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Treatment of the textile wastewater by electrocoagulation Economical evaluation

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Abstract

This paper presents the comparative results with respect to electrode configurations on the economic performance of treatment of textile wastewaters by electrocoagulation (EC) process. Aluminum and iron electrode materials were used as sacrificial electrode in parallel and serial connection modes. Various direct and indirect cost items including electrical, sacrificial electrodes, labor, sludge handling, maintenance and depreciation costs were considered in the calculation of the total cost per m^3 of wastewater taken from a textile plant with a capacity of $1000\,m^3$ per day. The results showed that monopolar-parallel mode (MP-P) was the most cost-effective for Fe and Al electrodes. These electrodes showed similar results in removal efficiency of COD and turbidity, but Fe electrode was preferred due to its low cost. pH 7 for Fe electrode and pH 5 for Al electrode were found suitable in terms of removal efficiency of COD and turbidity from textile wastewater. Meanwhile, $30\,A\,m^{-2}$ of current density and 15 min of operating time were found to be sufficient for Fe and Al electrodes. Finally, a comparative study showed that EC was faster and more economic; consumed less material and produced less sludge, and pH of the medium was more stabilized as compared to chemical coagulation (CC) for percentage removal efficiency of COD and turbidity from textile wastewater. The treatment cost of EC at optimum conditions was 3.2 times cheaper than that of CC.

Keywords: Textile wastewater; Electrocoagulation; Economic analysis; Operating cost

1. Introduction

Electrocoagulation (EC) is an attractive method for the treatment of various kinds of wastewater, by virtue of various benefits including environmental compatibility, versatility, energy efficiency, safety, selectivity, amenability to automation, and cost effectiveness [1–3]. This process is characterized by simple equipment, easy operation, a shortened reactive retention period, a reduction or absence of equipment for adding chemicals and decreased amount of precipitate or sludge which sediments rapidly.

Textile wastewaters are one of the significant pollutants for the environment due to their characteristics such as high COD concentration, strong color, high pH and temperature, and low biodegradability [4]. Several conventional methods have been carried out for this purpose such as adsorption, coagulation, flocculation, biological and chemical oxidation [5]. Although these methods have been widely applied, but they have some disadvantages. For example, adsorbents are usually difficult to regenerate [6], chemical coagulation causes additional pollution due to the undesired reactions in treated water and produces large amounts of sludge [4] and biological methods are not suitable for most textile wastewaters due to the harmful effects of some commercial dyes on the organisms used in the process. Moreover, these conventional methods are also usually expensive and treatment efficiency is inadequate because of the large variability of the composition of textile wastewaters [7].

Despite to the impressive amount of scientific research on the treatment of various industrial wastewaters by EC, a few researches have been done on the economic analysis [8,9]. Thus, a detailed research has been performed in order to assess both the technical and economic aspect of EC for the treatment of textile wastewater. The technical evaluation has been presented previously [10]. In this study, the operating cost analysis of the process is considered.

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Table 1
Economical data used in calculation of the operating cost

Item	Cost ($)
Rectifier installing cost	10,000
EC tank installing cost	500
Maintenance ($\$ m^{-3}$)	0.003
Electricity ($\$ kWh^{-1}$)	0.06
Labor costs ($\$ m^{-3}$)	0.06
Sludge transportation and disposal ($\$ kg^{-1}$)	0.01
Materials and chemical costs	
Fe electrode ($\$ kg^{-1}$)	1.8
Al electrode ($\$ kg^{-1}$)	0.3
Chemicals ($\$ m^{-3}$)	0.025
$FeCl_3 \cdot 6H_2O$ ($\$ kg^{-1}$)	0.34
$Fe_2(SO_4)_3 \cdot 7H_2O$ ($\$ kg^{-1}$)	0.4
$AlCl_3 \cdot 6H_2O$ ($\$ kg^{-1}$)	0.8
$Al_2(SO_4)_3 \cdot 18H_2O$ ($\$ kg^{-1}$)	0.4

2. Experimental

2.1. Materials

The wastewater was obtained from a tank containing a mixture of exhaust dyeing solutions at a textile factory in Gebze (Turkey) producing approximately 1000 m^3 of wastewater per day.

