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Optimization of the operating parameters of electrocoagulation using aluminum electrode and application to the Dam waters of Sidi Said Ben Mâachou

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Abstract : The objective of this work was to optimize electrocoagulation treatment parameters for the removal of colloidal suspension in dam water, reducing the cost and improving the quality of the treatment. For this purpose, we studied the impact of optimizing the volume of treated water and the agitation speed on the efficiency of electrocoagulation treatment of synthetic water simulating surface water. After the optimization of these parameters, we proceeded to apply it on the waters of the Sidi Said Ben Mâachou dam. The electrocoagulation test was realized in a batch reactor with two flat, parallel aluminum electrodes powered by a direct voltage of 12 V DC voltage. The ions released by electrolysis are stirred using a mechanical stirrer with flat blades. Performance monitoring was carried out using the following parameters: pH, conductivity, turbidity. The analysis of the various monitoring parameters showed that the performance of electrocoagulation is affected by the factors studied. The results obtained showed that intensive agitation of the solution leads to the destruction of the flocs, which subsequently minimizes the efficiency of the treatment.

Keywords: electrocoagulation, electrodes, treatment, surface water, turbidity, stirring speed.

1. Introduction

The surface water is affected by many factors, mainly the organic matter and suspended matter. They make it difficult to treat them [1]. Which sometimes requires the use of more or less elaborate treatment regimens to eliminate undesirable elements effectively [2,3]. Indeed, the removal of these elements requires the use of a number of techniques, such as membrane filter technology, electrocoagulation, sonochemical methods, electrochemical oxidation, photocatalytic oxidation, adsorption on activated carbon and enhanced coagulation [4]. However, electrocoagulation has great benefits due to the cost and duration of the process, and the energy dissipated during the treatment, including coagulation, which involves the use of cations, that reduces the negative potential (Potential zeta ζ) created by the double-layer surrounding the colloidal particles [5].

Electrocoagulation, derived from conventional coagulation, is increasingly used in water treatment, including the removal of suspended and natural organic matter (NOM) from surface waters [6-8]. It is based on the principle of coagulation by cations released under the action of a direct electrical voltage between two opposite metal plates made of iron or aluminum [9,10] Figure 1. Often electrocoagulation is associated with electroflotation (ECF), due to the action of gas bubbles released at the electrodes [11,12] Figure 1.

Three stages of electrocoagulation technology implicate in the purification of wastewater are as: (1) electrolytic oxidation of sample water to generate coagulants; (2) pollutant destabilization, emulsion, deterioration and particle suspension; (3) agglomeration of resultant particles to generate flocs: comprised of colloids entrapped sludge blanket formed from coagulation reaction. These flocs are similar to chemical flocs and are larger acid-resistant, bounded less water and stable, that’s why can be easily separated out by rapid sand filtration [13]. The electrocoagulation process is economical as it produces relatively less amount of

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sludge in comparison with conventional processes. Often electrocoagulation is associated with electroflotation [11,12] Figure 1, the electrochemical reactions take place at anode and cathode as discussed in equations 1-5. During electrocoagulation, H_2 is evolved at cathode in the form of bubbles, that discards particles by flotation known as electroflotation [14]

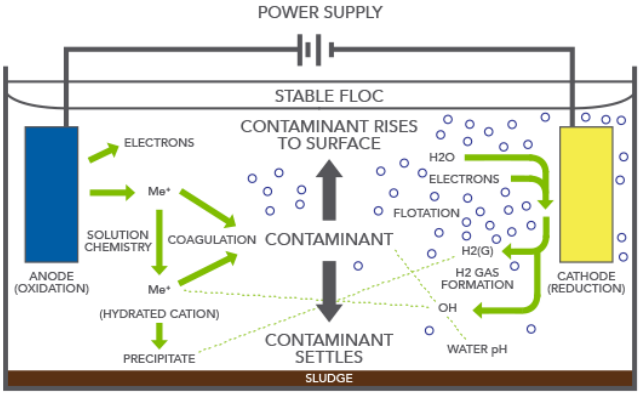


Figure 1. electrocoagulation setup

The main reactions that occur at the electrodes (in the case of aluminum electrodes) are [15] :

