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Removal of humic acid from water using adsorption coupled with electrochemical regeneration

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Abstract−A novel and economic waste water treatment technology comprised of adsorption coupled with electrochemical regeneration was introduced at the University of Manchester in 2006. An electrically conducting adsorbent material called Nyex^{TM} 1000 (Graphite intercalation based material) was developed for the said purpose. This adsorbent material delivered significantly lower adsorption capacity for the removal of a number of organic pollutants. With the aim to expand the scope of newly developed adsorbent material called Nyex^{TM} 2000, we studied the adsorption of humic acid followed by electrochemical regeneration. Nyex^{TM} 2000 is a highly electrically conducting material with an adsorption capacity almost twice that of Nyex^{TM} 1000 (intercalation based graphite compound) for humic acid. The adsorption of humic acid onto both Nyex^{TM} adsorbents was found to be fast enough keeping almost the same kinetics with approximately 50% of the adsorption capacity being achieved within the first twenty minutes. The parameters affecting the regeneration efficiency, including the treatment time, charge passed and current density, were investigated. The regeneration efficiency at around 100% for Nyex^{TM} 1000 & 2000 adsorbents saturated with humic acid was obtained using the charge passed of 8 and 22 Cg^{-1} at a current density of 7 mA cm^{-2} during a treatment time of 30 minutes, respectively.

Key words: Humic Substances, Nyex^{TM} Materials, Adsorption, Electrochemical Regeneration, Electrical Conductivity

INTRODUCTION

Humic substances are known to have been present well before human existence. These are derived from dead living organisms as a result of complex natural reactions under the surface of earth. The exact set of physical and chemical properties of humic substances depends on the source and the origin of the soil and the conditions under which they are formed. Humic acid is the principal component of humic substances and is a common constituent of soil which is a complex mixture of aromatic molecules linked with phenolic and carboxylic groups [1]. The presence of functional groups (phenolic and carboxylic) imparts charge properties and determines the reactivity of humic acid. Humic acids behave as mixtures of dibasic or tri surface basic acids [2]. In China, a few threats in terms of endemic disease such as blackfoot and keshan were linked up with excessive ingestion of humic acid [3]. The inner-action of humic acid was also found to be damaging to human red blood cells [1]. The discharge of humic acid through industrial effluents may cause soil erosion along with damage to both marine water and life [4]. Chlorination of water containing humic acid may produce carcinogenic compounds such as $CHCl_3$. The removal of humic acid from water has already been studied using coagulation, membrane separation, advanced chemical oxidation and by adsorption on graphite oxide [5-9]. However, adsorption of humic acid onto the graphite based adsorbent followed by electrochemical regeneration has not been studied. Various parameters such as bacteria, temperature and initial adsorbate concentration may affect the adsorption of humic acid. The amount of humic acid was reported to be increased with an increase of temperature, and it was justified with increased diffusion rate of humic acid molecules across the internal pores of the adsorbent particle [10]. High initial concentration of humic acid was reported to significantly increase the uptake of humic acid from aqueous solution [11]. Fenton's reagent was used to oxidize humic acid molecule and then was compared with biological degradation of humic acid. The highest removal at 30% was obtained when the ratio of humic acid to reagents (H_2O_2 and Fe^{+2}) was adjusted at 1 : 11200 : 2240. In comparison, two microorganisms, pseudomonas fluorescens and Lactococcus lactis for the degradation of humic acid, were employed. The highest removal of 28% was obtained using Lactococcus lactis cultured within 20 days [12]. Off-site regeneration of adsorbents can be costly and dumping of low cost adsorbents used on once through basis may be environmentally undesirable. Thermal regeneration of carbon based adsorbents is extensively applied; however, it requires high energy along with 5-10% material losses [13-15]. With the aim of reducing operating and maintenance costs, various alternate regeneration methods have been investigated such as microbial regeneration [16] wet oxidative regeneration [17] ultrasonic [18] and electrochemical regeneration [19,20]. Narbaitz & Cen and Zhang [19-21] investigated the electrochemical regeneration of granular activated carbon loaded with phenol. Long regeneration time (in the order of hours) due to intraparticle diffusion within the porous

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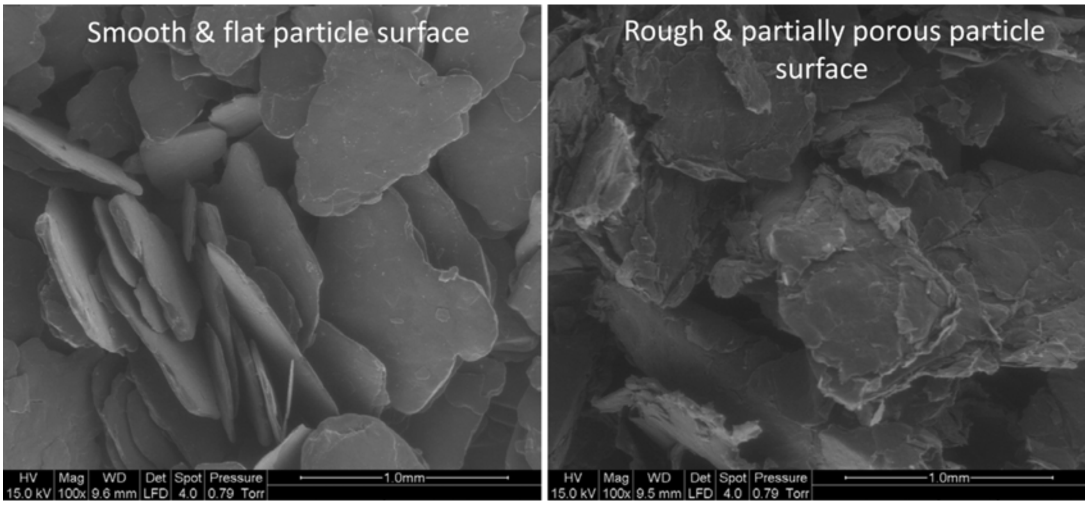

