Full Paper

EVALUATION OF AN ELECTROCHEMICAL METHOD OF COAGULATION FOR SURFACE WATER TREATMENT

K.T. Oladepo
Department of Civil Engineering
Obafemi Awolowo University, Ile-Ife, Nigeria
koladepo@oauife.edu.ng

I.A. Oke
Department of Civil Engineering
Obafemi Awolowo University, Ile-Ife, Nigeria

M.O. Ogedengbe
Department of Civil Engineering
Obafemi Awolowo University, Ile-Ife, Nigeria.

ABSTRACT

An electrochemical reactor was developed for the treatment of raw surface water. The reactor was made up of three stainless steel cathodes interspersed with two aluminium anodes connected in parallel using a monopolar configuration. Treatment performance was assessed in terms of changes in turbidity, pH, electrical conductivity, chloride and sulphate ions, and operational cost. For the purpose of comparison, the raw water was chemically coagulated with alum and performance evaluated. The water coagulated with alum was found to be acidic and had higher levels of turbidity, sulphate and chloride ions and conductivity than the water obtained from the electrochemical method. In term of the operational cost, the electrochemical technique was found to be much cheaper than chemical coagulation with alum. It was concluded from the overall results that the electrochemical technique performed better than the chemical coagulation method.

Keywords: *Chemical coagulation, conductivity, electrochemical method, filtration, monopolar electrodes, stainless steel*

1. INTRODUCTION

Water is an indispensable commodity. This is why it has been made an important component of the Millennium Development Goals (MDGs) set by the United Nations; to reduce by half the number of people without access to safe drinking water by 2015. In many developing countries, there have been challenges in the prospect of meeting this goal. For instance, in Nigeria, it was reported that water supply coverage in the urban area was 50%, small towns 20% and rural areas 10% (FMWR, 2000). The declining level of access to safe water in urban and semi-urban areas of Nigeria was reported by Fellows et al. (2003). Despite Nigeria's involvement in a wide variety of global efforts and initiatives aimed at addressing the problem with low access to safe water, the situation has continued to exacerbate. It was also reported that less than half of the population (44%) had access to improved sanitation facilities (UNICEF, 2007). On a global scale, lack of access to safe water is responsible for 4 billion cases of diarrhea each year and this results in the deaths of 1.7 billion people, most of whom are children under the age of five years. In Nigeria, diarrhea is the second largest killer of children and is the cause of 17 percent of deaths of children under the age of five. This is traceable to unsafe water and poor hygiene.

The main goal of drinking water treatment is to provide potable and aesthetically pleasing water through conventional and non-conventional treatment processes. A conventional filtration plant employs aeration, rapid mixing, flocculation, sedimentation, filtration and disinfection to remove turbidity, colour, taste and odour, and bacteria (Davis and Cornwell, 1998). The raw water from a lake or a reservoir is passed into the aeration unit (usually with the aid of low-lift pumps) where it is exposed to the atmosphere thereby stripping it of dissolved gases (such as carbon dioxide, methane, and hydrogen sulphide) and adding oxygen. At the coagulation unit, the coagulant is added to the incoming water and mixed rapidly with it so as to ensure dissolution and dispersion through the water. The coagulant reacts with the impurities (colloidal particles) in the water and forms precipitates (called flocs) that are slowly brought into contact with one another at the flocculation unit. During flocculation, the flocs collide with one another and agglomerate to form bigger particles that are removed by gravity in the sedimentation tank (clarifier). The water is then passed through the filter, which marks the final particulate removal step. The filtrate is disinfected by the addition of chemicals such as chlorine (gas or solid) to kill or reduce the number of pathogenic organisms. The disinfected water is then passed into the storage tank (clear well) where it is distributed (through high-lift pumps) to the targeted community.

The coagulant of choice in most treatment plants is aluminium sulphate (alum). The cost of achieving a desired level of treatment in a conventional treatment plant depends, among other things, on the cost of chemicals, alum being one of these. In many developing countries, alum is expensive because it often has to be imported in hard currency. Added to this is the instability of the economy of those nations that makes prices of commodities to be unstable and sometimes prohibitive. In the face of dwindling resources, this phenomenon might result in the inability of the treatment authorities to acquire adequate chemicals for clean water production.

The water schemes in many developing countries are large-scale centralized conventional water treatment plants. This overcentralisation of a water supply system often results in the requirement of a large number of pipes, pumps and appurtenances to transport the water to the point of need. A typical example of this phenomenon is the Ede Water Supply Scheme that is providing

potable water for 13 of the 30 Local Government Areas of Osun State of Nigeria (Ojo et al., 2006; Ojo, 2011). It has a large number of high-capacity pipes, storage reservoirs and booster pumps to get the water to the required destination. Despite this source of water, there are many rural and semi-urban communities in the State that are still yearning for water supply. Many of them have ample surface water that could be treated to potable standard but because of the huge investment required for constructing a conventional treatment system they have continued to watch the water flowing away. Their case is just like the aphorism 'water water everywhere but there is none to drink'.

An alternative to chemical coagulation with alum is the use of electrochemical methods that employ electrons for water treatment instead of chemicals. The electrocoagulation process involves the generation of metallic ions in the water being treated using the principle of electrolytic dissolution of aluminium or iron anode while hydrogen gas is evolved at the cathode. This process leads to the formation of a range of coagulant species and metal hydroxides that destabilize and aggregate the suspended particles or precipitates and adsorb dissolved contaminants. The cathode may be made of aluminium, iron, or stainless steel (Picard et al., 1999; Holt et al., 2002; Jiang et al., 2002a).

