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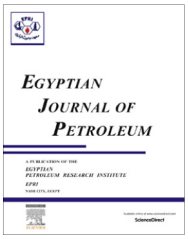

FULL LENGTH ARTICLE

Removal of Cr(VI) ions from waste water by electrocoagulation using iron electrode

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Abstract The performance of electrocoagulation using iron electrodes for the treatment of aqueous solutions containing chromium hexavalent ions using fixed bed electrochemical batch reactor was studied. A new anode design consisting of hex nuts was connected together with a thin rode of iron. The helical shape in the nuts increases the anode surface area allowing high chromium removal rate within very short coagulation time. The effect of different parameters affecting the electrocoagulation process, such as initial hexavalent chromium concentration, applied current, electrolyte type [sodium chloride and sodium sulfate] concentration and initial pH of the solution was investigated. The optimum conditions for the EC process by using the present cell based on minimum initial hexavalent chromium concentration, energy consumption and operating cost were 100 mg of Cr(VI)/l, 0.55 A, 1.5 g of sodium chloride/land pH of 1.

1. Introduction

Water pollution by heavy metals, especially chromium; has sparked much concern to societies and regulation authorities around the world. Due to wide usage of chromium by different industries such as metal plating, paints and pigments, leather tanning, textile dyeing, printing inks and wood preservation, huge quantities of wastewater containing chromium are discharged into the environment to trivalent and hexavalent chromium ions. Hexavalent chromium compounds are toxic and carcinogenic. In contrast, toxicity of Tetravalent Chromium is relatively low and in its trace amounts, it is not a problem for the environment [1]. Electrocoagulation is a process consisting of creating metallic hydroxide flocks within the wastewater by electrode dissolution of soluble anodes [2].

Abbreviations: EC, electrocoagulation; DC, direct current; E, cell voltage (Volt); I, applied current (A); t_{EC}, electrocoagulation time (h); F, Faraday's constant (96485 C/mol); M, molecular weight of Fe (55.845 g/mol); Z, number of electron transfer (Z_{Fe} = 2); C, initial compound concentration, (mg/l); C_t, concentration at time t (mg/l); V, treated volume (L); C_{energy}, energy consumption (kWh/g hexavalent chromium removed); $C_{electrode}$, electrode consumption (g Fe/g hexavalent chromium removed); a, electrical energy price (EGP/kWh); b, electrode material price (EGP/kWh).

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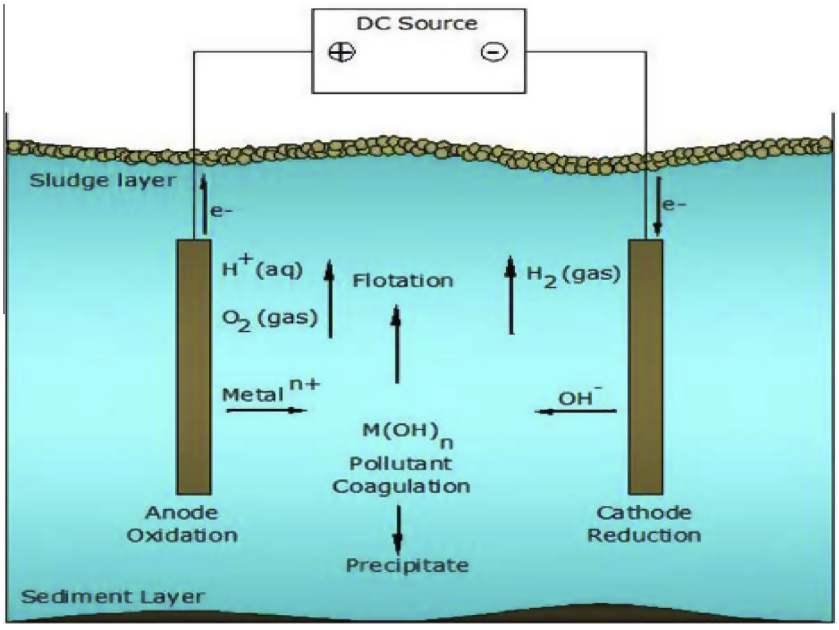

Figure 1 Schematic diagram of bench-scale two-electrode electrocoagulation.

The electrocoagulation has successfully been employed for treatment of different wastewaters such as urban wastewaters [3], textile industries [4–6], laundry wastewater [7], restaurant wastewater [8], electroplating wastewater [9], chemical mechanical, polishing wastewater [10,11], olive mill wastewater [12], laundry wastewater [13], dairy and tannery wastewater [14,15], pulp and paper mill industry wastewater [16,17], baker's yeast wastewater [18] and slaughterhouse wastewater [19]. Also EC removes bacteria, viruses, and cysts [20]. Meanwhile, EC process has been widely used in the removal of arsenic [21], phosphate [22], sulfide, sulfate and sulfite [23], boron [24], nitrate [25], fluoride [26], and chromium [27–29].

Electrocoagulation as depicted by Fig. 1 involves the following successive stages of coagulant formation and subsequent reduction of hexavalent chromium to trivalent chromium.

The first stage is the formation of coagulants by electrolytic oxidation of the anode. In this process, a potential is applied to the metal anodes, typically fabricated from either iron or aluminum, which causes generation of the corresponding metal ions, which almost immediately hydrolyze to polymeric iron or aluminum hydroxides. The following mechanisms describe the formation of the iron hydroxides.

