

## Removal of Heavy Metals Using Chemicals Precipitation

Dr. Mahmood M. Brbooti\*, Dr. Balasim A. Abid\*\*  
& Dr. Najah M. Al-Shuwaiki\*\*

Received on: 2/9/2009

Accepted on: 2/12/2010

### Abstract

The single component and multi-component hydroxide precipitation and adsorption were studied for different heavy metals namely Iron (III), Chromium (III), Copper (II), Lead (II), Nickel (II), and Cadmium (II) from aqueous solutions. By using the jar tester Magnesia (MgO) was used as a precipitator at different doses and compared with other chemicals like lime (CaO) and caustic soda (NaOH). The treatment involves the addition of either magnesia or lime-water suspensions (combined with cationic polyelectrolyte, CPE) in various doses, 1.0 – 5.0 g/l for the metal samples to study the effect of varying doses on the treatment efficiency. The results show that the percent removal of metal ions increases to about 99 % with increasing the MgO dose to some limits. The optimum values of MgO doses were found to be 1.5-3.0 g/l. The pH value ranges are 9.5 to 10 with MgO precipitant and pH of 11.5 to 12 with CaO precipitant. In the jar experiment the rotation speed, N, 180-200 rpm, (G of 460-480 s<sup>-1</sup>) of mixing for two minutes was the most favorable speed of rapid mixing and the slow mixing speed of 15-30 rpm, G of (14-35 s<sup>-1</sup>), for twenty minutes gave the best results. At the best operating conditions of the pilot plant, the removal efficiency of metal ions was more than 97% at doses of MgO (1.0-4.0 g/l).

**Keywords:** Removal; Heavy metals; Hydroxide Precipitation, Magnesium Oxide, Lime, Adsorption

### ازالة المعادن الثقيلة باستخدام الترسيب بالمواد الكيميائية

#### الخلاصة

لقد تم في هذا البحث دراسة عمليات الترسيب الكيميائي والامتزاز لمعادن كثيرة مختلفة، احيانا سوائل لمعدن مفرد واحيانا سوائل لعدة معادن مجتمعة. ان المعادن التي درست في محاليلها المائية المحضرة مختبريا هي الحديد، الكروم، النحاس، الرصاص، النيكل، والكاديوم. بواسطة جهاز فحص الجرة تم استخدام مادة اوكسيد المغنيسيوم بكميات مختلفة و كذلك تم مقارنتها مع مواد كيميائية اخرى مثل اوكسيد الكالسيوم (النوره) وهيدروكسيد الصوديوم. ان المعالجة تتضمن اضافة معلق اوكسيد المغنيسيوم - الماء او اوكسيد الكالسيوم - الماء بالاضافة الى بوليمر موجب بجرعات مختلفة من (1-5) غم / لتر لمحاليل المعادن لدراسة اثر تغير كميات الجرعات على كفاءة العملية. النتائج تشير ان معدل ازالة ايونات المعادن تزيد الى 99% مع زيادة كمية اوكسيد المغنيسيوم الى حد معين. ان انسب الكميات لجرعات اوكسيد المغنيسيوم وجدت هي ( 1.5-3.0 ) g/l لمحاليل المعادن.

ان استخدام اوكسيد المغنيسيوم يؤدي الى حفظ ال pH متوازنة بحيث لا تتجاوز 9.5-10.0 اما باستخدام اوكسيد الكالسيوم فان قيمة pH تتراوح بين 11.5-12.0, لقد وجد ان الخلط السريع (180-200) دورة بالدقيقة لمدة دقيقتين يليه خلط بطيء (15-30) دورة بالدقيقة لمدة عشرين دقيقة يعطي افضل النتائج في كفاءة ازالة الملوثات. عند افضل الظروف التشغيلية في المنظومة الريادية

\*Applied Science Department, University of Technology /Baghdad

\*\*Chemical Engineering Department, University of Technology/ Baghdad

تم الحصول على نسبة 97% وأكثر في كفاءة ازالة المعادن الثقيلة باستخدام كميات (1.0-4.0) غم/لتر

