Preconcentration of trace amounts of cadmium in aqueous samples on minicolumns packed with Chromosorb series gas chromatographic stationary phases and its determination by electrothermal atomic absorption spectrometry

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The adsorption characteristics of five commercially available Chromosorb GC stationary phases towards Cd^{2+} and their application to the preconcentration and ETAAS determination of Cd^{2+} in several water samples were studied. The experimental results indicated that although all of the five Chromosorb GC stationary phases studied can retain Cd^{2+} quantitatively from aqueous solutions at appropriate pH values without adding chelating reagent, Chromosorb 105 displayed the highest adsorption capacity. A highly sensitive, simple methodology for preconcentration and ETAAS determination of trace amounts of cadmium in natural water samples using a Chromosorb 105 packed minicolumn is proposed. Conditions for quantitative and reproducible preconcentration, elution and subsequent ETAAS determination were established. The high retention efficiency ($>95\%$) for Cd^{2+} provides a sensitivity enhancement of 100-fold for a 200 mL sample volume with a detection limit of 6.2 ng L^{-1} (3σ).

1. Introduction

Cadmium is one of the metals of prime environmental concern because of several dangerous effects that it may have on humans.^{1,2} Its wide technological uses in fertilizers, mining and pigments, and its emission from oil and coal burning and residue incineration, result in substantial anthropogenic contamination of the environment such as air, soil and water. Its ubiquitous existence in the general environment can lead to humans being exposed to excessive levels of cadmium, resulting in its accumulation in various organs such as the kidney, liver, lungs and gastrointestinal tract, where it can cause progressively various toxic effects including cancer, renal damage and hypercalciuria.^{3–7} Hence a reduction in human exposure to cadmium is one of the main objectives of hygienists and public authorities, and appropriate analytical techniques that could provide accurate data on cadmium concentrations at very low levels in environmental samples with complex matrices are in great demand. Flame and electrothermal atomic absorption spectrometry (ETAAS)^{8,9} and inductively coupled plasma atomic emission spectrometry¹⁰ are among the most widely used methods for the determination of cadmium at trace levels, but their sensitivity and selectivity are usually insufficient for the determination of cadmium at very low concentrations in complex matrix environmental samples. Because of its excellent sensitivity, precision and accuracy, inductively coupled plasma mass spectrometry occupies an invaluable position in the modern analytical laboratory and it has been applied to the determination of cadmium in various samples.^{11,12} Unfortunately, its analytical application remains limited mainly owing to its susceptibility to the complex matrix of some samples. Furthermore, the relatively high cost of the instrumentation restricts its availability in many analytical laboratories. Therefore, a preconcentration step that can not only concentrate the analyte but also simplify the matrix of the samples is usually strongly desired. There are many kinds of preconcentration methods, such as precipitation and coprecipitation,¹³ liquid–liquid extraction¹⁴ and ion exchange,¹⁵ that

have been used for the separation and enrichment of trace amounts of cadmium from aqueous solutions. These classical preconcentration methods are usually time consuming and tedious. Furthermore, these methods usually require large amounts of high purity organic solvents, which is harmful to health and creates environmental problems.

Since the introduction of the concept of the solid phase extraction (SPE) technique about 20 years ago, there has been sustained interest in the application of this technique to various contaminants in complex matrix environmental samples.^{16–19} This preconcentration technique has the advantages of high recovery, short analysis time, high enrichment factor, low cost and low consumption of organic solvents.^{17,18} Up to now, several kinds of sorbents, such as chelating resins,²⁰ activated carbon,^{21,22} activated alumina,²³ polymeric supports^{24,25} and C-18 bonded silica,²⁶ have been used for the preconcentration and determination of cadmium. Of these, C-18 bonded silica, a hydrophobic solid phase extractant, which shows a very strong retention of non-polar derivatives of the target, *i.e.*, Cd^{2+} , is the most widely used.

Chromosorb series gas chromatographic (GC) stationary phases, another class of hydrophobic polymer material, have been extensively used in GC for the separation of various organic compounds.^{27,28} However, to the best of our knowledge, there have been no reports on the SPE of trace metals with Chromosorb series GC stationary phases except for that by Elci *et al.* on the SPE of Pb^{2+} with Chromosorb 102.²⁹ In that report, it was mentioned that Chromosorb 102 not only retains Pb^{2+} –diethyldithiocarbamate (DDC) complexes, but also retains Pb^{2+} in the absence of DDC with a slightly lower signal.