- Mechanism 1
  - o Anode:

$$4Fe_{(s)} \rightarrow 4Fe^{2+}_{(aq)} + 8e^{-} \quad (1)$$

$$4Fe^{2+}_{(aq)} + 10H_2O_{(l)} + O_{2(g)} \rightarrow 4Fe(OH)_{3(s)} + 8H^{+}_{(aq)} \quad (2)$$

  - o Cathode:

$$8H^{+}_{(aq)} + 8e^{-} \rightarrow 4H_{2(g)} \quad (3)$$

  - o Overall:

$$4Fe_{(s)} + 10H_2O_{(1)} + O_{2(g)} \rightarrow 4Fe(OH)_{3(s)} + 4H_{2(g)} \quad (4)$$

- Mechanism 2
  - o Anode:

$$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^{-} \quad (5)$$

$$Fe^{2+}_{(aq)} + 2OH^{-}_{(aq)} \rightarrow Fe(OH)_{2(s)} \quad (6)$$

  - o Cathode:

$$2H_2O_{(l)} + 2e^{-} \rightarrow H_{2(g)} + 2OH^{-}_{(aq)} \quad (7)$$

  - o Overall:

$$Fe_{(s)} + 2H_2O_{(1)} \rightarrow Fe(OH)_{2(s)} + H_{2(g)} \quad (8)$$

The $Fe(OH)_{n(s)}$ formed remains in the aqueous stream as a gelatinous suspension, which can remove the pollutants from wastewater by coagulation. These polymeric hydroxides are excellent coagulating agents [30].

As shown from the following Equation oxygen may be formed at the anode

$$2H_2O \rightarrow 4H^{+}_{(aq)} + O_{2(g)} + 4e^{-} \quad (9)$$

The oxygen formedables to oxides dissolved iron (II) to iron (III). The equation below describes this reaction [31]:

$$4Fe^{2+} + O_2 + 2H_2O \rightarrow 4Fe^{3+} + 4OH^{-} \quad (10)$$

The second step is destabilization of the contaminants, particulate suspension and chromium reduction. This may be summarized as follows:

- Compression of the diffuse double layer around the charged species by the interactions of ions generated by oxidation of the sacrificial anode.

- Charge neutralization of the ionic species present in wastewater takes place due to the counter ion produced by the electrochemical dissolution of the sacrificial anode. These counter ions reduce the electrostatic inter particle repulsion to the extent that the van der Waals attraction predominates, thus causing coagulation.
- The floc formed as a result of coagulation creates a sludge blanket that entraps and bridges colloidal particles still remaining in the aqueous medium [30].

For hexavalent chromium concentrations < 520 mg/L, by taking into account the pH range (0.9 < pH < 6.5) it may be concluded that chemical reduction of hexavalent chromium by iron (II) ions electrogenerated at the anode occurs according to the following reaction:

$$HCrO_4^-(aq) + 3Fe^{2+}_{(aq)} + 7H^+_{(aq)} \rightarrow Cr^{3+}_{(aq)} + 3Fe^{3+}_{(aq)} + 4H_2O_{(l)} \quad (11)$$

when the medium pH values are in the range of 6.5–7.5, the reaction can be written as:

$$CrO_4^{2-}(aq) + 3Fe^{2+}_{(aq)} + 4H_2O_{(l)} \rightarrow 3Fe^{3+}_{(aq)} + Cr^{3+}_{(aq)} + 8OH_{(aq)} \quad (12)$$

For pH values above 7.5, the corresponding reaction scheme is [31]:

$$CrO_4^{2-}(aq) + 3Fe(OH)_2 + 4H_2O_{(l)} \rightarrow Cr(OH)_3 + 3Fe(OH)_3 + 2OH_{(aq)} \quad (13)$$

For hexavalent chromium concentrations > 520 mg/l, by taking into account the pH range (0.9 < pH < 6.5) it may be concluded that iron (II) ions can also reduce hexavalent chromium ions, the reaction can be written as:

$$Cr_2O_{7^{2-}_{(aq)}} + 6Fe^{2+}_{(aq)} + 14H^+_{(aq)} \rightarrow 2Cr^{3+}_{(aq)} + 6Fe^{3+}_{(aq)} + 7H_2O_{(l)} \quad (14)$$

However, the iron (III) ions may undergo hydrolysis depending on the pH of the solution $Fe(OH)^{2+}$, $Fe(OH)_2^+$ and $Fe(OH)_3$ species may be present under acidic conditions.

The reactions involved are:

$$Fe^{3+}_{(aq)} + H_2O_{(l)} \rightarrow Fe(OH)^+_{(aq)} + 2H^+_{(aq)} \quad (15)$$

$$Fe^{3+}_{(aq)} + 2H_2O_{(l)} \rightarrow Fe(OH)^{2+}_{(aq)} + 2H^+_{(aq)} \quad (16)$$

$$Fe^{3+}_{(aq)} + 3H_2O_{(l)} \rightarrow Fe(OH)_3 + 3H^+_{(aq)} \quad (17)$$

Under alkaline conditions, $Fe(OH)^{6-}$ and $Fe(OH)^{4-}$ ions may also be present [30].

2. Methods

2.1. Experimental set-up

The electrocoagulation set-up is schematically shown in Fig. 2. The electrocoagulation reactor consists of a circular batch cylindrical reactor with 11 cm in diameter made of glass with 2 L capacity of aqueous solution. The cathode consists of a circular horizontal iron plate that has a 11 cm diameter and placed at the cell bottom; its back is insulted with epoxy resin. The anode was made of 4 arrays of separated horizontal rods, each rod is 15 cm long and 0.3 cm diameter and has a7 hex nuts, and the rods in the array are separated by a distance of 0.87 cm. The horizontal rods were fixed at their ends to two iron rods, each of the cathode and anode is held in position

