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Cementation of lead from mono-metallic nitrate solution using a modest-agitated reactor.

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ABSTRACT

The cementation of lead from mono-metallic nitrate solution onto iron powder in a modest agitated reactor was investigated in this paper. The influence of several parameters such as initial Pb^{+2} ions concentration, initial pH of the solution, stirring speed, reaction temperature and mass of iron powder on lead removal were inspected. Analysis of lead cementation kinetics was also performed so as to elucidate the influence of each parameter on the apparent rate constant of the cementation reaction. Eventually, a correlation for predicting the rate constant was obtained by using statistical and least square multivariate regression technique. R^2 of the acquired correlation was 93 %.

Keywords: Heavy metals; Cementation; kinetics; Lead removal

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INTRODUCTION

As yet the lead has a number of significant uses in the current day such as manufacture of storage batteries, cables, solders and steel products, ammunition, shielding systems from radiation and X- rays, circuit boards in computers and electronic equipment, superconductor and optical technology, printing, paint and dying processes, photographic material, matches and explosives manufacturing. In spite of its wide use, it is one of the most polluting heavy metals (HMs). As it accumulates in the human body, it causes harmful effects such as anemia, brain damage, anorexia, malaise, loss of appetite, damage of liver, kidney, gastrointestinal, and mental retardation in children. Therefore, US-EPA dictated that the maximum contaminant limit of lead in water streams must be less than 0.006 mg/l [1]. Therefore, lead must be removed, as much as technically possible, from wastewater streams, before being disposed off, in order to avoid these toxic impacts.

There are numerous methods used to remove/recovery of lead from wastewaters streams such as chemical-precipitations, cementation, crystallization, solvent-extraction, flotation, ion-exchange, adsorption onto different adsorbents, reverse-osmosis, electro-dialysis, electro-winning and electro-deposition; a comprehensive review was given by Kurniawan et al. [2].

Cementation or metal substitution reaction is one of the most prevalent methods for removal/recovery of metallic ions from their solutions. It is an electro-chemical process by which a less active metal ion is deposited from solution by a more active metal in the electro-motive series. This process has been stratified in metallurgy and metal finishing industries to regain metals from waste streams [3, 4]. Cementation reactions are basically oxidation-reduction reactions that take place in solutions or melts [5, 6 and 7]. A cementation reaction can be depicted as

$$\mathbf{mN^{n+} + nM^{o} \longrightarrow mN^{o} + nM^{m+}} \qquad (1)$$

Where M is the more active metal (less noble) and m is its valence; and N is the less active metal (more noble) and m is its valence.

The cementation process has some advantages such as low energy utilization, simple control requirements, recovery of valuable high purity metals and Low cost process; as the precipitant metals (e. g. Fe or Zn) are not expensive. Some authors Panão et al. [8] reported that cementation suffers from some disadvantages such as lower cementation rates, utilization of expensive sacrificial metal when it is used in special geometric form, and the dissolution of the sacrificial metal into the solution especially at low pH values. Therefore, an important aspect of this process is the use of non-toxic precipitant metal.

The removal of lead from simulated solutions by cementation has been previously presented in some manuscripts. These manuscripts reveal that the process is affected by the following operating parameters: the initial pH (pH_o) of the treated solution, the initial concentration (C_o) of lead ions, solution temperature, agitator speed or solution flow rate, and mass of the used sacrificial metal.

Considering the effect of pH_o, Makhloufi et al. [9], Nosier and Sallam [5], Farahmand et al. [10], Valeriu G. G. et al. [11], Angelidis et al. [12] and Mona & Ahmed [13] did not study the effect of pH_o. Angelidis et al. [14] using iron disc reported that at low pH values (< 1.8) hydrogen evolution hinders the deposition of lead, at higher pH values (>2) iron is passivated by an adsorbed oxygen film and at pH values between 1.8 and 2 the cementation rate is a maximum. Abdollahi et al. [15] using aluminum powder adduced that increasing pH from 4 to 6 decreases the cementation efficiency and acquired this to the formation of lead and aluminum hydroxides on aluminum surface. In their paper, as well, the authors reported that at pH < 4 the lead recovery is reduced due to hydrogen evolution at aluminum surface.

For the effect of initial lead ion concentration (C_o) on lead cementation, Valeriu G. G. et al. [11] did not consider it. Angelidis et al. [12] reported that the lead removal and excess iron consumption are approximately independent of initial Pb^{2+} concentration. Angelidis et al. [14] and Makhloufi et al. [9] studied the effect of (C_o),only for solutions in which the initial concentration did not exceed 100 mg/L for all runs, and reported that cementation rate increases with increasing C_o and attributed this behavior to the increase of surface area of sacrificial metal as a result of deposited lead. Nosier & Sallam [5] reported that the cementation rate, expressed as solid–liquid mass transfer coefficient, increases with increasing C_o from 100 to 300 mg/l and attributed this to the change of lead deposit structure from fine-grained compact structure to a dendritic porous one.

The effect of flow rate was studied by Angelidis et al. [12], Angelidis et al. [14], Makhloufi et al. [9] and Mona & Ahmed [13]. Angelidis et al. [12] reported that the rate of cementation increased with increasing rotational speed up to 250 rpm and at 400 rpm the cementation rate decreased. The authors explained such a behavior by reporting that "at all stirring speeds, iron powder was not dispersed in the solution but coagulated at the depth of the vessel with metallic lead removed from solution. At high stirring speeds, small compact balls of iron powder and cemented lead were formed, so diffusion through the mass of the deposit became the rate controlling step, the kinetics of the reaction changed and the rate decreased". Angelidis et al. [14], Makhloufi et al. [9] and Mona & Ahmed [13] reported that the cementation of Pb^{2+} increased with increasing rotational speed. Abdollahi et al. [15] reported that maximum recovery was obtained at rotational speed of 100 rpm, at stirring speed < 100 the remained aluminum powders were surrounded by the precipitated lead particles that decreased the contact surface for the cementation reaction and at high stirring speed > 100 rpm dissolved oxygen lead to decrease in the cementation recovery. Some other authors, Angelidis et al. [16], Farahmand a et al. [10] and Valeriu G. G. et al. [11], did not investigate the effect of rotational speed on cementation of lead.