The electrocoagulator was made of plexiglas with the dimensions of 120 mm × 110 mm × 110 mm. Al and Fe electrode materials were used as sacrificial electrode in parallel and serial connection modes. Both aluminum or iron cathodes and anodes were made from plates with dimensions of 45 mm × 53 mm × 3 mm. The total effective electrode area was 143 cm^2 and the spacing between electrodes was 20 mm. The electrodes were connected to a digital dc power supply (Topward 6306D; 30 V, 6 A) operated at galvanostatic mode. The EC reactor is operated in batch mode. Characteristics of wastewater used have the following properties: chemical oxygen demand (COD): 2031 mg l^{-1}, total suspended solids (TSS): 102 mg l^{-1}, Conductivity: 2310 mS cm^{-1}, turbidity: 671 NTU, pH: 8.88 and procedures are reported elsewhere [10].

2.2. Economic analysis

Total operation cost has been calculated for a plant with a capacity of 1000 m^3 wastewater per day which includes direct cost items such as electricity, material (electrodes and chemical reagents), sludge transportation and disposal costs, as well as indirect cost items such as labor, maintenance and depreciation of the major equipments including rectifier and electrocoagulator. Values of the total operating cost are calculated based on economic data obtained from Turkish market in 2005, shown in Table 1.

3. Results and discussion

This study is focused on the selection of the sacrificial electrode type and electrode connection mode with respect to the treatment efficiency and operating cost. Before the economical analysis, important costs items namely; sacrificial electrode and electrical energy consumptions and amount of the sludge formed are represented as function of important design variables such as, pH of wastewater, current density, operating time and connection mode, respectively.

3.1. Effect of initial pH

pH is an important operating factor influencing the performance of EC process [11,12]. In this study, experiments have been conducted to determine the pH effect on cost items at constant current density of 30 A m^{-2} and operating time of 15 min.

For a given connection mode, the electrode consumption is found to be weakly dependent on the initial pH (Fig. 1). The highest electrode consumption is obtained with bipolar-series mode (BP-S); approximately 0.27 kg m^{-3} for Fe electrode and between 0.18–0.23 kg m^{-3} for Al electrode. Monopolar-parallel (MP-P) mode shows the lowest electrode consumption for both electrode materials; 0.12 kg m^{-3} for Al electrode and 0.16 kg m^{-3} for Fe electrode.

When energy consumptions are compared, as seen in Fig. 2, weak dependence on pH is observed for all of the systems; it may be concluded that, for Al electrodes, there were clear dependencies on pH for MP-S and BP-S modes. MP-S and BP-S modes exhibit high consumptions since consequence of the serial connection requires made higher potential. The lowest consumption values are approximately 0.63 kWh m^{-3} for Fe electrode and 0.7 kWh m^{-3} for Al electrode when MP-P mode is used.

Effect of the initial pH on the sludge amounts is depicted in Fig. 3. Sludge amounts vary from 0.65 to 1.0 kg m^{-3} for Fe electrode and from 0.9 to 1.3 kg m^{-3} for Al electrode. In general, more sludge is produced with BP-S mode and less sludge with MP-P mode.

As seen in Figs. 4 and 5, MP-P mode for both electrode materials is economically more feasible owing to having low electrical energy consumptions and amount of sludge produced.