### Introduction

The increasing level of heavy metals in the environment represents a serious threat to human health, living resources and ecological systems. Although there are many sources of heavy metals, some industrial sectors are at present contribute the most to environmental pollution with these toxic metals. Among such industrial sectors, the metal finishing industry, the electrochemistry, leather tanning, and metal plating industry are important ones. These contaminants must be removed from wastewaters before discharge as they are considered persistent, bioaccumulative and toxic substances. The wastewater is highly toxic in nature because of the presence of metals such as copper, nickel, zinc, cadmium, chromium, and cyanides. A variety of specialized treatment processes for the removal of heavy metals prior to their discharge into the environment have been developed. Among them, the simple precipitation of metals as insoluble hydroxides, carbonates, or sulfides is used in about 75% of electroplating facilities to treat wastewater (Karthikeyan et al., 1995 as cited by Esmaili et al., 2005). In conventional treatment, precipitation is the technique of choice for the removal of dissolved heavy metals. Precipitation of heavymetals lowers the concentrations of all metals. The solubility of precipitated metal compounds is the key to this method's success; if a metal can form an insoluble compound, then the compound can be removed via clarification and filtration. Of the few precipitation methods, hydroxide and

sulfide are the two main methods currently used, and hydroxide precipitation is by far the most widely used method. Of all the treatment techniques, heavy metal hydroxide precipitation is the most commonly employed because of its low-cost and simplicity. This process is as simple as increasing the pH of the effluent using lime (CaO), caustic soda (NaOH) or (MgO) as a precipitator and hence immobilizes the heavy metals as their respective hydroxides (Esmaili et al., 2005). At low pH value, magnesium oxide was found as a good adsorbent to remove the heavy metal ions from their aqueous solutions.

### Experimental Studies

#### Materials and Chemicals

The coagulants and chemicals used to enhance the removal efficiency (more data can be seen by Al-Shuwaiki N.M.A., 2009) are:

1. Magnesia, magnesium oxide 99% from CARLO ERBA, Italy. Its molecular weight, molecular volume and density are 40.32 g/gmol, 11.2 cm<sup>3</sup> /gm, and 3.6 g/cm<sup>3</sup> respectively.
2. Lime, calcium oxide, 99% from CARLO ERBA, Italy. Its molecular weight is 56.1 g/gmol.
3. Caustic soda, sodium hydroxide 99% from CARLO ERBA, Italy. Its molecular weight is 40.0 g/gmol.
4. Cationic polyelectrolyte (polyacrylamide), figure (1), of molecular weight range between 10000 and 500000 is used and is known commercially as (polyalkyenimine) from MERCK, Germany.

5. Hydrochloric acid, HCl, 0.1 molar (Fluka, Switzerland).
6. Various metal salts, 99 % purity, as listed in table (1).

Simulated heavy metals solutions of different types of metals (Fe, Cr, Cu, Pb, Ni, and Cd) in different concentrations were prepared.

A. Different metal solutions were prepared as 10.00, 7.50, 5.00, 2.50 g/l of tap water. Most of the experiments were done at 5.00 g/l solutions.

B. Specific calculated amounts of metal salts were dissolved each into (1- liter) of water to give 500 mg/l (500 ppm) of each ion metal separately and then all of them were combined together. These amount were 127.0 mg/l of cupric sulfate, 219.0 mg/l of cadmium sulfate, 100.0 mg/l of nickel nitrate, 78.0 mg/l of chromium sulfate, 156.0 mg/l of lead nitrate and 110.0 mg/l of ferric chloride.

#### Measuring Instrumentations and Equipments

Jar Tester

Jar test model (Floc Tester CHC) Hoelze and Chelus Com. KG was used in tests techniques to determine the best type and dose of the desired precipitator.

pH Meter

pH 211, produced by HANNA with accuracy of 0.1% instruments was used in pH test, temperature and electrical conductivity.

