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Application of Multiwalled Carbon Nanotube-Cyclodextrin Polymers in the Removal of Heavy Metals from Water

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Abstract: The aim of this study was to synthesize oxidized multiwalled carbon nanotube-cyclodextrin polymer and explore the possibility of using this polymer for the remediation of heavy metal contamination in the aquatic environment. Herein we report the results obtained from testing the polymer for the removal of lead and cobalt from synthetic water solutions. The performance of the polymer was matched against pristine and oxidized multiwalled carbon nanotubes. The polymer was found to perform better at lower concentrations (10 mg L^{-1}) with adsorption capacities of 4.08 and 3.89 mg g^{-1} for lead and cobalt, respectively. These correspond to 68.0 and 64.8% removal of lead and cobalt, respectively. The maximum adsorption capacity of the polymer from the Langmuir isotherms was calculated to be 28.86 and 21.44 mg g^{-1} for lead and cobalt, respectively, at an initial concentration range of $10\text{-}50 \text{ mg L}^{-1}$. Competitive adsorption studies revealed that lead is adsorbed better than cobalt. Furthermore, the adsorption capacity of the polymer is lower in the competitive adsorption than in the single metal ion adsorption, suggesting competition between the lead and cobalt ions.

Key words: Adsorption, cobalt, cyclodextrins, lead, oxidized multiwalled carbon nanotubes

INTRODUCTION

Pollution of our water sources by inorganic pollutants with special reference to the heavy metals (lead, mercury, zinc, cobalt, cadmium, nickel, chromium, etc.) presents a massive threat to human health (Li *et al.*, 2003). Although heavy metals occur naturally, pollution by these metals results to abnormally high concentrations (Parsons and Jefferson, 2006). Heavy metals often find their way into aquatic ecosystems from geochemical sources, agricultural materials, metallurgical industries and battery industries (Parsons and Jefferson, 2006; Aloy and Ayres, 1997). Once in the aquatic environment heavy metals can be absorbed by living organisms and accumulate to acute concentrations as they move up the food chain (Wan-Ngah and Hanafiah, 2008; Rao *et al.*, 2007). This leads to toxicity problems making it essential to monitor and remove these heavy metals from water.

Several methods and materials have been proposed and used for the removal of heavy metals from water namely: chemical precipitation, coagulation-flocculation, membrane filtration, electrochemical techniques, ion exchange, chelating agents and adsorption processes (Droste, 1997; Kurniawan *et al.*, 2006). However, some of these processes are often associated with many problems which make their use ineffective. High operational costs

and the inability of these processes to remove the heavy metals to the acceptable levels are the most common shortcomings of some of these processes (Kurniawan *et al.*, 2006). The adsorption processes are found to be the most promising techniques for the removal of heavy metals from water with functionalized carbon nanotubes as superior adsorbents.

These materials have shown good adsorption capacity for zinc, lead, copper, nickel, chromium, cadmium and mercury (Li *et al.*, 2002, 2003; Lia *et al.*, 2003; Lu and Chiu, 2006; Lu *et al.*, 2008; Rao *et al.*, 2007; Yang *et al.*, 2009).

Previous work in our laboratory showed that oxidized MWCNTs copolymerized with CDS have the ability to remove organic compounds to ppb levels (Salipira *et al.*, 2007). In this study, oxidized MWCNT-CD polymer was tested in order to evaluate its ability to remove lead and cobalt from synthetic water solutions. Both lead and cobalt are documented as having devastating health effects when they accumulate in the human body above the accepted maximum limits (ATSDR, 2004, 2007). For example, the maximum accepted levels for lead according to the South African and World Health Organization's Drinking Water Standards are 20 and 10 ppb, respectively (Mamba *et al.*, 2008). Moreover, both metals have also been labelled as possible carcinogens (ATSDR, 2004,

2007). Current water treatment technologies are specific for either organic or inorganic pollutants whereas both organic and inorganic pollutants coexist in the aquatic environment. Ideally this lead to the suggestion of creating a material with dual applicability that would be capable of effectively and simultaneously removing both organic and inorganic pollutants from water.

This study evaluates the ability of the polymer to quantitatively remove lead and cobalt as a function of initial metal concentration and contact time. In addition competitive adsorption studies were conducted and are presented in this article. Information from this latter study helped to evaluate the performance of the polymer in removing one metal while in the presence of the other.

MATERIALS AND METHODS

The work reported in this study was conducted between June 2009 and December 2009. All chemicals and reagents used in this study were of high purity and were used without further purification. All solvents were dried and distilled according to standard procedures and were stored under anhydrous conditions (Armarego and Perrin, 2002). Reactions were carried out in an inert atmosphere with either argon or nitrogen gas.

Preparation of adsorbents

Synthesis, purification and functionalization of MWCNTs: MWCNTs were synthesized in our laboratory using the nebulized spray pyrolysis method as described in literature (Vivekchand *et al.*, 2004; Salipira *et al.*, 2008). Toluene was used as a carbon source with ferrocene acting as a catalyst as well as an additional carbon source. Argon was used as the carrier gas. The produced MWCNTs were then purified by removing amorphous carbon and fullerenes following methodology outlined in literature (Ndzimandze, 2007). Purified MWCNTs were oxidized at 55°C for 24 h using a 3:1 H₂SO₄:HNO₃ mixture. The oxidized MWCNTs were filtered and washed until a neutral pH was achieved and then dried in an oven to remove the water (Ndzimandze, 2007).