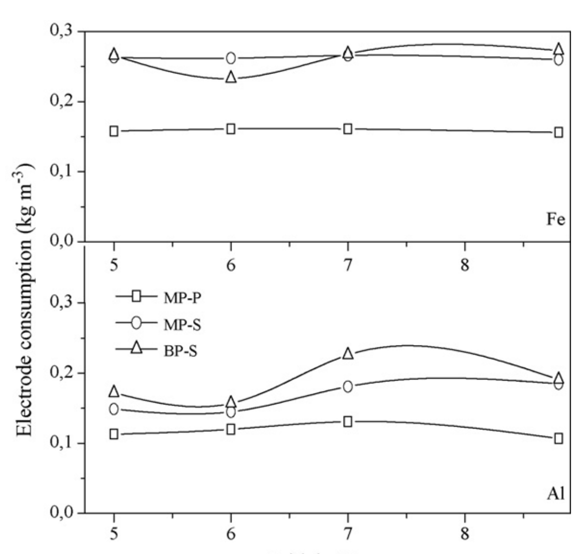

Fig. 1. Effect of initial pH on sacrificial electrode consumption.

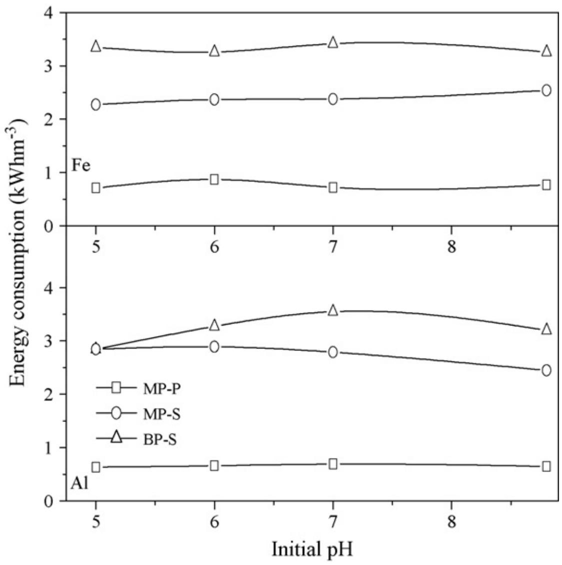

Fig. 2. Effect of initial pH on energy consumption.

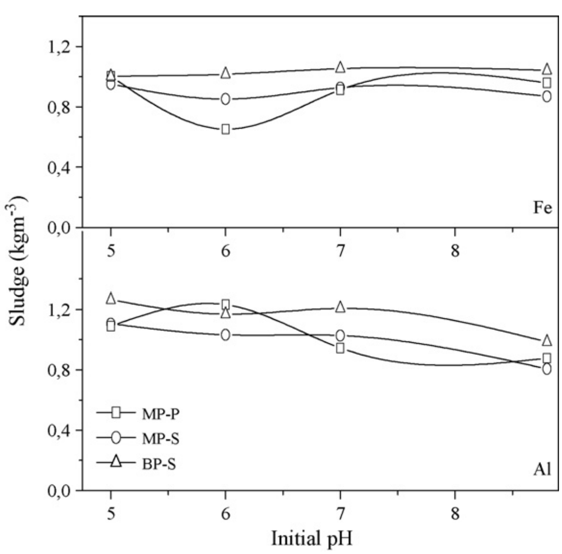

Fig. 3. Effect of initial pH on sludge formation.

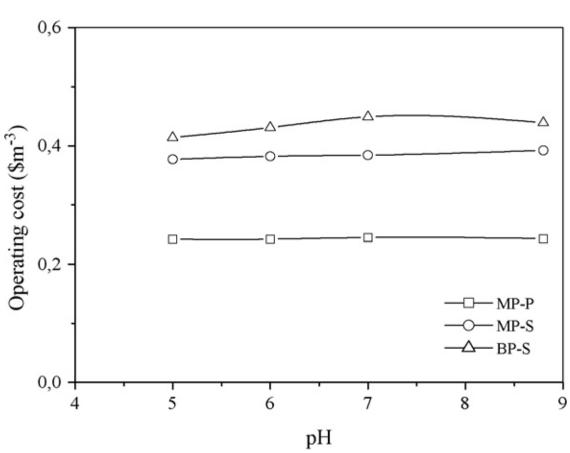

Fig. 4. Effect of initial pH on operating cost for iron electrodes.