Considering the effect of temperature on lead cementation, several researches Angelidis et al. [12], Angelidis et al. [14], Makhloufi et al. [9], Nosier and Sallam [5], Farahmand a et al. [10], Mona and Ahmed [13] and Valeriu G. G. et al. [11] reported that the rate of removal of Pb^{2+} ions increased with increasing temperature. On the other hand, Abdollahi et al. [15] reported that increasing temperature lead to a small increase in lead recovery and attributed this to the increase in the diffusion of reduced metal across the formed film on oxidized metal surface.

For the effect of mass of the sacrificial metal used, Angelidis et al. [12], Valeriu G. G. et al. [11] and Farahmand a et al. [10] reported that the cementation efficiency increased while increasing the amount of sacrificial metal added to the solution. As the amount of sacrificial metal increased, its surface area increased which results in more contact with lead ions and increased removal efficiency.

In view of this abbreviated literature survey, there is a need to investigate the effects of the aforementioned parameters on lead removal/recovery from mono-metallic solution containing it.

The aim of this paper is to study the removal/recovery of lead from mono-metallic solution by cementation with iron powder. This aim will be accomplished by establishment of the following research objectives:

- Investigating the effect of various parameters such as pH_o, C_o, solution temperature, rotational speed and mass of iron metal on the cementation of lead.
- After concluding the experimental work, attention was directed towards the appreciation of cementation kinetics. This Multiple regression analysis method was exercised so as to obtain a correlation for predicting the apparent rate constants of lead cementation on iron.

EXPERIMENTAL WORK

1. Set up:

Figure (1) shows a schematic drawing of the experimental set up. The details of the set up are given elsewhere [17].

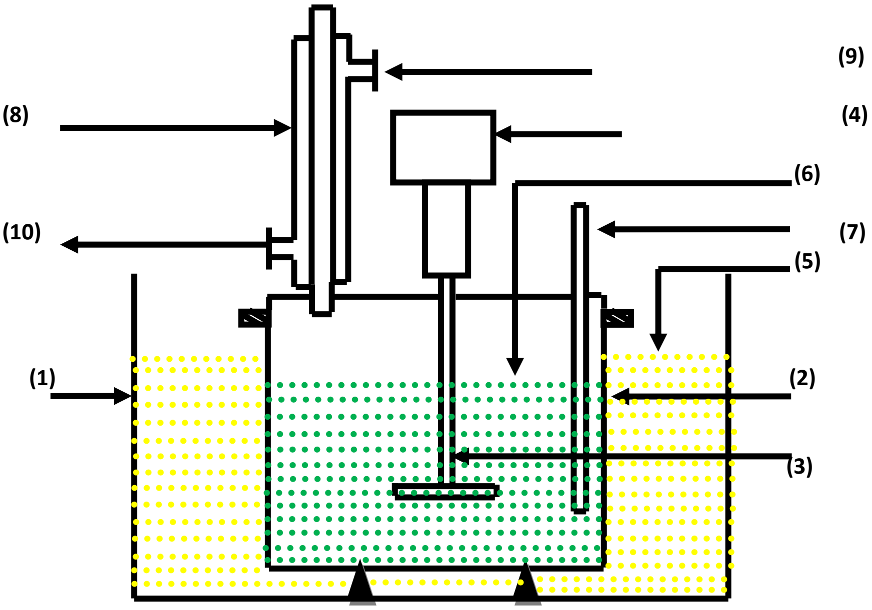

Figure (1) Experimental set up

1. Rectangular water bath	**6.** Electrolyte level
2. Cylindrical glass container	**7.** Thermometer
3. Agitator	**8.** Condenser
4. Variable speed motor	**9.** Input cooling water
5. Water level	**10.** Output water

MATERIALS

All materials used in the experimental work, listed in Table (1), are laboratory-grade and brought from El-Gomhouria Company for Trading Chemicals and Medical Appliances; Egypt.

Table 1: Chemicals used in the experimental work

Item No.	Species name	Chemical formula	Purity/ Concentration
1	Lead nitrate	$Pb(NO_3)_2$	98 %
2	Nitric acid	HNO_3	65 %
3	Sodium hydroxide Pellets	NaOH	98 %
4	Acetone	C_3H_6O	99 %
5	Iron powder & sheet	Fe	99 %
6	Zinc sheet	Zn	99.9 %

METHODOLOGY

Solution of a pre-specified Pb^{2+} concentration was prepared by dissolving the proper amount of lead nitrate in freshly distilled water. The initial pH of the solution was adjusted by adding drops of either (0.1 M) nitric acid or (0.1 M) sodium hydroxide solution. The pH was measured by using (JENWAY, 3505 pH meter of accuracy ± 0.02).

In each run 500 ml of the synthetic solution was placed in the cylindrical glass container (reactor). The temperature of the treated solution was adjusted to the required value. The agitator was, then switched on and its rpm was adjusted. Into the agitated solution a particular mass of the precipitant metal (iron powder) was added. At specified time intervals, samples were withdrawn by a pipette for measuring their pH. Two ml of the sample was then diluted with demineralized water and lead concentration was measured by atomic absorption spectrophotometer (Perkin Elmer 2280).

The removal of lead was studied under distinct factors in order to assess the ultimate convenient removal conditions. Table (2) shows all the studied parameters and their ranges. In else experiments zinc (sheet) and iron (sheet) were used in lieu of iron powder under the noticed convenient conditions; so as to appreciate the influence of altering the precipitant metal on removal of lead.