- At the anode:

The oxidation of the metal:

$$Al \rightarrow Al^{3+} + 3e^- \quad (1)$$

This reaction can be accompanied by the formation of oxygen by electrolysis of water at high current densities:

$$2H_2O\ (l) \rightarrow 4H^+\ (aq) + O_2\ (g) + 4\ e^- \quad (2)$$

- At the cathode:

The reduction of water:

$$H_2O + e^- \rightarrow 1/2\ H_2 + OH^- \quad (3)$$

For high pH values, the cathode can be attacked by OH^- ions according to the following reaction:

$$2\ Al\ (s) + 6\ H_2O\ (l) + 2\ OH^-\ (aq) \rightarrow 2\ [Al(OH)_4]^-\ (aq) + 3\ H_2\ (g) \quad (4)$$

In an acidic medium, Al^{3+} hydrolyzes to give rise to hydrolyzed monomeric and polymer complexes [16], such as $Al(OH)_2^+$, $Al(OH)^{2+}$, $Al(OH)_4^-$, $Al_6(OH)_{15}^{3+}$, $Al_7(OH)_{17}^{4+}$, $Al_8(OH)_{20}^{4+}$, $Al_{13}O_4(OH)_{24}^{7+}$, $Al_{13}(OH)_{34}^{5+}$. These entities neutralize, with their positive charges, (zeta potential). When the pH ≥ 4 hydrolyzed complex of polynuclear structure [17] $Al_{13}O_4(OH)^{247+}$, gives by precipitation $Al(OH)_3$ Reaction 5.

$$Al^{3+}\ (aq) + 3\ OH^- \rightarrow Al(OH)_3\ \text{precipitated} \quad (5)$$

$Al(OH)_3$, as well as other polymers that may form in the pH range between [18] 4 and 9, can contribute to the adsorption removal of soluble organic compounds and suspended matter.

2. Materials and Methods

2.1. Synthetic Solutions

In the first part, the tests were realized on synthetic solutions prepared in the laboratory from distilled water and clay to obtain a water similar to surface water. The clay-water mixture is left to settle for a few minutes, and then the supernatant undergoes several adjustments to get a synthetic solution with the desired turbidity.

Figure 2. Dam location and water withdrawal

2.2. Dam Water

In the second part, the optimized parameter tests were made on dam waters of Sidi Said Ben Mâachou located on the Oum Er Rbia river Figure 2. This dam is one of the main sources that feed the south of Greater Casablanca.

2.3. Tests Realised

In this work, we studied the effect of these parameters (stirring rate, power/volume of the synthetic solution) on the efficiency of electrocoagulation treatment. So, we proceeded with the tests based on agitation with two speed 20 rpm and 60 rpm in a synthetic solution of 1 liter. Then, the same tests were carried out on a 5-liter synthetic solution. Finally, tests were achieved with two blades of different surfaces.

Electrocoagulation tests were also carried out on real water from the Sidi Said Ben Mâachou dam, using the optimized parameters in the previous tests.

2.4. Parameters and Measurement Methods

After every ten minutes of electrocoagulation treatment, a 20 mL sample is taken and allowed to settle for 15 minutes. The parameters measured are turbidity, pH, conductivity, and temperature. Turbidity is measured using a Palintest 7000 photometer turbidimeter. The pH is measured using a HACH pH meter of type HQ40D, whose probe also measures the temperature. The conductivity is measured by an Orion model 125 conductivity meter. A DRX analysis was performed using a Bruker D8 Advance diffractometer to identify the structure of the sludge and soil.

2.5. Electrocoagulation Materials

Electrocoagulation was performed as shown in Figure 1.2 parallel flat electrodes (14,5cm*2cm *0,2 cm) wide with an inter-electrode distance of 3 cm, dipping to a depth of 6 cm into a cylindrical glass beaker (1 liter and 5 liters). They are made of aluminum and powered by a DC electric generator with variable potential (0 to 30 Volts), model AL 823 working under a voltage of 220 V and having a power of 550 W. The direct voltage applied to both electrodes is 12 V. A mechanical paddle stirrer is immersed in the solution to be treated. The blades are located below the lower ends of the electrodes to maintain the mixing of the formed aggregates Figure 3.