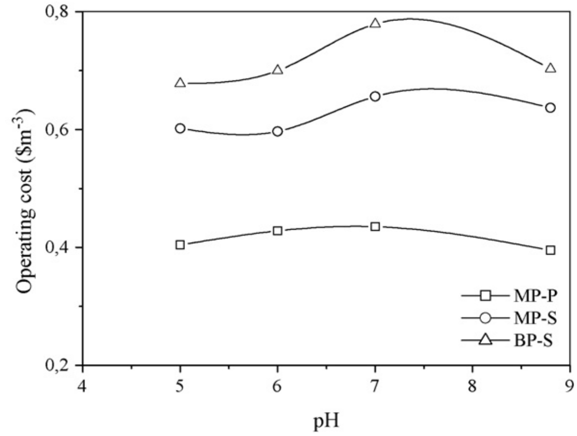

Fig. 5. Effect of initial pH on operating cost for aluminium electrodes.

The operating cost for Al and Fe electrodes were 0.23 and 0.42$ m^{-3}. BP-S mode has the highest cost values which is 0.78$ m^{-3} for Al electrode and 0.43$ m^{-3} for Fe electrode.

3.2. *Effect of current density*

Experiments have been performed to determine the effect of the current density at pH 7 for Al electrode and at pH 5 for Fe electrode at 15 min of operating time.

Electrode consumption values increase with increasing current density, as shown Fig. 6. Electrode consumption value for BP-S mode reaches its highest value of 0.58 kg m^{-3} for Fe electrode and 0.32 kg m^{-3} for Al electrode at 60 A m^{-2} current density, while the lowest electrode consumption with MP-P mode is 0.27 kg m^{-3} for Fe electrode and 0.11 kg m^{-3} for Al electrode, respectively. It is clear that electrode consumptions are higher with Fe electrode material, based on a weight basis. By considering atomic weights of Al (27 g mol^{-1}) and Fe (56.5 g mol^{-1}), the consumption on molar basis are not very

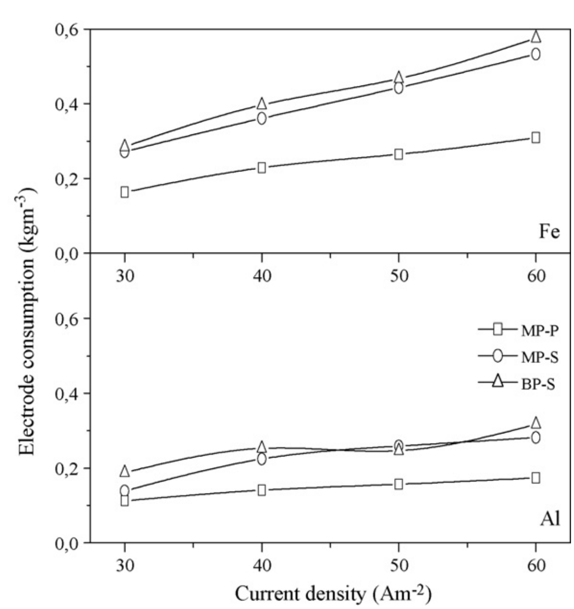

Fig. 6. Effect of current density on sacrificial electrode consumption.

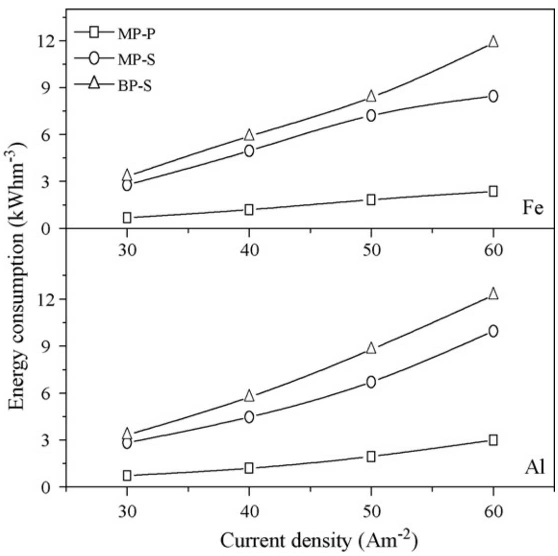

Fig. 7. Effect of current density on energy consumption.