#### Heavy Metals Measures

Atomic Absorption Spectrophotometer analytic from Jena Nov AA 300 Germany, was used in the labs of the Ministry of Environment to measure the metal ion concentration. In the AAS as shown in Appendix (A) the fuel used was acetylene  $C_2H_2$  and the oxidant used was the air or nitro oxide  $N_2O$  for

stronger flames, air /  $C_2H_2$  or  $N_2O$  /  $C_2H_2$ .

#### Pilot Plant System

The pilot plant includes mixing tank provided with a mechanical mixing motor with a six-bladed disc turbine agitator as impeller, settling tank, sand filter, collection and storage tanks, dosing pump, chemicals mixing tank with motor and agitator, U -tube manometer, valves flow meter and drain tanks as can be seen in figure (2).

#### Results and Discussion Effect of the Precipitator Type and Dose

Different coagulants like magnesia, lime, caustic soda, cationic polyelectrolyte (CPE) and their combinations were applied to select the suitable ones with optimum removal efficiency. Magnesium oxide is found to be very effective in removing the metals used in the experiment even in small doses. Before the increase in pH it started to precipitate the metals by adsorption. This is not the case with CaO and NaOH which are mainly dependent on pH. Figures (3 to 5) show that MgO is the best precipitator of iron and copper. The removal efficiency of the metal from its solution is calculated as:

$$(C_i - C) / C_i * 100 \%$$

Where  $C_i$  is the initial concentration of the metal in its solution before adding the coagulant and C is the final concentration of the metal after adding the coagulant.

For chromium metal, figure (6), this result is in good agreement with the fact that CaO reacts with Cr (III) to give  $CaCrO_4$  which is almost soluble in water which leads to keep the Cr (III) in solution. MgO reacts with Cr (III) to give  $MgCrO_4$  which is insoluble and easily precipitates in solutions (Fran 2006). For all metals,

even small doses of MgO would affect the precipitation of metals because the adsorption starts to happen. But with CaO and NaOH which are soluble in water (high TDS), no adsorption happens and the precipitation would depend only on increasing the pH of solution by increasing the chemical dose (hydroxide precipitation).

#### Effect of Settling Time and Settling Velocity

Settling time required is one of the key factors in the treatment processes, since settling kinetic governs the treatment efficiency and performance. From the settling behavior it can be observed that when using MgO in colored samples the settling time is slightly longer than the time when using CaO because it has smaller molecular weight and the dyes adsorbed by it (organic compounds) are of small molecular weight too, Al-Shuwaiki 2009, but with metals the opposite case happens and the settling time is shorter with MgO. The metals adsorbed by MgO are of high molecular weights (52-207) g/g mol. This leads to rapid settling of metals adsorbed. From the lab experiments for different metals and by using the stop watch, the average settling velocities of MgO, CaO, and NaOH were 60-80 cm/min, 30-40 cm/min, and 1-3 cm/min respectively. The ratio of settling velocity by MgO, CaO, and NaOH was 6:3:1 as shown in figure (7). The combination of MgO and CPE gave a shorter settling time and consequently a greater settling velocity. The settling time is affected by the different metals used as can be seen in figure (8) where lead settles more rapidly than nickel because of its higher molecular weight (207.2 greater than 58.7 g/g mol). After starting the mixer at 180-200 rpm for samples of metals for 1-3

min after adding the chemical (coagulant solution), then the paddles speeds were reduced to 20-40 rpm for an additional 30-50 minutes to have slow mix. At the end of the slow mix period, the paddles were then removed from the jars and the flocs were allowed to settle. The time for all of the flocs to settle to the bottom of the beakers is observed. Results of these tests are shown in figures (7) and (8) where the removal of turbidity, TSS can be achieved at time range of (35-45 min). Esmaeili and Mesdaghi, 2005 found and proved that the time needed for rapid mixing of MgO is longer than that of CaO and NaOH for the precipitation of Cr (III).