Fig. 1. SEM images of Nyex^{TM} 1000 (left) at 100x magnifications and Nyex^{TM} 2000 (right) at 100x magnification.

activated carbon was found to be required along with high electrical consumption because of low electrical conductivity. Brown et al., introduced a graphite intercalation compound (GIC) based adsorbent capable of performing relatively fast adsorption and electrochemical regeneration in minutes [22-24]. This adsorbent, called Nyex^{TM} 1000, was a non-porous and electrically conducting material. Relatively small electrical energy was found to be required for regeneration of Nyex^{TM} adsorbent loaded with phenol, crystal violet, atrazine and chlorinated hydrocarbons. Asghar et al. studied the removal of acid violet 17 from aqueous solution using graphite based material, called Nyex^{TM} 2000. This adsorbent exhibited double the electrical conductivity to that of Nyex^{TM} 1000 (GIC based material), and thus the energy consumption during regeneration was found to be relatively small [25]. The process of adsorption coupled with electrochemical regeneration using Nyex^{TM} 1000 is currently being commercialized by Arvia Technology Ltd., who demonstrated the process for a number of water and waste water treatment applications [26]. Intensive review containing waste water treatment strategies suggested the role of cell viability to determine the performance of the biological waste water treatment operations. The implementation of the process system engineering techniques was expected to play a significant role in managing wastewater treatment processes by reducing operational cost and enhancing the effluent quality [27].

The objectives of this study were (1) to expand the scope of a recently developed adsorbent material, called Nyex^{TM} 2000, which is a modified form of Nyex^{TM} 1000 (the adsorbent material currently being used by Arvia Technology Ltd.), (2) to determine the comparative performance of this new adsorbent (Nyex^{TM} 2000) and the existing adsorbent (Nyex^{TM} 1000), and (3) to investigate the adsorption kinetics, isotherms and electrochemical regeneration parameters such as treatment time, current density and charge passed for Nyex 1000 & 2000 when loaded with humic acid as an adsorbate.

MATERIALS AND METHODS

1. Materials

1-1. Sorbate

Aqueous solutions of humic acid were prepared using de-ionized water and analyzed using a spectrophotometer (Shimadzu, UV-250 1 PC) at a wavelength of 254 nm [2]. Humic acid of technical grade was provided by Sigma Aldrich UK.

1-2. Sorbents

Two adsorbents, Nyex^{TM} 1000 & 2000, were trailed for the removal of humic acid from aqueous solution. Nyex^{TM} 2000 was prepared through successive chemical, thermal and mechanical treatment of Nyex^{TM} 1000 with the aim to increase its specific surface area in order to address low adsorption capacity of Nyex^{TM} 1000. The SEM images of both Nyex^{TM} adsorbents are shown in Fig. 1.

2. Material's Characterization

As previously reported [25] the particles of Nyex^{TM} 1000 are non-porous with flake-like morphology compared to Nyex^{TM} 2000 found to be with rough surface morphology as evident in SEM Fig. 1. The average particle size of Nyex^{TM} 1000 and 2000 was found to be in the order of 500 and 784 μm, respectively, as determined using a Malvern laser diffraction particle size analyzer. The BET surface area as determined through N_2 adsorption method for Nyex^{TM} 1000 and 2000 was found to be 1 and 17 m^2g^{-1}, respectively [25]. Boehm surface titration as described in [28] was carried out to determine the concentration of various chemical functional groups on the surface of both the adsorbent materials. Nyex^{TM} 2000 was made from Nyex^{TM} 1000 by using proprietary chemical, thermal and mechanical steps. To investigate the structural changes taking place during manufacturing steps, both adsorbents were analyzed by XRD analysis. Electrical conductivity for the bed of each adsorbent material was determined as described in [25].

3. Bed Electrical Conductivity

The electrical conductivity of an adsorbent bed has a significant role in influencing the regeneration cost. The electrical conductivity of an adsorbent bed of variable thicknesses and applied currents was investigated. These beds were arranged in PVC tubes of various lengths (1 to 5 cm) with cross-sectional area of 6 cm^2. Each adsorbent bed consisted of a mixture of Nyex 1000 or 2000 and 3% H_2SO_4 solution. The bed was acidified to simulate the conditions that prevailed during electrochemical regeneration in an electrochemical cell.