different; with MP-P mode, for example, the calculated values are 4.78 mol g m^{-3} for Fe electrode and 4.07 mol g m^{-3} for Al electrode, respectively.

As shown in Fig. 7, all of the systems exhibit similar trends with respect to energy consumption as a function of current density; it increases with increasing current density. Similar to pH effects on energy consumption, BP-S mode requires higher energy values, while MP-P mode is the most economical at 30 A m^{-2} of current density. Its consumption values are 0.68 kWh m^{-3} for Fe electrode and 0.72 kWh m^{-3} for Al electrode.

Sludge formation dependence on the current density is depicted in Fig. 8. Amount of sludge increases with increasing current density for all connection modes and electrode materials. BP-S and MP-S modes have similar values. MP-P system produces the lowest amount of sludge as 0.81 kg m^{-3} and 0.9 kg m^{-3} for Fe and Al electrodes at 30 A m^{-2}. When

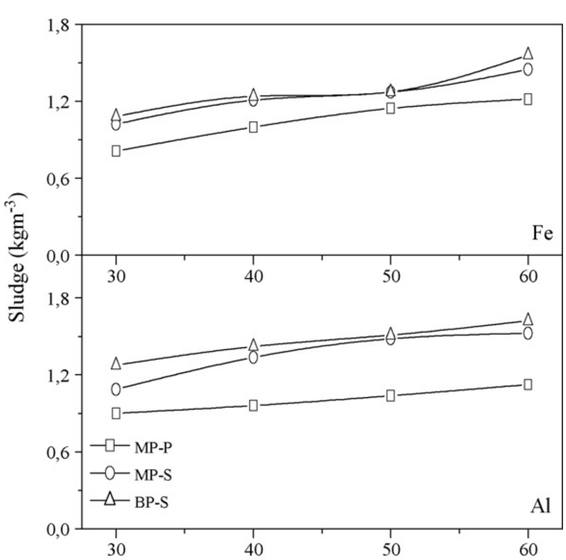

Fig. 8. Effect of current density on sludge formation.

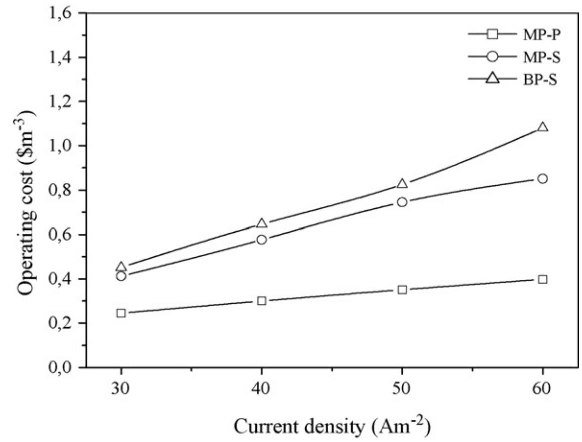

Fig. 9. Effect of current density on operating cost for iron electrodes.

