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ADSORPTION PERFORMANCE OF ACTIVATED CARBON PELLETS IMMOBILIZED WITH ORGANOPHOSPHORUS EXTRACTANTS AND AN AMINE: A CASE STUDY FOR THE SEPARATION OF Pt(IV), Pd(II), AND Rh(III) IONS IN CHLORIDE MEDIA

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ADSORPTION PERFORMANCE OF ACTIVATED CARBON PELLETS IMMOBILIZED WITH ORGANOPHOSPHORUS EXTRACTANTS AND AN AMINE: A CASE STUDY FOR THE SEPARATION OF Pt(IV), Pd(II), AND Rh(III) IONS IN CHLORIDE MEDIA

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ABSTRACT

We attempted to anchor polymeric functional molecules on the activated carbon surface such that precious metal ions bind selectively in a mixed chloride solution. We immobilized Cyanex 301 (bis(2,4,4-trimethylpentyl)dithiophosphinic acid), MSP-8 (bis(3-ethylmethyl)monothiophosphoric acid) and a primary amine (tris(hydroxymethyl)aminomethane) on the surface of activated carbon (SUPRA Norit, 0.8), which served as a polymeric support. X-ray photoelectron spectroscopy results showed that ketones, esters, and carboxylic acids on the carbon surface interacted covalently with the amino group or sulfur groups from the organophos-

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phorus extractants. The characteristic binding energies of N 1s, S 2s, and P 2s were recorded qualitatively at 399, 167.4, and 164 eV, respectively. The optimum sorption of amine, MSP-8, and Cyanex 301 acid by activated carbon averaged 15, 75, and 150 mg/g, respectively. Amine-treated activated carbon exhibited an affinity for platinum ions while thiophosphate-treated activated carbons showed an affinity for palladium ions in chloride media. Rhodium complex ions were not adsorbed by the chemically treated carbons. Excess sorption of organophosphorus extractants or the amine significantly increased the hydrophobicity of activated carbon pellets and consequently affected adsorption of metal ions.

INTRODUCTION

The surface properties of activated carbons are generated or altered by means of oxidation under air/steam at elevated temperatures (1–3) followed by pretreatment with chemical reagents such as HNO_3 and KOH (4,5). Consequent upon oxidation, activated carbons exhibit acidic and basic properties depending on the nature of surface functional groups. Surface chemical groups such as carboxyls, phenols, esters, and ketones constitute the active sites of activated carbons necessary for adsorbing gaseous (6) and organic molecules (7). Recently, pretreatment of the carbon surface with azo and amino groups improved the adsorption of polymers or enhanced the adhesive bonding between the carbon surface and an epoxy matrix (8,9). Furthermore, Kaminski, Nunez, and Visser (10) reported the use of organophosphorus-treated ferromagnetic microparticles to recover Cd and Zn from an industrial waste solution. Alexandratos, Kaiser, and Grady (11) had earlier reported on molecular recognition by polymer-supported reagents.

The concept of anchoring organic functional groups on a carbon surface so that they can specifically bind precious metal ions has not been investigated. In this study, we immobilized 3 types of chemical compounds on the surface of activated carbon pellets: commercial thiophosphoric acid (MSP-8), dithiophosphinic acid (Cyanex 301), and an amine (Tris(hydroxymethyl)aminomethane). The chemically pretreated, activated carbon pellets were subsequently used in the separation of Pt(IV), Pd(II), and Rh(III) in a mixed chloride solution. By attaching the molecules of organophosphorus extractants and amine onto the carbon adsorbent, we hoped that the selectivity that these organic ligands exhibit in the liquid-liquid extraction of palladium and platinum would be induced on the activated carbon surface. According to the papers published by Kakoi, Goto, and Nakashio (12) and Baba and Hirakawa (13), extractants that contain sulfur as a donor atom have a high selectivity for palladium ions, while extractants possessing amino groups effectively recover platinum ions. Furthermore, Buttry et al. (9) elucidated

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the mechanism by which nucleophilic amines (RN(R′)H) react with electrophilic double bonds on the carbon surface to form covalent bonds. The nucleophilic alkyl-sulfur group, R—SH, readily attaches (releases a proton) to the ketone group to form an ensemble of R—S—C (or mercaptal thioacetyl) groups on a carbon surface (14). The adsorption of R—S—C groups serves to protect the surface of carbon materials and is reversible in acidic media.

Surface morphology and properties were studied with the help of scanning electron microscopy (SEM) and X-ray photoelectron spectroscopy (XPS). An attempt was made to quantify the amount of extractants adsorbed onto the carbon surface from the bulk organic solution and to ascertain through XPS analyses the presence of organic molecules adsorbed on the carbon surface. Finally, we applied the chemically pretreated carbon pellets to the sequestering of platinum, palladium, and rhodium platinum group metals (PGM) ions from multicomponent chloride solutions. Alloys of PGMs are used as autocatalysts for eliminating toxic and environmentally harmful gases. Therefore, spent automobile catalysts have emerged as the major source of recyclable PGMs in secondary metal industries.