Polymerization of oxidized MWCNTs with cyclodextrins:

A literature procedure was adopted for the polymerization reaction (Salipira *et al.*, 2008). Typically, β-CD (8 g) was polymerized with oxidized MWCNTs (0.4 g) under the appropriate conditions using hexamethylene diisocyanate (HMDI) as a linker. This gave a 5% MWCNT-CD polymer in terms of the mass of the oxidized MWCNTs relative to the mass of the CDS.

Adsorption experiments

Preparation of Pb²⁺ and Co²⁺ solutions: Stock solutions (1000 ppm) of Pb²⁺ and Co²⁺ were prepared by dissolving

Pb(NO₃)₂ (1.599 g) and Co(NO₃)₂·6H₂O (4.938 g), respectively in 100 mL of deionised water in 1 L volumetric flasks. The flasks were then made up to the mark using deionised water. From each of the stock solutions, 2.5, 5, 7.5, 10 and 12.5 mL was pipetted into 250 mL volumetric flasks then diluted to the mark to make solutions of 10, 20, 30, 40 and 50 ppm of Pb²⁺ and Co²⁺. In all the adsorption experiments 0.05 g of the adsorbent and 30 mL of the metal solution was used. The adsorption experiments were all done at room temperature with the pH of the metal solutions kept between values 5 and 6.

Investigating the effect of the initial metal concentration:

Metal solutions of concentrations 10-50 ppm were added into 100 mL glass bottles containing each of the adsorbents i.e., pristine MWCNTs, MWCNT-COOH and MWCNT-CD. The bottles were mounted on a Merx 261 orbital platform shaker and shaken at 140 rpm for 4 h. Solutions from each adsorbent were filtered using 0.45 μm membrane filters and then analysed.

Effect of contact time: To investigate the effect of contact time on the adsorption of each metal ion, a working concentration of 10 ppm was used. The bottles containing the metal solutions and the adsorbent were shaken from 20 to 20 min at 20 min intervals.

Competitive adsorption: The ability of the three adsorbents to remove each of the metal ions in the presence of the other was investigated using binary solutions of the two metals. The metal concentrations were kept equal in the binary solutions. The effect of initial metal concentration and contact time were investigated.

Analytical instruments: An FT-IR spectrometer (MIDAC, model 400) was used to confirm the polymerization reaction and functionalization of the MWCNTs. To investigate the purity and surface morphologies of the adsorbents a scanning electron microscope (JEOL, model 5600 SEM) was used. The surface area analyses of the adsorbents were done on an automated gas adsorption analyzer (TriStar, model 3000). The concentrations of the metal ions were determined after adsorption using an atomic absorption spectrometer (Varian AAS, model SpectrAA 200).

RESULTS

Characterization of unfunctionalized and oxidized MWCNTs:

The SEM image of unfunctionalized MWCNTs is shown in Fig. 1 and it illustrates relatively clean and well aligned MWCNTs. After oxidation (Fig. 2), the MWCNTs lost their well aligned structure. FT-IR

