

Article

Adsorption characteristics of a novel ceramsite for heavy metal removal from stormwater runoff☆



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ABSTRACT

Urban sediments have rapidly increased in recent years around the world, and their effective management has become an important problem. To remove heavy metals from stormwater runoff and use sediments as a resource, a novel ceramsite was developed using sewer pipe sediments (SPS), river bed sediments (RBS), urban water supply treatment sludge (WSTS), and wastewater treatment plant excess sludge (WWTS). The optimal composition was determined based on the Brunauer–Emmett–Teller specific surface area and an orthogonal test design. The adsorption characteristics of the novel ceramsite for dissolved heavy metals (Cu^{2+} and Cd^{2+}) were investigated through adsorption isotherms and kinetic experiments at $(25 \pm 1)^\circ\text{C}$. Both Cu^{2+} and Cd^{2+} were effectively removed by the novel ceramsite, and their equilibrium adsorption was $4.96 \text{ mg} \cdot \text{g}^{-1}$ and $3.84 \text{ mg} \cdot \text{g}^{-1}$, respectively. Langmuir isotherms and a pseudo-first-order kinetic equation described the adsorption process better than other techniques. Characterization analysis of the ceramsite composition before and after heavy metal adsorption showed that the Cu^{2+} and Cd^{2+} contents in the ceramsite increased after adsorption. The results revealed that adsorption is both a physical and chemical process, and that ceramsite can be used as a bioretention medium to remove heavy metals from stormwater runoff while simultaneously converting problematic urban sediments into a resource.

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1. Introduction

Owing to rapid urbanization, impervious surfaces have markedly increased in urban areas, and stormwater runoff has increased both in total volume and peak flow rate [1]. Consequently, urban surface water quality has deteriorated as sewer pipe sediments (SPS) and river bed sediments (RBS) have become increasingly serious under stormwater flushing [2–4]. In addition, with increasing populations and industrialization, larger amounts of municipal sludge such as water supply treatment sludge (WSTS) and wastewater treatment sludge (WWTS) are being produced [5,6].

SPS presents a widespread and serious problem owing to stormwater flushing and a lack of daily sewer maintenance (especially in the old districts of many cities), because the sediments reduce the capacity of drainage pipes, increase hydraulic resistance, and produce overflow pollution in heavy rainfall events [3]. Although several studies on SPS have mainly

focused on the relationships influencing its flushing, composition, and impacts on receiving waters [7–11], research on SPS disposal methods is limited. Likewise, RBS pollution has become more serious owing to the accumulation of toxic pollutants, and its unreasonable disposal has been investigated by some researchers. Nevertheless, owing to its inorganic particles, RBS has been examined as a resource (e.g. for making bricks and ceramsite) and an agricultural input [4,12,13].

Conventional water supply treatment usually includes coagulation, flocculation, filtration, sedimentation, and disinfection, and generates WSTS that contains large amounts of Fe and Al [5,14,15]. Owing to its chemical properties, WSTS has been studied as a low-cost adsorbent for removing pollutants such as ammonium [16], phosphorus [17], and arsenate [18]. Similarly, WWTS is generated during wastewater treatment after dewatering of excess activated sludge. It contains large quantities of organic matter, pathogenic bacteria, and harmful substances. Some researchers have shown that WWTS could be used as a foaming agent in ceramsite production [5,19].

Currently, the disposal of the four sediments, SPS, RBS, WSTS, and WWTS, has been attracting widespread attention. Owing to increasingly stringent sludge disposal regulations, both public and private sediment generators are being forced to re-evaluate their sediment management strategies. As a result, new energy-saving and environment-friendly urban sediment management techniques are urgently needed.

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Nowadays, sustainable development and natural resources preservation have gained significant importance. With the restriction of clay brick and its products, the application of clay as a raw material of ceramsite is limited [20]. According to He *et al.* [5], a variety of raw materials can be used to form ceramsite if the chemical composition of the materials (without any additives) is in the following ranges (%): SiO₂, 48–68; Al₂O₃, 12–18; Fe₂O₃, 5–10; and K₂O + Na₂O, 2.5–7.0. As the four urban sediments contain inorganic components such as Al₂O₃, SiO₂, Fe₂O₃, CaO, MgO, Na₂O, and K₂O (Table 1), these problematic sediments have the potential to be the raw materials for the development of a novel ceramsite. In addition, some researchers have shown that heavy metals in sludge-based ceramsite were immobilized and could not be easily released into the environment to cause secondary pollution [21–24]. Therefore, a new effective approach to manage the four urban sediments is to produce ceramsite, which can both overcome constraints on raw material use and convert the problematic sediments into a resource.

Table 1
Chemical characteristics of the four sediments (%)

Type	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	Burning loss
SPS ^①	29.6	9.1	4.49	7.44	2.31	0.96	1.39	40.5
WSTS ^②	5.97	6.61	16.1	1.42	0.37	0.13	0.13	66.5
RBS ^③	34.8	10.6	3.25	4.6	2.54	0.90	1.58	38.5
WWTS ^④	2.6	2.47	1.24	2.8	0.43	0.11	0.16	83.6

① Sewer pipe sediments.

② Water supply treatment sludge.

③ River bed sediments.

④ Wastewater treatment sludge.

Heavy metal contamination is a serious problem that has prompted considerable research. In contrast to most of the organic pollutants, heavy metals are difficult to degrade in the natural environment and are easily accumulated in living organisms, thereby causing various diseases and disorders [25–27]. Cd is readily taken up by growing plants from contaminated soil and enters the human food chain, leading to acute and chronic diseases [28–30]. Excessive intake of Cu by humans may irritate the mucous membranes, leading to hepatic and renal damage, widespread capillary damage, and central nervous system problems [31–33]. Various methods have been developed to remove heavy metals from water such as chemical precipitation, membrane filtration, and adsorption [23,34,35]. Among them, adsorption has been regarded as an important process owing to its simplicity and efficiency [36–39].