EXPERIMENTATION

Reagents

Activated carbon pellets (SUPRA, Norit 0.8) (sieve particle size 0.7–1.0 mm; porosity 13%; apparent density 180 g/L), purchased from Norit Company, Atlanta, GA, USA, were selected for use in this research. High-grade standard solutions for analytical use of $RhCl_3$, $PdCl_2$, and H_2PtCl_6 were supplied by Kishida Chemicals Co, Osaka, Japan. The commercial suppliers of MSP-8 and 2-amino-2-hydroxymethyl-1,3-propanediol are Cyanamid Co, Cleveland, OH, USA, and Wako Chemical Co, Tokyo, Japan, respectively. All chemicals were used without further purification.

Chemical Pretreatment of AC Pellets: Immobilizing the Organic Functional Groups

Prior to surface modification tests, a stock sample of carbon pellets was dried in an oven at 373 K for 72 hours. Thereafter, known weights of carbon pellets from the stock sample were contacted with *n*-heptane that contained either MSP-8 or Cyanex 301 in the solid/liquid ratio of 0.2 g:25 mL. The dosage of organophosphates in 100 mL of organic solution was varied in the range 0.001–0.2% (wt/wt), while the weight of carbon (0.2 g) was kept constant. High dosages were used to assess the optimum adsorption capacity of carbon. The carbon-ligand solution mixtures, placed in airtight 40-mL bottles, were agitated in a constant temperature water bath (313 K) for 72 hours. Then, the chemically treated carbon pellets were separated from the solution by decantation, washed in excess *n*-heptane solution (to remove residual thiophosphate molecules), filtered, and dried in a vacuum ($10^{-2} - 10^{-1}$ mm Hg) at room temperature (298 K) for 48 hours. The pretreatment of carbons was repeated using various concentrations of tris(hydroxymethyl)aminomethane dissolved in distilled water (pH 5). The carbon pellets were washed in deionized water after pretreatment to remove excess water-soluble amino groups from the carbon surface. All the pretreated carbon samples were kept in an airtight desiccator away from light.

UV/VIS Spectrophotometer and X-ray Photoelectron Spectra

To quantify the amount of organic molecules attached to the carbon surface, we first calibrated the absorbance of the amine and organophosphorus extractants against their concentrations in aqueous solution and in *n*-heptane. To measure absorbance, we used the UV/VIS spectrophotometer (JASCO V-560). We found a linear relationship between concentration of organic molecules bound by carbon and their respective absorbance in all the cases. Therefore, the actual concentrations of the adsorbed molecules remaining in the organic solutions were evaluated by comparing chemical absorbance values on the standard absorbance-concentration graphs. The characteristic wavelengths were: 240, 215, and 195 cm^{-1} for Cyanex 301, MSP-8, and amine, respectively.

The binding energies of organophosphorus extractants, amine, and the functional chemical groups on the carbon surface were determined through XPS data. The Kratos (AXIS-165, SAC) X-ray photoelectron spectrometer with a mono Al Kα (pass 80 eV, 7 mA, 15 kV) was employed as the source of X-rays.

Specific Surface Area of Carbon Pellets

Nitrogen isotherms were measured with an ASAP 2000 micropore analyzer (Micromeritrics, USA) at 77 K. The isotherm plots were used to calculate the specific surface area (N_2/BET (Brunauer, Emmett, and Teller) method) and average pore diameter of original carbon pellets, while micropore volume was calculated from the volume of nitrogen adsorbed at p/p_o 0.973 (volume of pores that have a diameter less than 74.1 nm).

Batch Equilibrium Adsorption Tests

In the batch adsorption tests, we contacted 0.02 g of modified carbon pellets with 15 mL of a multicomponent chloride solution. The chloride solution pH was varied between 0.8 and 2.4. The adsorbent-feed solution mixtures were placed in a thermostated mechanical shaker for 48 hours at 303 K. After attaining equilibrium conditions, the modified carbon pellets and depleted solution were separated by decanting. The suspended microparticles in the decanted solution were filtered through 0.2-μm micromembranes (Advantech Millipores). The clear solution samples obtained after microfiltration were analyzed for residual metal ions by means of a sequential plasma spectrometer (SHIMAZU, ICPS-5000).