To explore the great potential of Chromosorb series GC stationary phases as the matrix for the sorption and preconcentration of trace metal ions from aqueous solution without a chelating reagent, a systematic study of the extraction characteristics of Cd^{2+} with Chromosorb series GC stationary phases was carried out in this work. Parameters influencing the analytical performance, including pH of the sample, flow rate of the sample, sample volume, eluent volume and interfering effect

of co-existing ions, were studied in detail. A procedure is proposed for the trace enrichment of Cd^{2+} in aqueous solutions.

2. Experimental

2.1. Apparatus

Trace concentrations of Cd were determined by ETAAS using a Model WFX-1B atomic absorption spectrometer (No. 2 Optical Instrument Factory, Beijing, China) equipped with a Model HGA-400 graphite furnace (Perkin-Elmer, Norwalk, CT, USA) and a Model 056 recorder (Hitachi, Tokyo, Japan). A cadmium hollow cathode lamp (General Research Institute for Non-Ferrous Metal, China) was applied as a radiation source at 228.8 nm (bandpass 0.2 nm) and was operated at 5 mA. Peak height signals were recorded by the recorder and deuterium arc background correction was used for determination of cadmium. Standard graphite tubes (Perkin-Elmer) were used for atomization of cadmium and 20 μL of sample solution were injected into the graphite tube for analysis. The graphite furnace time–temperature program recommended by Perkin-Elmer in the HGA-400 Graphite Furnace Operator's Manual was adopted throughout the experiments and is shown in Table 1. All solutions were delivered to pass through the minicolumn packed with Chromosorb adsorbents by a laboratory-developed peristaltic pump.

2.2. Reagents and materials

All reagents were of analytical-reagent grade unless stated otherwise, and doubly distilled, de-ionized water was used throughout the experiments. By dissolving appropriate amount of $\text{CdCl}_2 \cdot 2.5\text{H}_2\text{O}$ (Beijing Chemicals) in 5% v/v nitric acid, a stock standard solution of 1 mg mL^{-1} Cd^{2+} was prepared. Working standard solutions were prepared daily by appropriate dilution of the stock standard solution with 5% v/v nitric acid. The nitric acid and ammonia (Beijing Chemicals) were of high purity grade. Stock standard solutions of other metals (Mg^{2+} , Ca^{2+} , K^+ , Na^+ , Fe^{3+} , Al^{3+} , Co^{2+} , Ni^{2+} , Cu^{2+} , Zn^{2+} , Cr^{3+} , Pb^{2+} , Hg^{2+} , Mn^{2+} , Ni^{2+}) were prepared by dissolving the metal nitrate or pure metal in acid followed by appropriate dilution with 5% v/v nitric acid; the final solutions contained 10 mg mL^{-1} of each metal ion. Stock standard solutions of Cl^- , SO_4^{2-} and HCO_3^- were prepared by dissolution of their sodium salts.

Chromosorb series GC stationary phases were obtained from Phase Separations Inc., Norwalk, CT, USA, and their physical characteristics are listed in Table 2. In order to reduce the levels of organic and inorganic contaminants, they were washed successively with methanol, 1 mol L^{-1} nitric acid, doubly distilled, de-ionized water, 1 mol L^{-1} NaOH solution and doubly distilled, de-ionized water.

All beakers, calibrated flasks and other glassware were cleaned sequentially with tap water, neutral detergent and tap water, then soaked in nitric acid (1 + 1) for 48 h and cleaned with doubly distilled, de-ionized water.

Table 1 HGA graphite furnace time–temperature program

Step No.	Temperature/ $^{\circ}\text{C}$	Ramp/s	Hold/s	Argon flow rate/ mL min^{-1}
1	110	3	50	300
2	300	3	90	300
3	2000	0	10	300

2.3. Minicolumn and preconcentration system

To prepare the microcolumns used for the preconcentration of cadmium, 0.3 g of Chromosorb GC stationary phase was packed in short HPIC columns ($5.2 \text{ cm} \times 4.0 \text{ mm id}$), (Dionex Sunnyvale, CA, USA) made of polypropylene using the dry packing method. A small amount of quartz-wool was placed at each end of the minicolumns to prevent the loss of the Chromosorb adsorbents when the sample solutions passed through the columns. Upon completion of column preparation, the minicolumn was connected to a peristaltic pump with PTFE tubing (0.5 mm id). A diagram of the minicolumn and the preconcentration system is presented in Fig. 1.