The key objective of successful application of sorption technology is to find a cost-effective, environment-friendly, and high-performance sorbent. The traditional sorbents applied in the removal of Cd mainly include zeolites, clays, activated carbons, biomass, and polymeric materials, none of which are cost-effective. However, in recent years, some low-cost waste byproducts have been used as the sorbent for removing heavy metals. An *et al.* [26] investigated an adsorbent based on jujube for the removal of toxic heavy metals. Hegazi [40] showed that agricultural and industrial waste byproducts such as rice husk and fly ash could be used for removing heavy metals from wastewater. Chen *et al.* [41] demonstrated that a novel ceramic adsorbent developed with a mixture of akadama mud, wheat starch, and Fe₂O₃ could be used for arsenic removal from a water solution. Zou *et al.* [42] tested the nitrogen removal capacity of a self-made sludge-based ceramsite used as a carrier in a biofilter. Therefore, removal of Cu²⁺ and Cd²⁺ from stormwater runoff using a novel ceramsite adsorbent made from a mixture of four urban sediments seems reasonable, and if successful, could lay a foundation for applying ceramsite as a bioretention medium to reduce stormwater runoff pollution.

The objectives of this study were to develop a novel ceramsite based on the four urban sediments (SPS, RBS, WSTS, and WWTS) and Na₂SiO₃, and to evaluate its Cu²⁺ and Cd²⁺ adsorption properties through dynamic and isothermal experiments combined with material characterization analysis.

2. Materials and Methods

2.1. Optimization of ceramsite composition

SPS, RBS, WSTS, and WWTS were obtained from the following locations in Beijing, China: a road at Chegongzhuang West, a river near the Xizhimen subway station, the third water supply treatment plant of Beijing, and the Gaobeidian wastewater treatment plant, respectively. Na₂SiO₃ was used as an adhesive. The chemical characteristics of the four sediments are shown in Table 1.

The four sediments were dried by natural aeration, crushed into powders using a universal pulverizer, and mixed with Na₂SiO₃ according to the optimum ratio determined from orthogonal test. The factors and levels of the orthogonal design are shown in Table 2. The orthogonal test scheme and result analysis are presented in Table 3. The amount of SPS was considered to be a constant in the experiment, and the other four materials were considered as the main factors. Four levels of each factor were evaluated, creating an L₁₆ (4⁵) orthogonal design. The Brunauer–Emmett–Teller (BET) specific surface area of the ceramsite was used as the assessment indicator owing to its impacts on adsorption efficiency. The optimal mix (proportions of the four materials) was

Table 2
Factors and levels of the orthogonal design

Levels	Factors				
	A	B	C	D	E
1	0	0	0	0	1100
2	10	10	15	5	1100
3	15	15	20	10	1100
4	20	20	25	15	1100

Note: “A,” “B,” “C,” and “D” represent the proportions of wastewater treatment sludge (WWTS), water supply treatment sludge (WSTS), river bed sediments (RBS), and Na₂SiO₃, respectively, relative to the amount of sewer pipe sediments (SPS). “E” represents the roasting temperature in the muffle furnace.

Table 3
Orthogonal test and resulting BET values

Number	Factors					BET (k)
	A	B	C	D	E	
1	1	1	1	1	1	0.781
2	1	2	2	2	2	1.0024
3	1	3	3	3	3	0.5297
4	1	4	4	4	4	0.83
5	2	1	2	3	4	1.9377
6	2	2	1	4	3	1.1154
7	2	3	4	1	2	0.3053
8	2	4	3	2	1	1.2155
9	3	1	3	4	2	1.3262
10	3	2	4	3	1	0.6299
11	3	3	1	2	4	0.9572
12	3	4	2	1	3	2.7195
13	4	1	4	2	3	0.706
14	4	2	3	1	4	1.014
15	4	3	2	4	1	0.4796
16	4	4	1	3	2	1.9691
k ₁	3.1431	4.7509	4.8227	4.8198	3.106	k ₁ + k ₂ + k ₃ + k ₄ = 17.5185
k ₂	4.5739	3.7617	6.1392	3.8811	4.603	
k ₃	5.6328	2.2718	4.0854	5.0664	5.0706	
k ₄	4.1687	6.7341	2.4712	3.7512	4.7389	
R	2.4897	4.4623	3.668	1.3152	1.9646	

Note: The k values denote the BET values of 16 conditions; k₁, k₂, k₃, and k₄ are the sum of BET values of A, B, C, and D, respectively, in each column; R is the range value of k₁, k₂, k₃, and k₄. “A,” “B,” “C,” and “D” represent the proportions of wastewater treatment sludge (WWTS), water supply treatment sludge (WSTS), river bed sediments (RBS), and Na₂SiO₃, respectively, relative to the amount of sewer pipe sediments (SPS). “E” represents the roasting temperature in the muffle furnace.

determined as described previously [43]. Wet ceramsite samples of approximately 10 mm diameter were manually developed, dried for 30 min at 105 °C in an oven, pretreated for 20 min at 400 °C in a muffle furnace, roasted for 5 min at 1100 °C, and then cooled to obtain the ceramsite used in the experiments [5,14].

2.2. Adsorption experiments

2.2.1. Adsorption isotherms

Adsorption isotherms can be determined by the adsorption process and mechanism. Often, the Langmuir and Freundlich isotherm models are used to describe the adsorption process of a material. The Langmuir adsorption isotherm can be expressed as [44]:

$$\frac{C_e}{Q_e} = \frac{C_e}{Q_m} + \frac{1}{K_L Q_m} \quad (1)$$

where Q_e is the equilibrium absorption amount ($\text{mg} \cdot \text{g}^{-1}$), Q_m is the saturated adsorption amount ($\text{mg} \cdot \text{g}^{-1}$), C_e is the concentration of heavy metals (Cu^{2+} and Cd^{2+}) in solutions at equilibrium ($\text{mg} \cdot \text{L}^{-1}$), and K_L is the Langmuir adsorption constant.

