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Application of carbon foam for heavy metal removal from industrial plating wastewater and toxicity evaluation of the adsorbent

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HIGHLIGHTS

- Carbon foam can be applied to heavy metal removal from industrial plating wastewater.
- Carbon foam has a high sorption capacity compare than commercial materials.
- Cytotoxicity of carbon foam on human cells was sufficiently low to use.
- Carbon foam has a high sorption capacity for Cr in pilot plat system.
- Oxidation pretreatment can enhance heavy metal removal from plating wastewater.

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ABSTRACT

Electroplating wastewater contains various types of toxic substances, such as heavy metals, solvents, and cleaning agents. Carbon foam was used as an adsorbent for the removal of heavy metals from real industrial plating wastewater. Its sorption capacity was compared with those of a commercial ion-exchange resin (BC258) and a heavy metal adsorbent (CupriSorb™) in a batch system. The experimental carbon foam has a considerably higher sorption capacity for Cr and Cu than commercial adsorbents for acid/alkali wastewater and cyanide wastewater. Additionally, cytotoxicity test showed that the newly developed adsorbent has low cytotoxic effects on three kinds of human cells. In a pilot plant, the carbon foam had higher sorption capacity for Cr (73.64 g kg^{-1}) than for Cu (14.86 g kg^{-1}) and Ni (7.74 g kg^{-1}) during 350 h of operation time. Oxidation pretreatments using UV/hydrogen peroxide enhance heavy metal removal from plating wastewater containing cyanide compounds.

1. Introduction

The high levels of heavy metals in water represent a serious threat to aquatic life and humans. These harmful heavy metals are generated globally from a variety of activities, such as military, industrial, agricultural, and waste disposal (Zamil et al., 2009). Industrial plating wastewater is a major source of heavy metals. These wastewaters contain various types of harmful heavy metals (e.g., chromium, nickel, copper, zinc) in high concentrations, even up to several hundred mg L^{-1} (Malamis et al., 2012). The metals must be removed from the wastewaters prior to discharge because they are considered persistent, bioaccumulative, toxic substances (Liu et al., 2013b).

Various treatment technologies, such as precipitation, ion-exchange, adsorption, electro-coagulation, and membrane separation, have been developed for the removal of heavy metals from

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wastewater (Malamis et al., 2012; Tokuda et al., 2008; Panayotova et al., 2007; Sousa et al., 2009; Al-Shannag et al., 2015). Among these technologies, chemical precipitation is the most common method for removing heavy metals from industrial plating wastewater due to the simplicity of the process and the inexpensive equipment required. However, the process requires large amounts of chemicals and generates sludge with high water content, which incurs additional disposal costs (Chung et al., 2014). Ion exchange is another method to markedly reduce heavy metal concentrations in water. However, ion-exchange resins are not suitable for handling concentrated metal solutions, and the cost of the resins hinders their adoption by most industries (Silva et al., 2008). Other treatment techniques, such as membrane and electrochemical methods, have high operational costs related to energy consumption (Kurniawan et al., 2006).

Adsorption is also used widely in wastewater treatment due to the convenience of the operation. Recently, studies using a low-cost adsorbent have been performed intensively in the area of heavy metal removal. Many types of biosorbents such as bacteria, fungi, and algae were shown to have the ability to remove copper, zinc, cadmium, and lead from aqueous solution (Wang and Chen, 2009; Areco et al., 2012; Javanbakht et al., 2014; Amirnia et al., 2015). However, these biosorbents, just like ion-exchange resin, were only suitable for the treatment of low concentrations of heavy metals (Zamil et al., 2009; Liu et al., 2011). Carbonaceous adsorbents prepared from solid wastes are the most effective adsorbents for the removal of high concentrations of toxic heavy metals. Activated carbon derived from low-cost precursors (e.g., date pits, coconut shell, and *Typha latifolia* L. - cattail) was used for the removal of heavy metals from industrial wastewater (Al-Omair and El-Sharkawy, 2007; Bernard et al., 2013; Song et al., 2015).