At the anode, the reaction is as follows:

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

At the cathode, water is reduced to produce hydrogen gas bubbles as follows:

$$2H_2O + 2e^{-} \rightarrow H_2 \uparrow + 2OH^{-} \quad (2)$$

The Al^{3+} (or Fe^{3+}) ions hydrolyse in water to form a hydroxide with the dominant species determined by the pH of the solution. Fig. 1 shows the nature of the electrocoagulation process.

Many authors (such as Vik et al., 1984; Pouet and Grasmick, 1995; Mollah et al., 2004; Ugurlu, 2004) have elaborated on the advantages of electrochemical methods over chemical dosing. These include the following: the amount of chemicals which have to be transported is lower, it is characterized by simplicity of equipment and ease of operation, it does not require chemical dosing equipment such as dosing pumps, the smallest colloidal particles have a greater probability of being removed because of the electric field that sets them in motion, and it produces a relatively low amount of sludge, and it is cost effective.

However, these stated advantages have not translated to use of the method in municipal water treatment plants the world over because the level of practical knowledge of the process is very limited. A lot of research is being conducted on the use of electrochemical method for water and wastewater; some of them are discussed below.

The application of electrochemical techniques to water and wastewater treatment dated back to the late 19th century. Based on the technology, Vik et al. (1984) reported the construction of water treatment plants in London and Salford (England) in 1889, and also the operation of sludge treatment plants in Santa Monica (California) and Oklahoma City in 1911. Though these plants were reported to have been abandoned in 1930 owing to high cost of operation, the technology has continued to enjoy patronage for both water and wastewater treatment. For example, Robinson (2001) has reported the development of an automated transportable electroflocculation based water treatment system that can be installed at building site. The equipment can be hauled to the site on a trailer or truck and placed on a prepared flat horizontal stable earth surface. The equipment has been used on various occasions to process building site water to remove the suspended solids down to a level satisfactory for discharge into the environment. Similarly,

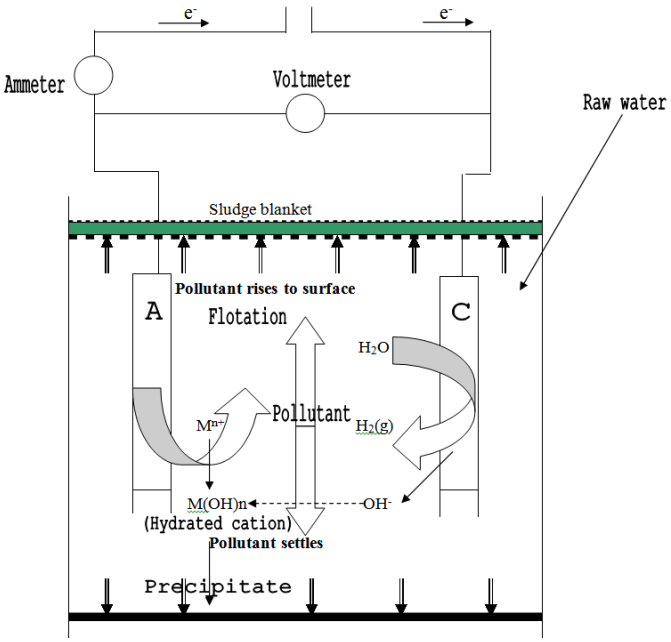

Figure 1: Schematic diagram of a two-electrode electrocoagulation cell (A – Anode, C – Cathode).

Source: Adapted from Holt et al. (2005) and Mollah et al. (2004)

Mollah et al. (2001) reported that the electrochemical technology has been used in the last decade for the treatment of industrial wastewater (containing metals) in South America and Europe, and that in North America it has been used to treat wastewater from pulp and paper industries, mining and metal-processing industries. Also,from literature, studies have been carried out on the use of the technique for the treatment of a wide variety of wastewaters such as paper mill effluent (Ugurlu, 2004), dairy wastewater (Sengil and Ozacar, 2006), poultry slaughterhouse wastewater (Kobya et al., 2006; Bayramoglu et al., 2006), textile wastewater (Gurses et al., 2002; Bayramoglu et al., 2004, 2007; Daneshvar et al., 2004; Can et al., 2006; Edwards et al., 2006; Kobya et al., 2003), tannery wastewater (Szpyrkowicz et al., 1995), olive mill wastewater (Khoufi et al., 2007), laundry wastewater (Ge et al., 2004), rose processing wastewater (Avsar et al., 2007), and urban wastewater (Pouet and Grasmick, 1995). Research works have also been reported on removal of fluoride from industrial wastewater (Shen, et al., 2003, Hu et al., 2005), removal of organic pollutants from industrial wastewater (Barrera-Diaz et al., 2008), boron removal from wastewater (Yilmaz et al., 2005), and separation of aqueous suspensions of ultrafine particles (Mattesson et al., 1995), and decolorization of a wide variety of dye solutions (Mollah et al., 2004; Daneshvar et al., 2004, 2006, 2007;Golder et al., 2005; Aleboyeh et al., 2007). The technique has also been applied to treat raw water for drinking purposes (Vik et al., 1984; Mameri et al., 1998; Mills, 2000; Jiang et al., 2002a, b; El-Masry et al., 2004).