Prior to use, the entire assembly was carefully rinsed successively with sufficient distilled water, 25 ml of 0.2 mol mL^{-1} nitric acid, and doubly distilled, de-ionized water until the pH value of the eluate was neutral.

2.4. Procedure

To study the pH dependence of Cd^{2+} sorption on the Chromosorb adsorbents under dynamic conditions, volumes of 50 ml of solutions containing 20 ng mL^{-1} of Cd^{2+} were adjusted to appropriate pH values over the range 1–10 by dropping appropriate amounts of nitric acid or ammonia solution in to them. Then the solutions were loaded on the minicolumns using a peristaltic pump at a flow rate of 10.3 mL min^{-1} (a preliminary test showed that quantitative recovery can be achieved at this flow rate). After washing the column with 20 mL of doubly distilled, de-ionized water with the same pH values as the influent, the trace amounts of cadmium retained on the Chromosorb adsorbents in the column was eluted with 2 mL of 0.2 mol mL^{-1} nitric acid at a flow rate of 10.3 mL min^{-1} . The concentrations of cadmium in the eluate solutions were determined by ETAAS to calculate the recovery of cadmium.

The effects of flow rate of the sample solutions and the volume of the eluent on the recovery of cadmium were also examined. The flow rate of the sample solution was varied over the range 3.2–20.4 mL min^{-1} and the volume of the eluent (0.2 mol L^{-1}) was varied from 0.5 to 5 mL.

To study the dynamic adsorption capacities of Chromosorb GC stationary phases towards Cd^{2+} , the capacity breakthrough curves of the minicolumns packed with 0.3 g of five different Chromosorb GC stationary phases were prepared. The break-

Table 2 Physical characteristics of chromosorb adsorbents

Chromosorb	Type ^a	Mesh size	Surface area/ $\text{m}^2 \text{g}^{-1}$	Pore size/nm
101	PSDVB	60–80	30–40	350
102	PSDVB	60–80	300–400	8.5
103	PS	80–100	15–20	350
104	PANDVB	60–80	100–200	60–80
105	PA	60–80	600–700	40–60

^a PSDVB = poly(styrene–divinylbenzene); PS = polystyrene; PANDVB = poly(acrylonitrile–divinylbenzene); PA = poly(acrylic acid).

Fig. 1 Schematic diagram of the system for column solid phase extraction of Cd^{2+} . S, sample solution; P, pump; C, HPLC column ($5.2 \text{ cm} \times 4.0 \text{ mm id}$); E, effluent solution.

through curves were obtained by pumping solutions containing $20 \text{ ng mL}^{-1} \text{ Cd}^{2+}$ solution at pH 9.0 through the five different minicolumns at a flow rate of 10.3 mL min^{-1} , continuously collecting each 25 mL of the column effluent to determine the concentration of Cd^{2+} by ETAAS, then plotting the extraction percentage against the total volume of effluent. The extraction percentage is equal to $(c/c_0) \times 100$, where c is the absorbance of the column effluent and c_0 is that of the column influent.

2.5. Recommended procedure for water sample analysis

Tap water samples were collected from water taps in our laboratory and the adjacent residential area, two brands of bottled natural mineral water for drinking were purchased in nearby stores and river water samples were collected from the section of Beijing in the Yongding River valley. The water samples were acidified to pH 2.0 by adding appropriate amounts of high-purity nitric acid and filtered through a Millipore cellulose membrane with a pore size of $0.45 \mu\text{m}$ immediately after sampling, and then stored at 4°C . Prior to analysis, 200 mL of acidified water samples were neutralized and adjusted to pH 9.0, then the solution was passed through the minicolumn at a flow rate of 10.3 mL min^{-1} . After passage of the solution, the minicolumn was washed with 20 mL of doubly distilled, de-ionized water with the same pH value as the sample solutions to remove the sample still present in the minicolumn and line. Finally, the cadmium retained on the minicolumn was eluted with 2 mL of 0.2 mol L^{-1} nitric acid to determine the Cd^{2+} concentration by ETAAS.