4. Adsorption Studies

Humic acid solutions were prepared in de-ionized water. The ad-

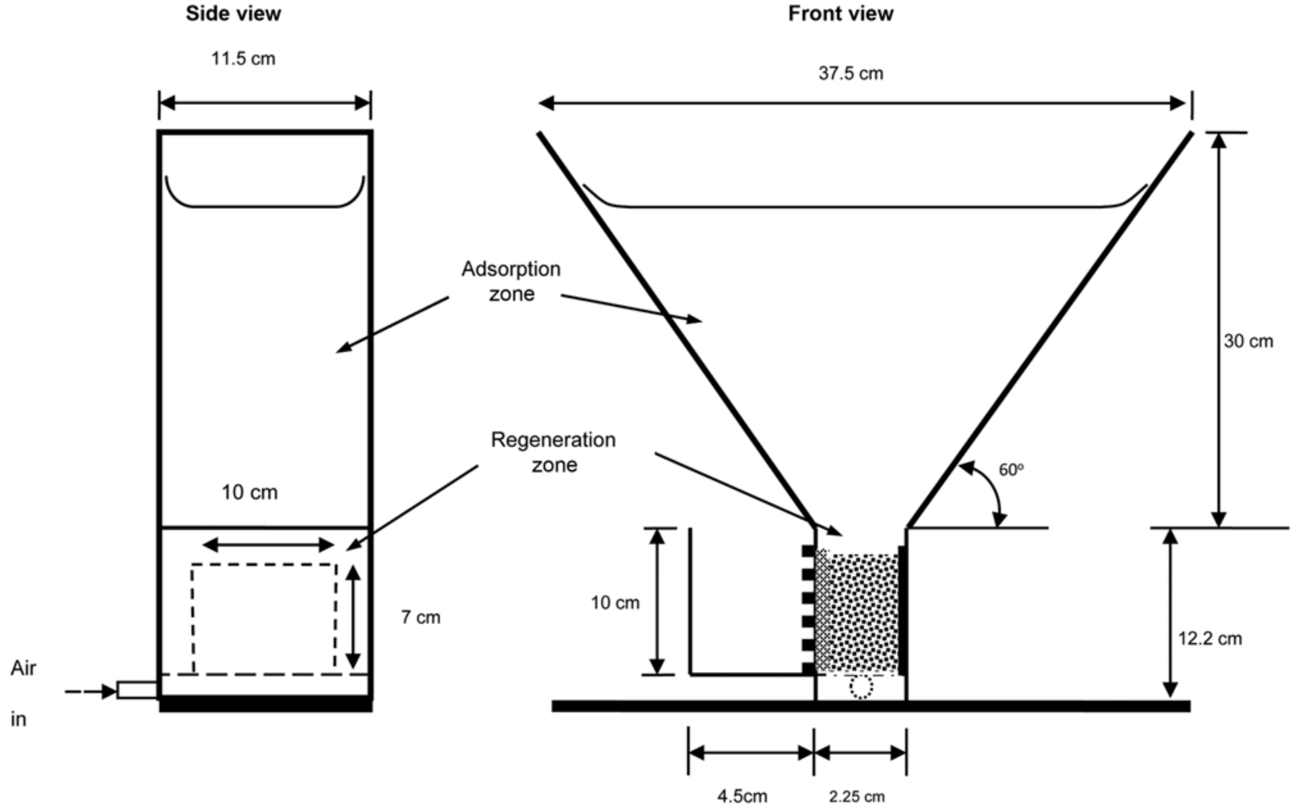

Fig. 2. Schematic diagram of the sequential batch electrochemical cell used for adsorption & electrochemical regeneration of Nyex™ adsorbents [25].