Holt and co-workers worked more on the science behind the electrocoagulation process for the removal of suspended clay particles. Holt et al. (1999) pointed out that a systematic, holistic approach was required to understand electrocoagulation and its controlling parameters. Holt et al. (2001) identified three separate sets of processes which operate synergistically to remove pollutant: electrochemistry, coagulation, and flotation/entrainment. By using a 7.1-L reactor with five steel cathodes interspersed with four aluminium anodes, and monitoring the turbidity, pH, conductivity, total dissolved solids, salinity and temperature in the reactor, mass-balance studies and impact of current were investigated. Settling

and flotation were found to be the two key removal processes with the operating current defining which was the dominant mechanism. At high current, flotation was observed to be the dominant removal mechanism while settling dominated at low current. Holt et al. (2002) developed first-order differential equations to describe the pollutant's settling and flotation characteristics and rate constants were calculated for each of the characteristics. Holt et al. (2005) examined and identified a conceptual framework for electrocoagulation that focused on the interaction between electrochemistry, coagulation and flotation; provided a detailed experimental data from a batch reactor system which was removing suspended solids; and finally presented a mathematical analysis, based on the 'white water' model, for the dissolved air flotation process. The conclusion was that electrocoagulation has a future as a decentralized water treatment technology.

Oke (2007) reported the performance of an electrolyzing equipment and carbon-resin electrodes developed from locally sourced materials. The developed electrodes and equipment then used to run experiments to investigate the effectiveness of the electrochemical method for the treatment of synthetic wastewater and selected industrial wastewaters. Oladepo (2009)the performance of an electrochemical method developed for the treatment of a surface water sample while Oke et al. (2010) provided information on factors that influence electrochemical treatment processes.

The objectives of the study reported here are to develop an electrochemical system for treating surface water and evaluate the physico-chemical quality of the water treated with the system. Chemical dosing by using alum was also employed to treat the surface water with a view to comparing the two methods of treatment. The operation costs of the two methods were compared for cost estimation

2. Materials And Methods

The materials used for the electrochemical process in this study included plexiglass sheet, aluminium sheet, stainless steel sheet, laboratory grade sodium chloride (NaCl) and aluminium sulphate (alum), hydrated lime ($Ca(OH)_2$), distilled water, and raw water from Opa Waterworks*. The plexiglass sheet was used for constructing the electrocoagulation reactors while the aluminium and stainless steel sheets were used for making the electrode plates. For the filtration experiments, erosion sand and gravel were used as the filter media with a cylindrical Perspex column of diameter 90 mm and height 1500 mm used as the model filter.

The items of equipment that were used during the study were DC power supply units (Kingshill Electronic Products Ltd, Model T18V5C), spectrophotometer (M.R.C. Ltd, Model V-325XS), conductivity meter (DBK Instruments, Model 5008/3), magnetic stirrer (Jenway, Model 1103), pH meter (Extech Instruments, Model 407227), digital multimeter (Model DT-9201A), drying cabinet (Genlab Model), weighing balance (Mettler Toledo, PB153), one-horsepower pump (DAB Pumps, Model Jet102), and a half-horsepower pump (Atlas, Model QB60). The water used for the study was stored in plastic tanks of varying capacities. Six of the tanks were connected together with plastic pipes and the associated appurtenances such as valves, union connectors, elbows, etc.

The erosion sand was collected from the vicinity of the Religious Centre of Obafemi Awolowo University, Ile-Ife. The sand was washed thoroughly with detergent and rinsed until the washwater was clean. The washed sand was then air-dried. The portions of the sand passing 0.850 mm sieve and retained on the 0.425 mm sieve were extracted and stocked for the filtration experiments (Ogedengbe, 1984). Gravel for the underdrainage system of the model filter was obtained from the stock in the Structural Engineering Laboratory, washed thoroughly with detergent, and air-dried. Portions of the gravel passing 10.0 mm sieve and retained on the 5.0 mm sieve and portions passing the 5.0 mm sieve and retained on 3.35 mm sieve were extracted and stored for use.

The model filter was constructed from a 90 mm-diameter cylindrical Perspex column by sealing its bottom with a plastic plate. A centrally-placed hole was made in the plate and a 125-mm plastic pipe was screwed into this hole to serve as the effluent drain for the filter. Six headloss ports were made along the side of the column and a hole was cut near the top of the column to serve as an overflow port (to maintain a constant head when the filter was being operated). A 150 cm x 31.5 cm x 1.5 cm wooden board was constructed to hold the six manometer tubes which were connected to the headloss ports with flexible rubber tubing.

The treatment performance of the electrochemical process was evaluated by using the raw water obtained from the Opa Waterworks. The raw water was abstracted just before the water was discharged (from the low-lift pump) into the aeration unit; the water was stored in Tanks 2 and 3. The set-up shown in Plate 1 was used to supply raw water to the continuous-flow reactor (Plate 2 and Fig. 2). The reactor consisted of three stainless steel cathodes interspersed with two aluminium anodes connected in parallel using monopolar configuration (Fig. 2). The raw water was supplied to Tank 5 with the aid of the 1-hp pump (Pump 1) in the pipe network of Plate 3.2. In order to supply water to tank 5, valves 3 and 4 were closed while valves 2, 3, 5, 7, 8, and 9 were fully opened. Valve 6 was gradually opened to allow any entrained gases to be released. It was closed when the valve outlet was filled with water showing that the pump was primed. The pump was then started and valve 12 gradually opened until water flowed into Tank 5. Overflows from Tank 5 were returned to Tank 3 by opening valve 10 and closing valve 11.

