



# Study on the Removal of Water Hardness by Electrocoagulation Technique

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## Abstract

An electrolytic cell was prepared to remove calcium and magnesium by electrocoagulation. The cell consisted of 2 L beaker. The cathode consisted of a square horizontal Al plate. The anode was made of 4 arrays of separated horizontal aluminium cylinders; each cylinder had a length of 1.8 cm and 1.2 cm diameter and had 17 cylinders total. The effects of different parameters including electrolysis time, initial calcium and magnesium concentration, initial solution pH, NaCl as an electrolyte concentration and stirrer velocity were evaluated. The study found that the percentage removal increase with increasing electrolysis time until an approximately constant removal has been reached after 60 minutes. The percentage removal increase with increasing the applied current density as it reached 53.53% calcium removed and 100% magnesium removed at 50.56 mA/cm<sup>2</sup> the effect of initial solution pH was maximum in the alkaline range at pH=10. In addition, it was found that the calcium and magnesium removal percentage decreased with increasing initial calcium and magnesium concentration, more over increasing NaCl concentration increased the removal percentage to reach 83.18% calcium removed and 100% magnesium removed when adding 3 g. NaCl/L and it was found that increasing stirrer velocity increase removal percentage until the optimum stirrer velocity 300 rpm then starts to decrease at 350 rpm.

**Key words:** Magnesium, Calcium, Electrocoagulation, Removal Percentage and Electrolytic Cell

**Full length article** \*Corresponding Author, e-mail: [ehssan.nassef@yahoo.com](mailto:ehssan.nassef@yahoo.com)

## 1. Introduction

Water hardness creates a lot of problems for life and industry. Except calcium and magnesium, iron, manganese and strontium and some other metals can cause water hardness too, but their amount in comparison to the amount of calcium and magnesium can be ignored. Considering the problems of water hardness, its removal is essential [1]. The principal natural sources of hardness in water are dissolved polyvalent metallic ions from sedimentary rocks, seepage and runoff from soils. Calcium and magnesium, the two principal ions, are present in many sedimentary rocks, the most common being limestone and chalk. They are also common essential mineral constituents of food; a minor contribution to the total hardness of water is also made by other polyvalent ions, such as aluminum, barium, iron, manganese, strontium and zinc [2].

Various physicochemical techniques for removing metal ions from water supplies include chemical precipitation, adsorption, ion exchange, extraction and

membrane processes are employed. WHO Recommendation for drinking water's hardness is based on maximum 500 mg/l calcium carbonate. Of different technologies which need adding chemicals for water softening, are chemical precipitation and ion exchange and those which do not need to add chemicals; include reverse osmosis, electro dialysis, nano-filtration, crystallization, distillation and evaporation [2]. Electrocoagulation (EC) is an electrochemical method which was developed to overcome the drawbacks of conventional treatment technologies and remove efficiently heavy metals from contaminated water and wastewater environments.

It is a simple, reliable, and low cost method, which uses a direct current source supply between metal electrodes immersed in polluted water, without any need for additional chemicals, while at the same time reduces the amount of sludge that should be disposed [3], EC has been successfully used to remove different kinds of pollutants such as organic compounds, dyes and textile wastewater, heavy metals [4], biodiesel wastewater, hardness [5], COD [6] and important

anions such as nitrate [7], fluoride and phosphate [8]. Using electricity to treat water was first proposed in UK in 1889 [9]. The application of electrolysis in mineral beneficiation was patented by Elmore in 1904. Electrocoagulation (EC) with aluminum and iron electrodes was patented in the US in 1909. It is an environment-friendly technique since the 'electron' is main reagent and does not require addition of the reagents/chemicals.

This will minimize the sludge generation to a great extent and eventually eliminate some of harmful chemicals used as coagulants in the conventional effluent treatment methods [10-12] also the equipment for adding chemicals decreased or neglected [13]. The EC technique can be conveniently used in rural areas where electricity is not available, since a solar panel attached to the unit may be sufficient to carry out the process [14]. Electrocoagulation process operates on the base of the principle that the cations produced electrolytically from iron and/or aluminum anodes which is responsible for the increasing of the coagulation of contaminants from an aqueous medium. Electrophoretic motion tends to concentrate negatively charged particles in the region of the anode and positively charged particles in the region of the cathode. The consumable metal anodes are used to continuously produce polyvalent metal cations in the region of the anode.

These cations neutralize the negative charge of the particles moved towards anodes by production of polyvalent cations from the oxidation of the sacrificial anodes (Fe and Al) and the electrolysis gases like Hydrogen evolved at the anode and oxygen evolved at cathode [15]. The objective of the present work is to study remove of the main source of hardness which is calcium and magnesium from water using a fixed bed electrochemical batch circular reactor with horizontal aluminium electrodes. The cathode is made of a horizontal aluminium plate rested on the cell bottom while the anode was made of an array of separated horizontal aluminium tubes placed above the cathode at a very short distance from it. The optimum conditions for the Ca and Mg removal have been investigated in relation to the following parameters: processing time, initial metal ion concentration, applied current density, electrolyte concentration, initial pH of the solution and agitation speed of the mechanical stirrer.

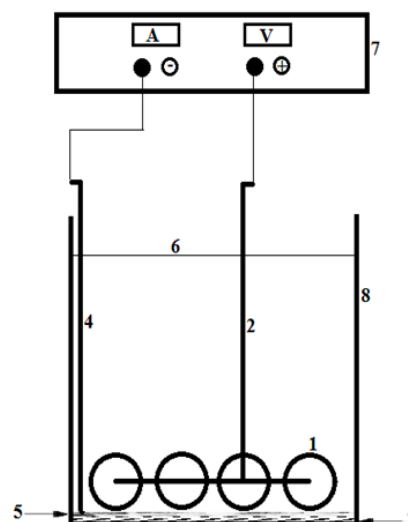
This design offers the following merits: The helical shape in the nuts increase the anode surface area. The small thickness of the perforated sheet decrease the IR drop. The cathodically evolved H<sub>2</sub> bubbles are uniformly distributed over the whole cross-sectional area of the cell, i.e. the floating ability of H<sub>2</sub> bubbles is uniform as opposed to the vertical cell where H<sub>2</sub> evolve in the form of a curtain beside the vertical cathode; besides, the thickness of the bubble layer increases along vertical electrode with a consequent

increase in the cell resistance and the nonuniform current distribution and locating the dissolving Al anode above the H<sub>2</sub> evolving cathode leads to improving mixing conditions at the anode surface by virtue of macro convection induced by rising swarm of H<sub>2</sub> bubbles. As a consequence, concentration polarization would decrease at the anode and dissolved Al<sup>+2</sup> and Al<sup>+3</sup> would be uniformly distributed in the aqueous solution.

## 2. Experiment

### 2.1. Experimental Set-up

Fig. 2.1 shows the cell and electrical circuit used in the present work, the electrical circuit consisted of 20V DC power supply. The cell consisted of 2 L beaker. The cathode consisted of a square horizontal Al plate that had a 9×9 dimensions and placed in the cell bottom; the back of it insulated with epoxy resin. The anode was made of 4 arrays of separated horizontal cylinders, each cylinder had a length of 1.8 cm and 1.2 cm diameter and had a 17 cylinders total, and cylinders in the array were separated by a distance of 0.87 cm, the volume of liquid treated is 1 L. The horizontal cylinders were fixed at their ends to two Al strips, the cathode and anode was held in position by a welded and insulated vertical Al strip to act as a current feeder. The cathode and anode was separated by a perforated plastic sheet of a 1 mm width this perforation allow H<sup>+</sup> ions to come out as bubbles from cathode, these bubbles make good mixing for solution which enhance rate of mass transfer.



**Fig. 2.1 Schematic diagram of electrocoagulation reactor**

**[(1) Anode (2) Insulated Anode Holder (3) Cathode (4) Insulated Cathode Holder (5) Perforated Plastic Sheet (6) Solution Level (7) Digital 20V DC Power Supply and (8) 2 Liters beaker]**

### 2.2. Chemicals Used

- ❖ Calcium Chloride (CaCl<sub>2</sub>·2H<sub>2</sub>O)

- ❖ Magnesium Chloride (MgCl<sub>2</sub>)
- ❖ Sodium Chloride (NaCl)
- ❖ Sulphuric Acid (1N H<sub>2</sub>SO<sub>4</sub>)
- ❖ Sodium Hydroxide (1N NaOH)

### 2.3. Electrocoagulation procedure

For each run a 1 L of the hard water solution was mixed with the appropriate amount of sodium chloride which was used as a conductor. A direct current source was used to supply the system with a constant current density; the effect of electrocoagulation treatment was determined by analysis using atomic adsorption at different time intervals. In order to achieve the desired pH, sulfuric acid (1N) or NaOH (1N) were used. Hard water samples of the initial concentrations (250 ppm to 1000 ppm) were prepared by mixing salts CaCl<sub>2</sub>·2H<sub>2</sub>O and MgCl<sub>2</sub> with distilled water.