The Freundlich adsorption isotherm can be expressed as [45]:

$$\ln Q_e = \frac{1}{n} \ln C_e + \ln K_f \quad (2)$$

where K_f is the Freundlich adsorption constant, n is a constant, and other terms are as defined previously.

To investigate the adsorption isotherm, 5 $\text{g} \cdot \text{L}^{-1}$ ceramsite was respectively placed in five conical flasks, each containing a different concentration of Cu^{2+} and Cd^{2+} solution (300 ml; from $\text{CuCl}_2 \cdot \text{H}_2\text{O}$ and $\text{CdCl}_2 \cdot \text{H}_2\text{O}$, respectively). The pH of these solutions was adjusted to 6.0–7.0, which is close to the pH of stormwater runoff (pH = 5–7). The Cu^{2+} concentrations used were 21.5, 22.2, 27.1, 29.4, and 32.1 $\text{mg} \cdot \text{L}^{-1}$, and the Cd^{2+} concentrations employed were 15.3, 17.0, 19.3, 23.5, and 32.1 $\text{mg} \cdot \text{L}^{-1}$. The five conical flasks were maintained at $(25 \pm 1)^\circ\text{C}$ and shaken at 160 rpm on a shaking table. During shaking, the samples were obtained at certain times to determine the point of adsorption equilibrium. Then, the correlation coefficients of adsorption isotherms, defined using Eqs. (1) and (2), were determined.

2.2.2. Adsorption kinetics

Adsorption kinetics models can be used to explain the inherent law and essential process of adsorption. Often, a pseudo-first-order kinetic equation and a pseudo-second-order kinetic equation are used. The pseudo-first-order kinetic equation can be given as [46]:

$$\lg(Q_e - Q_t) = \lg Q_t - k_1 t \quad (3)$$

where Q_t is the absorption amount at time t ($\text{mg} \cdot \text{g}^{-1}$) and k_1 is the equilibrium rate constant.

The pseudo-second-order kinetic equation can be expressed as [47]:

$$\frac{t}{Q_t} = \frac{1}{k_2 Q_e^2} + \frac{t}{Q_e} \quad (4)$$

where k_2 is the equilibrium rate constant.

The 5 $\text{g} \cdot \text{L}^{-1}$ ceramsite was chosen as the research object, and the experimental conditions included 160 rpm and $(25 \pm 1)^\circ\text{C}$. The Cu^{2+} concentrations employed were 21.5, 27.1, and 29.4 $\text{mg} \cdot \text{L}^{-1}$, and the Cd^{2+} concentrations used were 10.7, 17, and 23.5 $\text{mg} \cdot \text{L}^{-1}$. Sampling was performed at a certain time interval, and the samples were analyzed using a flame atomic absorption spectrophotometer (Z-2010, Hitachi, Tokyo, Japan).

2.3. Characterization methods

The specific surface area and pore-size distributions of the novel ceramsite were determined by gas adsorption using a BET specific surface analysis device (Mike ASAP 2020, USA). The chemical oxide composition was determined using a scanning wavelength dispersive X-ray fluorescence (XRF) instrument (Shimadzu XRF-1800). Scanning electron microscopy (SEM), energy dispersive spectrometry (EDS), and a Fourier transform infrared (FTIR) spectrometer (Vertex 20 V FTIR spectrometer, Bruker, Germany) were used to characterize the ceramsite before and after adsorption. The SEM and EDS were accomplished using a Hitachi SU8010 cold field emission scanning electron microscope.

3. Results and Discussion

3.1. Characterization of the novel ceramsite

The orthogonal test design and BET analysis results are presented in Table 3. The different range values were $R_A = 2.4897$, $R_B = 4.4623$, $R_C = 3.668$, and $R_D = 1.3152$. Thus, $R_B > R_C > R_A > R_D$, and the order of impact of the four materials on BET was as follows: WSTS > RBS > WWTS > Na_2SiO_3 . The orthogonal test revealed that the optimal mixture of the components for the development of novel ceramsite was A3B4C2D3, which consisted of (in proportions relative to SPS) 20% WSTS, 15% RBS, 15% WWTS, and 10% Na_2SiO_3 . Although the chemical composition of RBS is more consistent with the technical requirements for ceramsite developed, when compared with that of WSTS, the burning loss of WSTS during combustion is relatively higher, contributing to the formation of porous ceramsite [5,48]. Therefore, the mass of WSTS produced the highest influence on the BET of ceramsite. The addition of Na_2SiO_3 could initiate Al^{3+} and Si^{4+} to form a stable skeleton structure, resulting in certain solidity of the ceramsite and laying a foundation for its application as a filter medium [24]. The chemical composition of the ceramsite was similar to that reported previously [49,50] (Table 4). The BET specific surface area of the novel ceramsite was $0.4967 \text{ m}^2 \cdot \text{g}^{-1}$ and the pore size was 9.983 nm.