In order to operate the continuous-flow reactor (Plate 2), valve 14 was closed while valve 13 was opened fully. Valve 27 was then used to set the flow rate at the desired level. The effluent from the continuous-flow process was collected in Tank 10. When tank 10 was filled up, it was left for one hour to allow the electrocoagulated water to settle. The supernatant was then siphoned into Tank 9. The transmittance, conductivity and pH of the settled water were measured and recorded.

The raw water from Opa Waterworks was also treated with alum. The coagulation jar tests conducted on the raw water indicated that the addition of lime was required for adequate treatment of the water sample. The jar tests involved filling six beakers with 500 mL of raw water. Different volumes of 10% stock solution of alum (5, 10, 20, 30, 40, and 50 mL) were added to the raw water. The water samples were stirred rapidly for two minutes using the magnetic stirrer. The samples were removed from the stirrer and allowed to settle for 30 minutes. At the end of quiescent settling, approximately 5 mL of supernatant were decanted from each beaker using a syringe. The transmittance of the supernatant was measured for each sample. For the lime additions, 0.5% stock solution of hydrated lime was used for the jar tests. Lime stock solutions of volumes 10, 15, and 20 mL were employed in the study. Six beakers were filled with 500 mL of raw water samples. Different volumes of the 10% stock solution of alum (5, 10, 20, 30, 40, and 50 mL) were added to the raw water. Then 10 mL of the 0.5% lime stock solution was added to each of the six beakers. The water samples were stirred rapidly for two minutes using the magnetic stirrer. Supernatants were decanted after 30 minutes quiescent settling and the transmittance of each sample was measured and recorded. The experiments were repeated for 15 mL and 20 mL of 0.5% lime stock

* The water treatment plant of Obafemi Awolowo University, Ile-Ife.

Plate 1: Pipe network for circulating water during the study

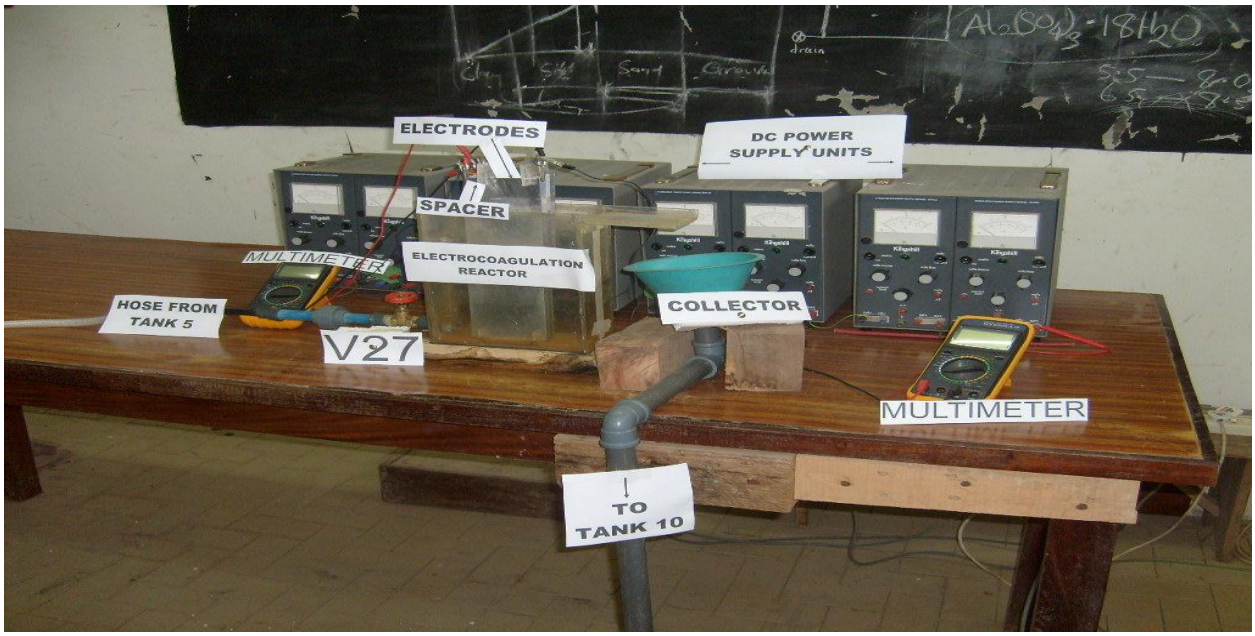

Plate 2: Laboratory set-up of the continuous-flow electrocoagulation process

solution. The quality of the water treated by each coagulation process was measured in terms of transmittance at 540 nm, pH, conductivity, sulphate and chloride contents.

The supernatant from the settled electrochemically treated water from the continuous-flow process was used as the influent into the model filter column. The filter column was charged with the media consisting of gravel and sand. This was achieved by first loosely dropping the coarse gravel (5.0 – 10.0 mm) to a depth of 10 cm and then the fine gravel (3.35 – 5.0 mm) to another 10 cm. This was followed by pouring the erosion sand (0.425 – 0.850 mm) to a depth of 60 cm. The filter column was then erected and the headloss ports were connected to the manometers with the aid of flexible rubber tubing. The filter was finally charged by backwashing with clean water to segregate the sand with the heaviest grains at the bottom and the lightest ones at the top. The set-up is as shown in Plate 3.