25 mL samples were drawn at the beginning of the run and after the following time intervals (5, 15, 20, 30, 45, 60, 90 and 120) minutes by pipette from centre of reactor above the stirrer and this position was kept constant during the whole run then pass through filter paper then diluted to 100 ml to be suitable for analysis by atomic adsorption.

The electrodes were washed one time with dilute HCl and three times with distilled water before each run in order to remove any adhering scales or oxides.

The efficiency of removal of hardness (calcium and magnesium) was calculated as:

$$\text{Removal Efficiency (\%)} = \frac{c_i - c_f}{c_i} \times 100$$

Where:

- ❖ C<sub>i</sub> initial sample concentration (mg/L)
- ❖ C<sub>f</sub> final sample concentration (mg/L)

### 2.4. Variables Studied

- ❖ Effect of electrolysis time (5, 10, 20, 30, 45, 60, 90 and 120)
- ❖ Effect of current density (12.61, 25.23, 37.85 and 50.46)
- ❖ Effect of initial pH (3, 5, 7, 9 and 10)
- ❖ Effect of the initial concentration of calcium and magnesium
  - (200 ppm Ca and 50 ppm Mg)
  - (400 ppm Ca and 100 ppm Mg)
  - (600 ppm Ca and 150 ppm Mg)
  - (800 ppm Ca and 200 ppm Mg)
- ❖ Effect of sodium chloride concentration (0.5, 1, 2 and 3 g/L)
- ❖ Effect of agitation speed (200, 250, 300 and 350 rpm)

## 3. Results and Discussion

### 3.1. Effect of Processing Time

The calcium and magnesium removal efficiency is a function of electrolysis time. The calcium and magnesium removal efficiency increases with increase in the electrolysis time. But beyond the optimum electrolysis time, the removal efficiency becomes constant and does not increase with an increase in the electrolysis time. The effects of processing time on the removal efficiency of calcium and magnesium by electrocoagulation process are shown in figure (3.1) and figure (3.2) which shows that % of calcium and magnesium removal after 60 minutes was constant and there was no removal. That's because the metal hydroxides are formed by dissolution of the anode. For a fixed current density, the number of generated metal hydroxides increases with an increase in the electrolysis time. For a longer electrolysis time, there is an increase in the generation of flocs resulting in increase in calcium and magnesium removal efficiency. For an increase in the electrolysis time beyond the optimum electrolysis time, the calcium and magnesium removal efficiency does not increase as sufficient numbers of flocs are available for removal of calcium and magnesium [16].

### 3.2. Effect of Current Density

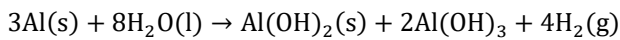
Figures (3.3), (3.4), (3.5) and (3.6) show the influence of current density, ranging from (12.61 to 50.46 mA/cm<sup>2</sup>) on the removal efficiency of calcium and magnesium from hard water by electrocoagulation. The percentage removal of calcium and magnesium at 250 ppm (200 ppm of Calcium and 50 ppm of Magnesium), 500 ppm (400 ppm of Calcium and 100 ppm of Magnesium) respectively, was studied and maximum hardness removal efficiency was found to be 53.53% calcium removed and 100% magnesium removed at 40.81 mA/cm<sup>2</sup>. It can be observed that, at the same electrocoagulation time and under the same operating conditions, the percentage removal of hardness increase with the increase of current density. This increase may be attributed due increase current density will increase the density of the bubbles while their size decrease their floatation will increase, it is also observed that the aggregation of induced flocs while increasing H<sub>2</sub> evolution [17], the direct proportionality between direct current field and potential electrolysis which implies more release of calcium and magnesium ions and thereby more generation of calcium and magnesium hydroxides necessary to form coagulants [18], Increasing the current density increase the rate of emulsification by electrophoresis and the increase in Al<sup>3+</sup> content of the emulsion according to Faradays law [19].

### 3.3. Effect of Initial pH of the Solution

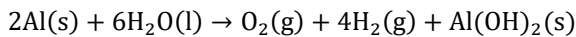
The pH of the solution is an important operational parameter in electrocoagulation. The maximum removal

efficiency is obtained at an optimum solution pH for a particular element. The precipitation of an element begins at a particular pH. The element removal efficiency decreases by either increasing or decreasing the pH of solution from the optimum pH. As the pH is one of the important factors affecting the performance of electrochemical process figures (3.7), (3.8), (3.9) and (3.10) show the effect of the initial pH of the solution on the percentage removal of hardness at 250 ppm (200 ppm of Calcium and 50 ppm of Magnesium) and 500 ppm (400 ppm of Calcium and 100 ppm of Magnesium). Effects of pH with pH increase, the rate of calcium and magnesium removal increase since the effect of pH on coagulants depends on the produced reactions on different conditions.

❖ In neutral conditions:



❖ In acid conditions:



❖ In alkali conditions:



Here,  $\text{Al(OH)}_3$  and  $\text{Al(OH)}_2$  settle while,  $\text{H}_2$  moves upward and causes flotation. As reactions show, in acidity condition  $\text{Al(OH)}_2$  and in alkali condition  $\text{Al(OH)}_3$  are produced. Since  $\text{Al(OH)}_3$  has higher weight and density it settles faster and has higher efficiency. They further reported that the pH of the synthetic solution after the EC process increased with an increase in the electrolysis time due to the generation of  $\text{OH}^-$  in the EC process [16].

### 3.4. Effect of initial calcium and magnesium concentration

To observe effect of initial calcium and magnesium concentration on the calcium and magnesium removal efficiency by EC, experiments were carried out for four different calcium and magnesium concentrations such as the 250 ppm (200 ppm of Calcium and 50 ppm of Magnesium) 500 ppm (400 ppm of Calcium and 100 ppm of Magnesium) 750 ppm (600 ppm of Calcium and 150 ppm of Magnesium) and 1000 ppm (800 ppm of Calcium and 200 ppm of Magnesium) for 60 min with constant current density of  $30.91 \text{ A/m}^2$ . Figure (5.13) and figure (3.14) shows the percentage removal of calcium and magnesium for different initial calcium and magnesium concentrations. As the results indicated, the calcium and magnesium removal efficiency decreased with an increase in initial calcium and magnesium concentration. For example after 60 min of operation, calcium removal decreases from 50% to 22.55% when calcium concentration was increased from 200 to 800 mg/L, and also after 60 min magnesium removal decrease from 100% to 93.44% when magnesium concentration was

increased from 50 ppm to 200 ppm. It was due to the fact that at constant current density and time, the same amount of aluminum hydroxide complexes was generated in all the solutions. Consequently, the same amount of flocs would be produced in the solutions. As a result, the flocs produced at high calcium and magnesium concentrations were insufficient to adsorb all of the calcium and magnesium molecules of the solution. For low concentration of calcium and magnesium, number of aluminum hydroxide complexes was higher compared to number of calcium and magnesium molecules. Hence higher calcium and magnesium removal was obtained in quick time in comparison with higher concentration. Therefore under present operating conditions, the lower is the calcium and magnesium concentration better would be the removal efficiency. The previous studies show that same results [20].

### 3.5. Effect of Electrolyte Concentration

$\text{NaCl}$  is usually employed to increase conductivity of the water or the wastes to be treated. The presence of the chloride ion in the solution has been reported to decrease passivation of Al surface and thereby increase the efficiency of electrocoagulation processes. Figures (3.15), (3.16), (3.17) and (3.18) show the influence of  $\text{NaCl}$  concentration, ranging from (0.5 to 3 g/L), on the percentage removal of Ca and Mg at 250 ppm (200 ppm of Calcium and 50 ppm of Magnesium) and 500 ppm (400 ppm of Calcium and 100 ppm of Magnesium) respectively. The results show that the increasing concentration of  $\text{NaCl}$  has improved percentage of removal of Calcium and Magnesium. Optimum condition of this study was  $\text{NaCl}=1 \text{ g/L}$  taking into consideration the slight increase in the removal percentage beyond 1 g/L. Previous studies have also showed the same behavior [21].

### 3.6. Effect of Agitation Speed

The agitation helps to maintain uniform conditions and avoids the formation of concentration gradient in the electrolysis cell the cell was first run without stirring there was a removal but was less than the removal while there is a stirrer. We use mechanical stirrer and speed was adjusted at 200 rpm, 250 rpm, 300 rpm and 350 rpm.

Further, the agitation in the electrolysis cell imparts velocity for the movement of the generated ions. With an increase in agitation speed up to the optimum agitation speed, there is an increase in the calcium and magnesium removal efficiency removal increase from 200 rpm to reach highest removal at 300 rpm then starts to decrease at 350 rpm. Figures (5.19 and 5.20) show that.

This is due to the fact that with an increase in the mobility of the generated ions, the flocs are formed earlier resulting in increase in the calcium and magnesium removal efficiency for particular electrolysis time. But with a further

increase in the agitation speed beyond the optimum value, there is a decrease in the calcium and magnesium removal efficiency because the high agitation speed makes the flocs degraded by collision with each other. These results are in accordance with previous studies which reached the same results [16].

