hygric, thermal and durability properties of autoclaved aerated concrete, Constr. Build. Mater., 41 (2013) 352–359.

[18] T. Bao, T. Chen, M.-L. Wille, D. Chen, J. Bian, C. Qing, W. Wu, R.L. Frost, Advanced wastewater treatment with autoclaved aerated concrete particles in biological aerated filters, J. Water Proc. Eng., 9 (2016) 188–194.

[19] U. Berg, D. Donnert, A. Ehbrecht, W. Bumiller, I. Kusche, P.G. Weidler, R. Nüesch, "Active filtration" for the elimination and recovery of phosphorus from waste water, Colloid. Surface. A: Physicochemical and Engineering Aspects, 265 (2005) 141–148.

[20] W.G. Fu, P.P. Li, Characteristics of Phosphorus adsorption of aerated concrete in wastewater treatment, Adv. Mater. Res., 183–185 (2011) 466–470.

[21] E. Oğuz, A. Gürses, N. Canpolat, Removal of phosphate from wastewaters, Cement Concrete Res., 33 (2003) 1109–1112.

[22] S. Malavipathirana, S. Wimalasiri, N. Priyantha, S. Wickramasooriya, A. Welagedara, G. Renman, Value addition to waste material supported by removal of available Phosphate from simulated brackish water—a low cost approach, J. Geosci. Environ. Prot., 01 (2013) 7–12.

[23] W. Li, L. Zeng, Y. Kang, Q. Zhang, J. Luo, X. Guo, A solid waste, crashed autoclaved aerated concrete, as a crystalline nucleus for the removal of low concentration of phosphate, Desal. Water Treat., 57 (2015) 14169–14177.

[24] H.K. Boparai, M. Joseph, D.M. O'Carroll, Kinetics and thermodynamics of cadmium ion removal by adsorption onto nano zerovalent iron particles, J. Hazard. Mater., 186 (2011) 458–465.

[25] I. Marzouk, C. Hannachi, L. Dammak, B. Hamrouni, Removal of chromium by adsorption on activated alumina, Desal. Water Treat., 26 (2012) 279–286.

[26] Q. Cheng, Q. Huang, S. Khan, Y. Liu, Z. Liao, G. Li, Y.S. Ok, Adsorption of Cd by peanut husks and peanut husk biochar from aqueous solutions, Ecol. Eng., 87 (2016) 240–245.

[27] H.K. Boparai, M. Joseph, D.M. O'Carroll, Cadmium (Cd(2+)) removal by nano zerovalent iron: surface analysis, effects of solution chemistry and surface complexation modeling, Environ. Sci. Pollut. Res. Int., 20 (2013) 6210–6221.

[28] T. Phuengprasop, J. Sittiwong, F. Unob, Removal of heavy metal ions by iron oxide coated sewage sludge, J. Hazard. Mater., 186 (2011) 502–507.

[29] W. Zheng, X.M. Li, F. Wang, Q. Yang, P. Deng, G.M. Zeng, Adsorption removal of cadmium and copper from aqueous solution by areca: a food waste, J. Hazard. Mater., 157 (2008) 490–495.

[30] M.Q. Jiang, X.Y. Jin, X.Q. Lu, Z.L. Chen, Adsorption of Pb(II), Cd(II), Ni(II) and Cu(II) onto natural kaolinite clay, Desalination, 252 (2010) 33–39.

[31] N. Sharma, K. Kaur, S. Kaur, Kinetic and equilibrium studies on the removal of Cd^{2+} ions from water using polyacrylamide grafted rice (Oryza sativa) husk and (Tectona grandis) saw dust, J. Hazard. Mater., 163 (2009) 1338–1344.

[32] D. Mohan, C.U. Pittman, M. Bricka, F. Smith, B. Yancey, J. Mohammad, P.H. Steele, M.F. Alexandre-Franco, V. Gomez-Serrano, H. Gong, Sorption of arsenic, cadmium, and lead by chars produced from fast pyrolysis of wood and bark during bio-oil production, J. Colloid Interf. Sci., 310 (2007) 57–73.

[33] A.E. Ofomaja, Y.S. Ho, Effect of pH on cadmium biosorption by coconut copra meal, J. Hazard. Mater., 139 (2007) 356–362.

[34] L. Zeng, Y. Chen, Q. Zhang, X. Guo, Y. Peng, H. Xiao, X. Chen, J. Luo, Adsorption of Cd(II), Cu(II) and Ni(II) ions by cross-linking chitosan/rectorite nano-hybrid composite microspheres, Carbohyd. Polym., 130 (2015) 333–343.