For metal solutions at mixing speed 15-30 rpm, the typical values for G for a detention time of about 20-30 minutes vary from (14 to 35 s<sup>-1</sup>). Values of Gt vary from (16800 to 63000) which is close to the reported values of (10<sup>4</sup> to 10<sup>5</sup>) obtained by (Mihelcic & Hand 2001).

#### Effect of Sludge Volume

A comparison of the sludge volume produced is showed in figures (9) when precipitating Cr by MgO, CaO and NaOH. It is seen that from the start of the experiment as the dose of the precipitant is increased the sludge volume also increases due to the increase in precipitated metals and that the sludge treated with NaOH is the least because the metal does not start to precipitate quickly. Then as the process proceeds the sludge volume became the largest for NaOH, and for MgO was the smallest. Sludge volumes of Cr, and all the other metals resulting from MgO were much smaller than the volumes when using NaOH and CaO. The average ratio of sludges of all metals was: Vol<sub>MgO</sub>: Vol<sub>CaO</sub>: Vol<sub>NaOH</sub> 60:180:240 = 1:3:4 as an average for all metals after

3-4 hours of settling time. Esmaeili, 2005 found similar ratio for Cr (III) precipitation of (1:2.5:3.3). Using MgO is important because it not only helps to reduce the volume of the treatment plants, but also recovering metals from such sludge is much easier than sludge with huge volumes. The sludges formed from NaOH and CaO were very gelatinous and the settling rates were slow and dewatering sludge was difficult. These results are similar to the results stated by Panswad et al., 1995 and Hemming et al., 1978 as cited by Esmaeili et al., 2005.

#### Metal Treatment by Hydroxide Precipitation

Metal precipitation is primarily dependent upon two factors: the concentration of the metal, and the pH of the water. Heavy metals are usually present in wastewaters in dilute quantities (1-100 mg/l) and at neutral or acidic pH values ( $\text{pH} < 7.0$ ). As metals enter the treatment process, they are in a stable, dissolved aqueous form and are unable to form solids. The goal of metals treatment by hydroxide precipitation is then to adjust the pH of the water so that the metals will form insoluble precipitates. High pH corresponds to high hydroxide concentrations. However, when one adds magnesia or lime to water which contains dissolved metals, the metals react with hydroxide ions to form metal hydroxide solids. Once the metals precipitate and form solids, they can then easily be removed, and the water, now with low metal concentrations, can be discharged or reused.

The jar tests consisted of evaluating metal removal using magnesium oxide (magnesia), calcium hydroxide (lime) and sodium hydroxide (caustic). Some jar tests was conducted to evaluate the impact

of adding polyelectrolyte. The results of these jar tests are presented. The different coagulants and their combinations were tried to select the suitable ones that provide higher removal efficiency.

For all metal solutions, as the concentration of the metal in the solution increased, the pH of the solution decreases and the TDS, EC values increases which require more doses of MgO for treatment as shown in figures (10 and 11) for copper and chromium solutions before treatment by any agent.

Figures (12 to 14) show the effect of the type of the precipitating agent and its increasing doses on the removal efficiency of Pb, Cd, and Ni. From the figures it is noticed that magnesia is better than lime for all metals especially with the small doses of the agent (1.0 to 2.0 g/l). At higher doses, about (3.0 to 4.0 g/l), the two agents have similar effects.

The representations of the pH values that promote metal precipitation are displayed in figures (15 and 16). Each curve represents the solubility of an individual metal at various pH values by using MgO and CaO. The only metals tested which were found to have a high metal solubility at the neutral pH values (7-9) were cadmium and nickel. Since all metals display similar effects, it is clear that the adjustment of pH is critical when the metal is to be removed from the wastewater. For solutions treated by CaO or NaOH the pH values greater than 10.0 were required to achieve the least solubility values. At high pH values ( $\text{pH} > 11$ ) excellent metal removal, more than 97%, was accomplished with lime for Cd and Ni metals except lead which had high residual concentration in the solution.