### 3.7. Energy consumption, aluminum consumption and total cost

The economic feasibility of electrocoagulation in comparison with other techniques, the energy consumption and Al metal consumption were calculated as follows [22]:

#### ❖ Energy consumption

$$(\text{kWh/g hardness removed}) = \frac{EIt_{EC}}{(C_0 - C_t)V}$$

Where

- E is the cell voltage (Volt)
- I is the current (A)
- $t_{EC}$  is the electrocoagulation time (h)
- $C_0$  initial compound concentration (mg/l)
- $C_t$  is the concentration at time t (mg/l)
- V is the treated volume (L)

#### ❖ The amount of Aluminium metal consumed in the electrocoagulation was calculated using Faraday's law as shown below:

$$\text{Al consumption (g Al/g hardness removed)} = \frac{ItM}{ZFV(C_0 - C_t)}$$

Where

- M is molecular weight of Al (27 g/mol)
- Z is number of electron transfer ( $Z_{Al} = 3$ )
- F is Faraday's constant (96,500 Columb)

The variation of electrical energy consumption and electrode consumption with current density, initial concentration of electrolyte, initial Calcium and Magnesium concentration and agitation speed were presented in Figures (3.21), (3.23), (3.25), (3.27) and (3.29).

Operation cost during hard water treatment processes includes cost of electricity, chemical reagents and cost of sludge disposal labors, maintenance and equipment. In electrochemical process the most important parameters that affect operating cost are cost of electrode material and consumed electrical energy. Thus these items are calculated in this research to determine operating cost [23]:

$$\text{Operating cost} = X\text{Energy}_{\text{Consumption}} + Y\text{Electrode}_{\text{Consumption}}$$

Where

$\text{Energy}_{\text{consumption}}$  and  $\text{Electrode}_{\text{consumption}}$  are consumption quantities per L of treated water unit prices, X and Y, given for Egyptian market, May 2015, are; electrical price 0.65 EGP/kWh, electrode material price 17.22EGP/Kg of Al.

#### 3.7.1. Effect of Current Density

Figure (3.21) was investigated, it was seen that increasing the current density caused an increase in energy consumption. In a similar trend in energy consumption, the electrode consumption increased with the increasing current density because the increase in current density has more dissolution of the aluminum electrode. They increase with increasing current densities which results in increasing the total operating cost of EC figure(3.22) [22].

#### 3.7.2. NaCl Concentration

When adding NaCl as an electrolyte this helps in decreasing the energy consumption figure (3.23), which subsequently leads to decrease of the total operating cost figure (3.24) and previous studies show same results [24].

#### 3.7.3. Effect of pH

Figure (3.25) shows that the energy consumption increases as the solution pH increase (from acidic to basic). While, the aluminum consumption decrease as the solution's acidity decrease to reach its minimum value in the alkaline range (pH=10). Total cost of EC increases with the increase of pH which follows same trend as the energy consumption figure (3.26) [25].

#### 3.7.4. Effect of Initial Concentration

As the calcium and magnesium concentration in the solution increased to 1000 ppm, the consumption of the electrode did not increase as much, but the calcium and magnesium removal efficiency has taken place, because much floc formation helped to sweep away calcium and magnesium and there was no need for as much electrode consumption as before. The relationship between electrical energy consumption and the concentration of calcium and magnesium are presented in figure (3.27). However, It can be concluded that total operating cost also decrease by increasing calcium and magnesium concentration as shown in the figure (3.28) [26].

#### 3.7.5. Effect of Agitation Speed

As seen in figure (3.29) as speed of stirrer increase energy consumption decrease only from 200 rpm to 250 rpm then starts to increase again while aluminum consumption decrease all along. Operating cost is seen in figure (3.30) to be the same as energy consumption following the same trend all along.

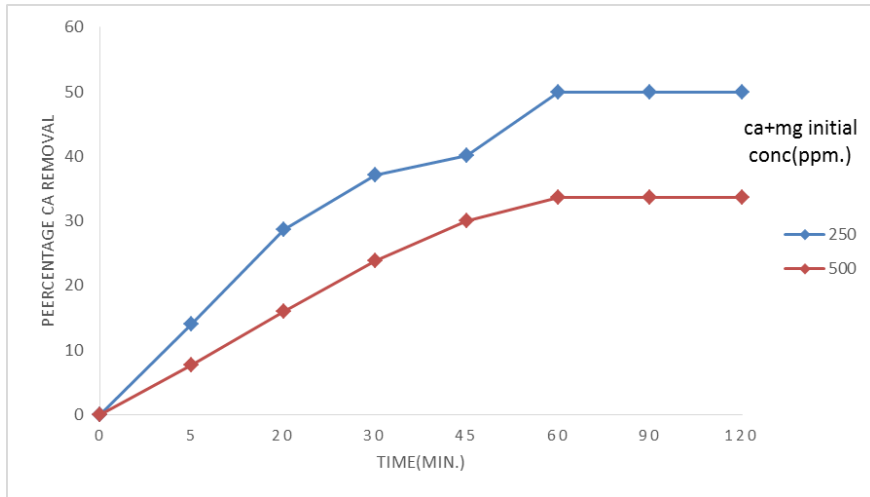


Fig. 3.1

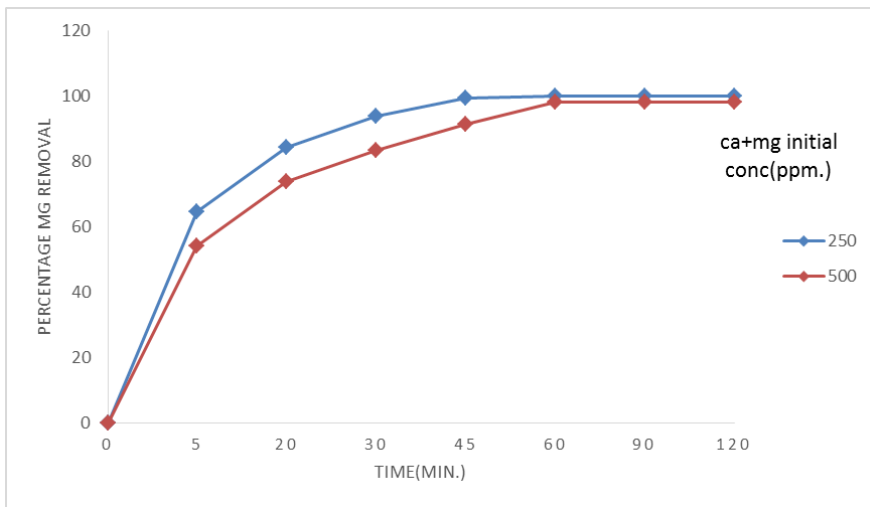


Fig. 3.2

Fig. 3.1 and Fig. 3.2: Effect of processing time on percentage removal of calcium and magnesium (Operating conditions: pH=7, NaCl concentration=1 g/L, Temperature=25°C and stirring velocity=200 rpm)

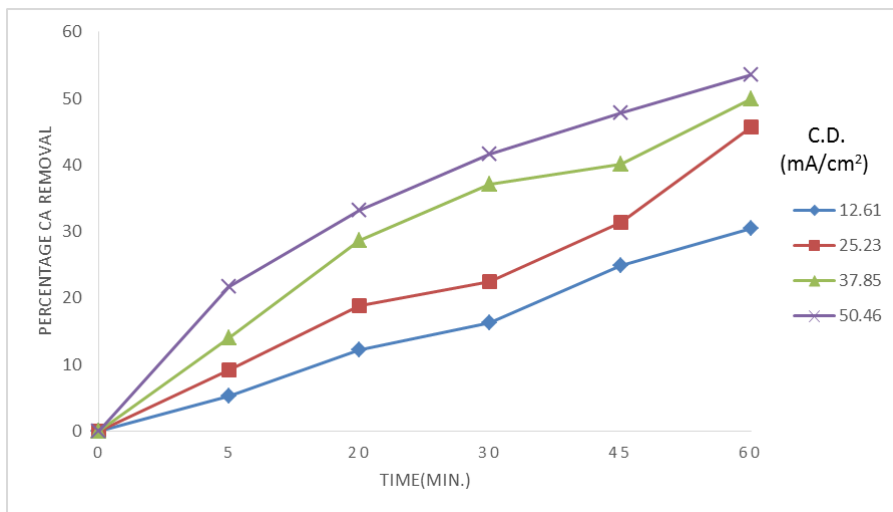


Fig. 3.3

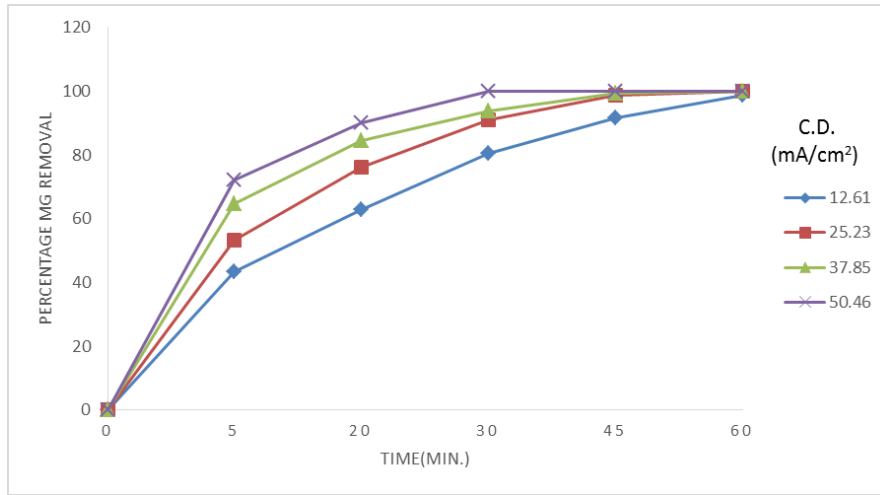


Fig. 3.4

Fig. 3.3 and Fig. 3.4: Effect of current density on percentage removal of calcium and magnesium (Operating conditions: C<sub>0</sub>=250 ppm (200ppm of Calcium and 50 ppm of Magnesium), pH=7, NaCl concentration=1g/L, Temperature=25°C and stirring velocity=200 rpm)