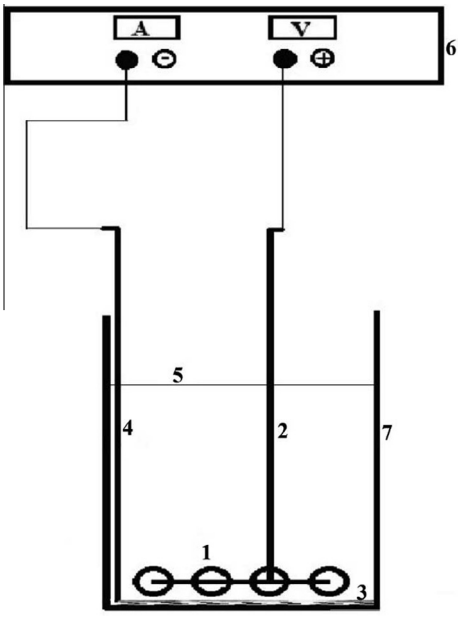

Figure 2 Schematic diagram of the electrocoagulation reactor. (1) anode, (2) insulated anode holder, (3) perforated plastic sheet placed above the cathode, (4) insulated cathode holder, (5) solution level, (6) A 20 V digital DC power supply, and (7) 2 L beaker.

by a welded and insulated vertical iron strip to act as a current feeder. The cathode and anode are separated by a perforated plastic sheet of a 1 mm thickness. The electrical circuit consists of a digital DC power supply (20 V, 5 A).

2.2. Reagents and analytical procedures

Before each run a known weight of potassium dichromate was dried in an oven for 30 min to remove any humidity inside it. Then stock solution of potassium dichromate was prepared by dissolving 2.82 g of the dried potassium dichromate analytical reagent in distilled water and diluted to 1L. The experimental desired concentrations were obtained by successive dilutions with distilled water. Sodium chloride salt (Merck, 99.9% purity) was used to adjust the initial solution conductivity. The pH of the solution was adjusted by adding hydrochloric acid solution or sodium hydroxide solution for each experiment. The pH-meter (Hana, Model pH211) was used to measure the pH of the solutions. The analytical determination of hexavalent chromium solutions was carried out by the colorimetric method using 1,5-diphenylcarbazide solution to give the red violet color complex [32], which was measured at wavelength of 540 nm using U.V. spectrophotometer (UNICO, Model 1200). At the end of each experiment, the treated solutions were filtered by using double ring No. 102 filter paper, before analysis.

2.3. Electrocoagulation procedures

Chromium solutions were prepared from the stock solutions by successive dilution to the desired concentrations. In each run 1.5 L of synthetic solution was mixed with the desired amount of sodium chloride or sodium sulfate as a conductor

material (Merck, 99.9% purity) and placed in the reactor cell. The pH of the solutions was adjusted by adding hydrochloric acid solution or sodium hydroxide solution for each experiment. The operation started when the current was adjusted to the desired value. During experiments, the samples were collected at different time intervals, filtered and analyzed for residual concentration of chromium ions. Each of the location of the drawn sample was kept constant for each run. Before each run the electrodes were dipped in sulfuric acid solution to remove any adherent oxides or impurities on the iron electrode surface. Following each run, the electrodes were washed with distilled water, and dried for another use. In the present work the following variables were investigated: Effect of electrolysis time, initial hexavalent chromium concentration, applied current, electrolyte type and initial pH of the solution.

3. Results and discussion

3.1. Effects of operating parameters

3.1.1. Effect of electrolysis time

Reaction time influences the efficiency of the electrocoagulation process. It determines the rate of production of iron (II) ions from iron electrode [33]. To investigate the effect of electrolysis time on the residual concentrations of Hexavalent Chromium ions, a series of experiments were carried out using solutions containing various initial concentrations of hexavalent chromium ranging from 40 to 200 mg/l at constant current (1 A) and subjected to different time of electrolysis.

As shown in Fig. 3 by increasing the electrolysis time to 14 min the residual Hexavalent Chromium concentration decreased from 40 to 0 mg/l, from 70 to 13.8 mg/l, from 100 to 43.7 mg/l, from 140 to 67.4 mg/l, from 170 to 71.5 mg/l and from 200 to 107 mg/l for concentrations 40, 70, 100, 140, 170, 200 mg/l respectively. It was observed that there was a complete removal after 14 min for the 40 mg/l concentration of hexavalent chromium.

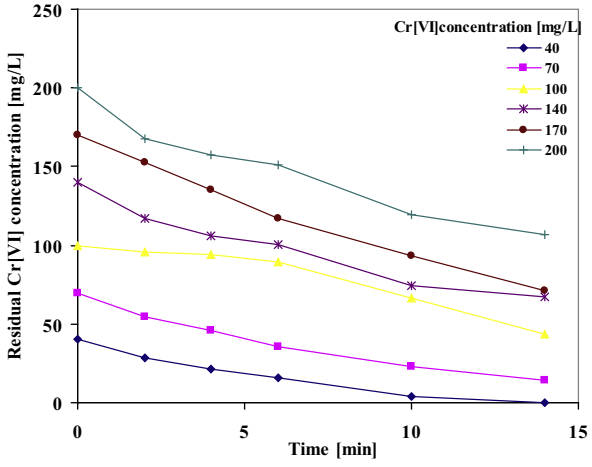

Figure 3 Effect of initial hexavalent chromium concentration on pH [sodium chloride concentration = 1 g/l, applied current = 1 A, original solution pH, the electrocoagulation time = 14 min].

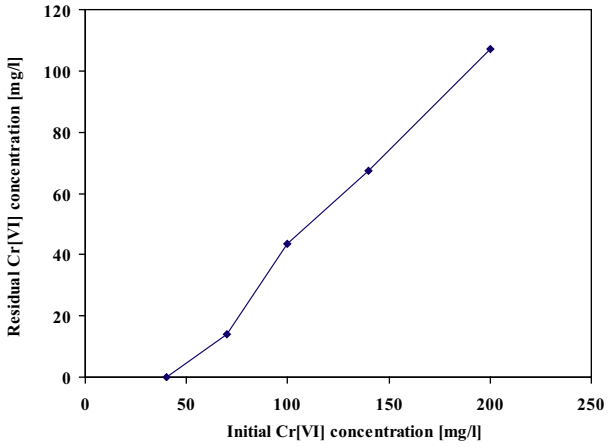

Figure 4 Effect of initial hexavalent chromium concentration on residual hexavalent chromium concentration [sodium chloride concentration = 1 g/l, applied current = 1A, pH = 4.66, the electrocoagulation time = 14 min].