The adsorption capacities and separation factors obtained for each type of modified carbon were recorded. The adsorption capacity, Q, is defined as:

$$Q = \frac{[\mathrm{Me}]_{\mathrm{ad}}}{\text{Mass of Carbon}} \frac{(\mathrm{mg})}{(\mathrm{g})} \tag{1}$$

where, the subscript ad refers to the adsorbed metal species. The separation factor, β, is defined as follows:

$$\beta_{[i/j]} = \frac{D_{\mathrm{Me,i}}}{D_{\mathrm{Me,j}}} \tag{2}$$

where,

$$D_{\mathrm{Me}} = \frac{\mathrm{Me}_{\mathrm{ad}}}{\mathrm{Me}_{\mathrm{sol}}} \tag{3}$$

and, subscripts i and j stand for different metal species. D_{Me}, the distribution coefficient, is the ratio between adsorbed metals and residual metals in solution at equilibrium.

RESULTS AND DISCUSSION

Immobilization of Organic Functionalities on the Carbon Surface

Figure 1 illustrates the chemical structures of the extractants applied in this study while Figs. 2a, 2b, and 2c show the SEM microphotographs of the original

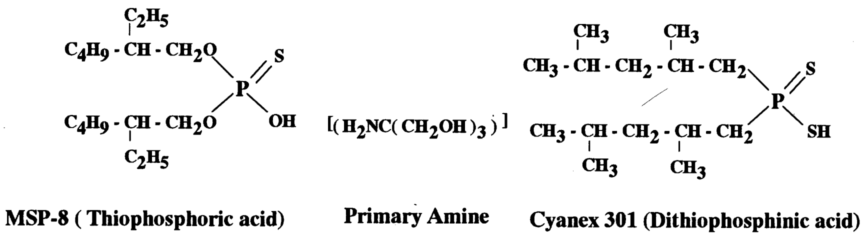

Figure 1. Structures of MSP-8 and Amine, Cyanex 301.

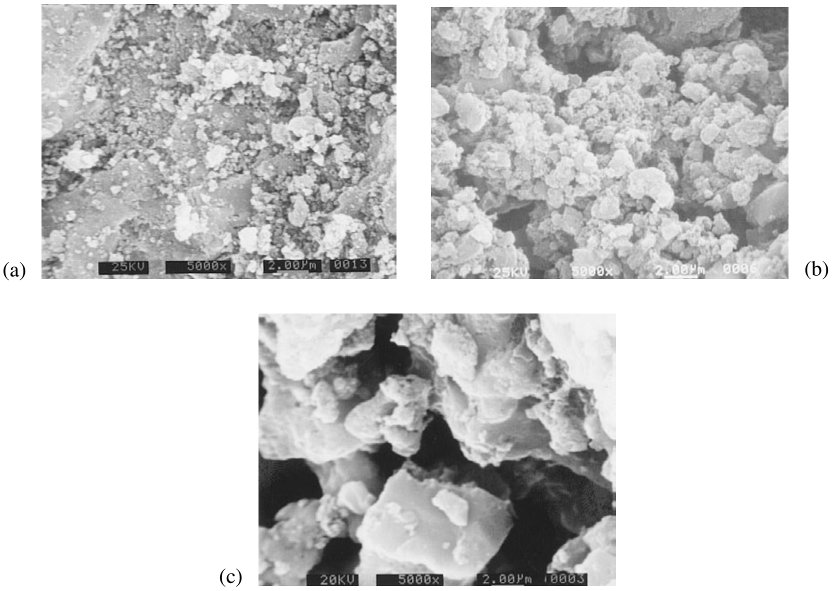

Figure 2. **(a)** SEM microphotograph of commercial activated carbon pellets (Norit 0.8) **(b)** SEM microphotograph of thiophosphate-treated carbon pellets illustrating the presence of a trace precipitate phase on the carbon surface. Applied dosage of MSP-8 = 0.05 g/L; Solid-liquid ratio = 0.2 g:25 mL; contact time 72 hours. **(c)** SEM microphotograph of dithiophosphinic acid–treated carbon pellets illustrating the presence of a second phase on the carbon surface. Applied dosage of Cyanex = 0.05 g/L; Solid-liquid ratio = 0.2 g:25 mL; contact time 72 hours.