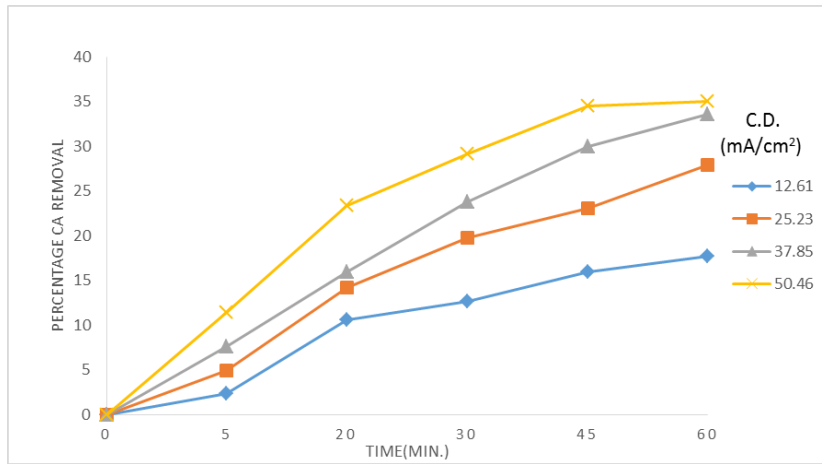


Fig. 3.5

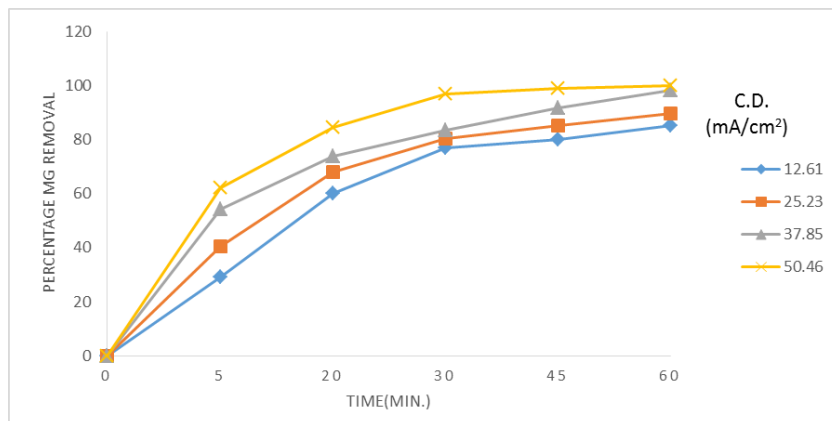


Fig. 3.6

Fig. 3.5 and Fig. 3.6: Effect of current density on percentage removal of calcium and magnesium (Operating conditions: C<sub>0</sub>=500 ppm (400 ppm of Calcium and 100 ppm of Magnesium), pH=7, NaCl concentration=1g/L, Temperature=25°C and stirring velocity=200 rpm)

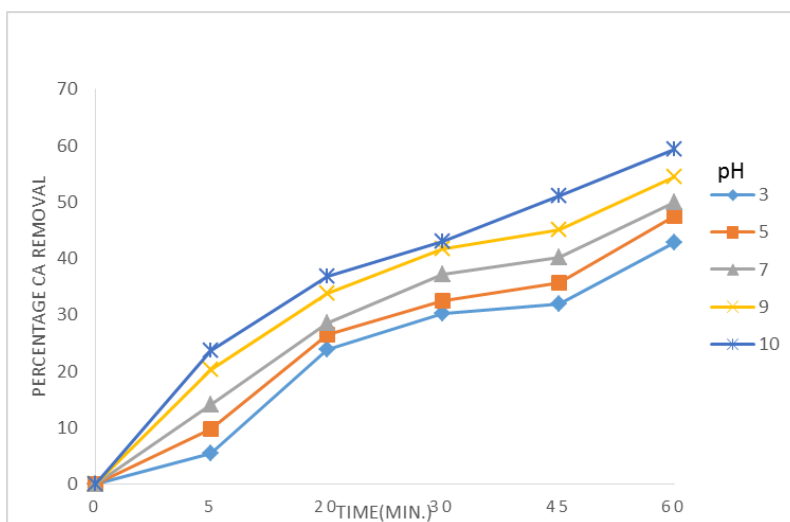


Fig. 3.7

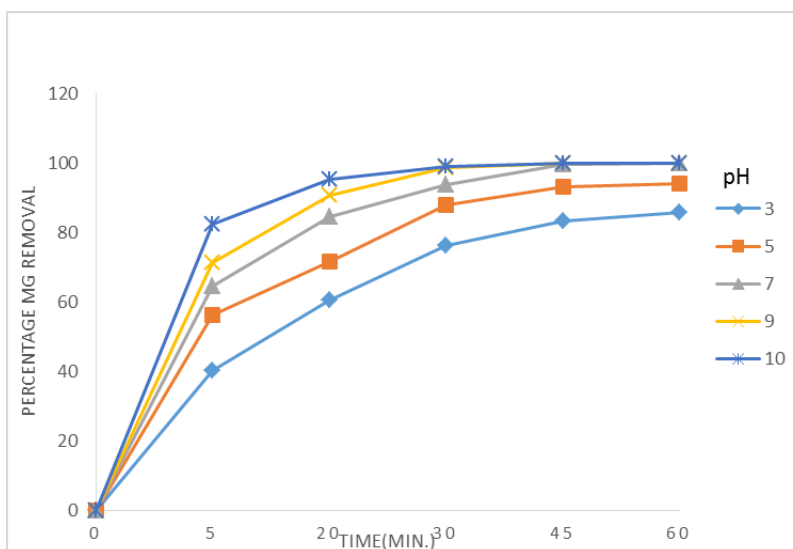


Fig. 3.8

Fig. 3.7 and Fig. 3.8: Effect of pH on percentage removal of calcium and magnesium (Operating conditions:  $C_o=250$  ppm (200 ppm of Calcium and 50 ppm of Magnesium), current density= $37.85$  mA/cm<sup>2</sup>, NaCl concentration= $1$ g/L, Temperature= $25^\circ$ C and stirring velocity= $200$  rpm)

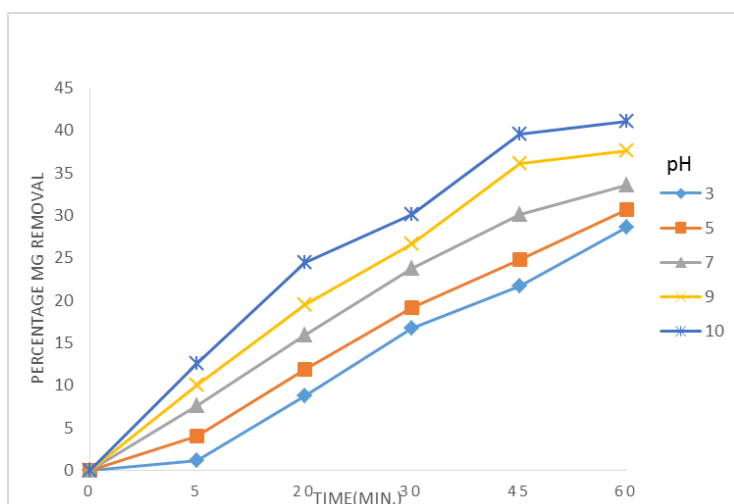


Fig. 3.9



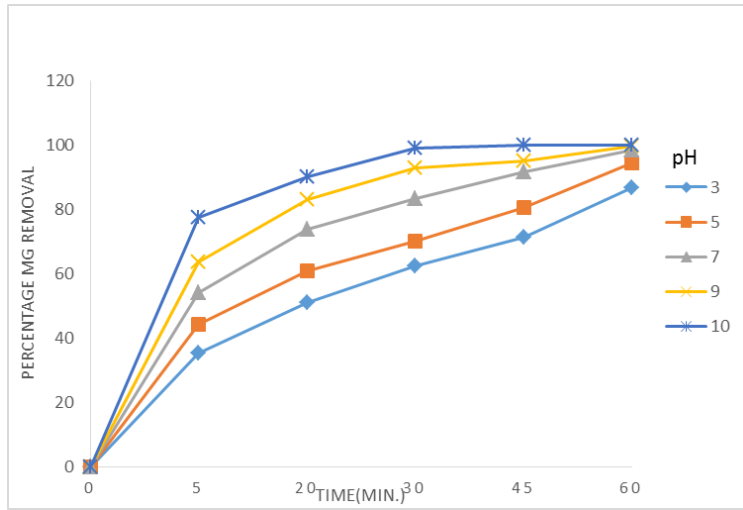


Fig. 3.10

Fig. 3.9 and Fig. 3.10: Effect of pH on percentage removal of calcium and magnesium (Operating conditions:  $C_o=500$  ppm (400 ppm of Calcium and 100 ppm of Magnesium), current density= $37.85$  mA/cm<sup>2</sup>, NaCl concentration= $1$ g/L, Temperature= $25^\circ$ C and stirring velocity= $200$  rpm)