The filtration process was commenced by feeding the water to be filtered into Tank 1 (Plate 1). Then valves 1, 2, 3, 7, 8, 9 and 11 were closed. The priming valve (V6) was operated to ensure that the pump was ready. The pump was started and valve 12 was adjusted to control the flow of water into Tank 5. Valve 13 was then closed and valve 14 opened to allow water to flow into the filter. When the water started overflowing into Tank 6, the air bubbles in the manometers were removed. Valve 19 was opened to begin the filtration process and a stopwatch was simultaneously started. Valve 18 had been set to a predetermined level to maintain a rapid-rate filtration condition through the filter. The headloss was monitored

Plate 3: Laboratory set-up for the filtration experiment

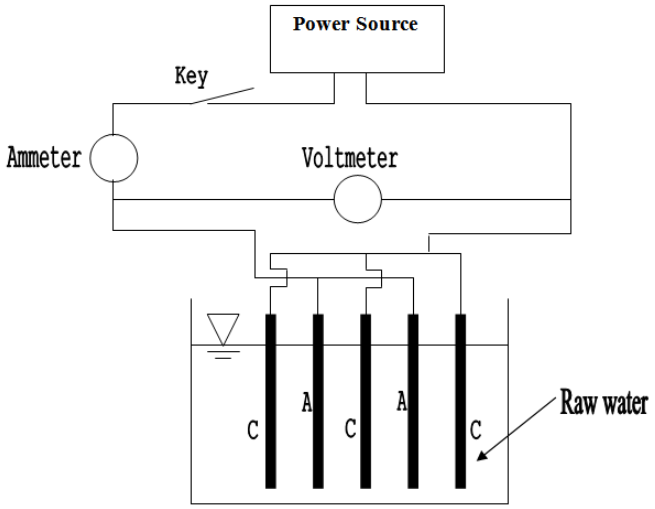

Figure 2: Schematic arrangement of the continuous-flow electrocoagulation process. (A – Anode, C – Cathode).

by recording the water levels in the manometers at intervals of 15 minutes during the filtration period. Filtration rate was also determined at the same time interval. The filter was operated in a declining-rate mode with the filtration process commenced at a high rate and allowed to decline with time. Filtration was stopped when the flow rate dropped below 65 L/min-m^2 (Hammer and Hammer, 1996). At the end of the filtration cycle, backwashing was carried out to clean the filter media and segregate the sand grains. For backwashing, valve 15 was opened fully while valve 26 (priming valve) was gradually opened to release any entrained air in Pump 2. Once the pump was primed, valves 18, 19, 20, 23, and 24 were closed while valves 21, 22 and 25 were fully opened. Pump 2 was started and valve 19 was gradually opened until the backwashing rate was sufficient to move the sand bed. The valve was opened until the bed was fluidized and the entrained materials were removed in the backwash water.

The raw water from Opa Waterworks was also treated with alum and allowed to settle for one hour. The supernatant was filtered through the sand bed by using the same procedures as described above for settled electrochemically treated water. Calibration curves were developed for the spectrophotometer so as to convert the measured transmittance readings to turbidity units (NTU).

3. Results And Discussion

The detention time for the continuous-flow reactor was 420 s while the average influent flow rate was 1.007 x 10^{-5} m^3s^{-1}. The total active aluminium plate area was 9.4 x 10^{-3} m^2. The applied current was maintained at 3 A, giving a current density of 319.149 Am^{-2}.

Table 1 shows the comparative performance of electrochemical coagulation and chemical coagulation with alum. The results showed that the performance of the electrochemical method was superior to conventional chemical coagulation method with alum in the treatment of raw water from Opa Waterworks. The higher conductivity of water treated with alum could be attributed to the presence of sulphate ions resulting from the reaction between alum and lime that were used during the coagulation process. On the other hand, in electrochemical coagulation, there was no need to add any chemical and hence, no increase in the ions concentration of the treated water; therefore no increase in conductivity. The alum-treated water was acidic because of the addition of alum which normally depresses the pH. There would be a need to raise the pH of such treated water by the addition of lime in order to prevent possible corrosive attack on conveyance and storage materials. The pH increase of electrochemically treated water could be attributed to the evolution of hydrogen at the cathode which, from Eq. 2, led to the production of OH^- ions in the solution.

Table 1: Some physico-chemical parameters of the water samples treated by using electrochemical method and alum dosing

Parameter	Raw Water	Electrochemically Treated Water	Alum Treated Water	WHO Standard
Turbidity (NTU)	80.4	4.7	7.8	≤ 5
pH	8.0	8.15	4.45	6.5 – 8.5
Conductivity (µS/cm)	200	180	860	≤ 1000
Cl^- (mg/L)	5.5	5.0	25.5	≤ 250
SO_4^{2-} (mg/L)	6.4	3.0	296.8	≤ 250

The variation of headloss with time during filtration of water coagulated by using electrochemical method and conventional chemical treatment with alum is presented in Tables 2 and 3 respectively. As expected, the headlosses increased with time during the filtration process. Though the starting filtration rate was set by the effluent valve and the setting was maintained throughout the period of filtration, it declined with time as shown in Tables 2 and 3. As filtration progressed, the flow rate declined because the size of the pores in the filter bed was decreased as the particulate materials which were removed clogged those pores. The rate of headloss development in the filtration of electrocoagulated water was very rapid compared to that of alum-treated water. The filtration of

electrochemically treated water reached the end of the cycle within six hours as the flow rate had reached the minimum level for rapid-rate filtration (65-195 L/min.m^2).