3.1.2. Effect of initial hexavalent chromium concentration

In order to evaluate the effect of initial hexavalent chromium concentration at constant current on residual concentration of solution containing Hexavalent Chromium ions, the solutions with different initial hexavalent chromium concentrations in the range of 40–200 mg/l were treated by EC using iron electrodes in the current of 1 A. As shown in Fig. 4 the initial hexavalent chromium concentration increased from 40 to 200 mg/l as the residual concentration increased linearly from 0 to 107 mg/l respectively. This behavior is due to the lack of flocs for adsorption of excess hexavalent chromium at high concentrations and also due to the lower rates of iron corrosion and increasing iron surface passivation at higher chromate concentrations [34]. The reason for decreasing the removal efficiency of hexavalent chromium with an increase in its initial concentration is deducible from Faraday's law. According to Faraday's law, when current density is constant,

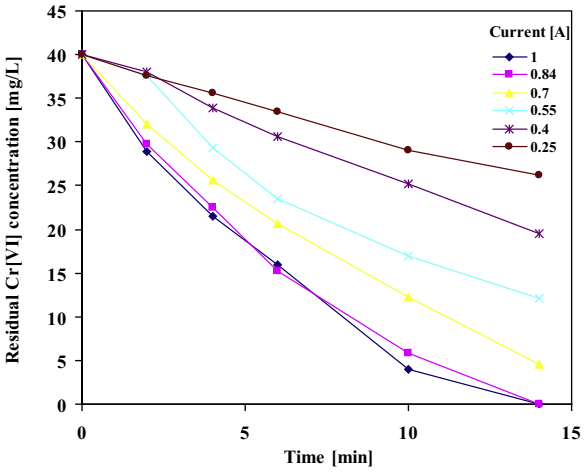

Figure 5 Effect of applied current on residual hexavalent chromium concentration [initial hexavalent chromium concentration = 40 mg/l, sodium chloride concentration = 1 g/l, pH = 4.66, the electrocoagulation time = 14 min].

a constant amount of Fe^{2+} is released to the solution. As a result, the Fe^{2+} ions produced at high initial hexavalent chromium concentrations are insufficient to reduce all of the hexavalent chromium ions [35] (see Fig. 5).

3.1.3. Effect of applied current

The current applied is an important parameter that influences the performance and economy of the electrocoagulation process [36]. In order to investigate the effect of applied current on electrocoagulation efficiencies, a series of experiments were conducted at current range from 0.25 to 1 A and applied for different initial hexavalent chromium concentrations (40, 140, 200 mg/l). These effects are shown in Figs. 6–8 for initial hexavalent chromium concentrations at 40, 140 and 200 mg/l respectively. The trend was observed for all previous figures, it was found that as the value of current increased the residual hexavalent chromium concentration decreased with complete removal of hexavalent chromium ions at concentrations 40, 140 and 200 mg/l and current of 1 A after14, 42 min respectively. This behavior is due to the applied current density that determines the coagulant dosage rate, the bubble production rate and size of flocs growth resulting in a faster removal of pollutants. The hexavalent chromium ions must first be reduced to Trivalent Chromium ions at the cathode, which then combine with the generated hydroxide ion ions and precipitate as insoluble chromium (III) hydroxide or are adsorbed to the iron (III) hydroxide flocs. Furthermore, hexavalent chromium ions can also be reduced to Trivalent Chromium ions by iron (II) ions which in turn are oxidized to iron (III) ions. The presence of ferrous ions enhances the reduction and removal of chromium. Consequently, the removal rate of chromium by electrocoagulation with iron electrodes is faster compared to that with aluminum electrodes [35]. In other words by increasing the current of the cell the amount of hydrogen bubbles at the cathode increases, resulting in a greater upwards flux and a faster removal of the pollutant and sludge flotation [37].

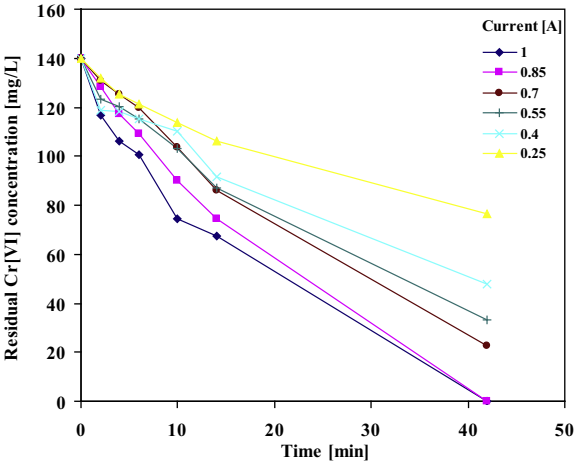

Figure 6 Effect of applied current on residual hexavalent chromium concentration [initial hexavalent chromium concentration = 140 mg/l, sodium chloride concentration = 1 g/l, pH = 4.66, the electrocoagulation time = 42 min].

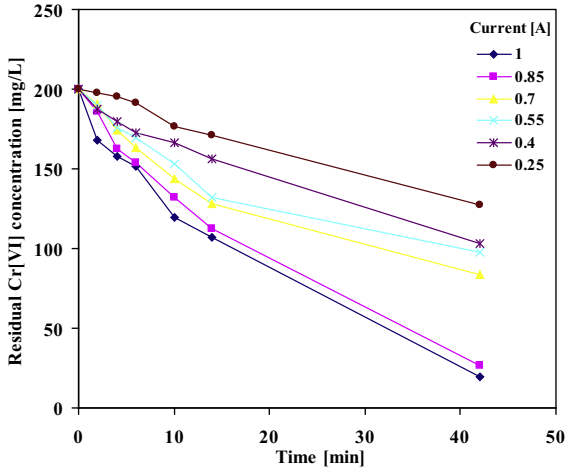

Figure 7 Effect of applied current on residual hexavalent chromium concentration [initial hexavalent chromium concentration = 200 mg/l, sodium chloride concentration = 1 g/l, pH = 4.66, the electrocoagulation time = 42 min].