activated carbon pellets (AC), MSP-8-treated carbons (MAC), and Cyanex 301-treated carbons (CAC). Although evidence of molecular interactions between a carbon surface and organic molecules could not be shown with an SEM microphotograph, the surface chemical interaction involving dithiophosphinic and activated carbon resulted in the precipitation of a second phase that could be observed (Fig. 2c). In this study, the surface morphology of amine-treated activated carbons (AAC) did not differ significantly from that of AC (SEM not shown), which indicates that an interaction of carbon functional groups with amines did not yield a precipitate under the experimental conditions. However, the SEM microphotographs of MAC and CAC show some traces of an adsorbed second phase. Although the nature of this precipitate is not fully understood, sulfurization of a carbonyl compound has been found to yield thioacetyl groups (C-SR) (14). By comparison, CAC showed significant amounts of the precipitated second phase of C-SR groups (Fig. 2c) while little traces of this sulfur-mediated precipitate were present in MAC (Fig. 2b). Because the mercaptans are readily washed off in acidic aqueous media, we decided to carry out an extraction test of the organic precipitate with an emulsion (water-in-oil) comprised of a 2-solution mixture: sorbitan mono-oleate surfactant (10 mmol/L) (commercial name, SPAN 80) dissolved in *n*-heptane and an acidified chloride solution (pH 2). The polymeric precipitate or 0.02 g of Cyanex 301-coated carbon pellets was easily washed off in less than one hour of mild shaking in 20 mL of emulsion and the original carbon surface morphology was restored (SEM not shown).

Adsorption Isotherms of Organophosphorus Extractants and Amine

The adsorption isotherms of CAC, MAC, and AAC are shown in Fig. 3. A maximum dosage of extractor was found such that the adsorption of organophosphorus extractants is not enhanced. The amounts of electron-deficient and polarized sites on the carbon surface serve as the limiting conditions for anchoring the organic molecules. Results showed that a higher number of dithiophosphinic groups was adsorbed onto the surface of activated carbon than the thiophosphate or amino groups under the experimental conditions. According to UV/VIS spectral analyses of residue organic solutions, the adsorption capacity of Cyanex 301 averaged 150 mg/g followed by MSP-8 with 75 mg/g, and the amino groups at 15 mg/g. Cyanex 301 was highly adsorbed, probably because 2 sulfur atoms are present in a single monomer. However, MSP-8 carries only 1 sulfur atom per monomer of extractant.

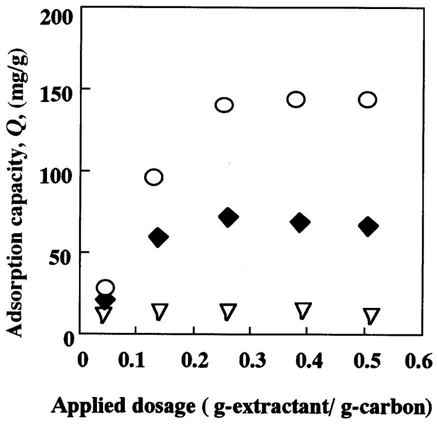

Figure 3. The adsorption isotherms of Cyanex 301, MSP-8, and amine. Solution carbon ratio = 25 mL:0.2 g. Contact time 72 hours. Reaction temperature = 313 K.

Determination of the Specific Surface Area of Modified Carbon Surface

The specific surface area, pore size, and volume of amine-treated carbons did not decrease significantly over those measurements of the original pellets. However, the decrease in pore volume and surface area of dithiophosphinic-treated carbons was significantly high, probably due to the presence of a precipitate constituting an ensemble of sulfur groups on the carbon surface. Table 1 compares the surface area and porosity properties of AAC, MAC, and CAC. Results showed that carbon pellets immobilized with sulfur-containing organic compounds showed a slight decrease in specific surface area and pore size.

X-ray Photoelectron Spectral Results

Figures 4a, 4b, and 4c show the wide-scan X-ray spectra of AC, AAC, and MAC, respectively. The X-ray spectrum of AC shows the reference carbon peak (C 1s, 285.6 eV) and the oxygen peaks (O 1s, 532.1 eV). The AAC spectrum elucidates the binding of the amine (N 1s, 399 eV), while for the MAC spectra the presence of sulfur and phosphorus were recorded (S 2s, 167.5 eV, and P 2s 164 eV) without the appearance of a N 1s peak.

Figures 5a, 5b, and 5c illustrate the high resolution X-ray spectra of C 1s from the surface AC, AAC, and MAC. The ketone and ether groups are found around the C$=$C bonds at 288.5 eV and 287.2 eV, respectively. After a primary amine was immobilized onto the AC surface (Fig. 5b), the intensity associated with the binding energy peaks of ketone and ester groups decreased significantly, and a new surface group (—C—O—) appeared on the carbon surface as shown by the peak 285.9. This result implied that the amine group reacted with the ketone/ester group to form a new —C—O group. The ether group from the activated carbon surface did not react with the amine. However, the X-ray spectrum of thiophosphate-

Table 1. Characteristics of Chemically Treated Carbons

Adsorbents	BET Surface Area (m^2/g)	Micropore Area (m^2/g)	Micropore Volume (cc/g)	Pore Diameter (nm) (4V/A by BET)
AC	951	637	0.34	2.510
AAC	948	635	0.32	2.493
MAC	915	619	0.28	2.370
CAC	868	588	0.19	2.258

AAC = amine-treated carbon; MAC = MSP-8–treated carbon; CAC = Cyanex-treated carbon; AC = untreated activated carbon.