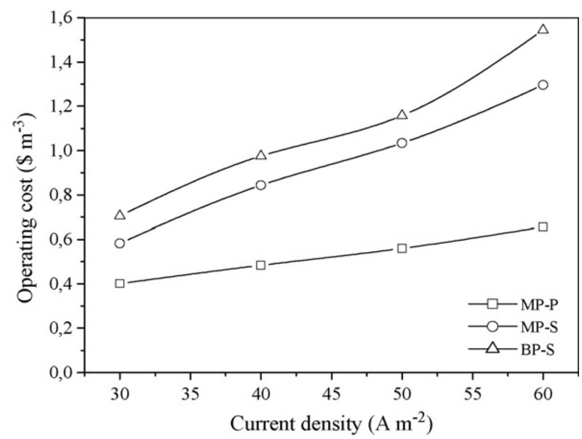

Fig. 10. Effect of current density on operating cost for aluminium electrodes.

these latter values are evaluated on a molar basis with respect molar electrode consumptions, it is seen that aluminum hydroxide flocs bound more water, chemically or physically, than iron hydroxide flocs do.

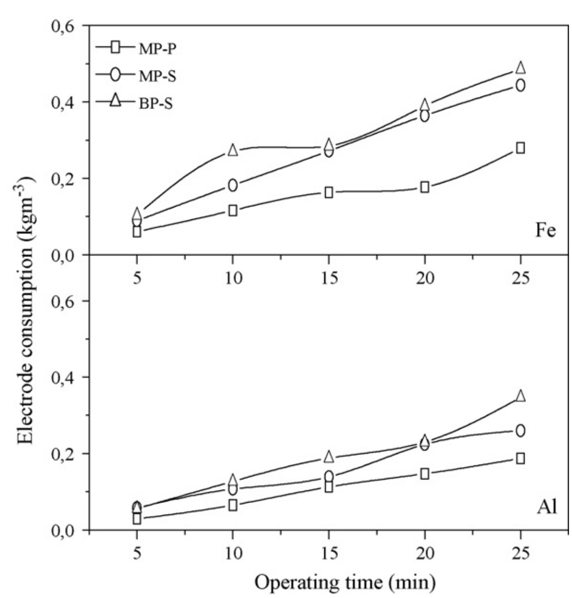

Fig. 11. Effect of operating time on sacrificial electrode consumption.

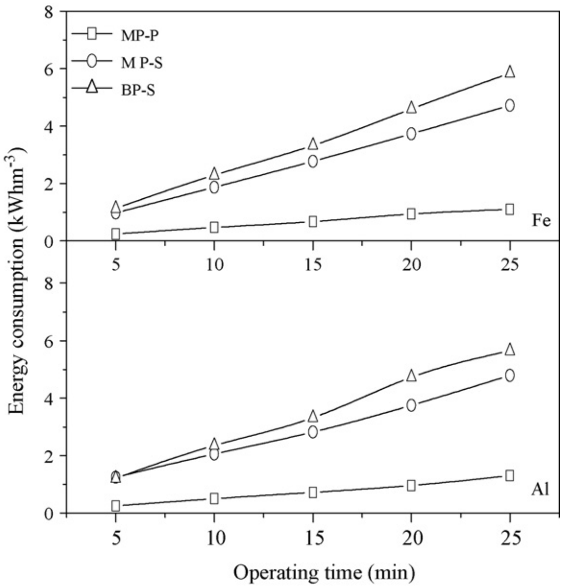

Fig. 12. Effect of operating time on energy consumption.

The effect of the current density on the operating cost of EC process is presented in Figs. 9 and 10. For both electrode materials, operating cost increases more rapidly for MP-S and BP-S modes when compared with MP-P mode. BP-S mode exhibits the highest cost values as 1.02\$ m^{-3} and 1.48\$ m^{-3} for Fe and Al electrodes, respectively. MP-P mode with Fe electrode material is the most economic with having 0.2\$ m^{-3} operating cost at 30 A m^{-2}.

3.3. *Effect of operating time*

Operating time experiments were carried out at pH 7 for Fe electrode, at pH 5 for Al electrode at 30 A m^{-2}. As seen in Fig. 11, Electrode consumption values are higher for Fe electrode. The electrode consumption is the highest in BP-S mode as compared to the other two modes.