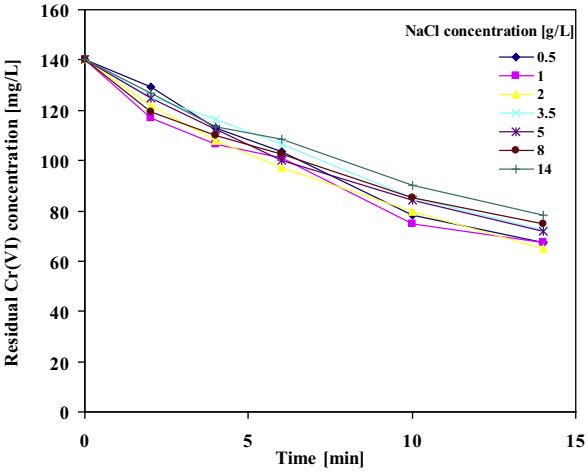

Figure 8 Effect of sodium chloride concentration on residual hexavalent chromium concentration [initial hexavalent chromium concentration = 140 mg/l, current = 1 A, pH = 4.665, the electrocoagulation time = 14 min].

3.1.4. Effect of electrolyte type and concentration

The effect of electrolyte type on electrochemical treatment has already been investigated in the past [38]. Generally, electrolyte is used to obtain the conductivity in the electrocoagulation process. Solution conductivity affects the current efficiency, cell voltage and consumption of electrical energy in electrolytic cells.

In fact, to investigate the effect of the common salt used in the electrocoagulation cells, a set of experiments was conducted at current 1 A, at initial pH of the original solution (4.66) and initial concentration of hexavalent chromium ions of 140 mg/l. It can be seen from Fig. 8 that as sodium chloride concentration increases from 0.5 to 1.5 g/l the residual hexavalent chromium concentration decreases from 67 to 60.9 mg/l because as the initial concentration of sodium chloride

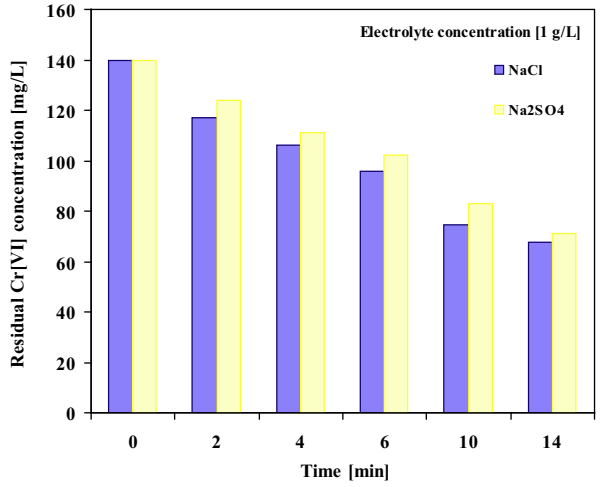

Figure 9 Effect of different types of electrolyte (sodium chloride and sodium sulfate) on residual hexavalent chromium concentration [initial hexavalent chromium concentration = 140 mg/l, applied current = 1 A, pH = 4.66, the electrocoagulation time = 14 min].

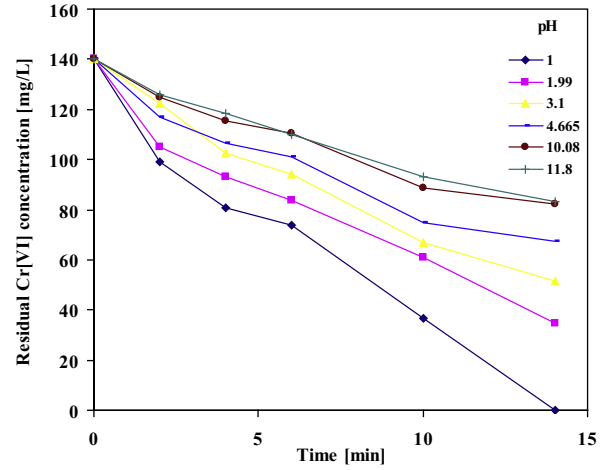

Figure 10 Effect of initial pH on residual hexavalent chromium concentration [initial hexavalent chromium concentration = 140 mg/l, sodium chloride concentration = 1 g/l, current = 1 A, the electrocoagulation time = 14 min].

increases the conductivity of the cell increased and the residual concentration decreases [39]. It is also obviously shown that beyond sodium chloride concentration of 1.5 g/l there was no effect on the conductivity. This is probably due to the fact that at high salt concentrations the salting out effect appears. But for lower concentration of sodium chloride (< 1.5 g/l), there was a decrease in the rate of removal, probably because there were not enough ions to conduct the current so the electrical resistance of the solution increases so the efficiency and the energy consumption of the process would decrease [40].

In order to evaluate the effect of the electrolyte type on the residual concentration, another set of experiments was conducted at current 1 A, the initial pH of the original solution (4.66), hexavalent chromium concentration of 140 mg/l and with adding 1 g/l of sodium sulfate instead of sodium chloride. From Fig. 9 it is shown that by changing the electrolyte type from sodium chloride to sodium sulfate the residual concentration increases. This increase can be due to the passivating effect of the sulfate ions that hinders the effective anodic dissolution of the electrode materials [41]. For instance it was recorded that when sulfate ions are the sole electrolytes, very high voltage needs to be applied to allow the breakage of the passive film and this corresponds to a significant waste electrical energy [42] (see Fig. 10).