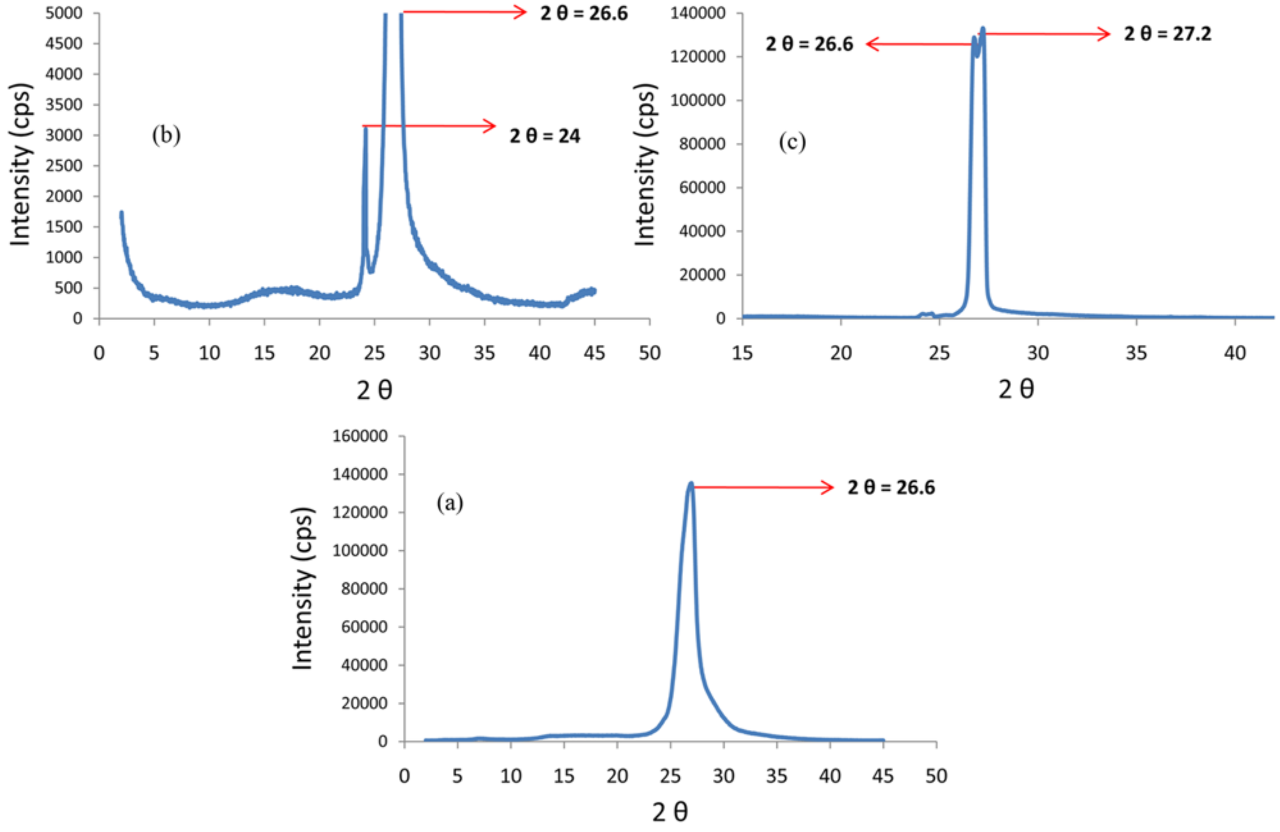

Fig. 3. XRD patterns of Nyex™ 1000 in raw form (a) and chemically treated (b) and thermally and mechanically treated (i.e., Nyex™ 2000, (c)).

sorption study was performed by mixing a known mass of adsorbent (10 g for each adsorbent) with 1 L of humic acid solution of known concentration. Mixing was achieved with a magnetic stirrer at 700 rpm. Five-milliliter samples were collected at regular intervals and analyzed for the concentration of humic acid by UV/Vis spectroscopy. Adsorption isotherm data were collected by adding 1 g of adsorbent to 100 ml of humic acid solution at a range of concentration from 30 to 70 mg L^{-1}. The mixing time of 50 minutes was provided to attain equilibrium. After adsorption, the solution was filtered with filter paper and analyzed for the concentration of humic acid left unadsorbed in the solution.

5. Electrochemical Regeneration

The electrochemical regeneration of Nyex™ 1000 and 2000 loaded with humic acid was investigated in an anodic compartment of sequential batch electrochemical cell as shown in Fig. 2. Technical details and design parameters of sequential batch electrochemical cell have already been reported in [25]. The cell was connected to a DC power supply for achieving electrochemical regeneration of the adsorbents. The regeneration efficiency of Nyex™ 1000 and 2000 when loaded with humic acid was determined by using the procedure given below.

5-1. Initial Adsorption

A known mass of Nyex™ was added to 1 L of aqueous solution of humic acid with a known concentration in sequential batch electrochemical cell (Fig. 3). Mixing for 60 minutes was obtained through air sparging from the base of the cell. After adsorption, the air flow was stopped and the adsorbent was allowed to settle into the anodic compartment of the electrochemical cell. A sample of treated solution was taken and analyzed for the equilibrium concentration of humic acid, and thus (by mass balance) the initial adsorbent loading q_i was determined.

5-2. Electrochemical Regeneration

A DC current was supplied to the cell for a specific time period. The only mixing was due to gas bubbles. After regeneration, the treated solution was drained off and a fresh batch of humic acid solution with same concentration was added.

5-3. Re-adsorption

Regenerated Nyex™ (contents of anodic compartment) was agitated through air sparging from the base of the cell. After repeating step i, the concentration of humic acid and thus (by mass balance) the adsorbent loading after regeneration q_r, was determined. From q_i and q_r, the regeneration efficiency R was determined as:

$$R=q_r/q_i * 100\% \tag{1}$$

To study the effect of multiple adsorption/regeneration cycles, steps ii and iii were repeated.

RESULTS AND DISCUSSION

1. Sorbent Characterization

The characteristics described in Table 1 for both the adsorbents have already been reported in [22] except XRD patterns. The electrical conductivity of a bed of Nyex™ 2000 has been reported to be 1.62 Scm^{-1} which is twice to that of Nyex™ 1000 (0.8 S cm^{-1}) [22]. Double bed electrical conductivity suggests Nyex™ 2000 being a preferred adsorbent material for electrochemical regeneration applications. The Tables 1-3 showing the results of particle characterization, Boehm surface titration, X-ray (EDS elemental analysis) have already been reported in [25], but are given here as a ready/quick reference.

To investigate the structural changes of Nyex™ 1000 and 2000, these were analyzed by using X-ray powder diffraction method. Data were collected at 2θ steps between 2 and 42 using Rijaku miniflex with Cu radiation at wavelength of 1.54 Å. By comparing the XRD results of Nyex™ 1000 and 2000 adsorbents, the formation of a new graphite based material is evident in Fig. 3.