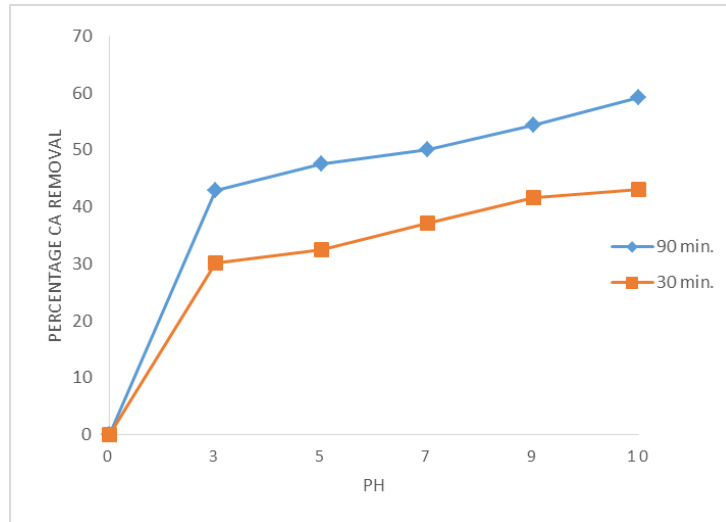


Fig. 3.11

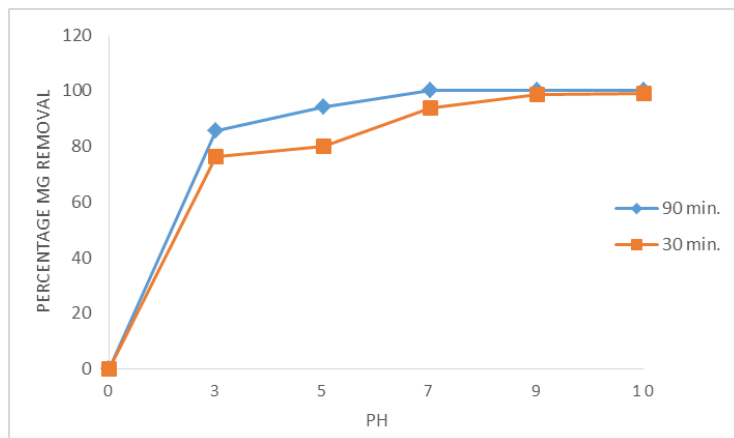
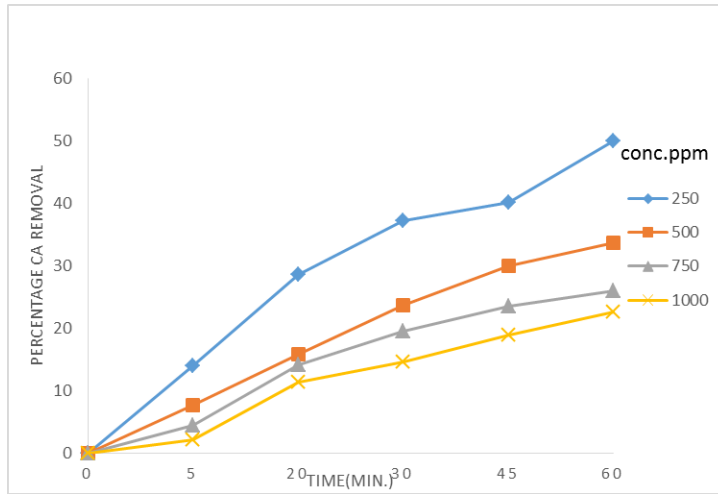
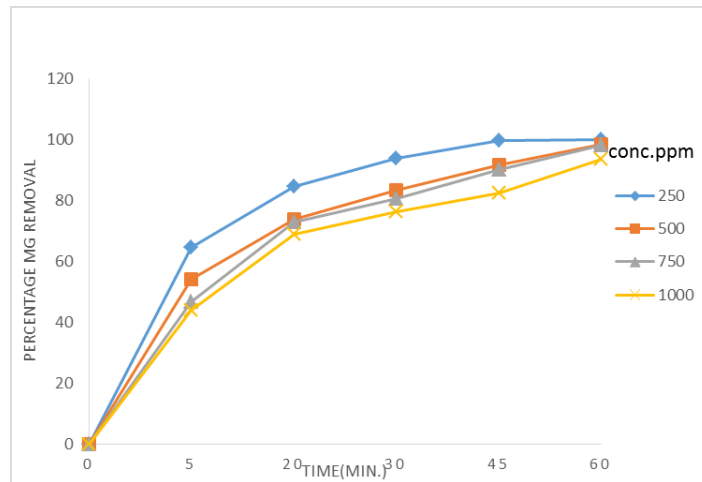


Fig. 3.12

**Fig. 3.11 and Fig. 3.12: Effect of pH on percentage removal of hardness (Operating conditions:  $C_0=250$  ppm (200 ppm of Calcium and 50 ppm of Magnesium), current density= $31.91 \text{ mA/cm}^2$ , NaCl concentration= $1 \text{ mg/L}$ , Temperature= $25^\circ\text{C}$  and stirring velocity= $200 \text{ rpm}$ )**

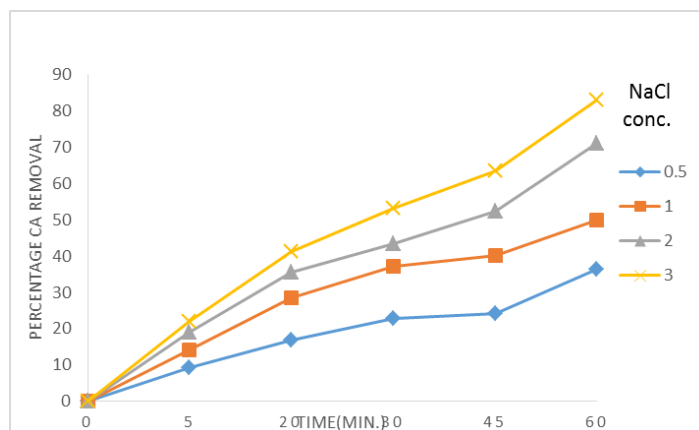


**Fig. 3.13**



**Fig. 3.14**

**Fig. 3.13 and Fig. 3.14: Effect of initial calcium and magnesium concentration on percentage removal of calcium and magnesium (Operating conditions:  $\text{pH}=7$ , Current density= $37.85 \text{ mA/cm}^2$ , NaCl concentration= $1 \text{ g/L}$ . Temperature= $25^\circ\text{C}$  and stirring velocity= $200 \text{ rpm}$ )**



**Fig. 3.15**

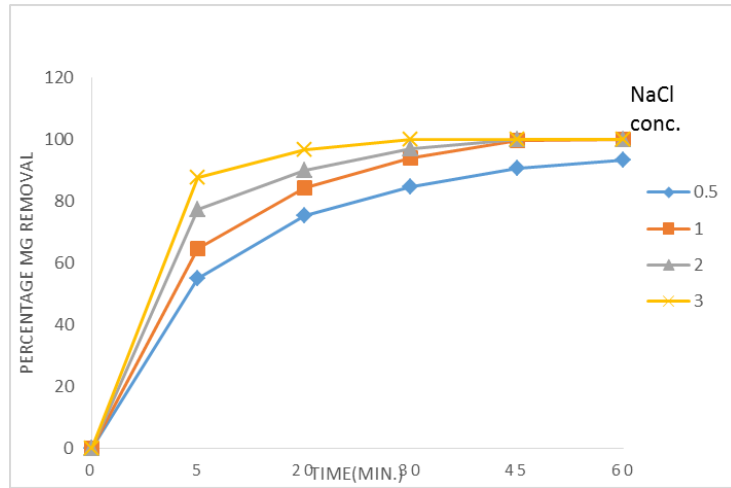


Fig. 3.16

Fig. 3.15 and fig. 3.16: Effect of NaCl concentration on percentage removal of hardness (operating conditions:  $C_0=250$  ppm (200 ppm of Calcium and 50 ppm of Magnesium), pH=7, current density=37.85 mA/cm<sup>2</sup> and Temperature=25°C)