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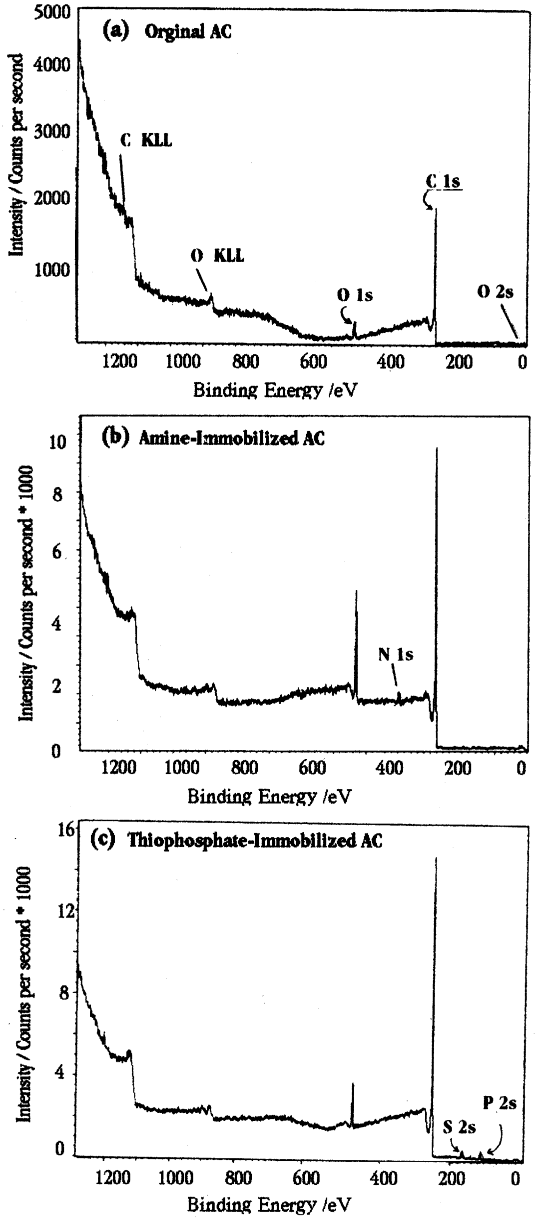


Figure 4. Wide survey-scan spectra for **(a)** AC pellets, **(b)** amine-treated AC, and **(c)** thiophosphate-treated AC.

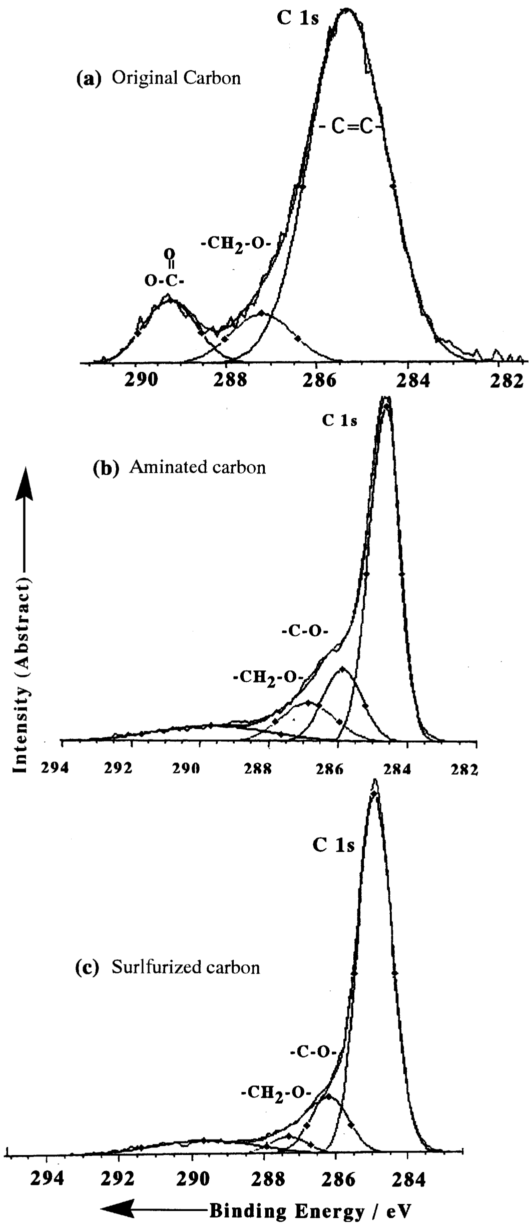


Figure 5. The comparison of high resolution XPS spectra for **(a)** native carbon **(b)** amine-treated carbon, and **(c)** for binding energy related to ethers and carbonyl groups after addition of amines and thiosulfates.

treated carbons did not show the presence of ketone groups (Fig. 5c) implying that the ketone groups served as the reactive site for the thiophosphorus molecules.