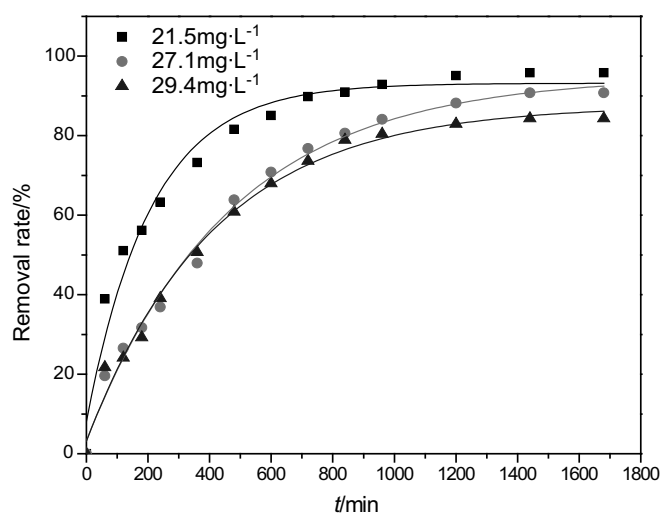
Table 4
Chemical analysis of the novel ceramsite composition

Constituent	Composition/%
Fe_2O_3	35.7782
SiO_2	27.5952
CaO	13.0748
Al_2O_3	8.8394
MgO	3.8286
ZnO	3.2876
K_2O	1.8048
Na_2O	1.7104
P_2O_5	1.5933
SO_3	1.0952
TiO_2	1.0656
SrO	0.3269

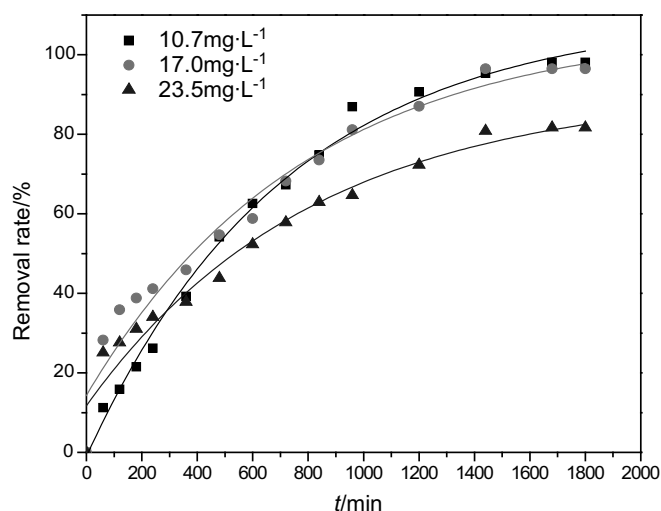
3.2. Adsorption characteristics

3.2.1. Cu^{2+} and Cd^{2+} removal efficiency of the novel ceramsite

Most of the previous studies have focused on methods of developing sludge ceramsite, and there are only a few studies on Cu^{2+} and Cd^{2+} adsorption by ceramsite. Fig. 1 shows that the equilibrium time of Cu^{2+} and Cd^{2+} adsorption by the novel ceramsite exceeded 20 h. The time to reach Cu^{2+} and Cd^{2+} equilibrium was about 950 and



(a)



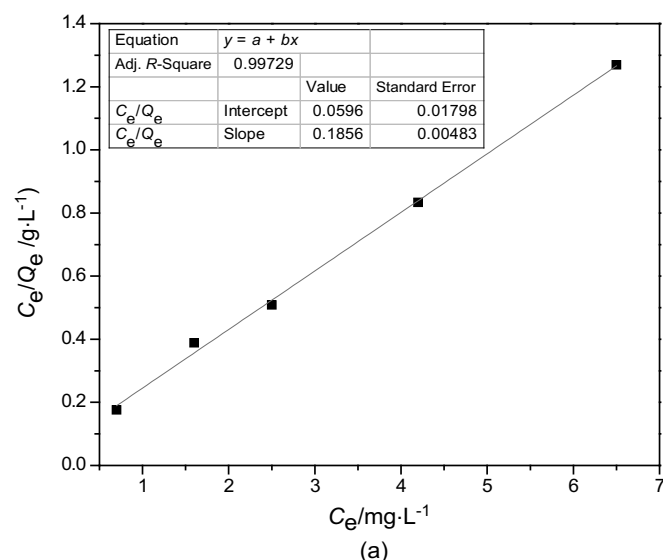
(b)

Fig. 1. The Cu^{2+} (a) and Cd^{2+} (b) removal rate (efficiency) of the novel ceramicsite.

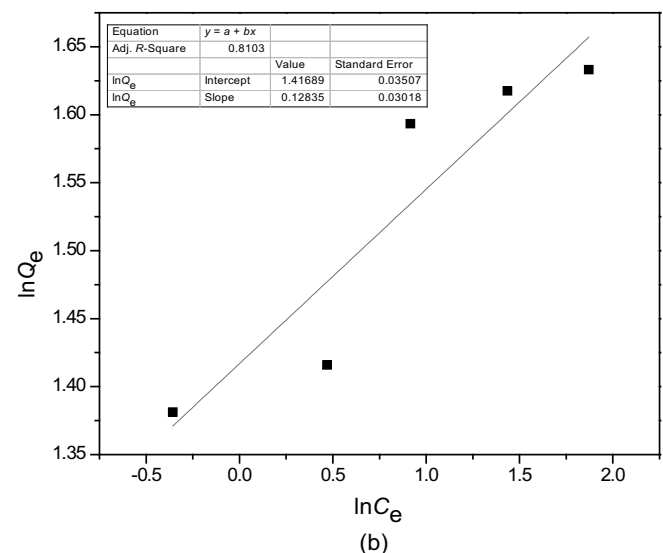
1700 min, respectively, and Cu^{2+} adsorption was more stable than Cd^{2+} adsorption. The best removal rate for both the metals was 100%, and the Cu^{2+} and Cd^{2+} equilibrium adsorption amount was 4.96 and 3.84 $\text{mg}\cdot\text{g}^{-1}$, respectively. These results confirmed that both Cu^{2+} and Cd^{2+} can be effectively removed by the novel ceramicsite. In a previous study, Xing *et al.* [39] showed that the maximum Cu^{2+} removal efficiency of red loess was 100% at pH 8. Qin *et al.* [51] demonstrated that ceramicsite made with lime mud and coal fly ash could be a high-performance product for wastewater recycling. In the present study, the longer equilibrium time and instability in the adsorption may be related to the adsorption mechanism, conditions of adsorption, and compositions of ceramicsite.