Table 2: Studied parameters and their ranges for lead removal

Parameter	values
Initial lead concentration (mg/l)	300-500-800
Rotational speed (rpm)	200-300-500-700
Temperature (C°)	30-40-50
pH	1.04-2-3-4.8
Mass of Fe (g)	0.75-1.5-2

RESULTS AND DISCUSION

1. Influence of distinct factors on the cementation of lead on iron powder

The cementation reaction between lead ions and metallic iron takes place according to the reaction:

$$\mathbf{Pb^{+2} + Fe^{\circ} \rightarrow Pb^{\circ} + Fe^{+}} \quad (2)$$

The standard reduction and oxidation potentials of the two metals are:

$$\mathbf{Pb^{+2} + 2e^{-} \rightarrow Pb^{o}\ (E^{o} = -o.126\ V)} \quad (3)$$

$$\mathbf{Fe^{o} \rightarrow Fe^{+2} + 2e^{-}\ (E^{o} = +\ 0.44\ V)} \quad (4)$$

The standard reaction potential (E_R^o) for reaction (2) is 0.314 V and lead can, therefore, easily be reduced on the surface of iron which is oxidized to Fe^{+2}. As 0.36 $> E_R^o >$ 0.06, a mixed chemical reaction/diffusion mechanism might be postulated [18].

Cementation reactions are heterogeneous in nature and involve nucleation and growth of the deposited metal on the surface of the precipitant metal. Actually, the steps that occur during cementation of lead on iron are:

1. Bulk diffusion of Pb^{2+} ions to the surface of the boundary layer.
2. Molecular diffusion of Pb^{2+} ions to the metal-solution interface. Initially the interface is between iron and solution and after some time, with progress of cementation process, this interface is between the deposited Pb and solution.
3. Transfer of electrons, produced by reaction 4, to the interface where the reduction of Pb^{2+} ions takes place. This is followed by the incorporation of Pb atoms into a crystal lattice.
4. Molecular diffusion of Fe^{+2}ions through the deposited Pb and the solution in the boundary layer.
5. Transfer of Fe^{+2} ions to bulk solution.

No doubt that the actual cementation rate depends on the five steps and the slowest step is the rate controlling one. It must be acknowledged that morphology (porosity) of the deposit has a significant effect on the kinetics of the process [19].

1.1 Influence of stirring speed

The influence of stirring speed on the cementation of lead was studied under the operating parameters of Pb^{2+} initial concentration (= 500 mg/l), temperature (= 40 °C), mass of iron (= 0.75g) and pH_o (= 2). The results are illustrated in Figure (2). The cementation rate increased with increasing stirring speed from 200 to 300 rpm which indicates that the process was mass transfer controlled and the deposited Pb had dendritic structure which allowed mass transfer between individual dendritic branches so that the effective surface area for mass transfer was increased by the deposit [20]. On increasing stirring speed, however, to 500 and 700 rpm the rate was decreased. A similar behavior was previously reported by Angelidis et al. [12] and Abdollahi et al. [15].

The decreased cementation rate with increasing stirring speed might be a consequent of two velocity effects. Firstly, since experiments were done under aerobic atmosphere, dissolved oxygen concentration increased at high stirring speeds and re-dissolution of deposited Pb occurred by reaction (5) [15];

$$\mathbf{Pb + 2H_2 + 1/2\ O_2 \rightarrow Pb^{2+} + H_2O} \quad \mathbf{(5)}$$

Secondly, at high speed the morphology of the deposited layer changed from the dendritic structure to a more compact layer **[20].** Therefore, the diffusion of Fe^{+2} ions through the mass of the deposit became the rate controlling step.

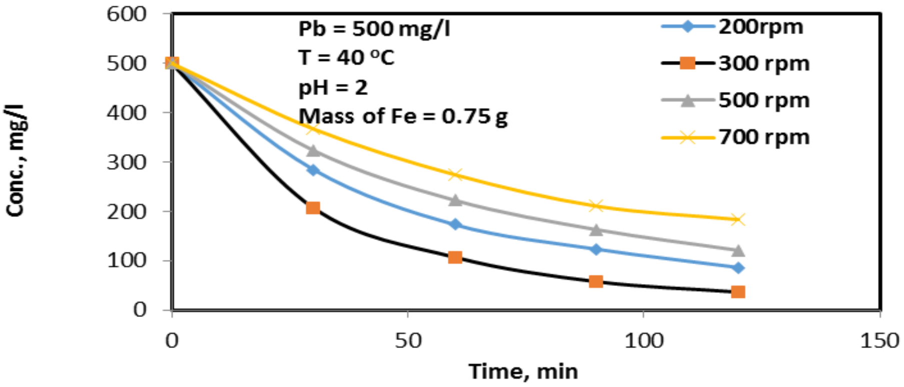

Figure (2) Concentration of lead ions vs. time at different stirring speeds

1.1 Influence of initial Pb^{+2} ions concentration

The influence of initial Pb^{2+} concentration on the rate of its cementation was performed by keeping temperature, stirring speed, mass of iron and pH at the values 40 °C, 300 rpm, 0.75g and 2, respectively. As shown in Figure (3), the rate of cementation decreases with increasing initial concentration. This decrease might be attributed to the increased mass of Pb deposited on the surface of iron particles with increased initial concentration; for instance after 30 minutes 190, 135 and 95 mg of Pb were deposited from the solutions containing 800, 500 and 300 mg/l initial Pb^{2+} concentration, respectively. As the thickness of the deposit increased the size of iron particles increased and consequently the effective surface area for mass transfer decreased; this is because the specific area of particles is inversely proportional to their average size. This observation might indicate that the morphology of the deposited lead layer changed from dendritic structure to a less porous one with increasing initial concentration [20].