The peak for Neyx 1000 without receiving any processing treatment appeared at 2θ=26.6, which corresponds to an interplanar distance of 3.35 Å as obtained using Bragg's equation [29]. The presence of new peak at 2θ=24 ensures the formation of a new graphite intercalation based material that corresponds to an interplanar distance of 3.72 Å [26]. Formation of intercalation based graphite compound is quite evident with a decrease in crystallinity due to intercalating species. After receiving thermal and mechanical treatment, crystallinity of Nyex™ 1000 was found to be further decreased as evident with the formation of a new peak at 2θ=27.2, which corresponds to an interplanar distance of 3.27 Å [30].

2. Adsorption Studies

We conducted experiments to determine the time required to get equilibrium for the adsorption of humic acid onto the Nyex™ 1000 and 2000 adsorbents. Adsorption kinetic results are shown in Fig. 4. The adsorption kinetics was found to be almost similar for both ad-

Table 1. Characterization of Nyex™ adsorbents [25]

Adsorbent type	BET surface area (m^2 g^{-1})	Pore volume (cm^3 g^{-1})	Pore diameter (Å)	Bulk density (g cm^{-3})	Average particle diameter (μm)
Nyex™ 1000	1.0	0.0038	134	0.89	484
Nyex™ 2000	17	0.068	163	0.22	754

Table 2. Boehm titration and surface pH of Nyex™ adsorbents [25]

Adsorbent	Carboxylic groups (moles g^{-1})	Lactonic groups (moles g^{-1})	Phenolic groups (moles g^{-1})	Basic groups (moles g^{-1})	Total acidic groups (moles g^{-1})	Total surface groups (moles g^{-1})	Surface pH
Nyex™ 1000	0.05	0.005	0.195	0	0.25	0.25	2
Nyex™ 2000	0.03	0.014	0.094	0	0.138	0.138	5

sorbent materials. The color removal during the first five minutes was found to be fast enough at the rate of 3.2 mg L^{-1} min^{-1} and gradually decreased to 0.28 mg L^{-1} min^{-1} during next twenty five minutes for both the adsorbent materials. After 30 minutes, the rate of dye removal further decreased to 0.03 and 0.1 mg L^{-1} min^{-1} for Nyex™ 1000 and 2000 adsorbents respectively.

Table 3. X-ray (EDS) elemental analysis of Nyex™ adsorbents [25]

Adsorbent	C (wt%)	O (wt%)	S (wt%)	Fe (wt%)	Si (wt%)
Nyex™ 1000	77.88	18.69	3.22	0.17	0.05
Nyex™ 2000	95.77	4.08	Nil	0.13	0.02

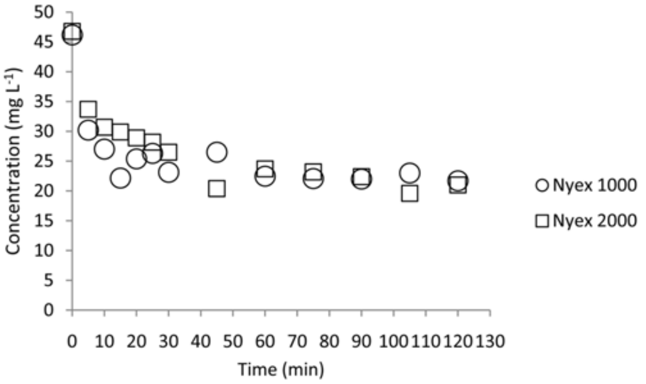

Fig. 4. Kinetic study for the adsorption of humic acid onto 10 g of Nyex™ 1000 & 2000 adsorbents, stirred in a 1,000 ml flask at 700 rpm with initial concentration of humic acid of ~50 mg L^{-1}.

It is evident in Fig. 4 that after 50 minutes, the concentration of humic acid remained approximately constant in each case, indicating that equilibrium was approached. A mixing time of 60 minutes was, therefore, adopted in order to get approximate adsorption equilibrium conditions. These kinetic results are consistent with those obtained for the removal of acid violet 17 from aqueous solution using both Nyex™ 1000 and 2000 adsorbents [25]. Figs. 5 and 6 show the adsorption isotherms obtained for the adsorption of humic acid onto both the Nyex™ adsorbents. Nyex™ 1000 gave an adsorption capacity at around 2.6 mg g^{-1} where as Nyex™ 2000 showed an adsorption capacity at around 3.5 mg g^{-1} for the removal of humic acid from aqueous solution (Figs. 5 & 6).