3.1.5. Effect of initial pH of the solution

It has been established that pH is an important operating factor influencing the performance of electrocoagulation process [43,44]. In this work, the examination of the pH effect on the elimination of hexavalent chromium by electrocoagulation was studied for pH ranging from 1 to 11.8. According to Fig. 11 the minimum residual hexavalent chromium concentration (0 mg/l) was achieved at high acidic mediums at pH = 1 and initial hexavalent chromium concentration of 140 mg/l after 14 min. This trend in acidic medium was expected due to that in the presence of high hydrogen ion concentration the hexavalent chromium ions were only reduced to Tetravalent Chromium ions and could not be precipitated. So in more acidic conditions the efficiency for hexavalent chromium removal is high.

Meanwhile with increasing pH in basic medium the residual hexavalent chromium concentration increased and this is due to the less hydrogen ions which were needed to facilitate the reduction of hexavalent chromium to Tetravalent Chromium. Consequently at alkaline pH values the reaction between iron (II) and hexavalent chromium occurred very slowly so the optimum pH for the hexavalent chromium removal is 1.

3.1.6. Electrical energy consumption and electrode consumption

It is clear that the major operating cost of the electrocoagulation process is associated with electrical energy during the process [45,46]. The electrical energy consumed during all experiments can be calculated from equation

$$\text{Energy consumption (kWh/g hexavalent chromium removed)} = \frac{EIt_{EC}}{(C_\circ - C_t)V} \tag{18}$$

where:
E is the cell voltage, (Volt).
I is the current, (A).
t_{EC} is the electrocoagulation time, (h).

The mass loss (or electrode consumption) of iron anode can be calculated from Faraday's law as follows [47]:

$$\text{Iron consumption (g iron/g hexavalent chromium hexavalent chromium removed)} = \frac{ItM}{ZFV(C_\circ - C_t)} \tag{19}$$

where:
F is Faraday's constant (96,485 C/mol).
M is the relative molecular mass of iron (55.845 g/mol).
Z is the number of electron transfer ($Z_{Fe} = 2$).
$C_\circ$ is the initial compound concentration, (mg/l).

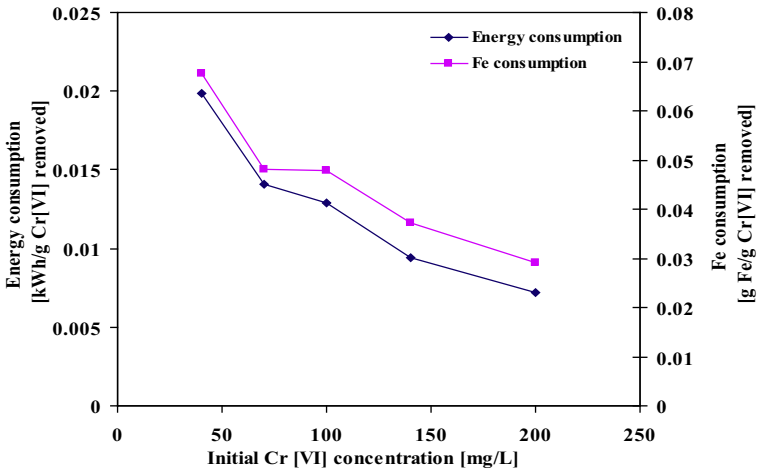

Figure 11 Effect of initial hexavalent chromium concentration on energy consumption and iron consumption [sodium chloride concentration = 1 g/l, pH = 4.66, applied current = 1 A, the electrocoagulation time = 14 min].

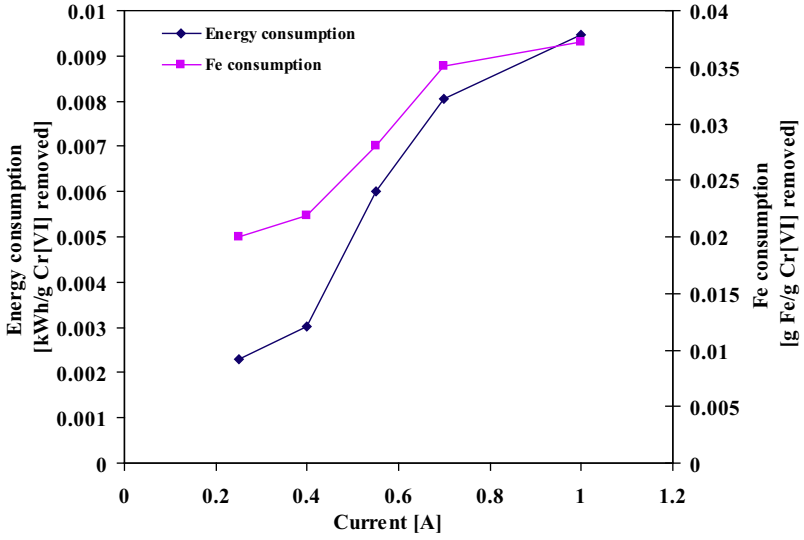

Figure 12 Effect of applied current on energy consumption and iron consumption [initial hexavalent chromium concentration = 140 mg/l, sodium chloride concentration = 1 g/l, pH = 4.66, the electrocoagulation time = 14 min].

C_t is the concentration at time t, (mg/l).

V is the treated volume, (L).