Carbon foam is a sponge-like carbon material with high strength, light weight, high potential for thermal/electrical management, and a large surface area with open cell structure (Chen et al., 2006; Tondi et al., 2010). Because of these inherent properties, carbon foam is used as catalyst support, filters for molten metal and corrosive chemicals, porous electrodes, and impact/energy/acoustic absorbers (An et al., 2011; Chun et al., 2012; Emmel and Aneziris, 2012; Kim and Cunningham, 2010; Kang et al., 2011; Grujicic et al., 2006; Shao et al., 2013; Amaral-Labat et al., 2013). Carbon foam has potential application as a low-cost adsorbent due to the low-cost of manufacturing, and large amounts of precursor can easily be obtained. Liu et al. (2013a) prepared carbon foam from larch sawdust and used the foam for the gas-phase toluene adsorption. Burke et al. (2013) conducted a study using carbon foam chemical oxidation for Pb(II) ion removal from aqueous solution.

In our previous study, the properties of phenolic resin-based carbon foam were investigated and a high capacity for adsorption of lead and copper was found (Lee et al., 2015). In this study, we tested carbon foam on real industrial plating wastewater. Batch experiments were conducted in laboratory, and the sorption capacity was compared with commercial ion-exchange resin (BC258) and commercial heavy metal adsorbent (CupriSorb™). In addition, a pilot plant test was conducted for verification of field application potential in the wastewater treatment plant of a plating industry cooperative. The toxicological effects of the carbon foam on several kinds of human cells and the effect of oxidation as pretreatment were also investigated.

Table 1
Characteristics of the materials.

Measuring quantity	Carbon foam	BC258	CupriSorb™
Bulk density (g cm^{-3})	0.88	1.17	0.60
Surface area (m^2 g^{-1})	545.99	0.086	1.47
pH	9.42	10.61	10.89
Zeta potential (mV)	−28.4 ± 6.75	−52.9 ± 5.83	−52.4 ± 6.20

2. Materials and methods

2.1. Carbon foam preparation and commercial materials

Phenolic resin-based carbon foam was prepared as described elsewhere (Lee et al., 2015). Briefly, the phenolic resin was synthesized in a laboratory by compounding with formaldehyde and a base catalyst. The mixture was neutralized using dilute sulfuric acid, and the moisture content was adjusted through dehydration under vacuum, with reduced pressure. Alkyl ether type surfactant, organic acid curing agent, and hydrocarbon foaming agent were mixed with the prepared phenolic resin, and the mixture was stirred thoroughly in a mold. The synthesized foam was aged in a convection oven. Then, the dried foam was carbonized at 900 °C in N_2 (Lee et al., 2015). The ion-exchange resin BC258 was supplied from Born Chemical (Seoul, Korea), and the adsorbent CupriSorb™ was obtained from Seachem Laboratories Inc. (Madison GA, USA).

The surface morphology and chemical composition of the adsorbents were analyzed using a scanning electron microscope (SEM, Inspect F50, FEI, USA) and energy dispersive X-ray analysis (EDAX, APOLLO X, AMETEK, USA) at 15.00 kV. The open cell contents of the carbon foam were measured using a gas pycnometer (ULTRAFOAM 1200e, Quantachrome, Germany). Nitrogen gas (N_2) adsorption–desorption experiments were performed using a surface area analyzer (ASAP 2000, Micromeritics, USA), and the specific surface area was calculated using the Brunauer–Emmett–Teller (BET) method. The surface charges of the materials were measured using a Zeta analyzer (Zetasizer, Nano ZS, Malvern, UK). The characteristics of each adsorbent are shown in Table 1.

2.2. Plating wastewater

Two types of plating wastewaters were collected from the wastewater treatment plant located in the Banwol Jungang Plating Industry Cooperative (Ansan, Korea): acid/alkali wastewater and cyanide wastewater. The heavy metal concentration in the wastewater was analyzed using an inductively-coupled plasma-optical emission spectrometer (ICP-OES, Prodigy ICP, Teledyne Leeman Labs, USA). Analysis kits were used to measure the cyanide concentration (HS-CN, Humas, Korea) and chemical oxygen demand (COD(Mn)-HR, C-mac, Korea). The solution pH was measured using a pH probe (8302BNUMD, Orion, USA). The concentration of heavy metals and other chemical constituents of the plating wastewater are shown in Table 2.

Table 2
Heavy metal concentration and other chemical compositions in industrial plating wastewater.

Wastewater type	pH (–)	Cr (mg L^{-1})	Cu (mg L^{-1})	Ni (mg L^{-1})	Zn (mg L^{-1})	CN (mg L^{-1})	COD_{Mn} (mg L^{-1})
Acid/alkali	2.19	93.25	36.16	50.94	–	–	86.35
Cyanide	4.01	12.42	2.06	22.34	196.72	4.64	80.7