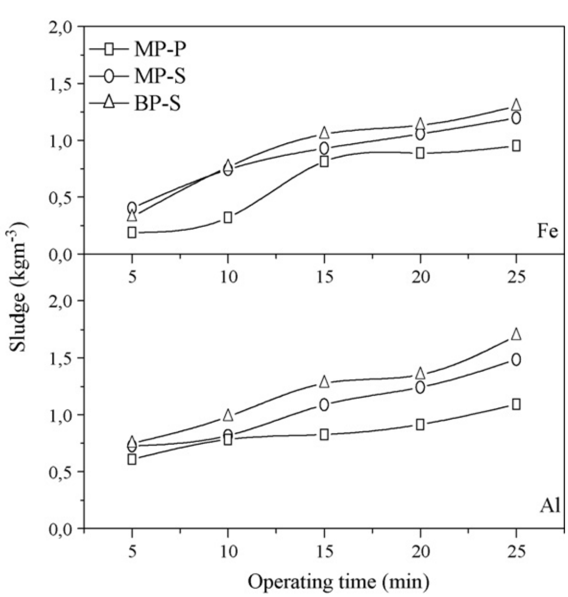

Fig. 13. Effect of operating time on sludge formation.

Table 2
Optimum operating conditions and operating cost for types of electrode material for EC

	Electrode material	
	Fe	Al
Electrode connection mode	MP-P	MP-P
Current density (A m^{-2})	30	30
Operating time (min)	15	15
Initial pH	7.0	5.0
Final pH	7.9	6.3
COD removal (%)	65	63
Turbidity removal (%)	83	80
Coagulant consumption (kg kg^{-1} COD)	0.126	0.096
Operating cost (\$ m^{-3})	0.25	0.40

Energy consumption versus operating time are presented in Fig. 12. Linear dependences are observed. MP-S and BP-S modes have similar slopes, almost 4–6.5 times greater than that of the MP-P mode. Thus, longer operating times may be used with MP-P mode, to obtain higher wastewater treatment efficiencies using less electric energy.

Effect of the operating time on sludge formation is presented in Fig. 13. It is not very profound as in the case of energy consumption. Generally, more amount of sludge is formed when Al electrode is used. BP-S mode gives rise to higher amount of sludge and MP-P mode to lower ones.

Operating cost values with regard to operating time is shown in Figs. 14 and 15. As expected, operating cost increases with increasing of operating time. All connection modes with Fe electrode exhibit low cost values than Al electrode. For an operating time of 25 min, the operating cost for Al electrode with BP-S mode has 5.5 times higher than the operating cost for Fe electrode with MP-P mode.

Optimum conditions from the experimental results are summarized in Table 2; from technical point of view, MP-P connection mode is the most appropriate one for both materials exhibiting similar performance in reducing removal efficiency of COD and turbidity. Fe electrode requires slightly acidic medium

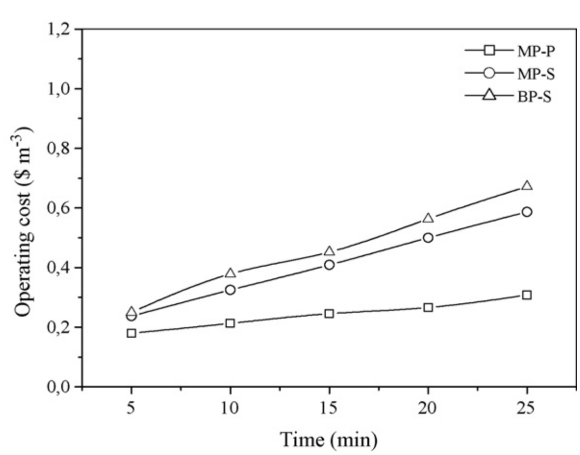

Fig. 14. Effect of operating time on operating costfor iron electrodes.