The variation of electrical energy consumption and electrode consumption with initial hexavalent chromium concentration, applied current, initial electrolyte concentration and initial pH of the solution are presented in Figs. 11–14. As seen from previous figures the experimental energy consumption values ranged from 0.02 to 0.007 kWh/g hexavalent chromium removed, 0.002–0.009 kWh/g Hexavalent Chromium removed, 0.014–0.003 kWh/g hexavalent chromium removed and from 0.0009 to 0.013 kWh/g hexavalent chromium removed. The variation of iron consumption ranged from 0.067 to 0.029 g iron/g hexavalent chromium removed for initial hexavalent chromium concentration, 0.02–0.37 g iron/g hexavalent chromium removed for initial hexavalent chromium concentration, 0.037–0.044 g iron/g hexavalent chromium removed for initial hexavalent chromium concentration and from 0.019 to 0.047 g iron/g hexavalent chromium removed for initial hexavalent chromium concentration. It is clear from these figures that

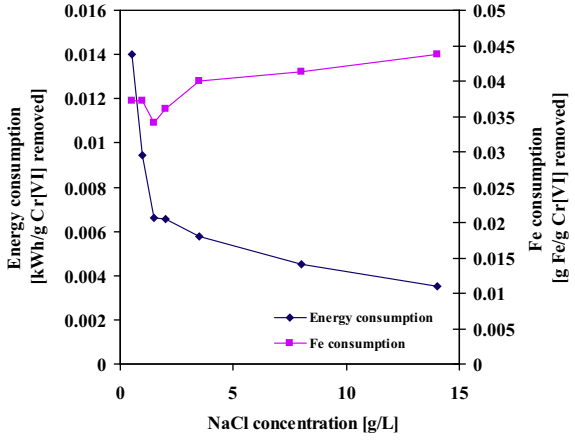

Figure 13 Effect of initial sodium chloride concentration on energy consumption and iron consumption [initial hexavalent chromium concentration = 140 mg/l, applied current = 1 A, pH = 4.665, the electrocoagulation time = 14 min].

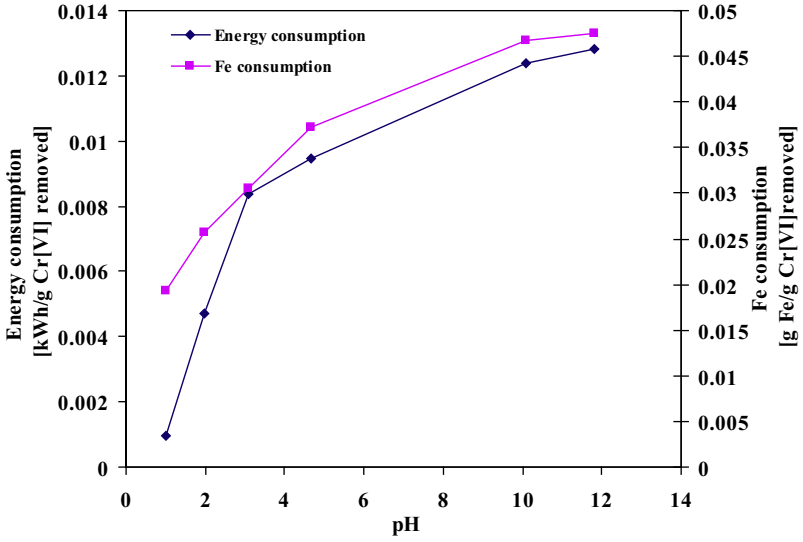

Figure 14 Effect of pH on energy consumption and iron consumption [initial hexavalent chromium concentration = 140 mg/l, sodium chloride concentration = 1 g/l, applied current = 1 A, the electrocoagulation time = 14 min].

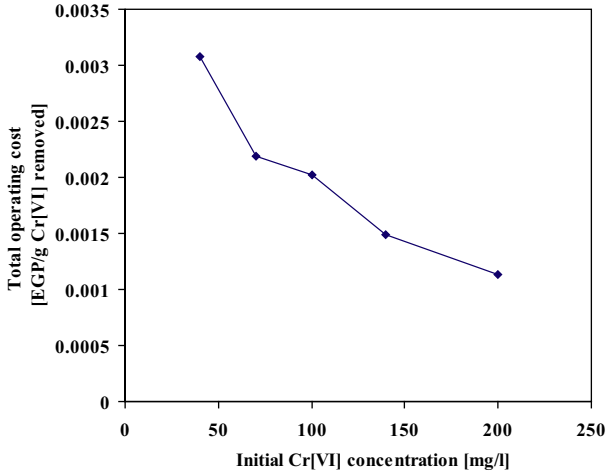

Figure 15 Effect of initial hexavalent chromium concentration on total operating cost [sodium chloride concentration = 1 g/l, pH = 4.66, applied current = 1 A, the electrocoagulation time = 14 min].

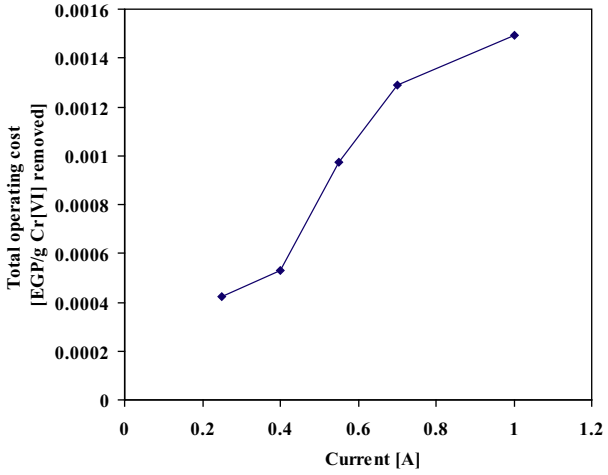

Figure 16 Effect of applied current on total operating cost [initial hexavalent chromium concentration = 140 mg/l, sodium chloride concentration = 1 g/l, pH = 4.665, the electrocoagulation time = 14 min].

energy consumption decreases with increasing initial concentration of hexavalent chromium removed and sodium chloride concentration, and increases with increasing pH and the applied current. Iron consumption decreases with increasing initial concentration of hexavalent chromium removed, and increases with increasing pH and the applied current [48,49].

3.2. Study of the EC process cost

Energy and electrode cost are the most important parameters that affect the application of any method of water and wastewater treatment. Operating costs in the electrocoagulation process may include costs of electrodes, electrical energy, chemicals, maintenance, sludge dewatering/disposal and fixed costs [50,51].