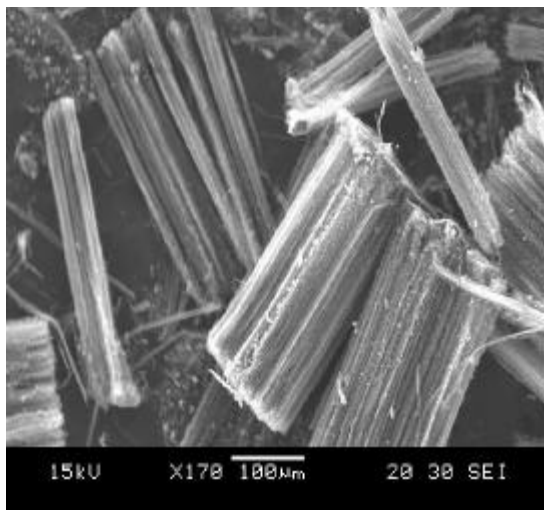


Fig. 1: SEM image of pristine MWCNTs

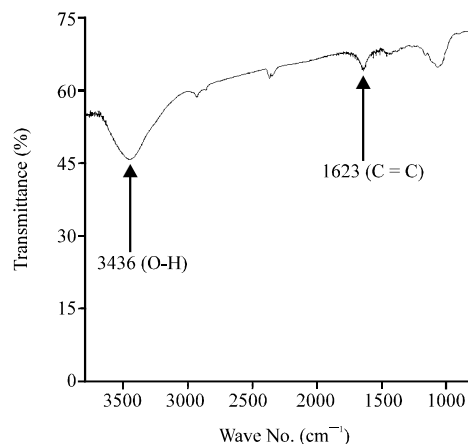


Fig. 3: FT-IR spectrum of unfunctionalized MWCNTs

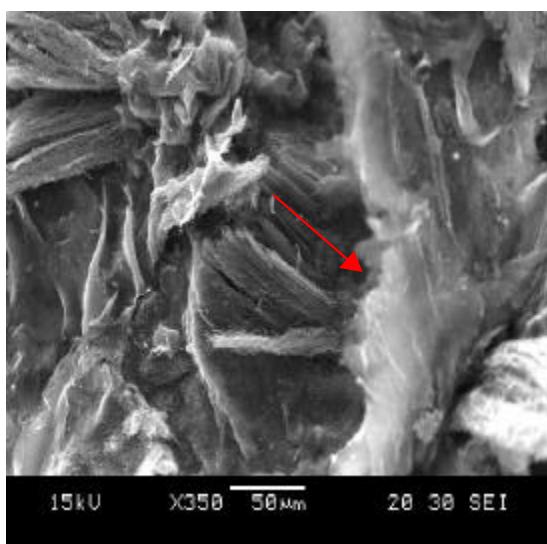


Fig. 2: SEM image of oxidized MWCNTs

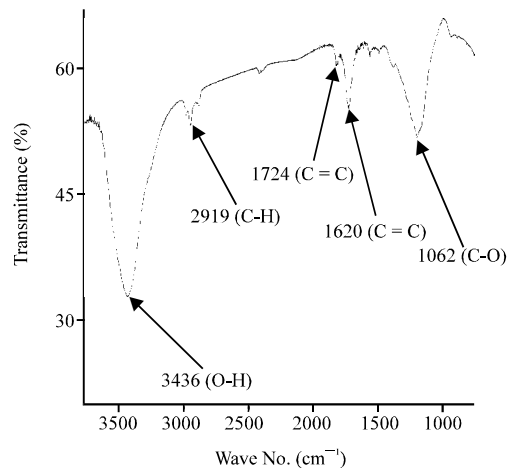


Fig. 4: FT-IR spectrum of oxidized MWCNTs

spectrum of unfunctionalized MWCNTs (Fig. 3) showed that the MWCNTs were relatively pure while the spectrum of the oxidized MWCNTs (Fig. 4) showed the presence of C = O and C-O groups, as a result of oxidation. From Table 1, the surface area of the unfunctionalized MWCNTs was found to be smaller ($39.24 \text{ m}^2 \text{ g}^{-1}$) compared to the oxidized MWCNTs ($78.61 \text{ m}^2 \text{ g}^{-1}$).

Characterization of MWCNT-CD polymer: SEM images (Fig. 5, 6) revealed that the polymer had a relatively non-uniform surface. The FT-IR spectrum of HMDI (Fig. 7) at the start of the reaction showed the isocyanate peak which decreased gradually with time until it

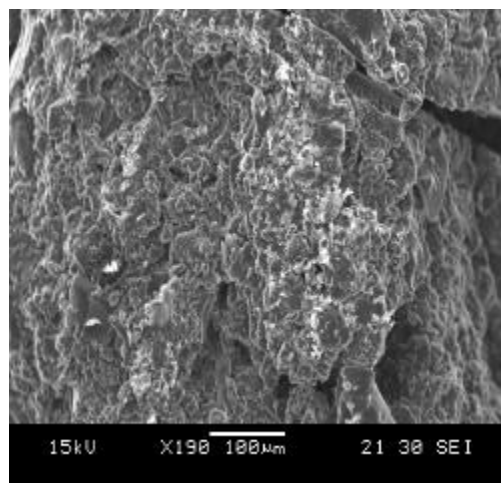


Fig. 5: SEM image of the MWCNT-CD polymer showing spongy appearance

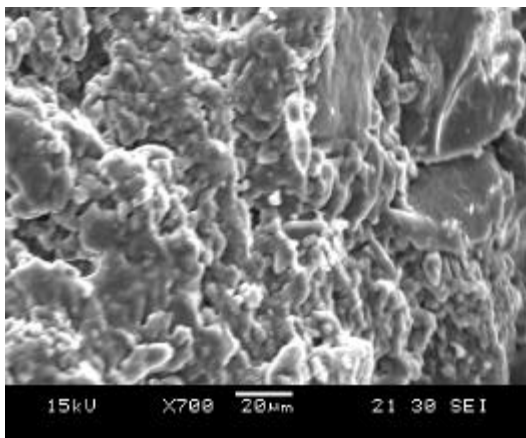


Fig. 6: SEM image of the MWCNT-CD polymer displaying a granular architecture

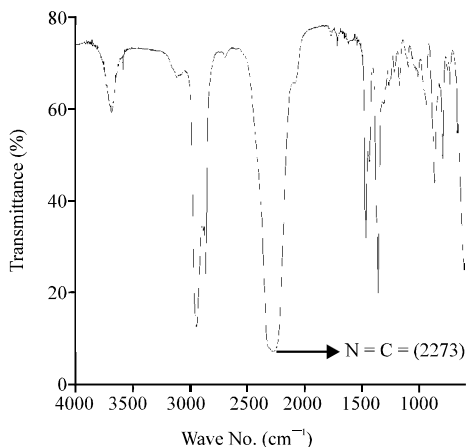


Fig. 7: FT-IR spectrum of HMDI showing the isocyanate peak at the start of the reaction

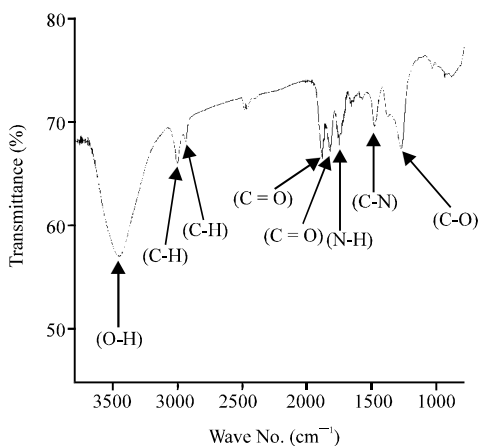


Fig. 8: FT-IR spectrum of the MWCNT-CD polymer

Table 1: BET analysis of the adsorbents

Adsorbents	Surface area (m ² g ⁻¹)	Pore volume (cm ³ g ⁻¹)	Pore diameter (nm)
Pristine MWCNTs	39.24	0.1267	12.88
Oxidized MWCNTs	78.61	0.2968	15.10
MWCNT-CD	5.46	0.0161	41.97