Figures 6a, 6b, and 6c show comparisons of high resolution X-ray spectra of O 1s from AC, AAC, and MAC. The data show that the ketone and ester groups

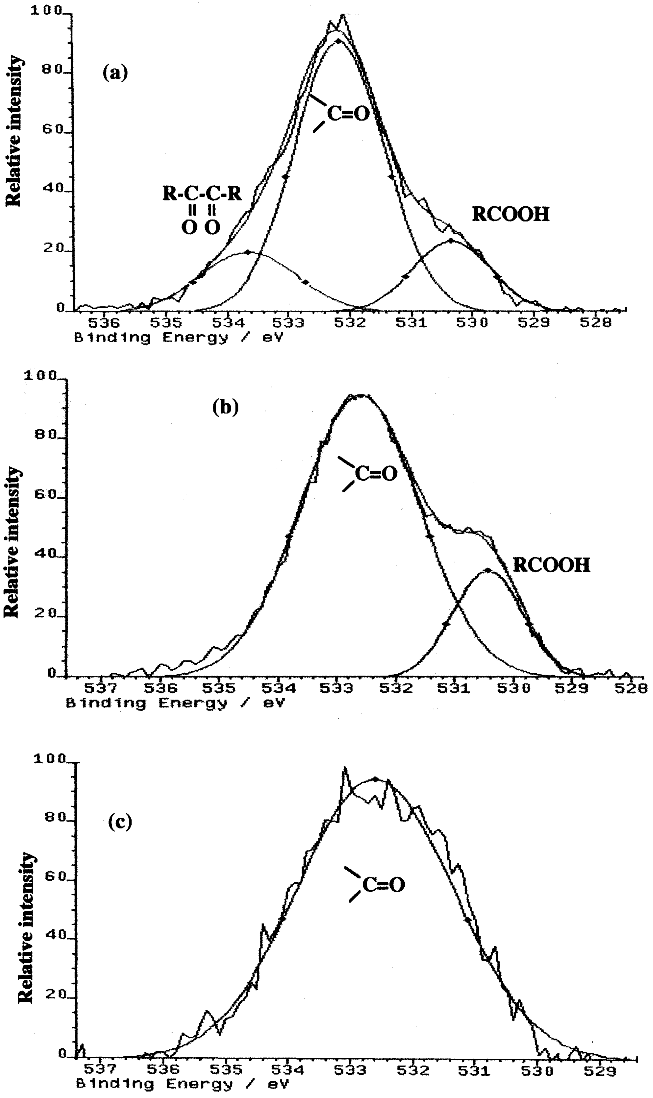
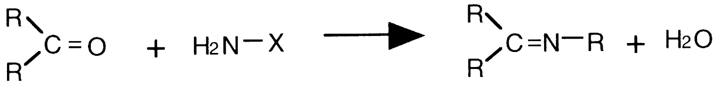


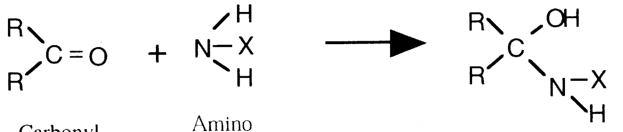
Figure 6. The comparison of high resolution O 1s spectra for **(a)** original carbon pellets, **(b)** amine-treated AC, and **(c)** thiophosphate-treated AC.

reacted with the amine (Figs. 6b and 6c) while the ester, ketone, and carboxyl groups reacted with organophosphorus groups (Fig.5b and 5c); a decrease in peak intensity was found for these functional groups. The chemical equations subsequently illustrated elucidate the possible reaction mechanisms between the carbonyl functional groups and adsorptive ligands (14).



(4)

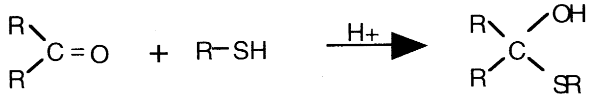
(Reductive Amination of Carbonyl Compound)



(5)

Carbonyl group

Amino group, X = **C(CH$_2$OH)$_3$**



(6)

Organophosphorus group

In this study, the adsorption mechanism of Pd(II) (as $PdCl_3(H_2O)^-$ or $PdCl_4^{2-}$) and $PtCl_6^{2-}$ is explained by an interaction between the attached ligand molecules and the carbonyl groups of the carbon support. However, Rh(III), existing in chloride solution as either $Rh(H_2O)_6^{3+}$ or $RhCl(H_2O)_5^{2+}$, would be repelled by the protonated ligand–carbon surface under low pH conditions.