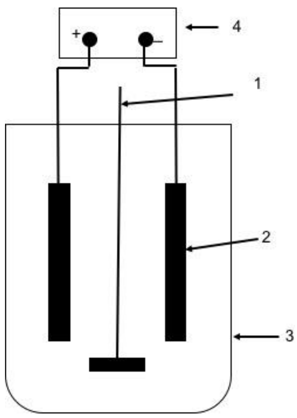


Figure 3. Experimental set-up of the electrocoagulation

(1) mechanical agitator (2) aluminum electrodes (3) electrocoagulation cell (4) DC generator

The following Table 1 gives the characteristics of the agitator :

Table 1. Agitator characteristics.

	Agitator
Form	flat blades
N_p	2
D_p (cm)	7,28
L_p (cm)	2
S_p/V_r (m^2/m^3)	1,4
D_p/D_r	0,693

Np: number of blades, Dp: blade diameter, Lp: blade width, Sp: blade surface, Dr: reactor diameter, Vr: reactor volume.

It should be noted that the gas bubbles of hydrogen and oxygen released at the cathode and anode respectively also contribute to the agitation of the solution.

The characteristics of the prepared synthetic solution are as follows Table 2:

Table 2. Characteristics of the synthetic solution.

pH	Conductivity (µS/cm)	Turbidity (NTU)
7,3	660	110

The characteristics of the Sidi Said Ben Mâachou dam waters are given in the following Table 3:

Table 3. Dam water characteristics.

pH	Conductivity (mS/cm)	Turbidity (NTU)
7,85	2,92	100

Treatment efficiency was assessed by the turbidity abatement rate. This allowance rate is determined according to the following formula:

$$\% \text{ abatement } (X) = \frac{Ci\ (X) - Cf\ (X)}{Ci\ (X)} \times 100$$

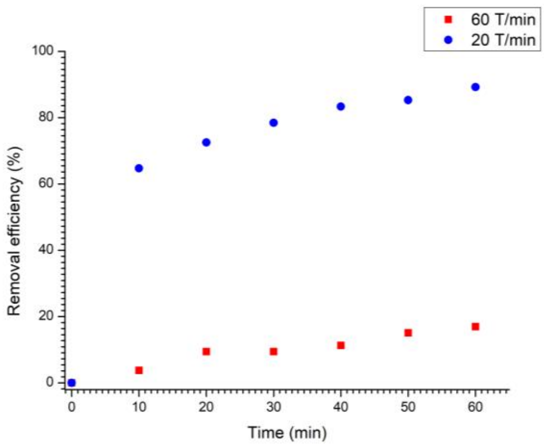
With Ci: initial turbidity of the synthetic solution and Cf: final turbidity of X.

3. Results and discussion

3.1. Synthetic waters

3.1.1. Effect of stirring speed

Electrocoagulation tests performed at two different speeds of 20 rpm and 60 rpm on a volume of 1 liter gave the turbidity results presented in the following Figures 4:



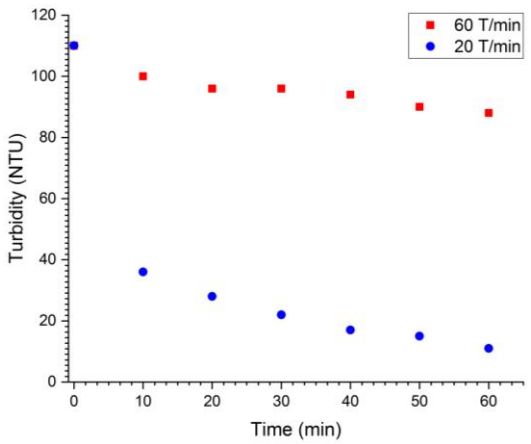


Figure 4. Turbidity abatement and performance as a function of time

For the test performed at 20 rpm, the turbidity removal reaches a 90% reduction rate after 60 minutes. For the 60 rpm speed, this rate is only at 17%. These results highlight the effect of agitation on the removal of suspended matter. Indeed, to ensure good coagulation, it is necessary to provide sufficient agitation energy to destabilize the suspended matter and aggregate it [19,20].