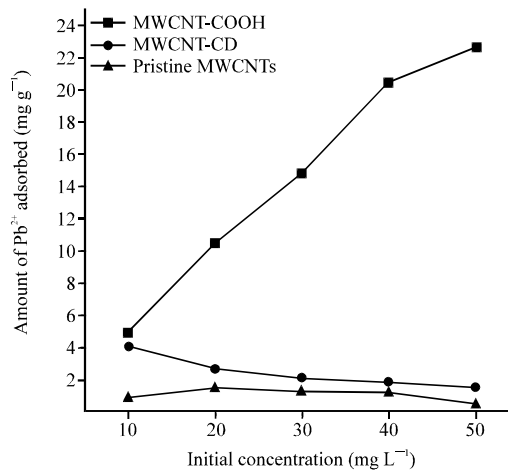


Fig. 9: Effect of initial concentration on the adsorption of Pb²⁺

completely disappeared after 24 h (Fig. 8). There was also emergence of peaks corresponding to amide functions, suggesting that polymerization of the oxidized MWCNTs and cyclodextrins did take place. The surface area of the polymer was found to be 5.46 m² g⁻¹ (Table 1).

Adsorption experiments: The amount of each of the metals adsorbed was calculated using the following equation:

$$q = (C_i - C_0) \frac{V}{m} \quad (1)$$

where, q is the amount of metal ions adsorbed (mg g⁻¹), C₀ is the initial metal concentration (mg L⁻¹), C_i is the final metal concentration after a specific time interval (mg L⁻¹), V is the volume of the metal solution used (L) and m is the mass of the adsorbent used (g).

Adsorption of Pb²⁺ ions using pristine MWCNTs, oxidized MWCNTs and MWCNT-CD polymer: Figure 9-11 show the performance of the three adsorbents for the removal of Pb²⁺ ions from synthetic solutions. The oxidized MWCNTs showed superior adsorption capacity as the concentration increased, followed by the polymer and lastly the pristine MWCNTs (Fig. 9). The oxidized MWCNTs and the polymer showed lightly increasing adsorption capacity as the time increased (Fig. 10). The

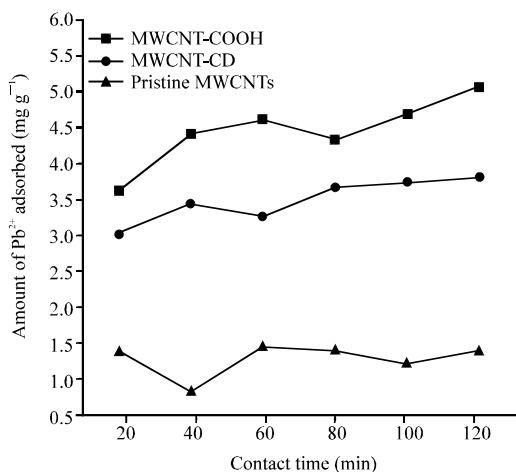


Fig. 10: Effect of contact time on the adsorption of Pb²⁺

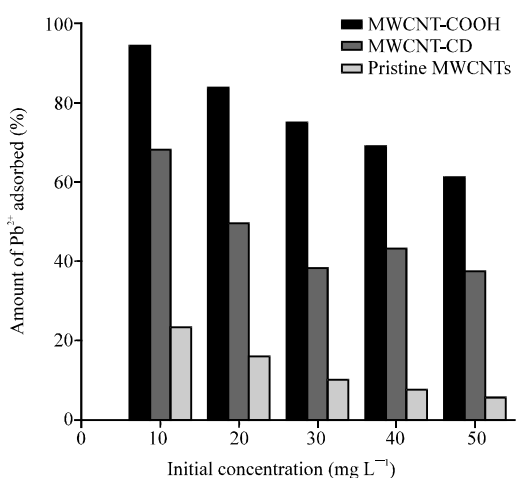


Fig. 11: Effect of initial concentration on the % removal of Pb²⁺

polymer recorded a maximum % Pb²⁺ removal of 68.0% at 10 ppm (Fig. 11) while it reaching a maximum % removal of 68.5% after 60 min (Fig. 12).

Adsorption of Co²⁺ ions by pristine MWCNTs, oxidized MWCNTs and MWCNT-CD polymer: The polymer showed a higher adsorption capacity at 10 ppm dropping remarkably as the concentration increased (Fig. 13). A similar adsorption pattern to that observed for Pb²⁺ ions as a function of contact time, by the polymer, was observed for CO²⁺ ions (Fig. 14). The oxidized MWCNTs recorded a higher % removal of CO²⁺ ions followed by the MWCNTs-CD polymer and lastly the pristine MWCNTs (Fig. 15, 16).