Distribution Coefficients of Pt(IV), Pd(II), and Rh(III)

Figures 7, 8, and 9 show the distribution coefficients of metal ions as a function of applied dosage of thiophosphoric acid, amino groups, and dithiophosphinic acid on the carbon surface, respectively. Table 2 illustrates the corresponding adsorption capacities and separation factors of the carbons that were tested.

In Fig. 7, MAC showed a high adsorption capacity for Pd(II) (12 mg/g) compared to Pt(IV) (6 mg/g) when the amount of MSP-8 immobilized on the carbon surface was in the range of 80–100 mg/g. MSP-8 showed selectivity for palladium ions in a ternary solution probably due to donor sulfur atoms. However, the adsorption capacity of untreated carbons, AC, is higher than that of all the chemically treated carbons (Table 2), but its selectivity is poor. Furthermore, adsorption on the carbon surface decreased with an increase in organic molecules concentration. This result was attributed to the presence of hydrophobic ligands

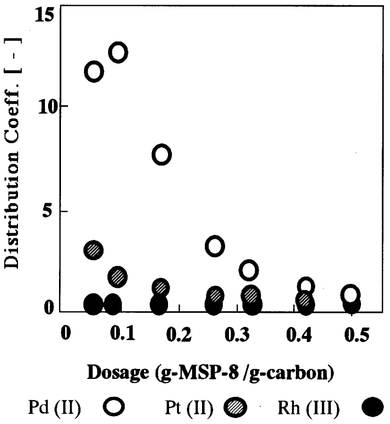


Figure 7. Distribution coefficients of Pd(II), Pt(IV), and Rh(III) on MSP-treated activated carbon pellets as a function of dosage.
$[Me]_O$ = 20.5 mg/L; feed solution pH_O = 1.0–2.0; reaction temperature = 303 K. Solid-liquid ratio = 0.02 g:15 mL; contact time = 48 hours.

on the carbon surface. When excess MSP-8 was immobilized on the carbon surface, its adsorption capacity decreased significantly probably due to formation of microprecipitates around the surface (Fig. 2b, MAC) as well as the increase in surface hydrophobicity. MAC showed poor affinity for cationic Rh(III) complex ions

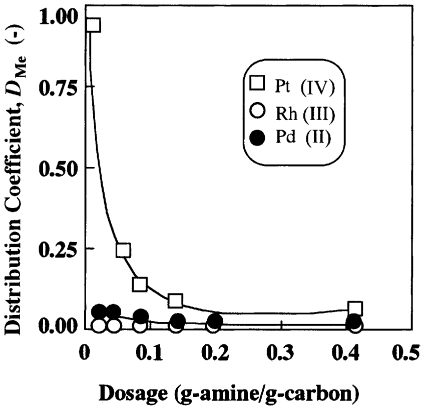


Figure 8. Distribution coefficients of Pd(II), Pt(IV), and Rh(III) on amine-treated activated carbon pellets as a function of dosage. Initial concentration of each metal = 20 mg/L feed solution pH = 2.4, reaction temperature = 303 K, solid:liquid ratio = 0.02 g:15 mL.

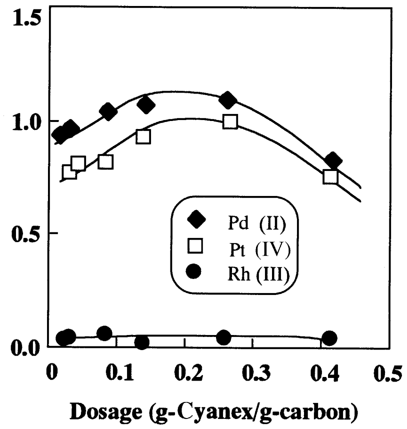


Figure 9. Distribution coefficients of Pd(II), Pt(IV), and Rh(III) on Cyanex 301–treated activated carbon pellets as a function of dosage. Initial concentration of each metal = 20 mg/L; feed solution pH = 2.4; reaction temperature = 303 K; solid-liquid ratio = 0.02 g:15 mL.

under low pH conditions as evidenced by low distribution coefficients (Fig. 7). In our previous report, untreated activated carbon pellets showed a significant adsorption capacity for Rh(III) only in a narrow pH range of 2.3–2.6 (15).