3.2.2. Adsorption isotherms

Figs. 2 and 3 show the Langmuir and Freundlich isotherms for Cu^{2+} and Cd^{2+} adsorption, respectively, and Table 5 presents the parameters of the Langmuir and Freundlich equations for Cu^{2+} and Cd^{2+} adsorption. The correlation coefficients showed that the Langmuir model described the adsorption process of Cu^{2+} and Cd^{2+} better than the



(a)



(b)

Fig. 2. Langmuir (a) and Freundlich (b) isotherms for Cu^{2+} adsorption.

Freundlich model, and that Cu^{2+} and Cd^{2+} adsorption on the ceramicsite was characterized by monolayer sorption. Similar results have also been reported in previous studies on Cu^{2+} and Cd^{2+} adsorption on other sorbent materials [39,52–56].

The value of the parameter R_L describes the affinity between adsorbent and adsorbate, which can reflect the adsorption process [57]. The R_L equation can be given as:

$$R_L = 1/(1 + K_L C_0) \quad (5)$$

where C_0 is the initial concentration of Cu^{2+} and Cd^{2+} in solution ($\text{mg}\cdot\text{L}^{-1}$). When $0 < R_L < 1$, the adsorption process proceeds easily; when $R_L = 1$, the adsorption process is a linear function; when $R_L = 0$, the adsorption is irreversible; and when $R_L > 1$, the system is not conducive to adsorption [58,59]. In the present study, all the R_L values were between 0 and 1; thus, it can be concluded that the developed ceramicsite exhibited good affinity for Cu^{2+} and Cd^{2+} and could feasibly be used for the adsorption and removal of these metals from water.

3.2.3. Adsorption kinetics

Figs. 4 and 5 show the kinetic curves depicting Cu^{2+} and Cd^{2+} adsorption by the developed ceramicsite, and Table 6 lists the parameters

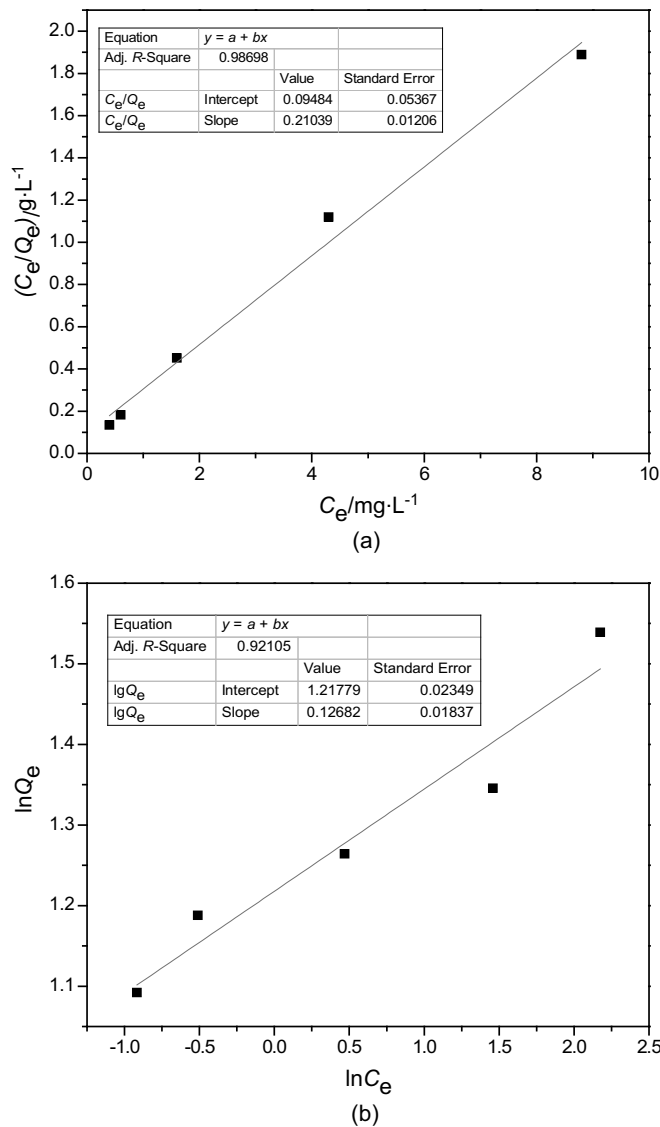


Fig. 3. Langmuir (a) and Freundlich (b) isotherms for Cd^{2+} adsorption.

Table 5
Parameters for Langmuir and Freundlich equations for Cu^{2+} and Cd^{2+} adsorption

Heavy metals	Langmuir adsorption parameters			Freundlich adsorption parameters		
	$Q_m/\text{mg}\cdot\text{g}^{-1}$	$K_L/\text{L}\cdot\text{mg}^{-1}$	R^2	$K_f/\text{L}\cdot\text{g}^{-1}$	$1/n$	R^2
Cu^{2+}	5.3879	3.1094	0.9973	4.1242	0.1284	0.8103
Cd^{2+}	4.7530	2.2184	0.9870	3.3797	0.1268	0.9211

for kinetic models describing the adsorption process. The comparison between pseudo-first- and pseudo-second-order kinetics revealed that the R^2 values (0.9971, 0.9846, 0.9811) of the pseudo-first-order kinetics model for Cu^{2+} adsorption were reasonably higher than those of the pseudo-second-order kinetics model (0.9985, 0.9769, 0.9772). Furthermore, the R^2 values (0.9591, 0.9556, 0.9705) of the pseudo-first-order kinetics model describing Cd^{2+} adsorption were obviously higher than those of the pseudo-second-order kinetics model (0.9340, 0.9447, 0.9443). Therefore, it can be concluded that pseudo-first-order kinetics provided a better description of both Cu^{2+} and Cd^{2+} adsorption (especially Cu^{2+} adsorption) by the novel ceramsite than the pseudo-second-order kinetics. This finding indicated that