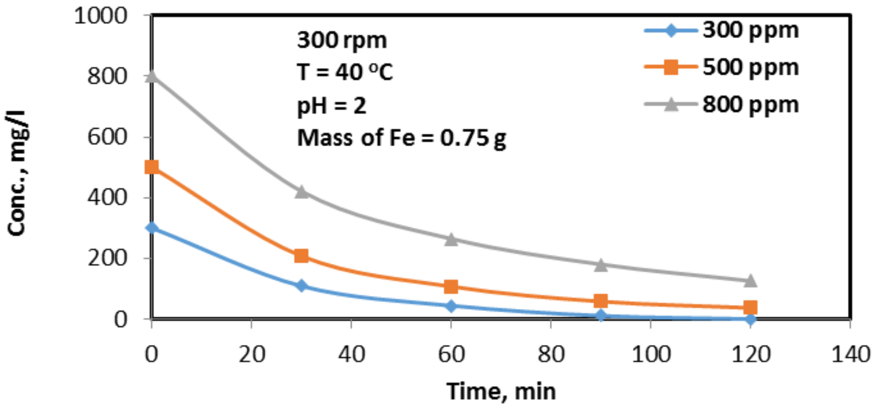

Figure (3) Concentration of lead ions vs. time at different initial concentrations of lead

1.2 Influence of temperature

The influence of temperature on the lead removal was investigated in the range of 30 - 50 °C. The other operating parameters were adjusted at Pb^{2+} initial concentration of 500 mg/l, stirring speed of 300 rpm, iron mass of 0.75 g and initial pH value of 2. The results of increasing temperature on the cementation rate are depicted in Figure (4). It is obvious that the cementation rate increased, not significantly, with the increase in temperature from 30 to 50 °C. Such increase might be a result of increased mass transfer due to the increase of diffusion coefficient of Pb^{2+} ions and decrease of the solution viscosity with increasing temperature.

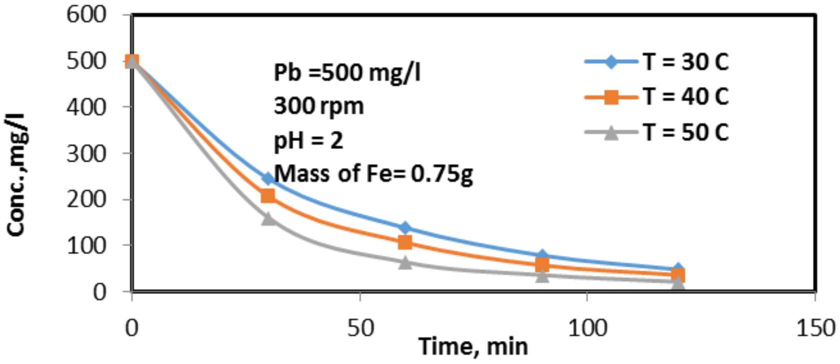

Figure (4) Concentration of lead ions vs. time at different temperatures

1.3 Influence of initial pH of the solution

The influence of pHₒ on the cementation of lead onto iron was investigated under different pHₒ values ranging from 2 to 4. 8 (free pH). The initial concentration of solution, stirring speed, Fe mass and temperature in these experiments were 500 mg/l, 300 rpm, 0.75 g and 40 °C, respectively. The results are presented in Figure (5). At the pHₒ of 2 the maximum cementation rate of lead was occurred. Increasing pHₒ to 4.8 resulted in significant decrease in cementation rate as iron was passivated by an adsorbed oxygen film **[14].** At the pH value of 3 a considerable decrease in the rate was observed which, as well, might be attributed to iron passivation but at lesser degree than at pH of 4.8. On the other hand, at pH of 1.04, small decrease in the rate was observed which might result from the formation of hydrogen bubbles on iron surface by the side reaction (6) **[12]** and consequently hindered the cementation of lead.

$$2H^+ + Fe \rightarrow Fe^{+2} + H_2 \qquad (6)$$

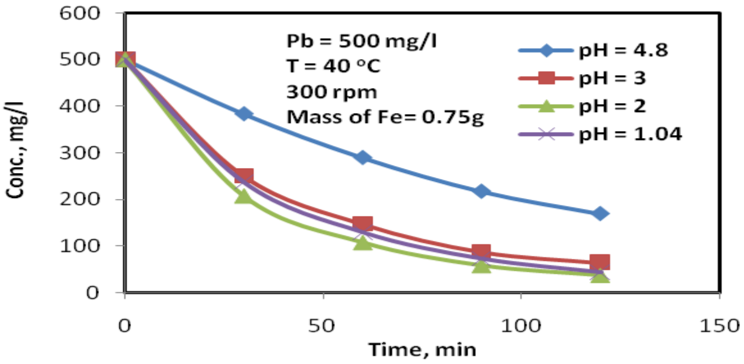

Figure (5) Concentration of lead ions vs. time at different pH values

1.2 Influence of mass of iron powder

The influence of the iron powder mass on cementation rate is demonstrated in Figure (6). Experiments were performed by changing mass of iron from 0.75 to 2 g while maintaining other operating parameters at constant values; i.e. temperature = 40 °C, stirring speed = 300 rpm, pH = 2 and initial Pb^{2+} concentration = 500 mg/l. It is clear that the rate of cementation increased with increasing the amount of iron added to the solution. This is simply due to increased surface area of iron as a result of the increased mass. It is important to address that as the mass of iron was increased the curves, describing the rate of cementation, got closer and it may coincide after a specific mass of iron. A similar behavior was observed by El-Astoukhy and Abdel-Aziz [21] when they used iron as sacrificial metal in the form of screens and reported that: "for a given rpm and initial concentration of the less active, metal mass transfer coefficient increases with increasing number of screens and then remains constant with further increase in the number of screens".