As show by Fig. 8, AAC showed affinity for Pt(IV) ions. The amino ligands are readily protonated under low pH, and therefore the adsorption of Pt(IV) anionic complexes ($PtCl_6^{2-}$) occurred at the positively charged —NH_2^+ sites. According to the speciation diagrams of platinum group metals in chloride media (16–18), the fractions of anionic Pd(II) complexes ($PdCl_4^{2-}$, $PdCl_3^-$) at pH 2.4 are significantly smaller compared to $PtCl_6^{2-}$ complexes in chloride media. This result explains why Pt(IV) anions were adsorbed selectively at pH 2.4 (data not

Table 2. The Separation Factors in Multicomponent Adsorption System

	Separation Factors			Q (mg/g)		
Adsorbents	$\beta_{[Pt/Pd]}$	$\beta_{[Pt/Rh]}$	$\beta_{[Pd/Rh]}$	Pt(IV)	Pd(II)	Rh(III)
AAC	16.74	∞	∞	7.51	0.82	0.00
MAC	0.17	20.10	115.35	6.24	12.25	0.51
CAC	0.77	21.35	27.71	6.47	7.46	0.50
AC	0.98	3.84	3.27	10.87	10.12	4.87

Q = Adsorption capacity. Batch adsorption conditions: Solid-liquid ratio = 0.02 g:15 mL; Temperature = 303 K, contact time = 48 hours.

shown). However in a dilute chloride solution of pH 0.8, a significant amount of Pd(II) anions exist in chloride media. In this case, the selective adsorption of $PtCl_6^{2-}$ anions in the presence of Pd(II) anions was attributed to the protonation of immobilized amino groups. AAC did not show an affinity for Rh(III) ions under the experimental conditions. We found that an increase in amino ligands on the carbon surface invariably led to a decrease in the adsorption capacity. We attributed this result to the increase in surface hydrophobicity caused by the presence of long-chain, nonpolar amine groups.

Figure 9 shows that selectivity of CAC for Pd(II) ions over that of Pt(IV) ions is unsatisfactory. The separation factor of Pd(II) from Pt(IV) ions did not exceed 1.2 in CAC. However, the separation factor of Pd(II) from Rh(III) ions was high at 27. This result implies that Cyanex-immoblized carbons did not sequester Rh(III) ions, and its application to the separation of Pt(IV) and Pd(II) ions is limited. CAC-treated carbons showed a substantial amount of precipitate that looked like a crystalline phase due to the excess amounts of R—CS groups. Because the carbon surface is covered by a second phase of R—CS groups (or elemental sulfur) (Fig. 2c), the CAC carbon does not interact with the adsorbent effectively. Hence the adsorption isotherm of CAC (Fig. 9) did not compare well with those of MAC and AAC (Figs. 7 and 8). However, at higher dosages of Cyanex 301 (precipitate region), the adsorption of Pd(II) ions did not reach a maximum and subsequently reduce to zero as recorded for MAC and AAC (Figs. 7 and 8); this result is probably due to a complex interaction between Pd(II) ions and the excess donor sulfur atoms in the precipitate layer. We did not carry out the stripping experiments for the adsorbed metal species. However, we will need to use water-in-oil emulsions to recover metal ions as well as to restore the original surface of activated carbons.

Table 2 shows the separation factors observed for all the modified carbons compared to the untreated carbons. AAC yielded the highest separation factor, $\beta_{(Pt/Pd)}$, between Pt(IV) and Pd(II) averaging 17. This result confirms that amino groups are effective for sequestering Pt(IV) ions from a ternary solution containing Pd(II) and Rh(III). Furthermore, the separation factor, $\beta_{(Pt/Rh)}$, between Pt (IV) and Rh(III) in AAC was so large that it approached infinity. Conversely, MAC exhibited great affinity for Pd(II) ions and yielded a separation factor, $\beta_{(Pd/Pt)}$, of approximately 6 in a mixed chloride solution (pH 1.0–2.4). Cyanex 301, having 2 donor sulfur atoms, showed selectivity for Pd(II) ions (like MSP-8) but its selectivity over Pt(IV) ions was adversely affected by the precipitate that appeared on the surface of CAC.

CONCLUSION

On the basis of the experimental results, we concluded that organophosphorus and amino groups are readily adsorbed onto a basic carbon adsorbent. Extractant-carbon interactions occur around the ester, ketone, and carboxylic reactive sites. Immobilized amino groups on the carbon surface facilitated selective adsorption of platinum ions in the presence of palladium and rhodium. However, the carbons with immobilized organophosphorus groups showed great potential for palladium ion–specific reactions. This novel method of creating specificity on the carbon surface by anchoring extractant molecules provides potential prospects of developing solid carriers of extractants that could be applied in the recovery process of precious metal. To strip the chemically treated activated carbons, W/O emulsions will need to be applied for the removal of organic molecules and metal ions. We observed that the dosage of extractants at which optimum adsorption occurred was extremely small, rendering this method attractive for the selective binding of precious metals. Also, carbon pellets immobilized with platinum-group metals could find wide application in the chemical catalytic industry.

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