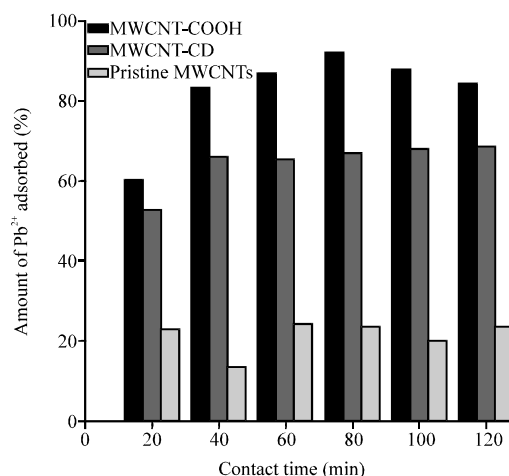


Fig. 12: Effect of contact time on the % removal of Pb²⁺

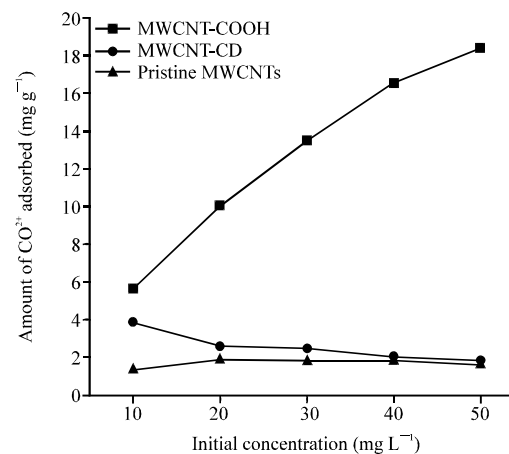


Fig. 13: Effect of initial concentration on the adsorption of CO²⁺

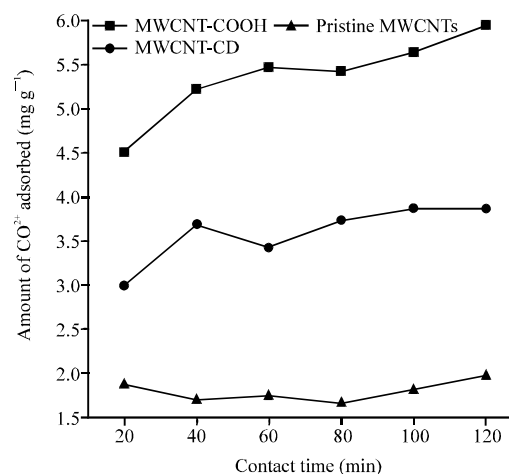


Fig. 14: Effect of contact time on the adsorption of CO²⁺

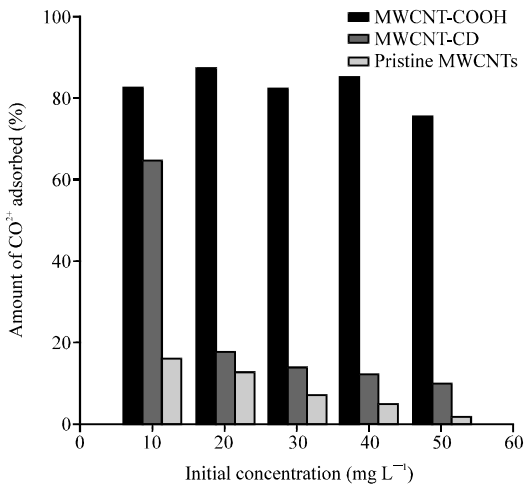


Fig. 15: Effect of initial concentration on the % removal of CO₃²⁻

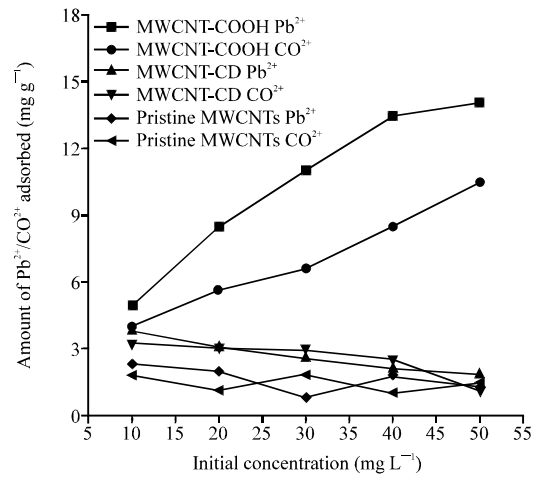


Fig. 17: Effect of initial concentration on the competitive adsorption of Pb²⁺ and CO₃²⁻