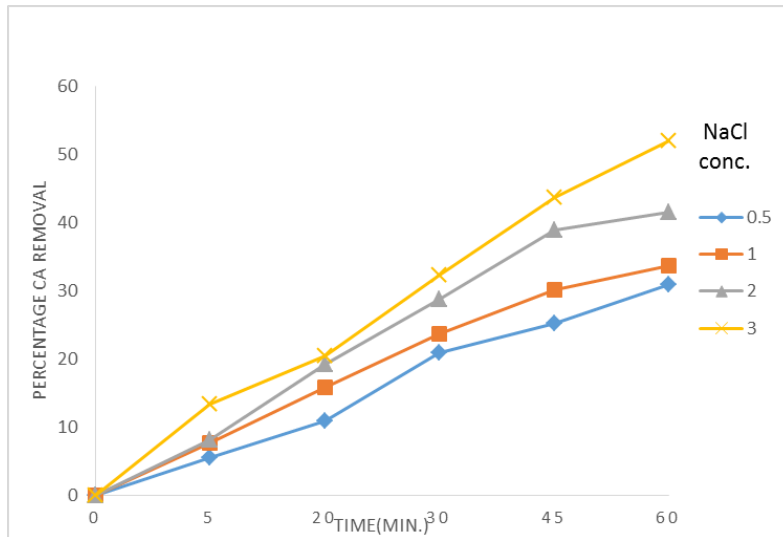


Fig. 3.17

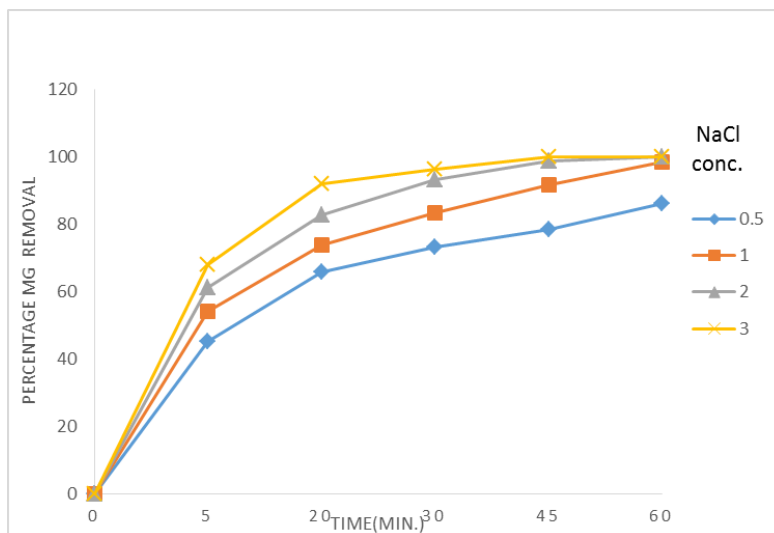
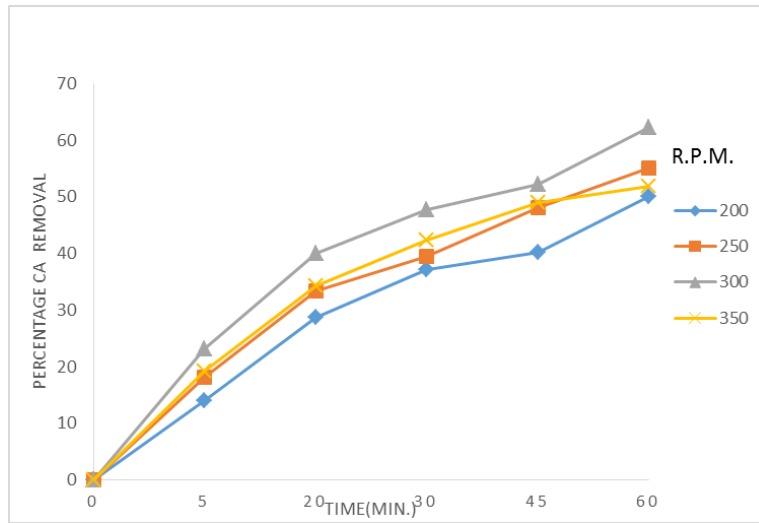
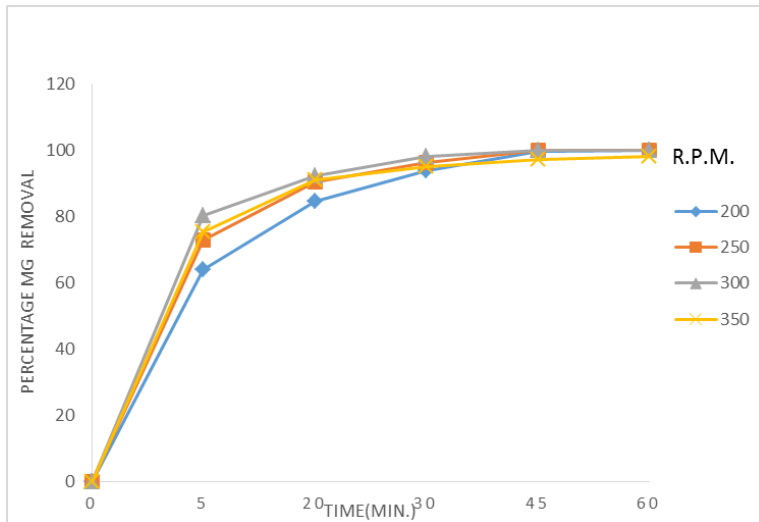


Fig. 3.18

**Fig. 3.17 and Fig. 3.18: Effect of NaCl concentration on percentage removal of hardness (Operating conditions:  $C_0=500$  ppm (400 ppm of Calcium and 100 ppm of Magnesium), pH=7, current density=37.85 mA/cm<sup>2</sup> and Temperature=25°C)**

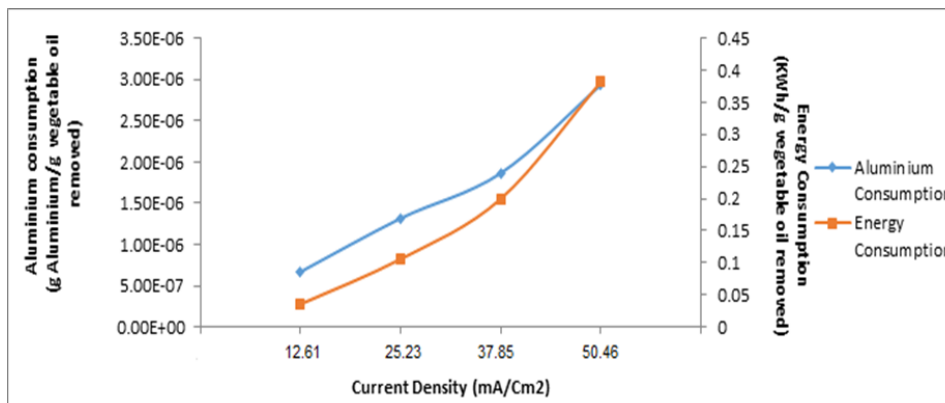


**Fig. 3.19**

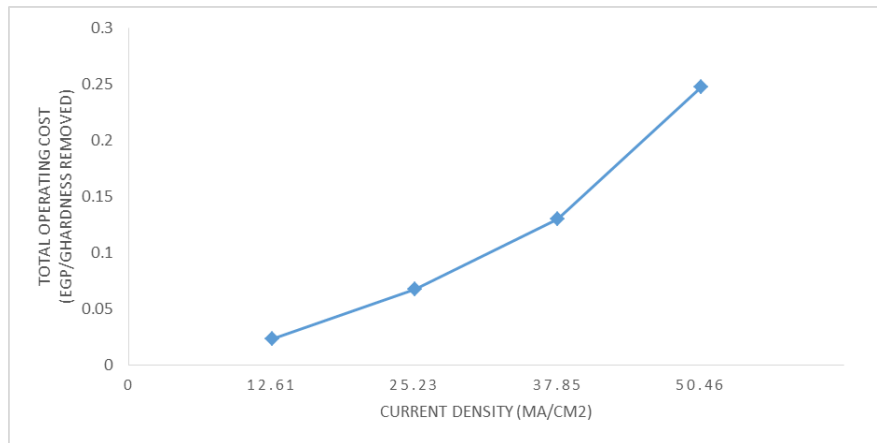


**Fig. 3.20**

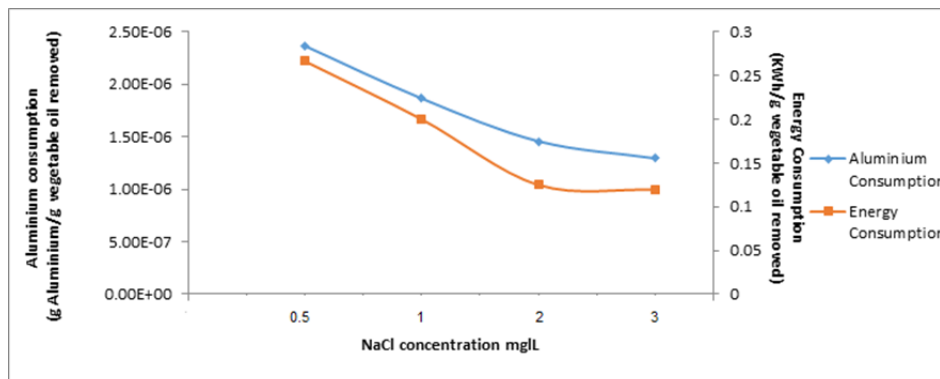
**Fig. 3.19 and Fig. 3.20: Effect of stirrer velocity on percentage removal of calcium and magnesium (Operating conditions:  $C_0=250$  ppm (200 ppm of Calcium and 50 ppm of Magnesium, pH=7, current density=39.91 mA/cm<sup>2</sup> and Temperature=25°C)**