Nyex™ 2000 was found to have improved adsorption capacity over that of Nyex™ 1000 for the removal of humic acid. Low concentration of oxygen-containing functional groups will assist to have improved adsorption of humic acid that otherwise attracts water molecules due to its polarity as a result of hydrogen bonding [31]. Both the Nyex™ adsorbents could not achieve an adsorption capacity as high as in case of acid violet 17 as adsorbate [25]. Small adsorptive capacity of both the adsorbents for the adsorption of humic acid can be explained due to complex and large molecular size of humic acid that could not develop high affinity towards the pore size and structure of the adsorbent materials. The role of surface

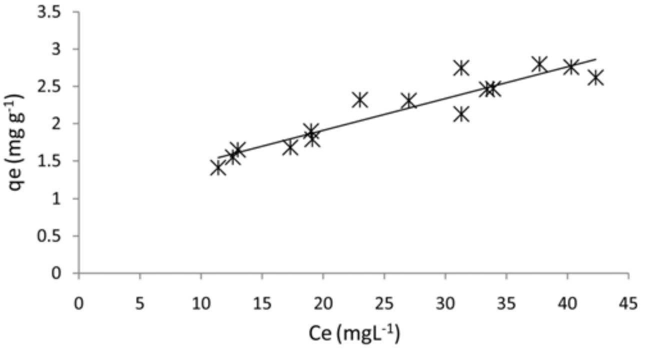

Fig. 5. Adsorption isotherms for the adsorption of humic acid onto Nyex™ 1000 adsorbent obtained in a 250 ml flask using a mixing time of 50 minutes to achieve equilibrium.

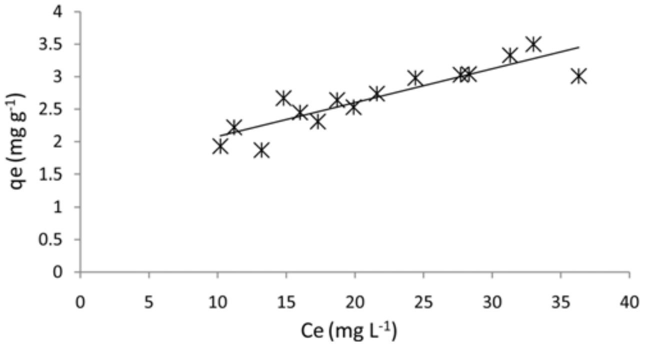

Fig. 6. Adsorption isotherms for the adsorption of humic acid onto Nyex™ 2000 adsorbent obtained in a 250 ml flask using a mixing time of 50 minutes to achieve equilibrium.

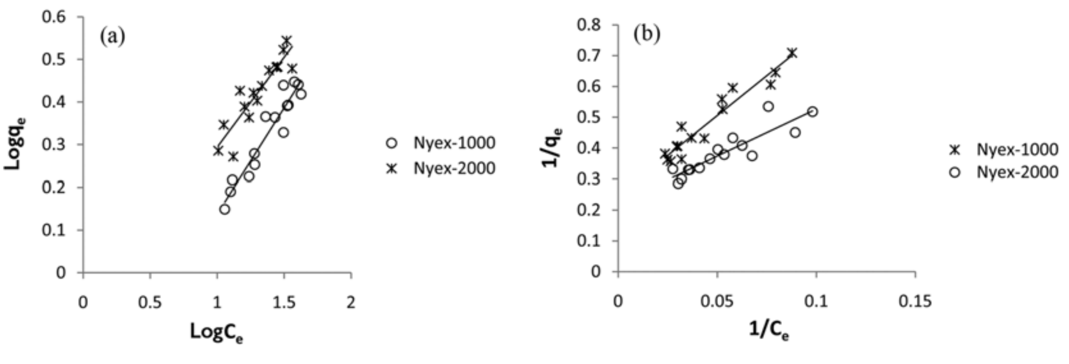

Fig. 7. Fitting of adsorption isotherm data to the linear form of the Freundlich and Langmuir models for the adsorption of acid violet 17 onto both Nyex™ adsorbents.

chemistry for the adsorption of humic acid requires careful consideration as water molecules are expected to have electrostatic interaction with oxygen-containing functional groups which are significantly dominant in case of Nyex™ 1000 compared with Nyex™ 2000. It can be speculated due to polarity of hydrogen bonding in water molecules, which is considerably larger than humic acid molecule. Strongly polar molecules will, therefore, induce affinity towards electrostatic interaction with surface functional groups of Nyex™ 1000 by suppressing the adsorption of humic acid molecules. Adsorbent materials with minimum surface oxygen-containing groups can be expected to present better adsorption performance than surface treated materials as evident in isotherm Figs. 5 and 6. Thus Nyex™ 2000 seems to be suitable material for the adsorption of humic acid, as it was characterized with significantly lower concentration of oxygen-containing functional groups (Tables 2-3). However, in addition to improved electrostatic interaction between Nyex™ 2000 and humic acid molecules, increased specific surface area of Nyex™ 2000 as shown in Table 1 contributed as a leading factor to increase the adsorption capacity by a factor of 1.4. The data obtained for the adsorption of humic acid onto both the Nyex™ adsorbents were analyzed by using the Freundlich and Langmuir models. Freundlich and Langmuir constants (K_F, n and K_L, q_m, respectively) were determined and are given in Tables 4 and 5, respectively.

The Freundlich and Langmuir models are frequently used to characterize the adsorption behavior [32]. These models were found to be in a best linear fit for the adsorption of humic acid onto Nyex™ 1000 and 2000 adsorbents as they showed higher values of coefficient of correlation, i.e., R^2 in the range of 0.92 and 0.91, respectively. It is also evident from q_m values presented in Tables 4 and 5 that both that adsorbent materials delivered small adsorptive capacity compared to that for acid violet 17 [26]. The K_L values given in Tables 4 and 5 indicate small surface energy for the adsorption of humic acid onto both the Nyex™ adsorbents; however, Nyex™ 2000 was found to have bit higher surface energy compared to that of Nyex™ 1000 [33]. The slope obtained through 1/n values predicted almost the same adsorption intensity for humic acid onto both the Nyex™ adsorbents [34]. It can also be verified from isotherm Figs. 5 and 6 where a small difference of adsorptive capacity for humic acid onto both the Nyex™ adsorbents was presented, although the Nyex™ 2000 adsorbent showed an increase of 1.7-fold in its specific surface area compared to that of Nyex™ 1000.