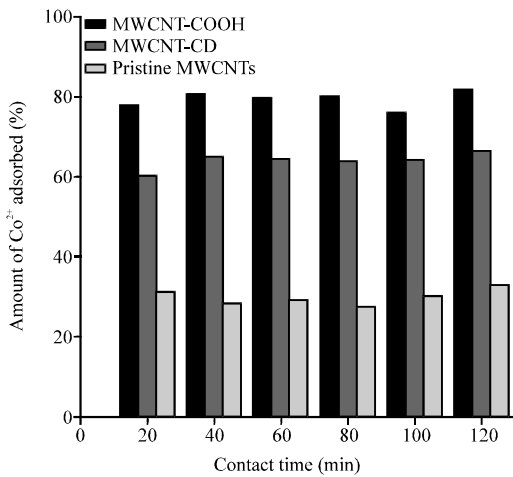


Fig. 16: Effect of contact time on the % removal of CO₃²⁻

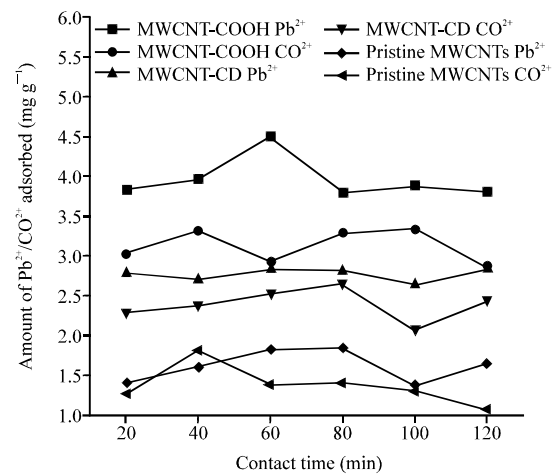


Fig. 18: Effect of contact time on the competitive adsorption of Pb²⁺ and CO₃²⁻

Competitive adsorption of Pb²⁺ and CO₃²⁻ ions: The competitive adsorption studies revealed that the adsorption capacity of all three adsorbents for both metal ions is lower in competitive adsorption compared to the single metal ion adsorption (Fig. 17, 18). The % removal of both metals by the three adsorbents was found to be lower in the competitive adsorption compared to the single metal ion adsorption (Fig. 19, 20). The polymer recorded a maximum % removal of 59.1% for Pb²⁺ ions and 55.7% for CO₃²⁻ at 10 ppm (Fig. 19).

Isotherm models: Adsorption of the two metal ions by the three adsorbents was studied using the Langmuir and Freundlich isotherm models. The following linearized Langmuir (Eq. 2) and Freundlich (Eq. 3) equations, respectively, were used:

$$\frac{C_t}{q_e} = \frac{1}{K_L q_m} + \frac{C_e}{q_m} \quad (2)$$

$$\log q_e = \log K_F + \frac{1}{n} \log C_e \quad (3)$$

where, C_t is the metal concentration after some time (mg L⁻¹), q_m is the maximum sorption capacity (mg g⁻¹), K_L is the Langmuir sorption constant (L mg⁻¹) and K_F, n are Freundlich constants related to the sorption capacity of the adsorbent and sorption energy, respectively.

The Langmuir and Freundlich parameters were calculated and presented in Table 2. The oxidized MWCNTs were found to have a maximum sorption capacity (q_m) of 54.38 and 49.94 mg g⁻¹ for Pb²⁺ ions and

Table 2: Calculated Langmuir and Freundlich constants for the adsorption of Pb²⁺ and CO²⁺

Sorbents- Metal ions	Langmuir q _m (mg g ⁻¹)	Freundlich K _f (L mg ⁻¹)	R ²	n	K _f (mg g ⁻¹)	R ²
MWCNT-COOH-Pb ²⁺	54.38	0.501	0.992	2.910	6.71	0.976
MWCNT-COOH-Co ²⁺	49.94	0.107	0.994	1.940	3.65	0.987
MWCNT-CD-Pb ²⁺	28.86	0.421	0.970	2.380	2.11	0.931
MWCNT-CD-Co ²⁺	21.44	0.130	0.982	4.650	1.52	0.930
MWCNT-Pb ²⁺	8.73	0.144	0.986	0.431	1.71	0.961
MWCNT-Co ²⁺	10.92	0.284	0.997	0.616	1.03	0.979

MWCNT = Pristine MWCNTs

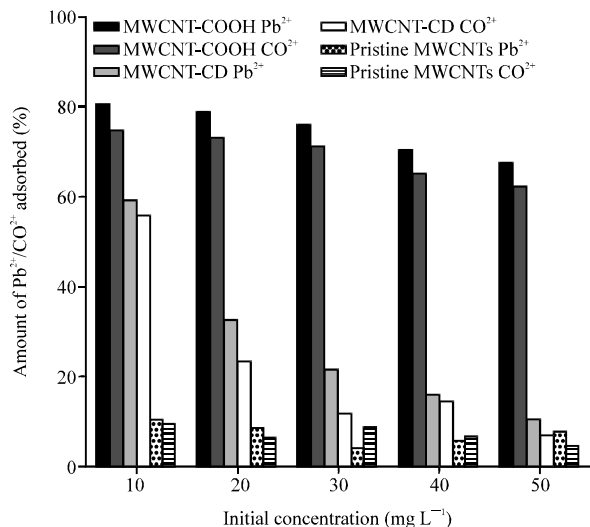


Fig. 19: Effect of initial concentration of the % removal of Pb²⁺ and CO²⁺

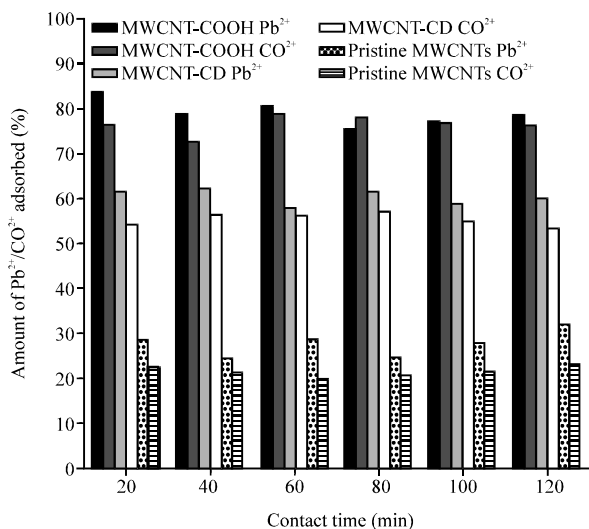


Fig. 20: Effect of contact time on the % removal of Pb²⁺ and CO²⁺

CO²⁺ ions, respectively. The polymer displayed a maximum sorption capacity of 28.86 and 21.44 mg g⁻¹ for Pb²⁺ ions and CO²⁺ ions, respectively.