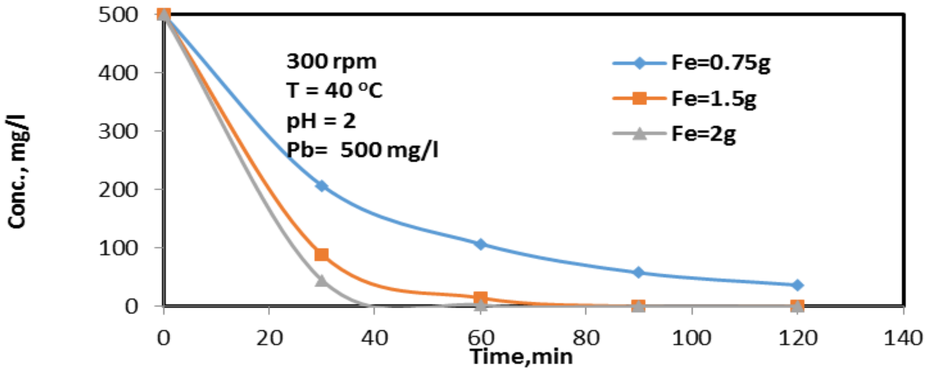

Figure (6) Concentration of lead ions vs. time at different iron masses

2. The cementation of lead by zinc and iron sheets

Zinc and iron sheets can also be used to cement lead. When using zinc the cementation reaction is

$$\mathbf{Zn^{o} + Pb^{2+} \rightarrow Zn^{2+} + Pb^{o}} \qquad \mathbf{(7)}$$

At standard conditions E° of this reaction is 0.63 V which is greater than that of reaction (2) and as a consequent Zn is stronger than Fe for removing lead.

A comparison between the cementation of lead by iron powder, iron sheet and zinc sheet is demonstrated in Figure (7). Experiments were carried out, using the same mass of the substrate, under the conditions shown in the figure. The results confirmed that the highest cementation rate of lead was achieved by using iron powder followed by using zinc sheet; a behavior which is rationally related to the increased surface area of iron powder than that of zinc sheet. However, it is important to mention that the recovery of deposited lead was easier in case of using sheets.

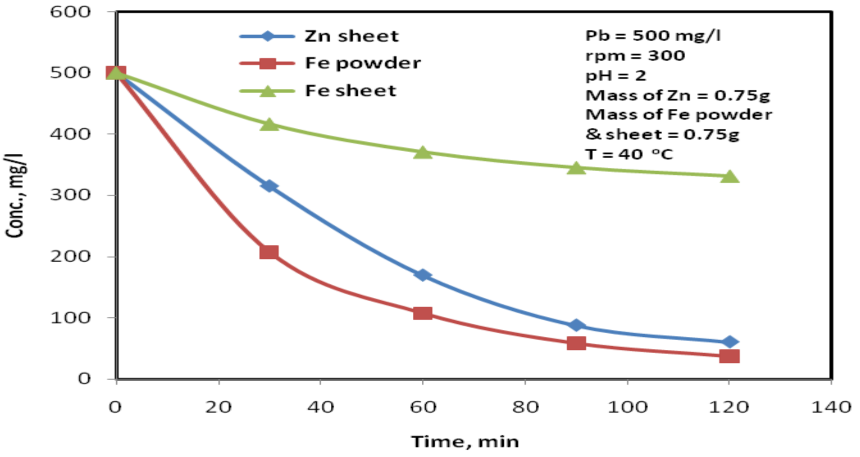

Figure (7) Concentrations of lead ions vs. time using iron powder, iron sheet and zinc sheet

KINETIC ANALYSIS

The kinetics of cementation of lead from nitrate solutions onto iron powder was studied under the diverse operating parameters reported in Table (2) in order to shed light on the influence of each operating parameter on the reaction rate constant and ultimately to find a correlation for predicting the rate constant.

Figure (8) depicts a plot of **ln(C_t)** versus time for different initial lead concentrations under the constant values, elucidated in the figure, of other operating parameters. The plotted results indicate that the cementation reaction follows a first order kinetics and the value of the rate constant (k) increases with decreasing initial concentration of lead. On plotting values of k versus C_o a linear relationship was obtained as shown in Figure (9).

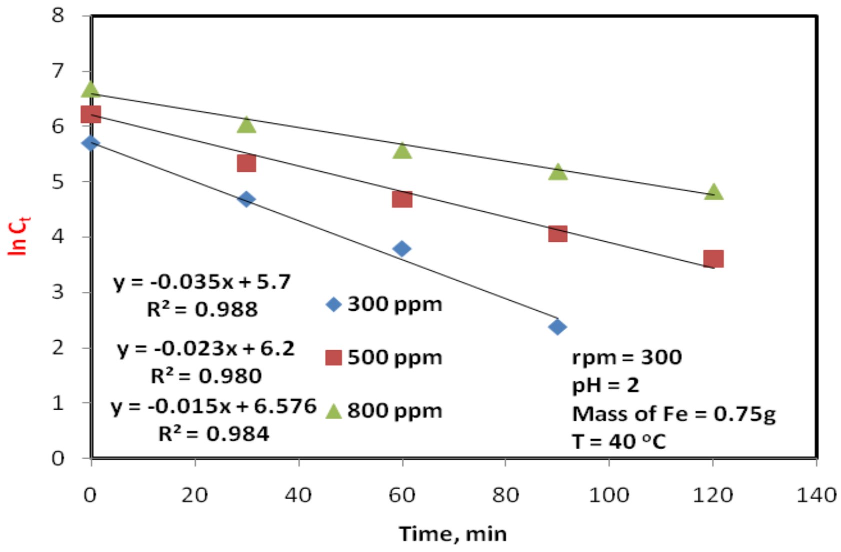

Figure (8) ln [C_t] vs. cementation time at different initial lead concentrations

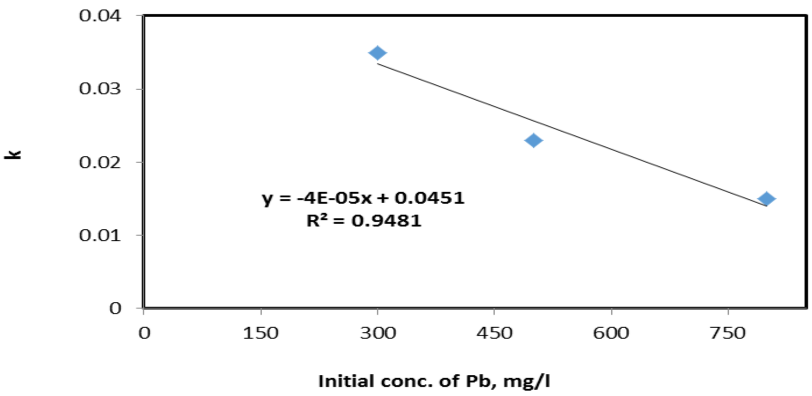

Figure (9) Rate constant vs. initial concentration of lead

The influence of the rotational speed on the kinetics of lead cementation is depicted in Figure (10). The results elucidate that the reaction rate obeys first order kinetics for this process and k increased with increasing the rotational speed from 200 to 300 rpm and decreased thereafter with increasing the agitator speed; this behavior is shown in Figure (11).