Table 4. Freundlich and Langmuir constants for the adsorption of humic acid onto Nyex™ 1000

Nyex™ 1000 - Humic acid			
Freundlich constants		Langmuir constants	
n	2.2	q_m	3.8
K_f	1.94	K_L	0.057

Table 5. Freundlich and Langmuir constants for the adsorption of humic acid onto Nyex™ 2000

Nyex™ 2000 - Humic acid			
Freundlich constants		Langmuir constants	
n	2	q_m	5
K_f	1.54	K_L	0.067

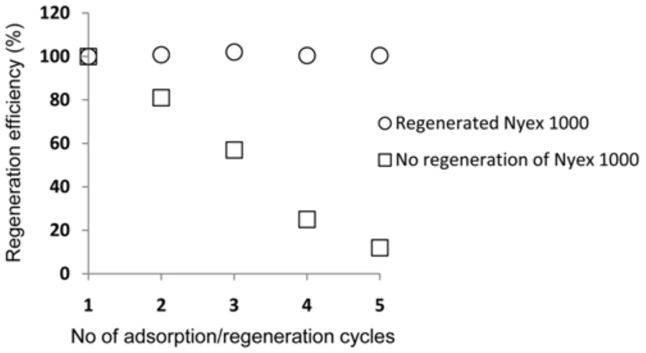

Fig. 8. Electrochemical regeneration efficiency over a number of adsorption and regeneration cycles with humic acid-Nyex™ 1000 (115 g) using sequential batch electrochemical cell. Operating parameters: regeneration time of 30 min at current density of 7 mA cm^{-2}.

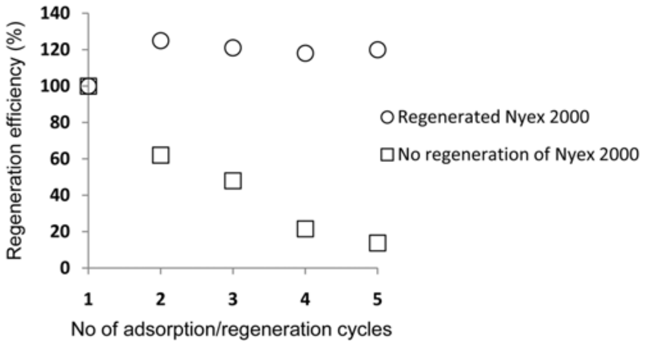

Fig. 9. Electrochemical regeneration efficiency over a number of adsorption and regeneration cycles with humic acid-Nyex™ 2000 (40 g) using sequential batch electrochemical cell. Operating parameters: regeneration time of 30 min at current density of 7 mA cm^{-2}.

3. Electrochemical Regeneration of Nyex™ Adsorbents

Experiments were performed to investigate the effect of electrochemical regeneration on desorption of adsorbed humic acid onto both the Nyex™ adsorbents. Figs. 8 and 9 show the regeneration efficiency observed over a number of adsorption/regeneration cycles, both with and without electrochemical regeneration of Nyex™ 1000 and 2000 adsorbents. A regeneration efficiency of around 100% was achieved for both Nyex™ adsorbent materials. It is evident in Figs. 8 and 9 that without electrochemical regeneration, the adsorptive capacity of both the Nyex™ adsorbents dropped rapidly during the first few cycles. Regeneration efficiencies greater than 100% were obtained particularly for Nyex™ 2000 adsorbent. It can be justified due to reduced surface pH (2-3) of the Nyex adsorbent during first cycle of regeneration process, which actually changed the surface chemistry (excess of protons) and made it feasible for strong electrostatic interaction with anionic sites of humic acid molecules. The same effect of reduced Ph contributing to increase the regeneration efficiency has already been reported in [22], where improved dye adsorption (anionic azo dye, acid violet 17) after first regeneration cycle was obtained. Similar effects of improved anionic dye adsorption in acidic pH range and cationic dye adsorption in