DISCUSSION

Characterization of unfunctionalized and functionalized MWCNTs: From the SEM image Fig. 1, the MWCNTs appear as straight bundles of uniform lengths. Each of the bundles consists of numerous closely packed MWCNTs ropes with no indication of surface modifications (Vivekchand *et al.*, 2004). After oxidation (Fig. 2), the MWCNTs lost their uniform and straight orientation. The oxidized MWCNTs appear highly distorted and surface modification is evident (see arrow insert).

The FT-IR spectrum of the pristine MWCNTs (Fig. 3) does not show the presence of any distinctive functional groups. The peak at 1623 cm⁻¹ corresponds to the C = C of the carbon nanotube skeleton and the peak at 3436 cm⁻¹ is due to moisture. On completion of oxidation (Fig. 4) peaks corresponding to C = O and C-O are observed at 1724 and 1062 cm⁻¹, respectively. This is an indication of the presence of carboxylic groups on the MWCNTs. The C-H peak also emerges at 2919 cm⁻¹ indicating a change of hybridization state from sp² to sp³, as a direct result from the attachment of the carboxylic groups. This clearly confirms that oxidation of the MWCNTs took place (Lu *et al.*, 2008).

Characterization of MWCNT-CD polymer: The SEM images show that the polymer has an uneven surface which appears to be porous or spongy. The spongy appearance is more evident at low magnification (Fig. 5) while at higher magnification the polymer appears to consist of numerous granular aggregates (Fig. 6).

Physically, the polymer also displays a non-uniform appearance as some of it is powdery while the other part of it is granular. The granular appearance could probably be as a result of a highly cross-linked structure of the polymer.

Characterization of the MWCNT-CD polymer: The polymerization of the functionalized MWCNTs and CDS was assessed by monitoring the disappearance of the isocyanate peak (2273 cm⁻¹) of the bifunctional linker (Fig. 7). After 24 h, the isocyanate peak had disappeared, marking the completeness of the reaction.

From the FT-IR spectrum of the MWCNT-CD polymer (Fig. 8), the peak at 3425 cm^{-1} is due to OH group while the two peaks at 2932 and 2850 cm^{-1} correspond to the C-H asymmetric and symmetric stretches respectively. The peaks at 1705 and 1640 cm^{-1} can be assigned to the C = O stretching vibrations of the carbonyl skeleton and the amide functions, respectively. The peak at 1558 cm^{-1} can be associated with the N-H bending vibrations of secondary acyclic amides (Silverstein *et al.*, 2005). The presence of these peaks gives an indication of the amide functions and confirms that polymerization took place. The C-N stretching vibration of the amide can be found at 1261 cm^{-1} while the C-O stretching vibration is observed at 1040 cm^{-1} (Yu *et al.*, 2008).

Surface area analysis of the adsorbents: The oxidized MWCNTs possess the largest surface area, followed by the pristine MWCNTs and lastly the MWCNT-CD polymer. The surface area of the MWCNTs increased remarkably after oxidation. This might be caused by the action of the acid by untying and separating the bundles of MWCNTs resulting in loose strands and therefore increasing the surface area of the oxidized MWCNTs. The polymer was found to have the lowest surface area but the highest pore diameter. The lower surface area of the polymer could probably be as a result of its granular nature.

Adsorption isotherms

Adsorption of Pb^{2+} ions: The absorption capacity of MWCNT-CD polymer for Pb^{2+} gradually decreased as the concentration increased from 10-50 ppm (Fig. 9). The highest amount of lead adsorbed was 4.08 mg g^{-1} at 10 ppm, dropping to a low 1.57 mg g^{-1} at 50 ppm. This could probably be due to the smaller surface area of the polymer which quickly becomes saturated by the adsorbate ions.

The highest % removal of Pb^{2+} was 68.0% at 10 ppm, dropping to 9.98% at 50 ppm (Fig. 11). An investigation into the effect of contact time on the adsorption capacity of the MWCNT-CD polymer indicated no significant change in the amount of Pb^{2+} adsorbed as the time increased (Fig. 10). The amount of Pb^{2+} adsorbed reached a maximum of 3.81 mg g^{-1} (68.5% removal) after 120 min (Fig. 12). The oxidized MWCNTs showed an increasing adsorption capacity of 4.94 mg g^{-1} at 10 ppm to 22.62 mg g^{-1} at 50 ppm. A maximum adsorption capacity of 5.05 mg g^{-1} (91.9% removal) was recorded after 120 min. As expected the pristine MWCNTs showed very little affinity for the metal and the lowest adsorption capacity was recorded.