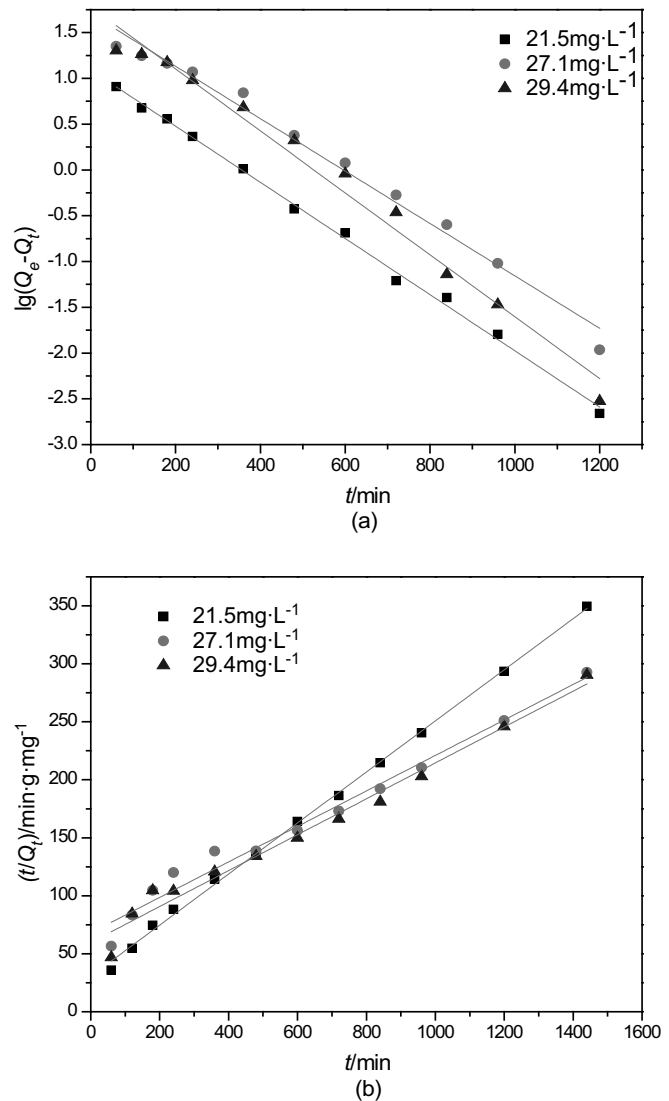


Fig. 4. Kinetic equation fitting curve depicting Cu^{2+} adsorption. (a) pseudo-first-order kinetics; (b) pseudo-second-order kinetics.

adsorption efficiency was related to the effective adsorption sites of the ceramsite, initial concentration of the heavy metal solution, adsorption rates, and increased interaction time. These results are similar to those reported by Azizian [60], Bhattacharyya and Gupta [61], and Liu *et al.* [62].

3.3. Adsorption mechanism analysis

Fig. 6 shows the SEM image of the novel ceramsite before and after Cu^{2+} and Cd^{2+} adsorption. It can be noted from the figure that the surface of the ceramsite became smoother after Cu^{2+} and Cd^{2+} adsorption, which could probably be owing to the filling of pores by Cu^{2+} and Cd^{2+} . Some tiny pores in ceramsite could provide the basis for the physical adsorption function. Fig. 7 presents the EDS results of the novel ceramsite before and after adsorption, which clearly show the adsorbed Cu and Cd elements. These results indicated that the novel ceramsite allowed physical adsorption of Cu^{2+} and Cd^{2+} . In a previous study, Frost *et al.* [63] reported that SEM imaging and EDS analysis could be used to demonstrate the presence of Al, F, and S in the sulfate mineral.

Fig. 8 illustrates the FTIR spectra of the novel ceramsite before and after Cu^{2+} and Cd^{2+} adsorption. Several peaks can be observed in the figure, suggesting that kaolinite is composed of various functional groups that are responsible for the binding of cations. It must be noted