For solutions treated with MgO, although, the pH values would not exceed 10; better metal removal efficiencies were accomplished in the range of 95%-99%. MgO solid particles did not completely dissolve in water (TDS = 270-400 mg/l), but they soaked in water for some time and then swallowed. These swallowed particles act as adsorbents and for this reason small doses of them would affect the precipitation of metals without the need to raise the pH range more than pH = 10.

From figures (15 and 16), it is observed that as pH increases the removal of metal increases to some limit by hydroxide precipitation according to the type of metal removed. Some of metal hydroxides disassociate with the resulting metal ions going back into solution as pH increases. For iron, the removal increases till pH of (4 to 5), and after that by increasing the pH value the metal removal decreases because the metal is redissolved and therefore its concentration in supernatant increases because it's lowest solubility is at a pH of (4 – 5). The pH ranges of chromium, copper, and lead are (7.5 - 8.5), (8-8.5), and (8.5-9). For nickel and cadmium the minimum solubility is at a pH of (10.5-11) and (10.5-11.5) respectively. These results fit with the data from Amer 2001.

When treating the metals with MgO, the important factor is its dose as shown in figure (17). It is more important than pH because although pH did not exceed 9.5 to 10, Cd and Ni are precipitated. In CaO solutions they need a pH value of more than 10.5 to precipitate. The relations of the concentrations of metals in solution and the MgO dose needed to precipitate these metals were studied and calculated by Statistica program for each metal.

The general equation that relates the removal efficiency of the metal, in the mixed solution of the initial concentration of 500 mg/l for each metal, with (x) the dosage of magnesia (MgO in g/l) is:

Removal Efficiency of Metal  

$$= a + bx + cx^2$$

$$\text{IRON} = 14.9103 + 34.4173*x - 3.264*x^2 \quad (3.1)$$

$$\text{CHROME} = -13.3076 + 31.7541*x - 2.1704*x^2 \quad (3.2)$$

$$\text{COPPER} = -10.6012 + 29.4775*x - 1.9195*x^2 \quad (3.3)$$

$$\text{LEAD} = -10.1992 + 20.1802*x - 0.6221*x^2 \quad (3.4)$$

$$\text{NICKEL} = -8.1917 + 13.1949*x + 0.3361*x^2 \quad (3.5)$$

$$\text{CADMIUM} = -8.9251 + 10.136*x + 0.7789*x^2 \quad (3.6)$$

a, b and c are constants related to each metal as shown in table (2) with the correlation coefficient and the average absolute error for each metal. As can be seen from the table, the relative errors range from 2.0% for iron to 19.7% for cadmium with correlation coefficients of 0.9755 and 0.9760 respectively.

These relations were done by Computer Statistica Program. All the equations of all the metals and their readings are listed in table (3) with the calculated average errors, residuals, observed and predicted values of all the measurements.

#### Conclusions

1. By using magnesia as the precipitating agent, high quality sludge with high settling rate and low volume is obtained. The sludge is grainy, dense, and easily settleable and dewatered not as the large, gelatinous, and low settling rate one obtained when using lime and caustic which causes difficult dewatering. The ratio of sludge of Vol<sub>MgO</sub>: Vol<sub>CaO</sub>: Vol<sub>NaOH</sub> was 1:3:4. Using MgO is important because it not only helps to

reduce the volume of the treatment plants, but also recovering metals from such sludge is much easier than sludge with huge volumes.

2. In all the experiments the pH would not exceed a value of 9.0-10 when MgO is used. When using CaO and NaOH, the pH value reaches 12 and 14 respectively. Hydroxide precipitation is a pH sensitive. Each metal has a narrow range of pH for the precipitation and beyond this range, the metal resolubilizes. Magnesia is a good precipitating agent even for nickel and cadmium which reach high pH ranges (10-11) in any other solution. But with MgO solutions, nickel will precipitate due to adsorption besides the hydroxyl precipitation without the need to raise the pH value.

3. The use of cationic polyelectrolyte, CPE, alone as a precipitating agent at concentrations of 1.25-1.5 mg/l. causes low pollutants removal efficiencies, and causes rapid clogging of sand filter due to its physical nature.