In this research, electrode material and electrical energy costs were taken into account as major cost terms in the calculation of operating costs (EGP/g hexavalent chromium removed) using the following equation [52].

$$\text{Operating cost} = aC_{\text{energy}} + bC_{\text{electrode}} \quad (20)$$

where:

C_{energy} is the energy consumption, (kWh/g Hexavalent Chromium removed).

$C_{\text{electrode}}$ is the electrode consumption, (g iron/g Hexavalent Chromium removed).

a is the electrical energy price, (EGP/kWh).

b is the electrode material price, (EGP/kWh).

The values of the operating costs are based on three factors:

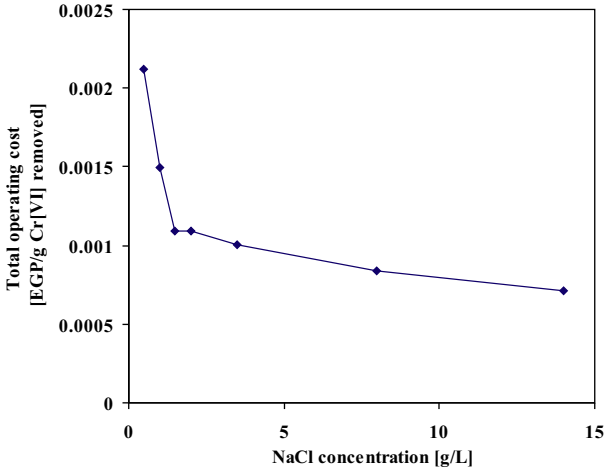

Figure 17 Effect of sodium chloride concentration on total operating cost [initial hexavalent chromium concentration = 140 mg/l, applied current = 1A, pH = 4.665, the electrocoagulation time = 14 min].

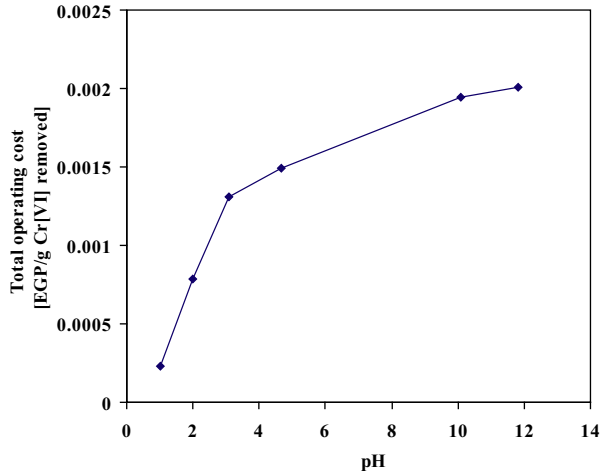

Figure 18 Effect of pH on total operating cost [initial hexavalent chromium concentration = 40 mg/l, sodium chloride concentration = 1 g/l, applied current = 1 A, the electrocoagulation time = 14 min].

1. Calculation of energy consumption according to Eq. (18).
2. Amount of metals dissolved per g of hexavalent chromium removed which could be evaluated by using Faraday's law (Eq. (19)).
3. The economic data obtained in May 2013 (the price 1 ton of iron = 5300 EGP and the price of 1 kWh = 0.137 EGP).

The variation of the operating cost with initial hexavalent chromium concentration, applied current, initial electrolyte concentration and initial pH of the solution are presented in Figs. 15–18. Considering the economic assumptions mentioned before, it has been found that the operating cost ranges from 0.00307 to 0.00114 EGP/g hexavalent chromium removed, from 0.00042 to 0.00243 EGP/g hexavalent chromium removed, from 0.0021 to 0.00071 EGP/g hexavalent chromium removed and from 0.000232 to 0.002 EGP/g hexavalent chromium removed. It is clear that the operating cost decreases with increasing initial concentration of hexavalent chromium removed and sodium chloride concentration, and increases with increasing pH and the current. Table 1 summarizes the optimum conditions for the EC process by using the present cell based on minimum residual hexavalent chromium concentration, energy consumption and operating cost.

Table 1 The optimum conditions for the EC process based on minimum residual hexavalent chromium concentration, energy consumption and operating cost.

Parameter	The optimum parameter value
Initial hexavalent chromium concentration	100 ppm
Current	0.55 A
Electrolyte [sodium chloride and sodium sulfate] concentration	1.5 g/l
Electrolyte type	Sodium chloride
pH	1

4. Conclusions

The present study attempted to investigate the applicability of an EC method in the treatment of aqueous solutions containing hexavalent chromium by using a fixed bed electrochemical batch reactor. This design offers high anode surface area (491 cm^2), very low current, voltage and IR drop so the hexavalent chromium concentrations decrease at short coagulation time. The influence of variables such as initial metal ion concentration, applied current, electrolyte [sodium chloride and sodium sulfate] concentration and initial pH of the solution was investigated.

The results showed that:

1. Residual hexavalent chromium concentration increased with increasing initial hexavalent chromium concentration and decreased with increasing the applied current and initial pH of the solution, by studying the effect of sodium chloride, it was found that residual hexavalent chromium concentration decreased with increasing sodium chloride concentrations at first and then the residual hexavalent chromium concentration gradually increased.
2. Iron consumption decreases with increasing initial concentration of hexavalent chromium ions, and increases with increasing initial pH of the solution and the current.By studying the effect of sodium chloride, it was found that iron consumption decreases with increasing sodium chloride concentration from 0.5 to 1.5 g/L. Beyond 1.5 g/L, the iron consumption increases.
3. Energy consumption and the operating cost decreases with increasing initial concentration of hexavalent chromium and sodium chloride concentration, and increases with increasing initial pH of the solution and the applied current.
4. The optimum conditions for the EC process by using the present cell based on minimum initial hexavalent chromium concentration, energy consumption and operating cost were 100 mg of hexavalent chromium ions/l, 0.55 A, 1.5 g of sodium chloride/l and pH of 1.

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