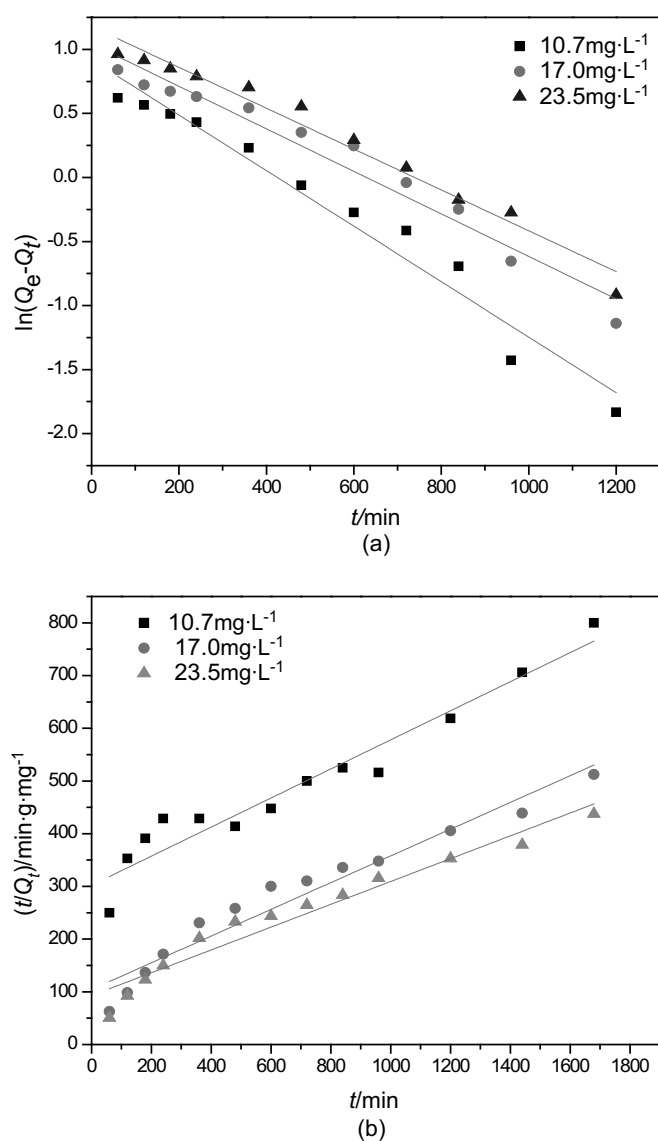


Fig. 5. Kinetic equation fitting curve depicting Cd^{2+} adsorption. (a) pseudo-first-order kinetics; (b) pseudo-second-order kinetics.

that the absorption band from 2360 to 4000 cm^{-1} was unaffected before and after adsorption, revealing the absence of smectite in kaolinite [64]. The absorption peaks near 1647 and 1057 cm^{-1} can be attributed to the angular vibration of structural water and C—O bond stretching vibration of a small amount of carboxylate, respectively, and the absorption peak at 1057 cm^{-1} corresponded to the carbohydrate from ceramsite and C—O stretching vibration. The Si—O stretching vibration was observed at 779 cm^{-1} , and the peak intensity recorded at 456 cm^{-1} can be attributed to Al—O—Si skeletal vibrations [65]. Similar spectra were noted after Cu^{2+} and Cd^{2+} adsorption by the novel

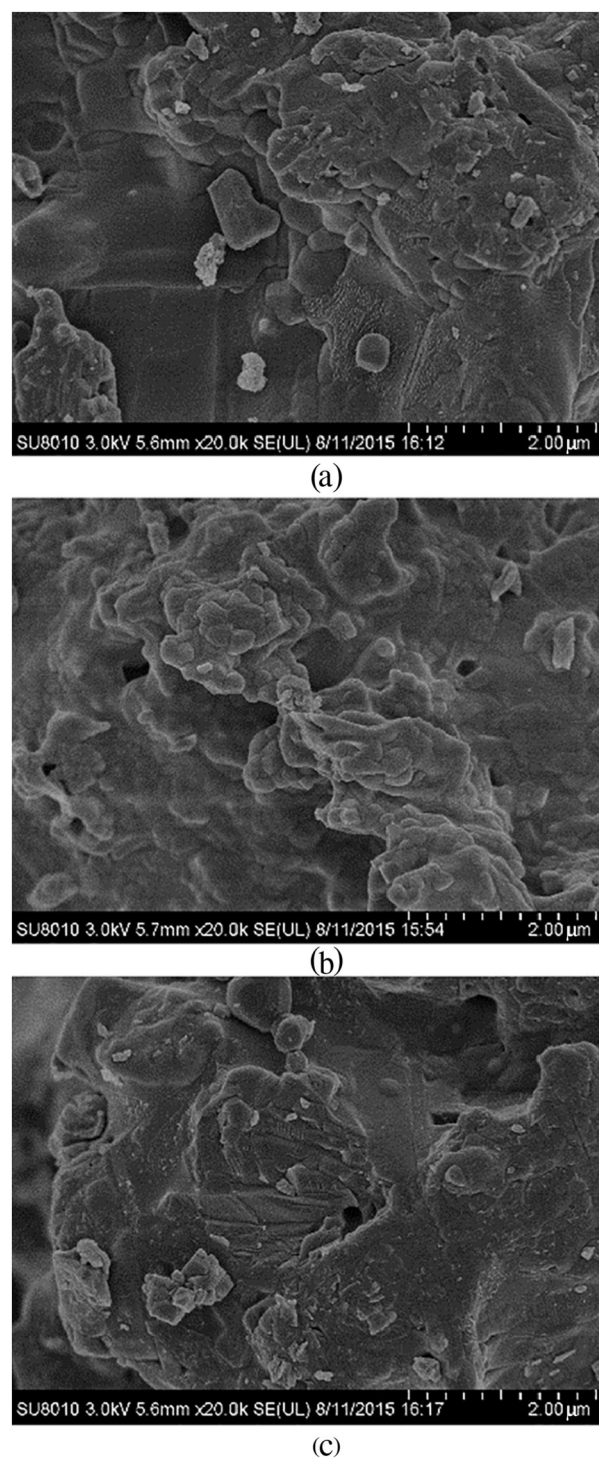
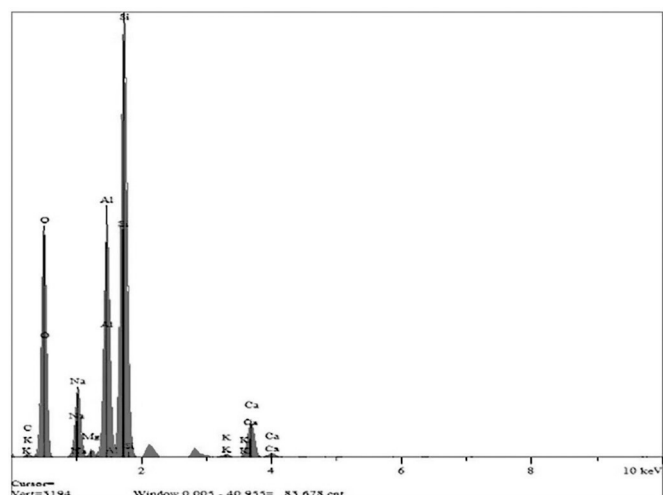


Fig. 6. SEM images of ceramsite before (a) and after adsorption of Cu^{2+} (b) and Cd^{2+} (c).