4. The best removal efficiencies can be achieved by applying velocity gradient of rapid mixing of  $460-480 \text{ sec}^{-1}$  for metal samples with detention time 2-3 min followed by slow mixing of gradient velocity, G, of 14- 35  $\text{sec}^{-1}$  for 20-30 min.

5. The best removal efficiencies were achieved by the pilot plant mechanical mixing model because of the adequate mixing followed by sedimentation and filtration. Flow rates at level of 85-100 l/hr, were found to be more efficient to produce high quality of the treated water.

#### References

- [1] Abdul Ghaffar (2008) "Removal of Lead (II) Ions From Aqueous Solutions Under Different Physiochemical Conditions Using

Various Sorbents", Arabian Journal for Science and Engineering, 33 (1A), pp. 55-61. [http://www.kfupm.edu.sa/publications/ajse/Articles/331A\\_P.6.pdf](http://www.kfupm.edu.sa/publications/ajse/Articles/331A_P.6.pdf).

- [2] [adin@vms.huji.ac.il](mailto:adin@vms.huji.ac.il)
- [3] Alexander A. and Taylor J.P., (1988) "Process for Removing Heavy Metal Ions from Solutions Using Adsorbents Containing Activated Hydrotalcite" Chemical Engineering pp 60-74.
- [4] Algarra M. and Jimenez M. V. (2005) "Heavy Metals Removal from Electroplating Wastewater by Aminopropyl-Si MCM-41" Chemosphere vol 59 (2005) pp 779-786, [www.elsevier.com/locate/chemosphere](http://www.elsevier.com/locate/chemosphere).
- [5] Al-Shuwaiki N.M.A. (2009) "Utilization of Magnesium Oxide for the Industrial Wastewater Treatment and Re-Use", PhD thesis, University of Technology, Iraq.
- [6] Amer S., Kanluen R. (2001) "Treating Plating Wastewater" Products Finishing .e-mail [info@aquachem-inc.com](mailto:info@aquachem-inc.com).
- [7] Ayres D.M., Davis A.P., Gietka P.M. (1994) "Removal Heavy Metals from Wastewater" University of Maryland. Engineering Report Center Report.
- [8] Barbooti M.M., Al-Zebiadi A .A. 2003 "Removal and Recovery of Chromium (III) from Tanning Wastewater Using Magnesium Oxide", University of Technology, Iraq.,
- [9] Barbooti M.M., Ajeena. N.A. and Tooma, M.A., Eng. Technology J., 26 (2008) p. 1396.
- [10] Cort Steven (2005) "Methods of removal heavy metals from water using chemical precipitation and

- field separation methods". United States Patent 6896815.
- [11] Esmaeili A. Mesdaghi A., Vazirinjad R. (2005) "Chromium (III) Removal and Recovery from Tannery Wastewater by Precipitation Process", American Journal of Applied Science 2(10): pp.1471-1473.
- [12] Fran and Ted Mooney (2006) "Using Magnesium Hydroxide in Metal Removal in Treating Wastewater"
- [13] Gary T., Joseph C., (2008) "Arsenic". Jour AWWA, Arizona
- [14] Holtzman S.A. (1994) "Cyanide and Heavy Metal Removal" Advanced Chemical Technology Inc. Funk & Wagnall's.
- [15] Horvath Imre (1984) "Modeling in the Technology of Wastewater treatment", Pergamon Press. Budapest.
- [16] Larous S., Meniai A. (2005) "The Use of Sawdust as Adsorbent of Tract Toxic Metals from Wastewater: Adsorption of Copper" E-mail [larous\\_soumsaya@yahoo.fr](mailto:larous_soumsaya@yahoo.fr).Algeria.
- [17] Lin X., Burns R.C., Lawrence G.A. (2005) "Heavy Metals in Wastewater: The Effect of Electrolyte Composition on the Precipitation of Cadmium (II) Using Lime and Magnesia" Australia. E-mail: Robert.Burn@newcastle.edu.au.
- [18] Mc Ketta, "Magnesium Oxide", Encyclopedia of Chemical Processing and Design. Vol. 28, pp. 463-466. Executive Editor John J. Mc Ketta.
- [19] Mihelcic J. R. and Hand D.W. (2001) "Water Supply and Treatment", Michigan University. Houghton, Michigan 49931. John Wiley & Sons, Inc, 1999. web site [www.cee.mtu.edu/~jm41/book/water.pdf](http://www.cee.mtu.edu/~jm41/book/water.pdf).