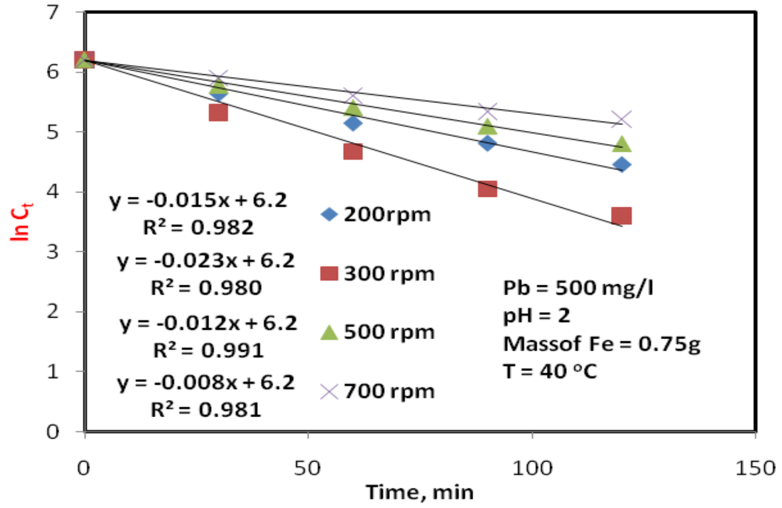

Figure (10) ln [C_t] vs. cementation time at different rotational speeds.

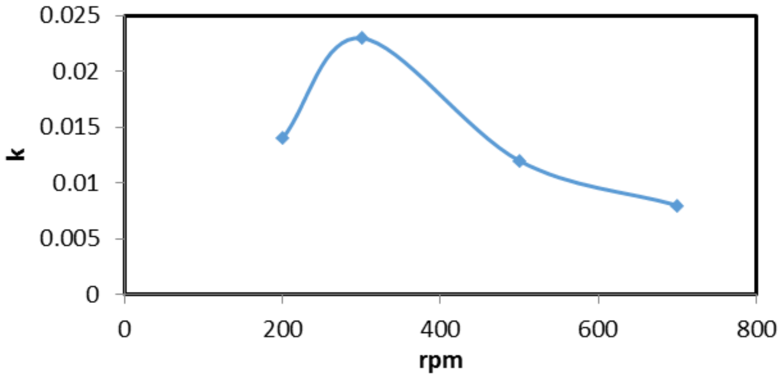

Figure (11) Rate constant vs. rpm

The influence of pH_o of the solution on the cementation rate is shown in Figure (12). For all values of pH_o, linear relationships between **ln(C_t)** and time were acquired and the slope of a line, the reaction rate k, decreased with increasing or decreasing the value of pH_o about 2. Figure (13) demonstrates the **non-linear** relationship between values of k and pH_o.

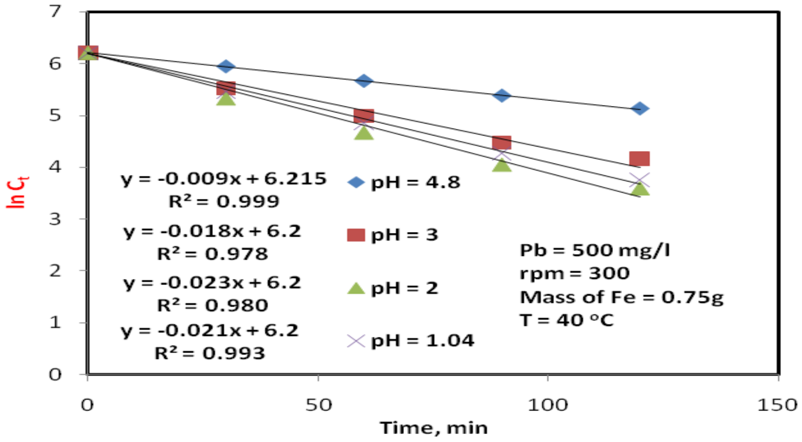

Figure (12) ln [C_t] vs. cementation time at different initial pH values

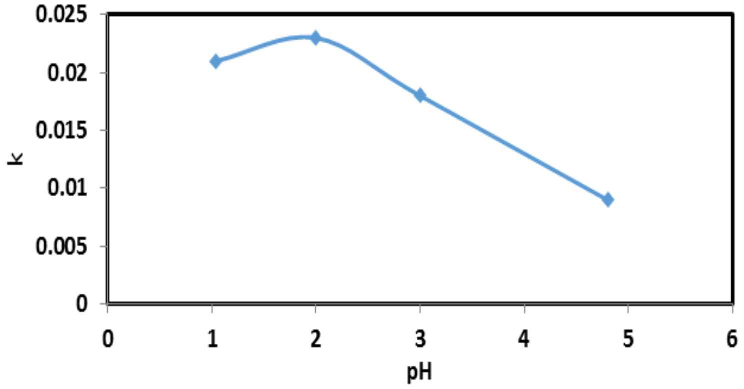

Figure (13) Rate constant vs. pH

The influence of mutable temperature at constant values of other operation parameters on the kinetics of lead removal was inspected. The results shown in Figure (14) also confirmed the first order kinetics of the process and the increase of rate constant k with increasing the temperature of reaction.