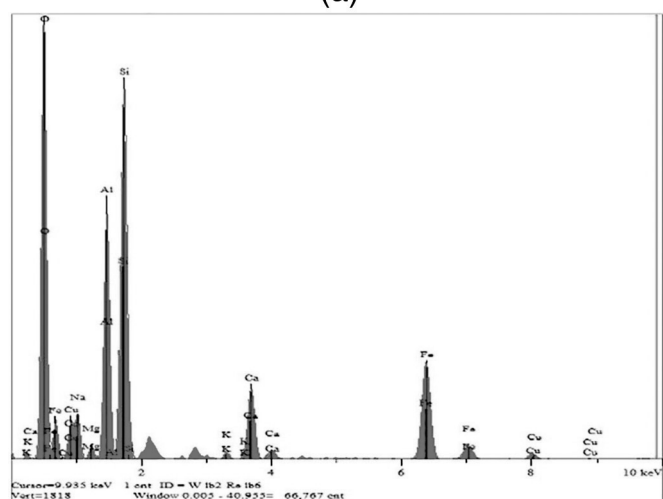
Table 6

Parameters for Cu^{2+} and Cd^{2+} adsorption kinetic models

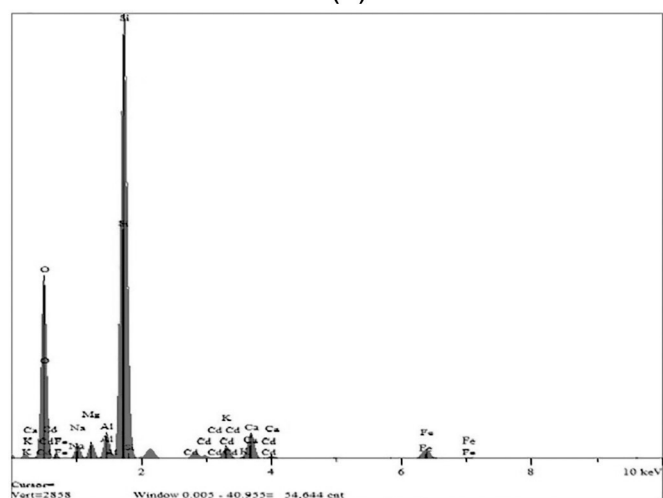
$C_0/\text{mg}\cdot\text{L}^{-1}$	Heavy metals	Pseudo-first-order kinetics			Pseudo-second-order kinetics		
		K_1/min^{-1}	$Q_e/\text{mg}\cdot\text{g}^{-1}$	R^2	$K_2/\text{g}\cdot\text{mg}^{-1}\cdot\text{min}^{-1}$	$Q_e/\text{mg}\cdot\text{g}^{-1}$	R^2
21.5	Cu^{2+}	0.0031	2.9792	0.9971	0.0016	4.5380	0.9985
27.5		0.0029	5.5025	0.9846	0.0003	6.5359	0.9769
29.4		0.0034	5.9223	0.9811	0.0004	6.4616	0.9772
10.7	Cd^{2+}	0.0022	2.5088	0.9591	0.0003	3.6269	0.9340
17.0		0.0017	2.8417	0.9556	0.0006	3.9452	0.9447
23.5		0.0016	3.2501	0.9705	0.0005	4.6202	0.9443



(a)



(b)



(c)

Fig. 7. EDS of ceramsite before (a) and after adsorption of Cu^{2+} (b) and Cd^{2+} (c).

ceramsite. The shifts in the C—O bond were observed from 1647 to 1636 cm^{-1} following Cu^{2+} adsorption, and from 1057 to 1038 cm^{-1} following Cd^{2+} adsorption. In addition, there was a shift in Si—O stretching vibration from 779 to 776 cm^{-1} and a minor shift in the Al—O—Si skeletal vibration. These results indicated that the novel ceramsite initiated chemical adsorption of Cu^{2+} and Cd^{2+} . Similar

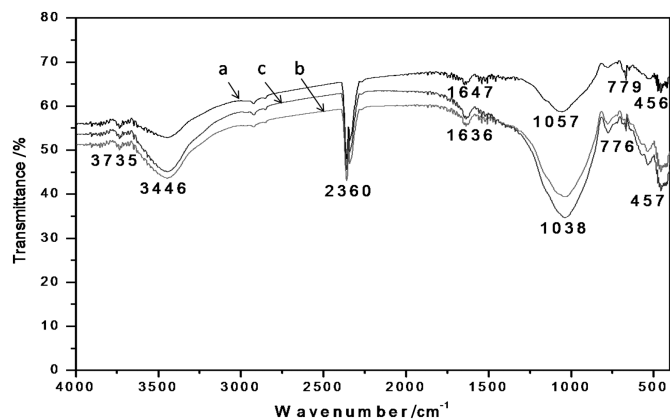


Fig. 8. FTIR spectrum of ceramsite before (a) and after adsorption of Cu^{2+} (b) and Cd^{2+} (c).

results were also reported by Dawodu and Akpomie [66] who analyzed the FTIR spectrum of chemical constitution changes before and after Cd(II) adsorption by Nigerian kaolinite clay.

4. Conclusions

A novel ceramsite was developed by combining four urban sediments (SPS, WSTS, RBS, and WWTS) and a binder (Na_2SiO_3) at an optimal composition of (in proportion relative to SPS) 20% WSTS, 15% RBS, 15% WWTS, and 10% Na_2SiO_3 . The novel ceramsite could effectively remove Cu^{2+} and Cd^{2+} , and the adsorption process could be better described by the Langmuir isotherm and pseudo-first-order kinetics. The adsorption of Cu^{2+} and Cd^{2+} by the novel ceramsite involved both physical and chemical processes. Therefore, the novel ceramsite can be used as a sorbent for removing dissolved heavy metals from stormwater runoff. In addition, the developed ceramsite presented the characteristic of solidity, suggesting its potential application as a bioretention medium to purify stormwater.

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