3. Results and discussion

3.1. Effect of pH on the retention of Cd^{2+}

As a generally accepted rule, a critical parameter in achieving quantitative adsorption and recovery of trace elements on hydrophobic adsorbents is pH. In order to optimize the sorption conditions for the retention of Cd^{2+} on minicolumns packed with the five different Chromosorb GC stationary phases, the recovery of Cd^{2+} was determined by changing the pH of the solutions that passed through the minicolumns in the range 1–10. Fig. 2 presents the experimental results on the effect of pH on the retention of Cd^{2+} . As can be seen, although these five different Chromosorb adsorbents have very different surface areas, pore diameter distributions and surface polarities, they behave very similarly with regard to the pH dependence of the recovery of Cd^{2+} . The highest recoveries were achieved for all five Chromosorb adsorbents in the pH range 8–10, which is roughly in agreement with that for the formation of a

Fig. 2 Effect of pH on recovery of cadmium (50 mL of $20 \text{ ng mL}^{-1} \text{ Cd}^{2+}$ solution). $\diamond$, Chromosorb 101; $\square$, Chromosorb 102; $\triangle$, Chromosorb 103; $\times$, Chromosorb 104; $\circ$, Chromosorb 105.

hydrophobic $\text{Cd}(\text{OH})_2$ precipitate.³⁰ As a class of macroporous polymeric GC stationary phases, the Chromosorb adsorbents provide large surfaces that exhibit strong adsorptive properties towards analytes that cover a wide range of hydrophobicity.³¹ Probably this can explain why the Cd^{2+} can be retained by the class of hydrophobic sorbents: in weakly basic solution, hydrophilic Cd^{2+} ion is transformed into hydrophobic $\text{Cd}(\text{OH})_2$ precipitate, then this hydrophobic precipitate is absorbed by hydrophobic adsorbents, e.g., the Chromosorb series adsorbents. According to these results, the selected pH was 9.0.

3.2. Adsorption capacities of the Chromosorb series adsorbents towards Cd^{2+}

The adsorption capacities of the Chromosorb adsorbents were studied under dynamic conditions, and the experimental results are presented in Fig. 3. As can be seen, these five adsorbents behave very differently in their adsorption capacities towards Cd^{2+} . Of the five different adsorbents, Chromosorb 105 exhibited the highest and Chromosorb 104 the lowest adsorption capacities. Therefore, Chromosorb 105 was selected in our experiments. Although the adsorption capacity of Chromosorb 105 adsorbent is not very high, it is large enough to preconcentrate trace elements from natural water samples in the light of the extremely minute amount of trace elements in natural water. Moreover, the large breakthrough volume of this minicolumn system provides the possibility of Cd^{2+} extraction under dynamic conditions with a high concentration factor.

From the data for the physical characteristics of the five adsorbents shown in Table 2, we could not find close correlations between the adsorption capacities and any single physical characteristic of the adsorbents. From generally accepted opinions, several factors, including surface area, pore diameter distribution, surface polarity, and solvent polarity, contribute to an adsorbent's capacity for a given solute.³² The results for the capacities of the five different Chromosorb adsorbents towards Cd^{2+} probably reflect the combined action of surface area, pore diameter distribution and surface polarity, of the adsorbents. Of the five adsorbents, Chromosorb 105 has the largest surface area and exhibits the highest adsorption capacities, so perhaps surface area is the key factor influencing an adsorbent's capacity for a given solute.

3.3. Effect of flow rate of the sample solutions

The flow rate of the sample solution through the minicolumn is a very important parameter, since it not only affects the recovery of Cd^{2+} , but also controls the time of analysis. Because a large

Fig. 3 Capacity breakthrough curves for cadmium on Chromosorb GC stationary phases. $\diamond$, Chromosorb 101; $\square$, Chromosorb 102; $\triangle$, Chromosorb 103; $\times$, Chromosorb 104; $\circ$, Chromosorb 105.

volume of sample solution is needed in the preconcentration, it is always expected that sample solutions can be pumped through the column at a higher flow rate without sacrificing the recoveries. The effect of the flow rate of the sample solutions on the recoveries of Cd^{2+} on a minicolumn packed with Chromosorb 105 was examined in the range $3.2\text{--}20.4\text{ mL min}^{-1}$. It was found that in the pH range chosen for our experiments the flow rate of the sample solutions had no obvious influence on the quantitative and reproducible recoveries of Cd^{2+} on the minicolumn. These experimental results show that the adsorption in this system is a rapid kinetic process. In order to avoid a high back-pressure arising from a too high flow rate, 10.3 mL min^{-1} was chosen as the flow rate of the sample solutions in subsequent experiments.