However, when the agitation is too intense, it can break up the aggregated particles. This is probably the case for the test at 60 rpm. The energy supplied per unit volume is higher than for the test at 20 rpm.

Some authors have done similar work. showed that cadmium removal was achieved very fast at a moderate stirring rate of 300 rpm-1. They proved that the adsorption of Cd (II) ions by the coagulating aluminum hydroxide $AlOH_3$ occurred very effectively at stirring rates of 300 and 450 rpm-1 compared to 600 rpm-1 where there was a slight decrease in treatment efficiency which explained this by the fact that excessive stirring causes a rupture to the flocs [21].

3.1.2. Effect of pH

It seems that pH has an important role in the tests performed, as shown by some authors [22]. Looking at the pH evolution Figure 5, we see that it increases rapidly and then stabilizes. During this first phase, when the increase can be attributed to hydroxide ions (OH^-) due to water reduction reaction 3, the suspended matter is removed by electrostatic coagulation. Over time, the pH stabilizes following the formation of $Al(OH)_3$ reaction 5 or other solids, as suggested by some authors [23,18], coagulation of suspended matter, in this case, is done by adsorption on the solids thus formed [24].

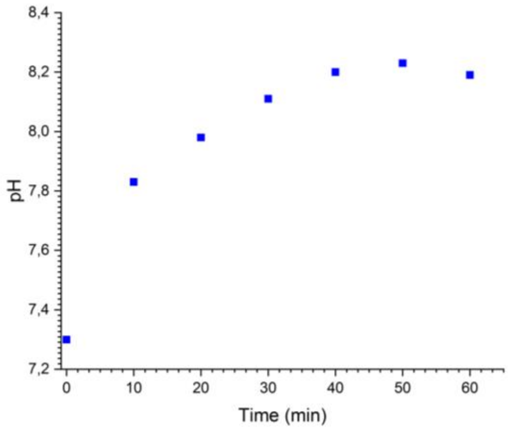


Figure 5. Evolution of pH as a function of time for stirring speed 20 rpm

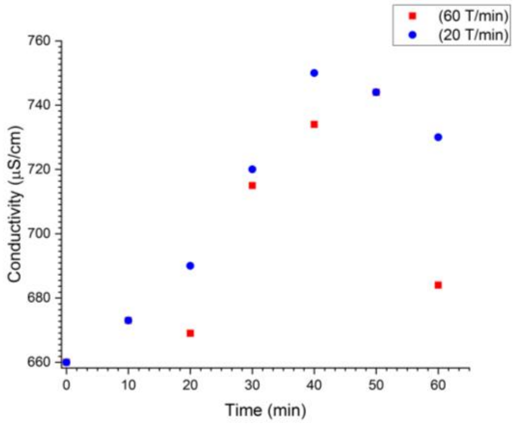


Figure 6. Evolution of conductivity as a function of time

3.1.3. Effect of conductivity

Examination of the conductivity evolution Figure 6 shows an increase, probably due to the release of Al^{3+} and OH- ions reactions 1, 2, and 3 [25]. From 40 minutes of electrocoagulation, a decrease in conductivity is observed, which can be explained by the adsorption of minerals on $Al(OH)_3$ particles and other solids that can form when the pH increases, as mentioned above, or by bridging the leaves of clay particles [1,26] from metal bridges with Al^{3+}.

The tests performed at 60 rpm for 1-liter and 5-liter volumes gave the results shown in Figure 7.