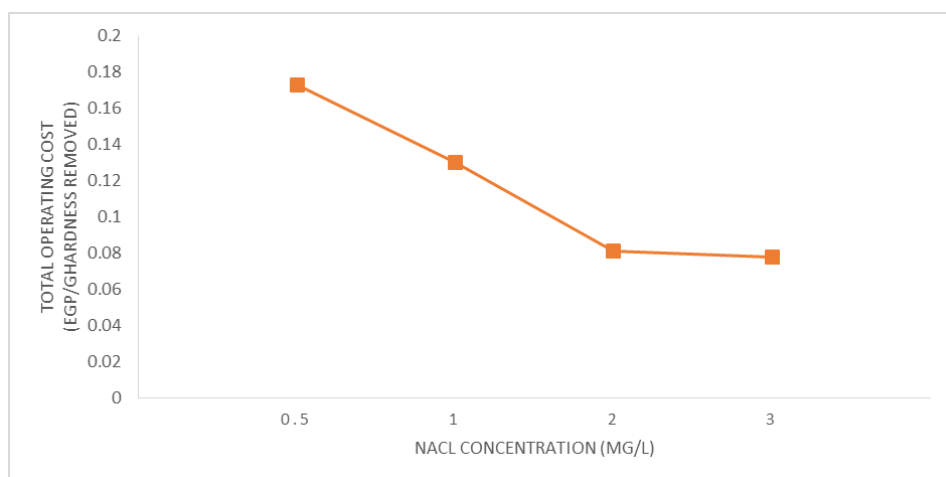
**Fig. 3.21: Effect of current density on energy consumption and aluminum consumption (Operating conditions:  $C_0=250$  ppm (200 ppm of Calcium and 50 ppm of Magnesium), pH=7, NaCl concentration=1 g/L, Temperature=25°C and stirring velocity=200 rpm)**



**Fig. 3.22: Effect of current density on total operating cost (Operating conditions:  $C_0=250$  ppm (200 ppm of Calcium and 50 ppm of Magnesium, pH=7, NaCl concentration=1g/L, Temperature=25°C and stirring velocity=200 rpm)**



**Fig. 3.23: Effect of electrolyte concentration on energy consumption and aluminum consumption (Operating conditions:  $C_0=250$  ppm (200 ppm of Calcium and 50 ppm of Magnesium), pH=7, current density=37.85 mA/cm<sup>2</sup>, Temperature =25°C and stirring velocity=200 rpm)**



**Fig. 3.24: Effect of NaCl concentration on total operating cost (Operating conditions:  $C_0=250$  ppm (200 ppm of Calcium and 50 ppm of Magnesium), pH=7, current density=37.85 mA/cm<sup>2</sup>, NaCl concentration=1 g/L, Temperature=25°C and stirring velocity=200 rpm)**

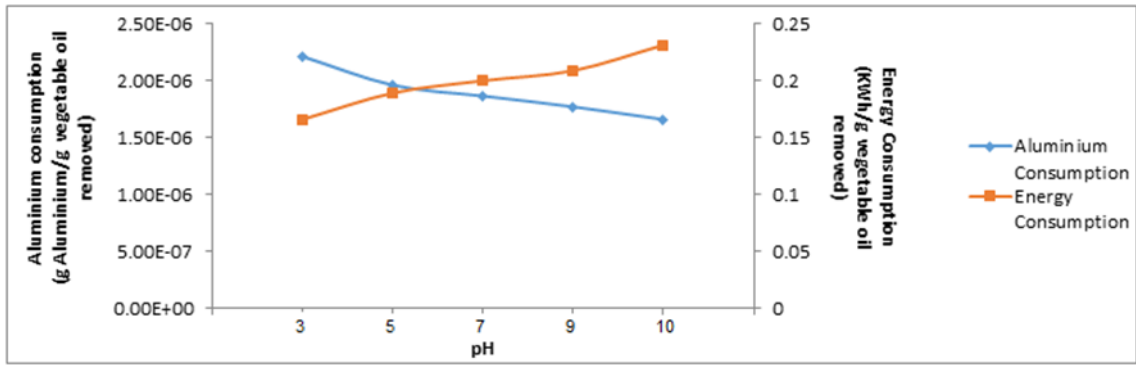


Fig. 3.25: Effect of pH on energy consumption and aluminum consumption (Operating conditions:  $C_0=250$  ppm (200 ppm of Calcium and 50 ppm of Magnesium), current density= $37.85 \text{ mA/cm}^2$ , NaCl concentration= $1 \text{ g/L}$ , Temperature= $25^\circ\text{C}$  and stirring velocity= $200 \text{ rpm}$ )

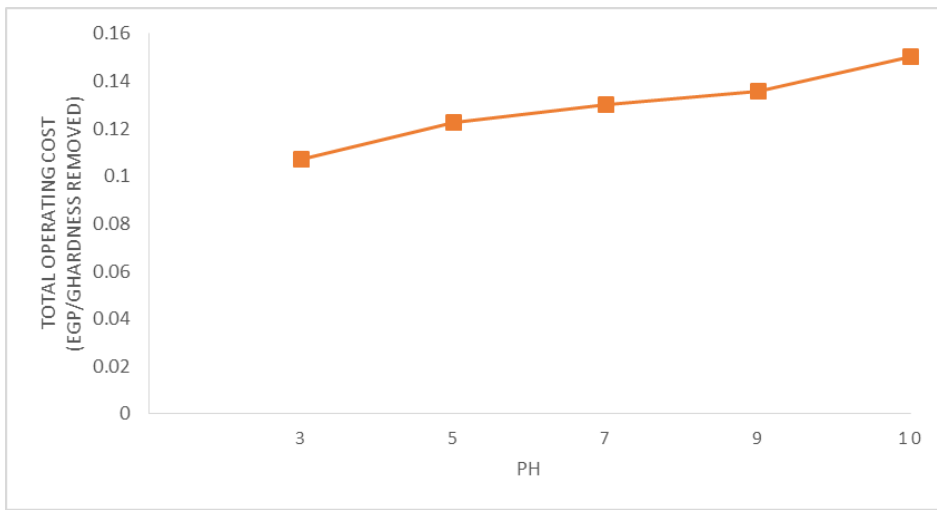


Fig. 3.26: Effect of pH on total operating cost (Operating conditions:  $C_0=250$  ppm (200 ppm of Calcium and 50 ppm of Magnesium), current density= $37.85 \text{ mA/cm}^2$ , NaCl concentration= $1 \text{ g/L}$ , Temperature= $25^\circ\text{C}$  and stirring velocity= $200 \text{ rpm}$ )

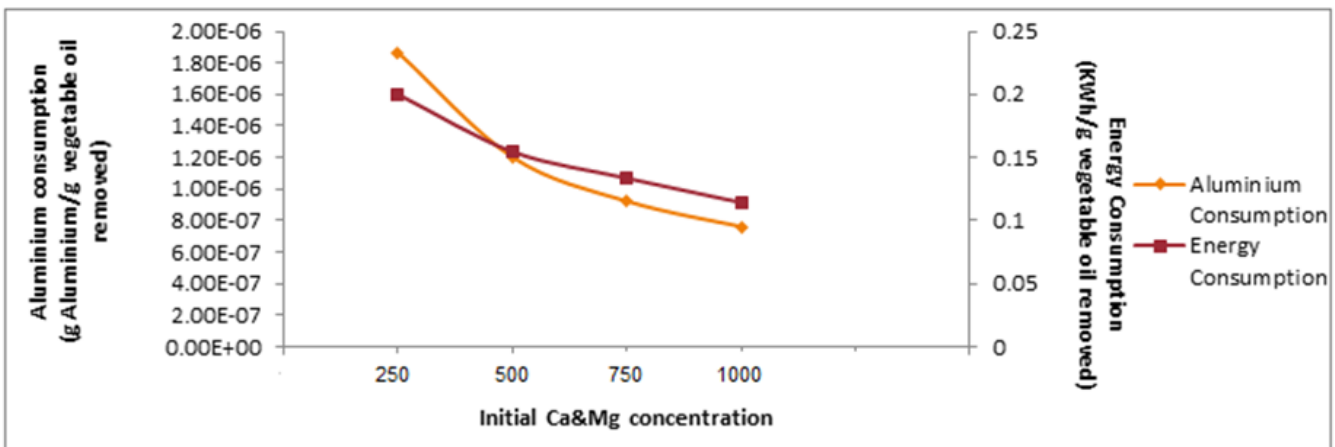


Fig. 3.27: Effect of initial Calcium and Magnesium on energy consumption and aluminum consumption (Operating conditions: pH= $7$ , current density= $37.85 \text{ mA/cm}^2$ , NaCl concentration= $1 \text{ g/L}$ , Temperature= $25^\circ\text{C}$  and stirring velocity= $200 \text{ rpm}$ )