3.4. Effect of eluent volume

In a preliminary test, it was found that 0.2 mol L^{-1} nitric acid was an effective eluent for the Cd^{2+} retained on the minicolumns. Various volumes of 0.2 and 2.0 mol L^{-1} nitric acid were used to elute the adsorbed Cd^{2+} and the results are shown in Fig. 4. As can be seen, quantitative recoveries ($>95\%$) could be achieved when the volume of 0.2 or 2.0 mol L^{-1} eluent was in the range $1.0\text{--}5.0\text{ mL}$, and further increases in the nitric acid concentration above 0.2 mol L^{-1} did not improve the recovery of Cd^{2+} . Because the application of a smaller volume of dilute eluent contributes to obtaining a higher preconcentration factor and a lower blank value in the subsequent ETAAS measurement, 2 mL of 0.2 mol L^{-1} nitric acid solution were adopted as the eluent throughout the experiments.

3.5. Stability of the minicolumn

As a class of SPE adsorbents, another advantage of the Chromosorb series stationary phases over C_{18} silica is that they can be used over the entire pH range, including strongly acidic and strongly basic pHs. Our experiments demonstrated that the high stability permitted hundreds of adsorption–desorption cycles process over a period of 2 months without a significant decrease in their adsorption capacities for Cd^{2+} .

3.6. Interferences

ETAAS is a highly selective detection method, the concentrations of heavy metal ions in which we are interested in natural water samples are very low and the Chromosorb 105 adsorbent that we adopted has a sufficiently high adsorption capacity, and therefore, it can be expected that any interferences will come mainly from the major matrix ions in the natural water samples

Fig. 4 Effect of eluent volume on recovery $\pm\sigma$ ($n = 3$) of Cd^{2+} on a column packed with Chromosorb 105. $\diamond$, 0.2 mol L^{-1} nitric acid; $\square$, 2.0 mol L^{-1} nitric acid.

such as Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Fe^{3+} , Al^{3+} , Co^{2+} , Cu^{2+} , Pb^{2+} , Hg^{2+} , Zn^{2+} , Mn^{2+} , Ni^{2+} , Cr^{3+} , Cl^- , SO_4^{2-} , HCO_3^- , etc. To investigate the effect of co-existing ions on the determination of Cd^{2+} , 200 mL of a binary solution of the Cd^{2+} and a single co-existing ion were prepared by varying the matrix ion concentrations whilst keeping the concentration of Cd^{2+} at 20 ng mL^{-1} and following the recommended procedure for water sample analysis. The results are given in Table 3. It can be seen that the major matrix ions in the natural water samples show no obvious interference with the preconcentration of Cd^{2+} .

3.7. Analytical performance

The high capacity of the Chromosorb 105 packed minicolumn permitted large sample volumes to be preconcentrated without degradation of the analytical performance. However, too large sample volumes required unreasonably long loading times. Therefore, 200 mL were chosen as the upper limit of the sample volume in our recommended procedure for water sample analysis. Following the recommended analytical procedure, we examined the analytical performance of the present method. Because of the quantitative recovery of Cd^{2+} achieved in the preconcentration system, the calibration curve method was used for the determination of cadmium in our experiment. Expressed as $3\sigma/kf$, where σ is the standard deviation of the procedural blank, k is the slope of the calibration curve and f is the preconcentration factor, the detection limit of cadmium in our recommended analytical procedure is 6.2 ng L^{-1} .

The proposed method was successfully applied to the determination of cadmium in tap water, bottled natural mineral water for drinking and river water. The analytical results together with the recoveries of the spiked analytes are given in Table 4. A reference ICP-MS method was also applied to determine cadmium in the river water samples, and the results are also given in Table 4. Table 4 indicates that the proposed method is highly reliable and valid, the recoveries were in the range $94\text{--}111\%$, and the results obtained by the proposed method agreed well with those obtained by ICP-MS.