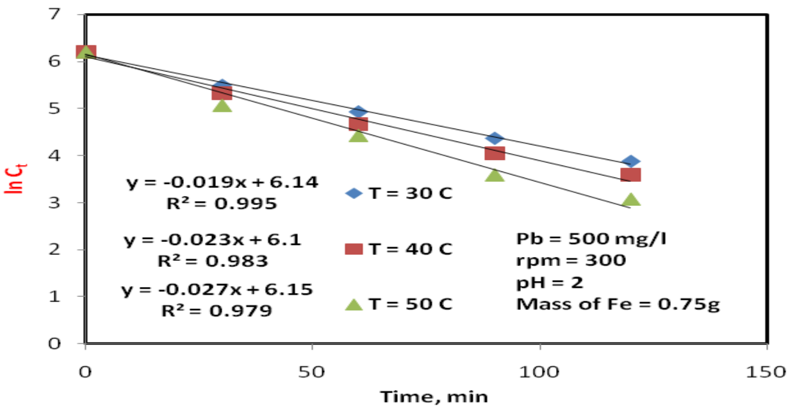

Figure (14) ln[C$_t$] vs. cementation time at different temperatures

Figure (15) depicts Arrhenius plot of the data presented in Figure (14). The figure indicates that the process progressed, under the operating conditions shown in the figure, in a single regime and had activation energy of 14.61 kJ/mol. It is embracing to find that Angelidis et al. [14] and Makhloufi et al. [9] reported activation energy of 4.4 kCal/mol (18.39 kJ/mol) and 9.6 kJ/mol, respectively, for the cementation of lead on rotating iron disc. The value of activation energy, obtained in this work, confirms that the mass transfer across the boundary layer is the rate-controlling step of cementation of lead with iron powder under the investigated range of operating parameters.

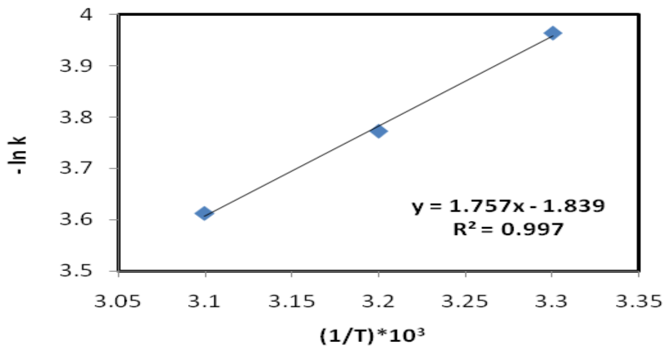

Figure (15) Arrhenius plot for Lead cementation reaction

Figure (16) illustrates the influence of iron mass on the cementation kinetics of lead. It is obvious that the reaction rate constant increased with increasing the mass of iron powder. This behavior is expected as the process rate is directly related to the mass transfer area. Figure (17) performs a linear relationship correlates k with the mass of iron powder.

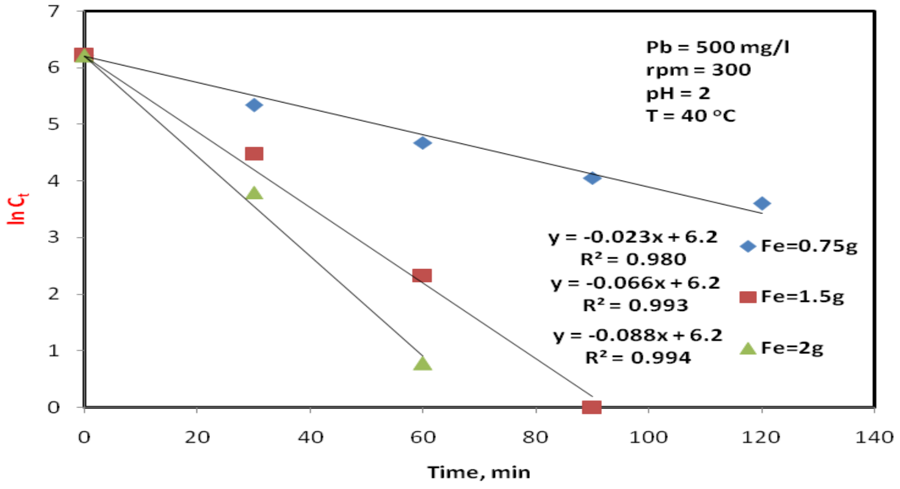

Figure (16) ln[C_t] vs. cementation time at different iron masses.

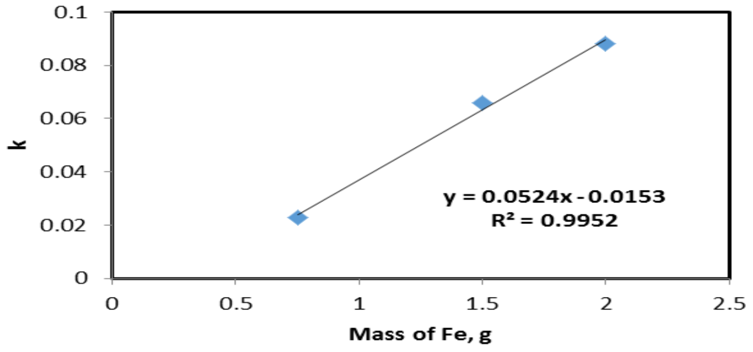

Figure (17) Rate constants vs. mass of iron

CORRELATION FOR PREDICTING k

To illustrate the influence of the operating parameters on the rate constant k of cementation of lead on iron powder, a mathematical correlation must be submitted. For first order kinetics, many authors, e.g. [5, 13], presented a rate equation of the form:

$$\ln(C_t/C_o) = - k(A/V)t \quad (8)$$

Where C_t is the concentration of **less active** metal at time t, k is the reaction rate constant, A is the effective mass transfer area and V is the volume of the treated solution. Equation (8) indicates that k is also a function of A on which lead is deposited. In cementation calculations, it will be erroneous to use the exposed geometrical area of the more active metal at t =0 as this area and its nature change with the progress of cementation. Therefore, equation (8) may be rewritten as:

$$\ln(C_t/C_o) = - k_{app}.t \quad (9)$$

Where k_{app} (= k (A/V) is the apparent rate constant. Based on the aforementioned results, k_{app} = **f** (rotation speed (RS), C_o, pH_o, T, and mass of substrate). In order to get a correlation which explicitly expresses the effect of all these operating variables on k_{app}, non linear statistical and least square multivariate regression technique was used. It should be mentioned that the influence of iron mass was ignored on account of the reason previously mentioned in 1.5. The correlation has the form:

$$k_{app} = b_o + b_1 f_1(pH_o) + b_2 f_2(C_o) + b_3 f_3(RS) + b_4 f_4(T) + \varepsilon \qquad (10)$$