Table 2: Variation of filtration rate and headloss with time during filtration of water which was electrocoagulated

Time (min)	Flow Rate (L/min.m^2)	Headloss (mm H_2O) at depths of 10 cm	20 cm	30 cm	40 cm	50 cm	T_E (%)*
15	130.992	93	145	195	178	269	97.3
30	127.200	159	207	254	294	332	97.2
45	125.947	208	255	300	341	377	97.5
60	119.891	267	312	356	394	429	97.3
75	116.400	323	368	410	446	482	97.3
90	115.800	375	418	459	494	528	97.4
105	119.248	447	491	532	567	602	97.2
120	116.625	493	538	578	613	647	97.4
135	114.320	537	582	621	655	689	97.4
150	134.921	641	694	743	786	826	97.4
165	134.956	693	746	792	831	870	97.5
180	126.855	737	787	831	870	908	97.1
195	122.452	777	828	869	905	943	97.1
210	117.893	824	871	912	947	981	97.0
225	98.701	791	832	867	896	926	97.3
240	94.605	837	877	910	937	966	97.1
255	90.476	880	918	949	976	1003	97.2
270	86.667	919	955	985	1009	1035	97.2
285	82.127	958	993	1021	1044	1069	97.2
300	74.206	993	1024	1030	1074	1097	97.4
315	71.660	1032	1064	1091	1111	1136	97.4
330	67.994	1061	1287	1113	1133	1154	97.3
345	71.237	1099	1128	1149	1168	1184	97.4
360	64.410	1128	1157	1179	1207	1214	97.2

T_E = Transmittance of the filtrate

On the quality of the treated water, the transmittance of the effluent from the electrochemically treated water was 97.2% (or 3.0 NTU) at the end of six hours of filtration while the alum-treated water had a transmittance of 96.4% (or 4.4 NTU).

Based on the above results, the electrochemically treated water performed better than alum treated water in terms of quality of the filtered water.

The operating cost which was considered in the study included the cost of chemicals, electrodes and electrical energy. Since this is a laboratory-scale study, the costs of labour, maintenance, sludge handling, depreciation of equipment, and so on were not included in the computation of the operating cost. The unit costs were based on the following market prices:

i. Aluminium sulphate : ₦70.00/kg;
ii. Lime: ₦25.00/kg;
iii. Aluminium plate: ₦115.00/kg; and
iv. Electricity: ₦6.00/kWh.

For the electrochemical process, the cell was run at an applied current of 3 A for a period of 10 h to produce a total of 360 L of treated water. The operating voltage of electrolysis was 21 V. The difference in weight of the aluminium plates at the end of the experiment was 31.020 g. Therefore, the cost of producing 1 m^3 of water using the electrochemical process was computed as follows:

Table 3: Variation of filtration rate and headloss with time during filtration of water which was coagulated with alum.

Time (min)	Flow Rate (L/min.m^2)	Headloss (mm H_2O) at depths of 10 cm	20 cm	30 cm	40 cm	50 cm	T_E (%)*
15	121.643	95	143	183	219	254	97.2
30	120.915	97	149	195	232	267	97.2
45	121.004	99	152	201	242	280	97.0
60	121.683	100	155	205	249	289	97.1
75	121.597	990	153	205	251	293	97.0
90	119.939	102	156	207	254	298	97.0
105	119.311	103	158	210	256	301	97.0
120	119.531	107	162	213	261	306	96.9
135	114.440	110	166	217	266	312	97.0
150	116.792	114	169	221	270	316	97.0
165	116.103	124	179	229	276	322	96.9
180	112.138	138	194	246	295	339	96.9
195	113.107	147	202	255	305	351	97.0
210	114.274	158	214	267	316	364	96.6
225	113.723	169	226	279	328	376	96.9
240	112.045	175	231	284	334	381	96.6
255	110.958	193	249	304	354	402	96.6
270	110.309	206	263	318	369	418	96.6
285	109.244	223	281	336	387	437	96.5
300	110.914	241	299	356	407	457	96.5
315	108.085	257	320	377	429	479	96.4
330	107.131	279	338	396	447	498	96.5
345	105.883	301	360	417	469	520	96.4
360	106.103	319	380	437	490	540	96.4

T_E = Transmittance of the filtrate

Energy (1.75 kWh@₦6.00)	₦10.50
Aluminum plate	₦ 9.91
Total	₦20.41

For chemical coagulation using alum, 1 m^3 of water was produced by using 200 g lime and 1000 g alum. Hence, the total cost was ₦94.00.

Therefore, based on the laboratory experiments, the operating cost for chemical coagulation was 4.6 times more expensive than that of electrocoagulation. This result is in line with reports in literature such as Jiang et al. (2002 a;b) and Avsar et al. (2007).

4. CONCLUSION

An electrochemical system of coagulation was developed for a continuous-flow process. The results showed that the performance of the electrochemical method was superior to conventional chemical coagulation method with alum in the treatment of raw water. The water coagulated with alum was found to have higher levels of turbidity, sulphate ions and conductivity than the water obtained from the electrochemical method. When water produced from the two methods was filtered through an erosion-sand medium, the water from the electrochemical method exhibited better characteristics than water treated with alum. The effluent water turbidity after six hours of filtration was 3.0 NTU for electrochemically-treated water and 4.4 NTU for alum treated water. From the results of the laboratory experiments, In term of the

operation cost, the electrochemical technique was found to be much cheaper than chemical coagulation with alum.

REFERENCES

Aleboyeh, A., Daneshvar, N. and Kasiri, M. . "Optimization of C.I. Acid Red 14 azo dye removal by electrocoagulation batch process with response surface methodology". Chemical Engineering and Processing, doi:10.1016/j.cep.2007.01.033. 2007.