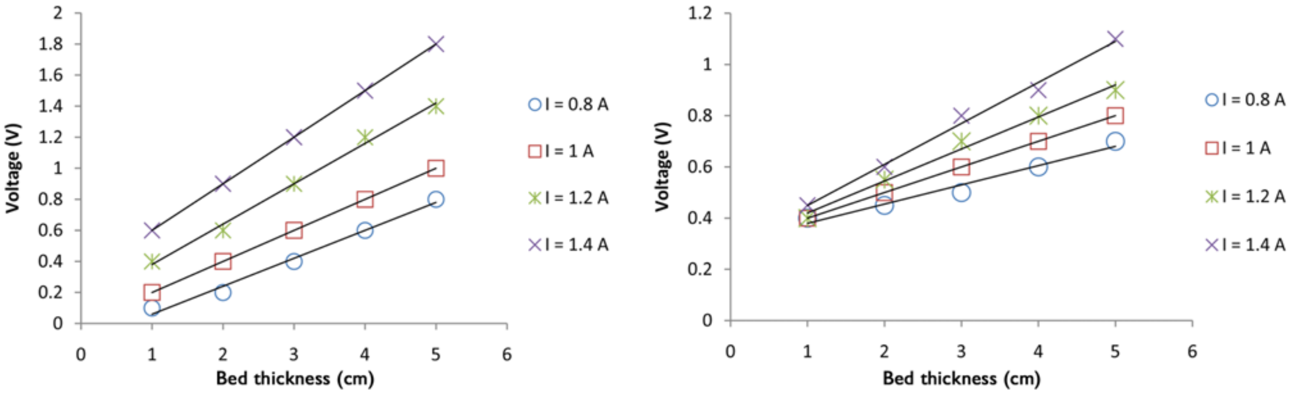

Fig. 10. Drop in voltage because of increased adsorbent bed thickness for Nyex 1000 (left) and 2000 (right). Data were collected at various current values ranging from 0.8 to 1.4 A.

alkaline Ph range have been reported in [35-40]. It was assumed that all the adsorbed species were mineralized into CO_2 and H_2O; however, chlorinated breakdown products may be expected because of 0.3% NaCl in catholyte. The function of adding NaCl was to stabilize the Daramic membrane, which requires neutral or acidic conditions. Previous studies have shown that these chlorinated compounds are adsorbed on graphitic adsorbents and oxidized to less harmful products [41]. Determination of break-down products is not the focus of this paper; however, being an important factor it will be considered in detail in future studies. Higher regeneration efficiency was obtained by applying a constant current density of 7 mA cm^{-2} through a 20 mm bed of adsorbent for 30 minutes. The charge required for achieving ~100% regeneration efficiency of Nyex™ 1000 and 2000 was found to be 8 and 22 Cg^{-1}, respectively. The lower current density of 7 mA cm^{-2} used for regeneration of both Nyex™ adsorbents saturated with humic acid is comparable with 14 mA cm^{-2} used for the regeneration of the same adsorbents when loaded with acid violet 17 [25].

Due to the complex nature of humic acid molecule, it was difficult to calculate the theoretical charge required for the oxidation of adsorbed humic acid, and therefore, in turn, it is difficult to explain the exact reason behind the small consumption of electrical charge (8 and 22 C g^{-1} for Nyex™ 1000 & 2000) [26] for achieving approximately 100% electrochemical oxidation of adsorbed humic acid when compared with acid violet 17 (36 and 80 C g^{-1} for Nyex™ 1000 and 2000 adsorbents) [25]. The average cell voltage was found to be 3.5 V during the regeneration of Nyex™ 2000, significantly lower than for Nyex™ 1000, which gave average cell voltage of 4.6 V. Lower cell voltage for Nyex™ 2000 is consistent with its higher bed electrical conductivity of 1.62 S cm^{-1} compared with bed conductivity of 0.83 S cm^{-1} for Nyex™ 1000. To validate the lower cell voltage for a bed of Nyex 2000, data were collected as presented in Fig. 10 showing the electrical resistance across beds of various thicknesses and applied currents. It is evident in Fig. 9 that Nyex 2000 presented small voltage at a wide range of bed thicknesses and applied currents. Therefore, the improved bed conductivity exhibited by Nyex 2000 may reduce the cost associated with electrochemical regeneration. The electrical charge required for 100% regeneration efficiency is much lower when compared with activated carbon. Narbaitz & Cen passed an electric charge of 1,500 C g^{-1} (100 mA for 5 hours) and obtained 95% regeneration efficiency of granular activated carbon when loaded with phenol. In contrast, Brown et al., 2004 obtained regeneration efficiencies around 100% by passing comparatively a small current at 25 Cg^{-1} using a current density of 20 mA cm^{-2}. It was reported due to higher bed electrical conductivities of Nyex material compared to that of granular activated carbon [22-25].

CONCLUSIONS

The new adsorbent (Nyex™ 2000) was found to have an adsorptive capacity 1.4 times higher than that of Nyex™ 1000 for the adsorption of humic acid. Significantly increased surface area of Nyex™ 2000 did not substantially contribute to increase the adsorptive capacity for humic acid removal from aqueous solution. The surface chemistry showed substantial increase in oxygen-containing functional groups for Nyex™ 1000, making this adsorbent unsuitable for the adsorption of humic acid because of strong electrostatic interaction of water molecule due to hydrogen bonding, which is lacking in humic acid molecule. An electrochemical regeneration efficiency of around 100% was achieved by applying a constant current density of 7 mA cm^{-2} through a 20 mm bed of adsorbent using a treatment time of 30 minutes. The charge required for achieving ~100% regeneration efficiency of Nyex™ 1000 & 2000 was found to be 8 and 22 Cg^{-1} for Nyex™ 1000 & 2000 adsorbents, respectively. A small cell voltage of 3.5 V was found to be associated with a bed of Nyex 2000, which is significantly lower than 4.5V obtained for a bed of Nyex 1000, thus making the regeneration process efficient with reduced maintenance cost.

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