Adsorption of CO^{2+} ions: Figure 13 and 14 show the effect of concentration and contact time, respectively, on the adsorption of CO^{2+} . The % removal of CO^{2+} at different concentrations and times is shown in Fig. 15 and 16, respectively. A similar trend to Pb^{2+} adsorption was observed for the CO^{2+} uptake by the MWCNT-CD polymer. A maximum uptake of 3.89 mg g^{-1} at 10 ppm was reached, dropping to 1.85 mg g^{-1} at 50 ppm.

The highest % removal of CO^{2+} was 64.5% at 10 ppm. As a factor of time, there was a slight increase in the amount of CO^{2+} adsorbed in the first 40 min, dropping after 60 min and increased again and reached maximum adsorption after 100 min. The oxidized MWCNTs showed an increasing adsorption capacity from 5.64 mg g^{-1} at 10 ppm to 18.32 mg g^{-1} at 50 ppm, with a maximum % removal of 87.4% at 20 ppm. The amount of CO^{2+} adsorbed with time by oxidized MWCNTs increased slightly from 2.99 mg g^{-1} to a maximum of 3.86 mg g^{-1} . The pristine MWCNTs displayed a similar performance to Pb^{2+} uptake and showed very low adsorption capacity for CO^{2+} .

Competitive adsorption of Pb^{2+} and CO^{2+} ions: From Fig. 17 it can be observed that the MWCNT-CD polymer adsorbed Pb^{2+} better than CO^{2+} from the binary solution with a maximum adsorption of 3.82 mg g^{-1} compared to 3.05 mg g^{-1} for CO^{2+} at 10 ppm. The polymer recorded a maximum % Pb^{2+} removal of 59.1% compared to 50.7% recorded for CO^{2+} (Fig. 19). As a factor of contact time (Fig. 18) the maximum absorption of Pb^{2+} by the polymer was found to be 2.84 mg g^{-1} after 60 min while for CO^{2+} was found to be 2.66 mg g^{-1} after 80 min. These values correspond to 60.9 and 55.5% Pb^{2+} and CO^{2+} removal, respectively (Fig. 20). The oxidized MWCNTs displayed an increasing adsorption capacity for both metals with increasing concentration. Pb^{2+} was adsorbed better than CO^{2+} with a maximum adsorption of 14.06 mg g^{-1} (80.5%) compared to 10.46 mg g^{-1} (74.7%) for CO^{2+} . A similar adsorption pattern was recorded for the pristine MWCNTs and as expected they displayed the lowest adsorption capacity for the metals.

The amount of both Pb^{2+} and CO^{2+} adsorbed by the polymer was lower in the competitive adsorption compared to the single ion adsorption. The same adsorption pattern was observed for the other adsorbents. This observation suggests a possible competition between the two metal ions for the adsorbents. The maximum % removal of both metal ions was also lower in the competitive adsorption than in the single ion adsorption. In the presence of the competing metal ions, the polymer managed to remove more than 55% of each of the metal ions.

Isotherm models: From Table 2, the q_m values for Pb^{2+} and CO^{2+} by the MWCNT-CD polymer were calculated as 28.86 and 21.44 $mg\ g^{-1}$, respectively. This is in agreement with the observed adsorption pattern of the two metals, where Pb^{2+} was adsorbed better than CO^{2+} . For the oxidized MWCNTs, q_m values were found to be 54.38 and 49.94 $mg\ g^{-1}$ for Pb^{2+} and CO^{2+} , respectively, indicating a superior adsorption capacity compared to the other two adsorbents. Pristine MWCNTs showed q_m values of 8.73 and 10.92 $mg\ g^{-1}$ for Pb^{2+} and CO^{2+} , respectively. The K_f values were also higher for the adsorption of Pb^{2+} than CO^{2+} which indicated better adsorption of Pb^{2+} compared to CO^{2+} . Except for the pristine MWCNTs the values for n were all close to the range of 2-10 which is an indication of good adsorption (Jiang *et al.*, 2009). For the pristine MWCNTs the values for n were below 1 which indicated poor adsorption and this observation was in line with earlier observations. The values for R^2 were close to 1; indicating good correlation and based on these values it was observed that the adsorption of Pb^{2+} and CO^{2+} by the three adsorbents can be better explained by the Langmuir model.

CONCLUSIONS

The results obtained from this study indicated that the MWCNT-CD polymer had a smaller surface area when compared to the oxidized MWCNTs and the pristine MWCNTs. The polymer showed better adsorption at 10 ppm for both metals and the adsorption capacity dropped drastically with increasing concentration owing probably to the smaller surface area of the polymer. In terms of the competitive adsorption studies, Pb^{2+} was found to be adsorbed better than CO^{2+} . Additionally, the adsorption capacity of the polymer as well as the other adsorbents for Pb^{2+} and CO^{2+} was found to be lower in the competitive adsorption than in the single ion adsorption, which suggests competition between the two metal ions. The oxidized MWCNTs showed a superior adsorption capacity for the two metals compared to the other two adsorbents used. The adsorption isotherms indicated that adsorption of the two metals by the three adsorbents can be explained by the Langmuir model, as evident from the larger r^2 values for the Langmuir isotherms compared to the Freundlich isotherms.

Although, the polymer did not display a higher adsorption capacity for the metals it can still be used as a dual water purification system for the removal of both organic and inorganic pollutants, especially at low concentrations. The polymer shows a greater applicability for metal concentrations around 10 ppm and below.

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