Avsar, Y., Kurt, U. and Gonullu, T.. "Comparison of classical chemical and electrochemical processes for treating rose processing wastewater". Journal of Hazardous Materials, doi:10.1016/j.jhazmat.2007.02.048. 2007.

Barrera-Diaz, C., Bilyeu, B., Roa-Morales, G. and Balderas-Hernandez, P. "A comparison of iron and aluminium electrodes in hydrogen peroxide-assisted electrocoagulation of organic pollutants". Environmental Engineering Science, 25(4):529-537, 2008.

Bayramoglu, M., Eyvaz, M. and Kobya, M. "Treatment of the textil wastewater by electrocoagulation – Economic evaluation". Chemical Engineering Journal, 128:155-161, 2007.

Bayramoglu, M., Kobya, M., Eyvaz, M. and Senturk, E. "Technical and economic analysis of electrocoagulation for the treatment of poultry slaughterhouse wastewater". Separation and Purification Technology, 51:404-408, 2006.

Bayramoglu, M., Kobya, M., Can, O.T. and Sozbir, M. "Operating cost analysis of electrocoagulation of textile dye wastewater". Separation and Purification Technology, 37(2):117-125, 2004.

Can, O.T., Kobya, M., Demirbas, E. and Bayramoglu, M. "Treatment of the textile wastewater by combined electrocoagulation". Chemosphere 62:181-187, 2006.

Chen, G. "Electrochemical technologies in wastewater treatment". Separation and Purification Technology, 38(1):11-41, 2004.

Daneshvar, N., Khataee, A.R., Ghadim, A. and Rasoulifard, M.H. "Decolorization of C.I. Yellow 23 solution by electrocoagulation process: Investigation of operational parameters and evaluation of specific electrical energy consumption (SEEC)". Journal of Hazardous Materials, doi:10.1016/ j.jhazmat.2007.03.028. 2007.

Daneshvar, N., Oladegaragoze, A. and Djafarzadeh, N. "Decolorization of basic dye solutions by electrocoagulation: An investigation of the effect of operational parameters". Journal of Hazardous Materials, B129:116-122, 2006.

Daneshvar, N., Sorkhabi, H.A. and Kasiri, M.B. "Decolorization of dye solution containing Acid Red 14 by electrocoagulation with a comparative investigation of different electrode connections". Journal of Hazardous Materials, B112:55-62, 2004.

Davis, M.L. and Cornwell, D.A. "Introduction to environmental engineering". 3rd ed. The McGraw-Hill Companies, Inc., New York, 1998.

Edwards, F.G., Fendley, D.L. and Lunsford, J.V. "Electrolytic treatment of an industrial wastewater from a hosiery plant". Water Environment Research, 78(4):435-441, 2006.

El-Masry, M.H., Sadek, O.M. and Mekhemer, W.K. "Purification of raw surface water using electro-coagulation method". Water, Air, and Soil Pollution, 158:373-385, 2004.

Fellows, W., Habila, O.N., Kida, H.M., Metibaiye, J., Mbonu, M.C. and Duret, M. "Reforming the Nigerian water and sanitation sector". Proceedings of the 29th WEDC International Conference, Abuja, Nigeria. Pp. 144-147, 2003.

FMWR. "National Policy on Water Supply and Sanitation", Federal Ministry of Water Resources, Abuja.

Ge, J., Qu, J., Lei, P. and Liu, H. "New bipolar electrocoagulation-electro-flotation process for the treatment of laundry wastewater". Separation and Purification Technology, 36:33-39, 2004.

Golder, A.K., Hridaya, N, Samanta, A.N. and Ray, S. "Electrocoagulation of methylene blue and eosin yellowish using mild steel electrodes". Journal of Hazardous Materials, B127:134-140, 2005.

Gürses, A., Yalçin, M. and Dogar, C. "Electrocoagulation of some reactive dyes: A statistical investigation of some electrochemical variables". Waste Management, 22(5):491-499, 2002.

Hammer, M.J. and Hammer, M.J., Jr. "Water and wastewater technology". 3rd ed. Prentice Hall, Englewood Cliffs, New Jersey, 1996.

Holt, P.K., Barton, G.W. and Mitchell, C.A. "Electrocoagulation as a wastewater treatment". The Third Annual Australian Environmental Engineering Research, M: 41-46, 1999.

Holt, P.K., Barton, G.W. and Mitchell, C.A. "The role of current in determining pollutant removal in batch electrocoagulation". 6th World Congress of Chemical Engineering, Melbourne, 2001.

Holt, P.K., Barton, G.W., Wark, M. and Mitchell, C.A. "A quantitative comparison between chemical dosing and electrocoagulation". Colloids and Surfaces A: Physicochemical and Engineering Aspects, 211(2-3): 233-248, 2002.

Holt, P.K., Barton, G.W. and Mitchell, C.A. "The future for electrocoagulation as a localized water treatment technology". Chemosphere, 59: 355–367, 2005.

Hu, C.Y., Lo, S.L., Kuan, W.H. and Lee, Y.D. "Removal of fluoride from semiconductor wastewater by electrocoagulation–flotation". Water Research, 39(5):895-901, 2005.

Jiang, J.Q., Graham, N.J.D., André, C.M., Kelsall, G.H. and Brandon, N.P. "Laboratory study of electro-coagulation-flotation for water treatment". Water Research, 36:4068-4082, 2002a.