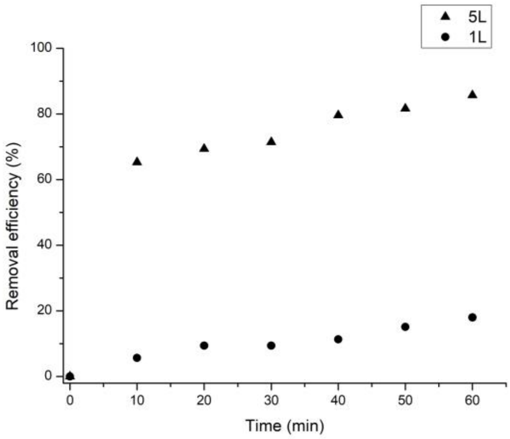


Figure 7. Evolution of turbidity as a function of time for the test at 60 rpm

These results confirm the effect observed in previous tests on specific power. The power dissipated in 1 liter being too high, not allowing good coagulation. This same power dissipated in 5 liters makes coagulation possible. It is improving, the abatement rate reaches 85.71% compared to 17% obtained for a stirring speed of 60 rpm for 1 liter.

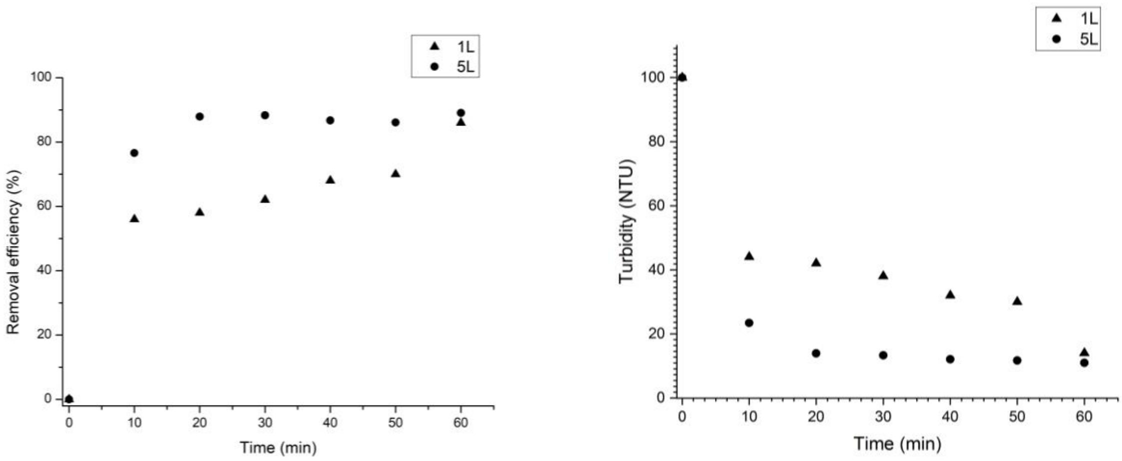


Figure 8. Turbidity abatement and performance as a function of time

3.2. Dam waters

The electrocoagulation tests on the dam water, performed at a stirring rate of 20 rpm, gave the results shown in Figure 8.

It can be observed that electrocoagulation performed at a speed of 20T/min in a volume of 5 liters makes it possible to achieve a reduction rate of 89% after 20 minutes. For a volume of 1 liter, the turbidity reduction reaches 86%, but after 60 minutes.

These results allow us to corroborate the performance of this treatment, which was applied with previously optimized parameters. These tests were performed to prove the effectiveness of our treatment.

The following Figure 9 show the appearance of the dam water before and after electrocoagulation.

Before treatment

After treatment

Figure 9. Observation of our solution before and after treatment

3.3. Fluorescence X

The results of the chemical analysis of the main elements of the raw clay and sludge are illustrated in the following two Tables 4, 5, respectively:

Table 4. Elemental chemical composition of clay.

Elements	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	MnO	SiO_2	SO_3	Cl	K_2O	P_2O_5
% massique	16,22	7,51	0,65	0,46	1,80	0,29	70,13	0,17	0,41	2,79	0,70

Table 5. Elemental chemical composition of the sludge.

Elements	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	MnO	SiO_2	SO_3	Cl	K_2O	P_2O_5
% massique	57,90	3,15	2,25	7,03	0,60	0,18	19,41	5,53	2,70	1,05	0,74

The elementary chemical analysis shows that the most abundant compounds in both samples are SiO_2 and Al_2O_3, this indicates the presence of Kaolinite ($Al_2Si_2O_5(OH)_4$) and illite [(K, H_3O) $Al_2Si_3AlO_{10}(OH)_2$] [27]. The SiO_2/Al_2O_3 mass ratio is 4.3 and 0.27, respectively, for raw clay and sludge, indicating the presence of free quartz [28] in the clay fraction. The low CaO content indicates a low quantity of calcium carbonate [29].