Where:

b_o to b_4 = the correlation coefficients,
pH_o = initial pH of solution,
C_o = initial concentration of Pb^{2+} ions in (mg/l),
RS = agitation speed in (rpm),
T = solution temperature (K), and
ε = the error which is the difference between the observed experimental values and the correlation prediction values.

The values and p-values of the correlation coefficients are given in Table (3). All the p-values are less than 0.001 which indicates that each term of the correlation is significant. The resulted correlation is

$$k_{app} = -1.0161 - 9.43E\text{-}05\,(pH_o)^{3.17} - 0.0085(C_o)^{0.3208} - 0.00066\,(RS)^{0.583} + 0.1948\ \ln T \qquad (11)$$

Table 3: Value and p-value of each term coefficient

Coefficients	Values	p-values
b_o	-1.0161	5.4658E-07
b_1	- 9.43E-05	0.005913379
b_2	- 0.00855	0.002684122
b_3	- 0.00066	0.003655546
b_4	0.1948	1.33935E-07

Coefficients b_1, b_2 and b_3 of the distinct parameters pH_o, C_o and RS, respectively, are negative but coefficient b_4 of distinct parameter T is positive which agrees well with the observed results.

Figure (18) depicts the normal probability of standardized residuals and the mean of correlation errors is equal to zero. The linear distribution of the residual errors reveals that the errors are normally distributed which indicates that the expectations of the model are not biased.

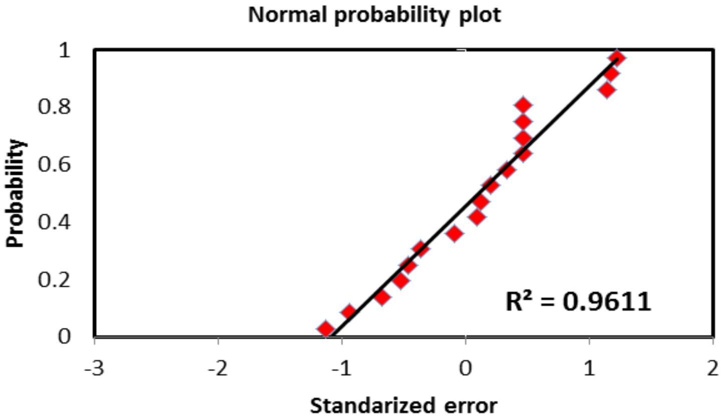

Figure (18) Normal probability of standardized errors

Figure (19) demonstrates that the obtained correlation fairly predicts the observed values of apparent rate constant.

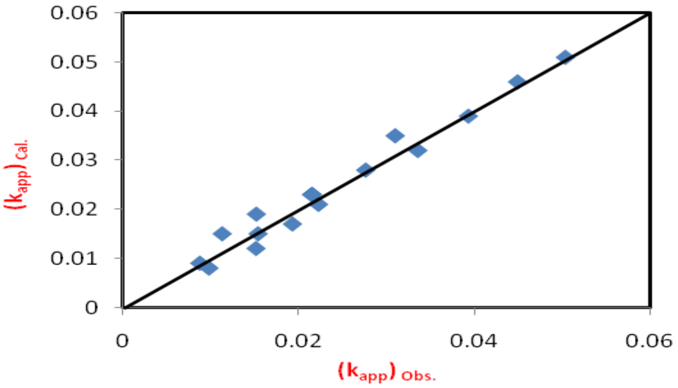

Figure (19) Calculated k_{app} vs. observed k_{app}

CONCLUSIONS

Cementation of lead with iron powder from mono-metallic simulated waste solution could successfully be done using a modest-stirred reactor. The results elucidated that:

1. The cementation of lead onto iron follows first order kinetics with respect to the concentration of lead ions in bulk solution and the rate of reaction is influenced by pH_o, C_o, RS and T.
2. Complete removal of lead needs about 3 hour operational time under the conditions: C_o = 500 mg/l, pH_o = 2, RS = 300 rpm and T = 313 K.
3. The cementation of lead on iron particles, under the conditions mentioned in item 2, proceeded in a single regime and had activation energy of 14.61kJ/mol; an observation that confirms that the controlling step is the mass transfer through the boundary layer.
4. Under the same operating conditions, the highest cementation rate of lead was achieved by using iron powder followed by using zinc sheet; a behavior which is rationally related to the increased surface area of iron powder than that of zinc sheet
5. A correlation for predicting the apparent rate constant was obtained by using least square multivariate regression technique. The correlation has the form:

$$k_{app} = -1.0161 - 9.43E\text{-}05\,(pH_o)^{3.17} - 0.0085(C_o)^{0.3208} - 0.00066\,(RS)^{0.583} + 0.1948\,\ln T$$

Nomenclature

C_o	Initial concentration of lead, mg/l.
T	The reaction temperature, K.
pH_o	The initial pH of solution.
k	Rate constant, m/min.
k_{app}	Apparent rate constant, min^{-1}.
ε	The error which is the difference between the observed experimental values and the correlation prediction values.
b_o to b_4	The coefficients of correlation (11).
E^o	Standard electrode potential, V.
E_a	The activation energy of reaction, kJ/mol.
E_R^o	Standard reaction potential, V.

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