Jiang, J.Q., Graham, N.J.D., André, C.M., Kelsall, G.H., Brandon, N.P. and Chipps, M.J. "Comparative performance of an electrocoagulation/flotation system with chemical coagulation/dissolved air flotation: a pilot-scale trial". Water Science and Technology: Water Supply, 2:289–297, 2002b.

Khoufi, S., Feki, F. and Sayadi, S. "Detoxification of olive mill wastewater by electrocoagulation and sedimentation processes". Journal of Hazardous Materials 142:58-67, 2007.

Kobya, M., Senturk, E. and Bayramoglu, M. "Treatment of poultry slaughter-house wastewaters by electrocoagulation". Journal of Hazardous Materials B133:172-176, 2006.

Kobya, M., Can, O.T. and Bayramoglu, M. "Treatment of textile wastewaters by electrocoagulation using iron and aluminium electrodes". Journal of Hazardous Materials B100:163-178, 2003.

Mameri, N., Yeddou, A.R., Lounici, H., Belhocine, D., Grib, H. and Bariou, B.
"Defluoridation of septentrional Sahara water of North Africa by electro-coagulation process using bipolar aluminium electrodes". Water Research, 32:1604-1612, 1998.

Matteson, M.J., Dobson, R.L., Glenn, R.W., Jr., Kukunoor, N.S., Waits, W.H., III and
Clayfield, E.J. "Electrocoagulation and separation of aqueous suspensions of ultrafine particles". Colloids and Surfaces A: Physicochemical and Engineering Aspects, 104(1):101-109, 1995.

Mills, D. "A new process of electrocoagulation". Journal AWWA, 92(6):34-43, 2000.

Mollah, M.Y.A., Morkovsky, P., Gomes, J.A.G., Kesmez, M., Parga, J. and Cocke, D.L. "Fundamentals, present and future perspectives of electrocoagulation". Journal of Hazardous Materials, 114(1-3):199-210, 2004.

Mollah, M.Y.A., Schennach, R., Parga, J.R. and Cocke, D.L. "Electro-coagulation (EC) — science and applications". Journal of Hazardous Materials, 84(1):29-41, 2001.

Ogedengbe, M.O. "Characterisation and specification of local sands for filters". Filtration and Separation, Sept./Oct., pp. 331-333, 1984.

Ogedengbe, M.O. "Nigeria's water-supply nightmare". Inaugural Lecture Series
No. 117, Obafemi Awolowo University Press Limited, Ile-Ife, Nigeria, 1997.

Ojo, O.E., Oladepo, K.T., Adewumi, I.K., Oke, I.A. and Ogedengbe, M.O.
"Characterisation of water supply in Osun State of Nigeria". Ife Journal of Technology, 15(1):27-37, 2006.

Ojo, O. "A Study of rural water supply demand situation in South west Nigeria". In: Water Resources Management VI, Brebbia, C.A. and Popov, V.(eds), WIT Transctions on Ecology and the Environment, WIT Press. www.wirpress.com, 2011.

Oke, I.A. "Development and performance-testing of an electrochemical treatment process for selected industrial wastewaters". Unpublished Ph.D. thesis, Department of Civil Engineering, Obafemi Awolowo University, Ile-Ife, 2007.

Oke , I.A., "Utilization of 2k factorial experiments for the determination of factors that influence electrochemical process". Ife Journal of Technology, 19(2):48-54, 2010.

Oladepo, K.T. "Development of an electrochemical method of coagulation for water treatment". Unpublished Ph.D. thesis, Department of Civil Engineering, Obafemi Awolowo University, Ile-Ife, 2009.

Picard, T., Cathaliffaud-Feullade, G., Mazet, M. and Vandensteendam, C.
"Cathodic dissolution in the electrocoagulation process using aluminium electrodes". J. Environ. Monit. 2: 77-80, 1999.

Pouet, M.-F. and Grasmick, A. "Urban wastewater treatment by electro-coagulation and flotation". Wat. Sci. Tech. 31:275-283, 1995.

Robinson, V. (2001). "The treatment of storm water runoff from building sites - Some case studies". http://www.electropure.com.au/techinfo/Stormwaterworkshop.html#top 10 March 2007.

Sengil, I.A. and Ozacar, M. "Treatment of dairy wastewaters by electro-
Coagulation using mild steel electrodes". Journal of Hazardous Materials B137:1197-1205, 2006.

Shen, F., Chen, X., Gao, P. and Chen, G. "Electrochemical removal of fluoride ions from industrial wastewater". Chemical Engineering Science, 58(3-6):987-993, 2003

Szpyrkowicz, L., Naumczyk, J. and Zilio-Grandi, F. "Electrochemical treatment of tannery wastewater using Ti/Pt and Ti/Pt/Ir electrodes". Water Research, 29(2):517-524, 1995.

Ugurlu, M. "The removal of some inorganic compounds from paper mill effluents by the electrocoagulation method". G.U. Journal of Science, 17:85-99, 2004.

UNICEF " Information Sheet-Water, Sanitation and Hygiene in Nigeria". United Nations Children Fund, Nigeria Country Programme, 2007.

Vik, E.A., Carlson, D.A., Eikum, A.S. and Gjessing, E.T. "Electrocoagulation of potable water". Water Research, 18(11):1355-1360, 1984.

Yilmaz, A.E., Boncukcuoglu, R., Kocakerim, M.M. and Keskinler, B. "The investigation of parameters affecting boron removal by electrocoagulation method". Journal of Hazardous Materials, B125:160-165, 2005.