Table 3
Optimum operating conditions and operating cost for types of coagulant for CC

Parameter	Coagulant			
	$FeCl_3 \cdot 6H_2O$	$Fe_2(SO_4)_3 \cdot 7H_2O$	$AlCl_3 \cdot 6H_2O$	$Al_2(SO_4)_3 \cdot 18H_2O$
Coagulant dosage ($mg\,l^{-1}$)[a]	1500	1500	1000	1500
Operating time (min)	25	25	25	25
Initial pH	7.0	7.0	6.0	6.0
Final pH	2.9	3.1	4.1	4.1
COD removal (%)	71	68	68	59
Turbidity removal (%)	87	63	89	90
Coagulant consumption ($kg\,kg^{-1}$ COD)	1.761	1.586	0.828	1.896
Operating cost ($\$\,m^{-3}$)	0.67	0.75	0.96	0.75

[a] CC processes occur in two phases: 5 min of rapid mixing at 250 rpm and 20 min of slow mixing at 50 rpm. Coagulant consumption values are given as salt dosage ($mg\,l^{-1}$).

(pH 5), while neutral medium (pH 7) is more suitable for Al electrode [10]. 30 $A\,m^{-2}$ of current density and 15 min of operating time are sufficient for both electrodes. From operating cost point of view, Fe electrode is clearly more economic material type than Al electrode.

For a concluding economic analysis, it is worth to compare technical–economical performances of EC and CC. Comparative results are given in Table 3. For CC, $FeCl_3$ is the preferable salt for its techno-economic performance.

The following results may be drawn when EC and CC are compared both technically and economically shown in Tables 2 and 3:

(1) The COD removal performance of CC is 10% higher than EC, the turbidity removal is nearly the same, but having 60% longer retention time for CC.
(2) With the same initial pH, the final pH is 7.9 in EC, but 2.9 in CC. The final acidic and chloride bearing medium is an important drawback of CC, causing severe corrosion problems which may necessitate high-cost building materials. From this point, $Fe_2(SO_4)_3 \cdot 7H_2O$ may be used despite of its higher operating cost.
(3) High coagulant consumption in CC means high chloride concentration in the effluent.

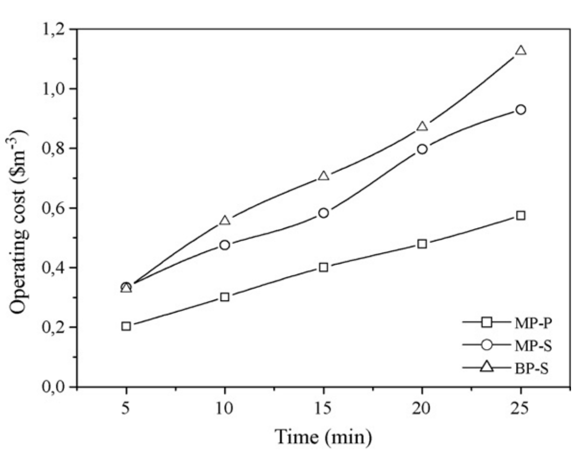

Fig. 15. Effect of operating time on operating costfor aluminum electrodes.

Finally, and more importantly, the operating cost of CC is 3.2 times as high as that of EC.

4. Conclusion

In this study, Al and Fe electrodes were used as sacrificial electrodes with parallel and series connection modes. Various cost items were considered in the calculation of the total cost for the treatment of wastewater from the textile plant. Results showed that MP-P mode was the most cost-effective for both electrodes. Similar results were obtained from Al and Fe electrodes for reducing COD and turbidity, but Fe electrode was found to be a low cost material. Optimum operating conditions were obtained for both electrodes as pH 7 for Fe, pH 5 for Al electrode, 30 $A\,m^{-2}$ of current density and 15 min of operating time.

A comparative study between EC and CC were carried out to determine for consumed electrode material and production of sludge with the same connection mode used. The EC process was faster and more economic than CC. The treatment costs of EC and CC at the optimum operating conditions were 0.25 and 0.80$ m^{-3}, respectively. The operating cost for CC was 3.2 times more expensive than that of EC.

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