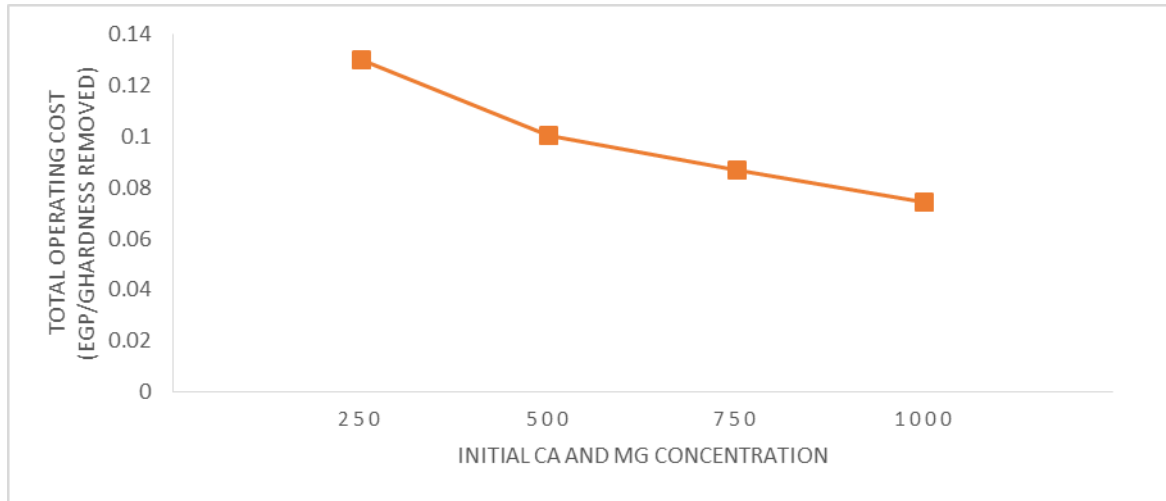


Fig. 3.28 Effect of initial Calcium and Magnesium concentration on total operating cost (Operating conditions: pH=7, current density=37.85 mA/cm<sup>2</sup>, NaCl concentration=1 g/L, Temperature=25°C and stirring velocity=200 rpm)

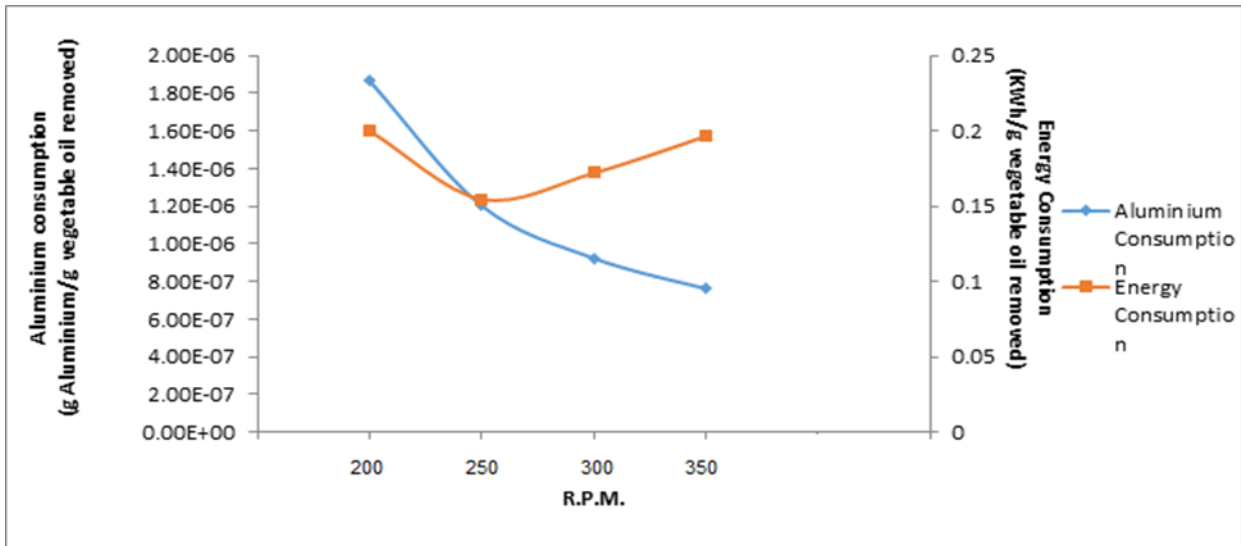


Fig. 3.29: Effect of speed of stirrer on energy consumption and aluminum consumption (Operating conditions: C<sub>0</sub>=250 ppm (200 ppm of Calcium and 50 ppm of Magnesium), pH=7, current density=37.85 mA/cm<sup>2</sup>, NaCl concentration=1 g/L and Temperature=25°C)

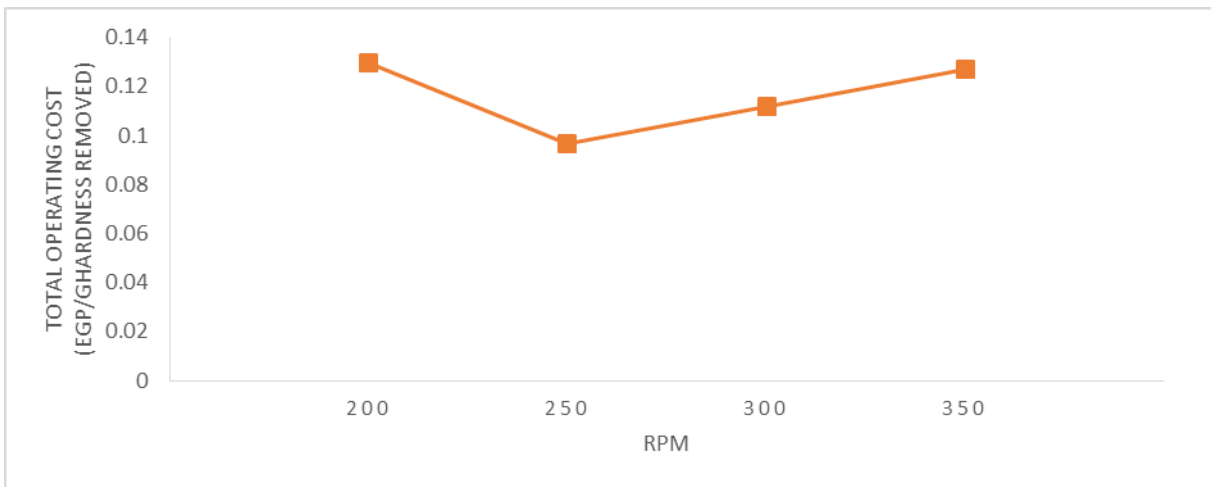


Fig. 3.30: Effect of speed of stirrer on total operating cost (Operating conditions: C<sub>0</sub>=250 ppm (200 ppm of Calcium and 50 ppm of Magnesium), pH=7, current density=37.85 mA/cm<sup>2</sup>, NaCl concentration=1 g/L and Temperature=25°C)

#### 4. Conclusions

Electrochemical treatment can be characterized as a process that uses simple tools and equipment, short retention time and simple operation. These characteristics help to decrease the costs of operation in scalable applications. The electrocoagulation (EC) process has been center of attention as compared to other approaches which use electrochemical technology and is now considered one of the widely used techniques for treatment of hard water.

The effects of different parameters including electrolysis time, initial calcium and magnesium concentration, initial solution pH, NaCl as an electrolyte concentration and stirrer velocity were evaluated. The study found that the percentage removal increase with increasing electrolysis time until an approximately constant removal has been reached after 60 minutes and then time has no significance. The percentage removal increase with increasing the applied current density as it reached 53.53% calcium removed and 100% magnesium removed at 50.56 mA/cm<sup>2</sup>. The effect of initial solution pH was the maximum in the alkaline range to reach 59.3% calcium removed and 100% magnesium removed at pH equals to 10. In addition, it was found that the calcium and magnesium removal percentage decreased with increasing initial calcium and magnesium concentration to reach 22.5% calcium removed and 93.44% magnesium removed at 1000 ppm (800 ppm of Calcium and 200 ppm of Magnesium) more over increasing NaCl concentration increased the removal percentage to reach 83.18% Calcium removed and 100% Magnesium removed when adding 3g of NaCl/L and finally, increasing stirrer velocity increase removal percentage until optimum stirrer velocity 300 rpm then starts to decrease at 350 rpm.

Calculations showed that by increasing the current density, both Aluminum and power consumption increased. As opposed to, by increasing the NaCl concentration both Aluminum and energy consumption decreased. Increasing the initial solution pH increased the total operating cost. While, increasing the initial solution concentration decrease the total operating cost.

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