3.4. X-ray diffraction:

The DRX diagrams for the solid phases (raw clay and electrocoagulation sludge) are shown in Figure 10.

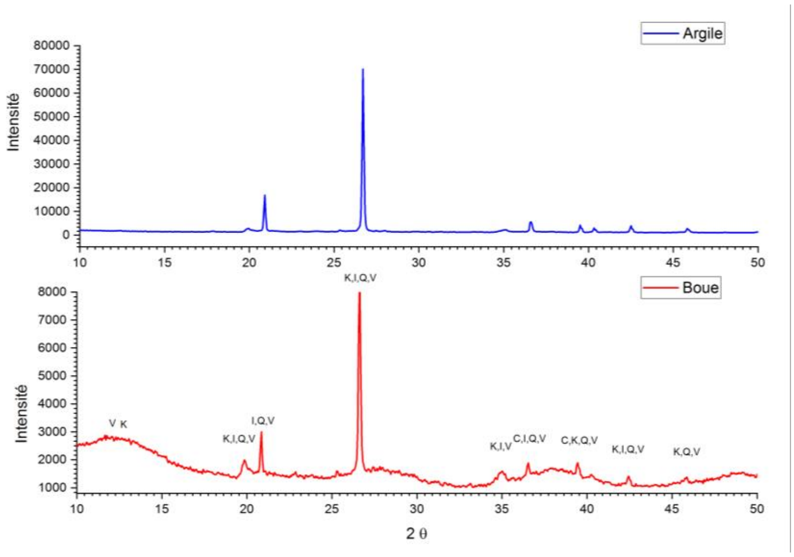


Figure 10. X-ray diffractogram of raw clay and sludge, with K = Kaolinite, I = Illite, Q = Quartz, C= Calcite, V= Vermiculite

From these diagrams, we can see that there are new peaks that appear in the second phase (Sludge). These are new structures that appear and others that disappear, probably as a result of a reaction between the two solids (clay and aluminum hydroxide).

The diffractograms also reveal the presence of clay minerals and crystalline phases, mainly in the form of tectosilicates (Quartz, feldspar...) [30]. Spectral analysis indicates that it is composed of Quartz (SiO_2), Calcite $Ca(CO_3)$, Kaolinite ($Al_2Si_2O_5(OH)_4$), Illite $[(K,H_3O)Al_2Si_3AlO_{10}(OH)_2]$ and vermiculite $[(Mg,Al)_3(Si,Al)_4O_{10}(OH)_2,4H_2O]$. It mainly reveals the presence of an intense peak, which corresponds to a mixture of Quartz, Illite, Kaolinite, and Vermiculite. The clay fraction of our material is constituted of Quartz as a major impurity in our sample, and this confirms the results of the X-ray fluorescence, which shows high proportions of SiO_2 (Quartz).

4. Conclusion

We have shown that the efficiency of electrocoagulation treatment depends on each of these two parameters: volume and stirring speed. For a volume of 1 liter of synthetic solution, the turbidity removal efficiency reaches 90% for a rotation speed of 20 rpm. This efficiency decreases to 17% at a rate of 60 rpm. The stirring power by unit volume is high. This is confirmed by the 60 rpm test on a 5-liter volume, which improved the efficiency, reaching 86% (compared to 17% for 1 liter).

The application of these optimized parameters to dam water confirmed the efficacy of the process. The turbidity removal efficiency obtained is 86% and 89% successively for 1 liter and 5 liters.

Sludge characterization using X-ray diffraction analysis shows the formation of new structures in the clay mixture and aluminum hydroxide flocs based on an interaction between clay and aluminum hydroxide flocs.

The results obtained in this work are compelling and show that the electrocoagulation system is a very interesting process for the elimination of turbidity.

The results obtained in this work are compelling and show that the electrocoagulation system is an exciting process for the elimination of turbidity. To make good exploitation of these results the continuation of our study will be the realization of this system for the treatment of wastewater and after an application to full scale.

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