4. Conclusions

The results obtained in this work indicate that Chromosorb series adsorbents, a class of hydrophobic polymeric GC stationary phases, can be used as effective solid phase extractants for the preconcentration of Cd^{2+} from water sample

Table 3 Effect of foreign ions on the recovery of Cd^{2+} ^a

Ion	Concentration/ $\mu\text{g mL}^{-1}$	Recovery ^b (%)
Na^+	1000	100.0 ± 4.6
K^+	1000	97.4 ± 5.8
Mg^{2+}	150	98.4 ± 2.3
Ca^{2+}	70	95.6 ± 8.1
Fe^{3+}	5	95.2 ± 4.2
Al^{3+}	3	96.1 ± 3.3
Co^{2+}	1	96.4 ± 7.5
Cu^{2+}	2	96.7 ± 6.5
Cr^{3+}	10	100.0 ± 4.5
Pb^{2+}	5	97.9 ± 3.7
Hg^{2+}	5	97.4 ± 3.5
Zn^{2+}	30	98.4 ± 6.1
Ni^{2+}	5	97.5 ± 6.2
Mn^{2+}	10	95.3 ± 2.9
Cl^-	1000	95.5 ± 3.7
SO_4^{2-}	400	94.7 ± 4.8
HCO_3^-	500	97.0 ± 5.1

^a Concentration of Cd^{2+} : 20 ng mL^{-1} . ^b Mean $\pm$ standard deviation for three determinations.

Table 4 Determination of cadmium in water samples and recoveries of spiked cadmium

Water sample	Added/ng mL ⁻¹	Found ^a /ng mL ⁻¹	Recovery ^a (%)	Found by ICP-MS/ng mL ⁻¹
<i>Tap water—</i>				
I	0	0.130 ± 0.004	—	—
	0.100	0.233 ± 0.006	102.0 ± 5.6	—
	0.250	0.393 ± 0.008	110.0 ± 3.2	—
II	0	0.048 ± 0.002	—	—
	0.050	0.099 ± 0.003	102.0 ± 3.3	—
	0.100	0.148 ± 0.003	100.0 ± 2.9	—
III	0	0.042 ± 0.001	—	—
	0.050	0.093 ± 0.002	102.0 ± 6.7	—
	0.100	0.144 ± 0.004	105.0 ± 4.4	—
<i>Bottled natural mineral water for drinking—</i>				
I	0	0.028 ± 0.001	—	—
	0.025	0.053 ± 0.001	100.0 ± 2.9	—
	0.050	0.079 ± 0.002	102.0 ± 3.2	—
II	0	0.082 ± 0.003	—	—
	0.050	0.129 ± 0.005	94.6 ± 5.6	—
	0.150	0.223 ± 0.007	94.0 ± 4.1	—
<i>River water—</i>				
I	0	0.035 ± 0.001	—	0.368
	0.050	0.082 ± 0.002	94.0 ± 4.4	—
	0.100	0.130 ± 0.004	95.0 ± 4.1	—
II	0	0.029 ± 0.001	—	0.319
	0.050	0.077 ± 0.001	96.0 ± 2.9	—
	0.100	0.126 ± 0.004	96.8 ± 4.5	—
III	0	nd ^b	—	0.002
	0.050	0.051 ± 0.001	102.0 ± 3.0	—
	0.100	0.103 ± 0.005	103.0 ± 4.5	—
IV	0	0.031 ± 0.001	—	0.0229
	0.050	0.084 ± 0.002	106.0 ± 4.2	—
	0.100	0.142 ± 0.005	111.0 ± 5.4	—

^a Mean ± standard deviation for three determinations. ^b Not detected.

solutions at appropriate pH values. High concentration factors (100) were obtained easily by this simple method in the presence of high concentrations of Ca²⁺, Mg²⁺, Na⁺, K⁺, Fe³⁺, Al³⁺, Co²⁺, Cu²⁺, Pb²⁺, Hg²⁺, Zn²⁺, Mn²⁺, Ni²⁺, Cr³⁺, Cl⁻, SO₄²⁻, etc. If the purity of the reagents and pure water used in the experiments were higher, the blank and the detection limits would be lower. Chromosorb series GC stationary phases possess high stability and they can be used stably over the entire pH range. This is an advantage over C₁₈ silica, which is unstable in strongly basic and strongly acidic media because of the hydrolysis of the bonded chain at low or high pH and the dissolution of the silica at high pH.^{33,34} Another advantage of the Chromosorb series adsorbents is that they are readily available commercially. Moreover, as Cd²⁺ can be pre-concentrated quantitatively over a wide pH range, no buffer is required to control the pH values precisely, which minimizes contamination. The fast adsorption and desorption kinetics of the Chromosorb series adsorbents make it possible to use a high flow rate for the column process to obtain quantitative recoveries. Finally, another attractive feature of this method is its simplicity, as no chelate agent is required.

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