**Table 1 Aqueous solutions of heavy metals used in the experiment.**

Metal Salts, 5g/l	Molecular structure	M.W. g/gm	Metal ion	Mass mg/l	Company
Cupric sulphate	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$	249.68	Cu (II)	1270	Fluka, Switzerland
Cadmium sulphate	$\text{CdSO}_4 \cdot 8/3\text{H}_2\text{O}$	256.5	Cd (II)	2190	Fluka, Switzerland
Nickel nitrate	$\text{Ni}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$	290.81	Ni (II)	1000	Fluka, Switzerland
Chromium sulphate	$\text{Cr}_2(\text{SO}_4)_3 \cdot 15\text{H}_2\text{O}$	662.41	Cr (III)	780	BDH England
Lead nitrate	$\text{Pb}(\text{NO}_3)_2$	331.2	Pb (II)	1560	BDH England
Ferric chloride	$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$	268	Fe (III)	1100	Fluka, Switzerland

Table 2 the parameters obtained by the Statistica Program for the metals.

NO.	Removal Efficiency	a	b	c	Mean	St. Deviation	Varian ce	Corel. Co. (R)	Relative Error
1	IRON	14.91	34.41	-3.26	80.735	29.230	0.9517	0.9755	2.0 %
2	CHROME	-13.30	31.75	-2.17	63.718	39.090	0.9615	0.9805	5.6 %
3	COPPER	-10.60	29.47	-1.91	62.750	37.746	0.9661	0.9829	5.1 %
4	LEAD	-10.19	20.18	-0.62	53.423	37.923	0.9547	0.9771	9.4 %
5	NICKEL	-8.19	13.19	0.33	47.801	38.118	0.9650	0.9823	10.3 %
6	CADMIUM	-8.92	10.13	0.77	44.176	39.163	0.9525	0.9760	19.7 %

Table 3 Removal efficiencies of all the metals used in the experiment

$$\text{IRON} = 14.9103 + 34.4173 * x - 3.264 * x^2$$

NO. (1)	MgO, g/l	Observed R.E. % (Fe)	Predicted R.E. % (Fe)	Residual	Relative error
1	0	0.00000	14.9103	-14.9103	
2	0.5	33.12000	31.3029	1.8171	0.054864
3	1	53.49000	46.0636	7.4264	0.138838
4	1.5	64.11000	59.1922	4.9178	0.076708
5	2	77.41000	70.6889	6.7211	0.086824
6	2.5	85.41000	80.5536	4.8564	0.05686
7	3	90.53000	88.7864	1.7436	0.01926
8	3.5	98.18000	95.3871	2.7929	0.02845
9	4	98.68000	100.3558	-1.6758	-0.01698
10	4.5	98.75000	103.6926	-4.9426	-0.05005
11	5	98.79000	105.3974	-6.6074	-0.06688
12	5.5	98.81000	105.4702	-6.6602	-0.06740
13	6	98.80000	103.9110	-5.1110	-0.05173
14	6.5	98.64000	100.7198	-2.0798	-0.02108
15	7	98.58000	95.8967	2.6833	0.02722
16	7.5	98.47000	89.4415	9.0285	0.09169

$$\text{CHROME Removal} = -13.3076 + 31.7541*x - 2.1704*x^2$$

No. (2)	MgO, g/l	Observed R.E. % (Cr)	Predicted R.E. % (Cr)	Residual	Relative error
1	0	0.00000	-13.3076	13.3076	
2	0.5	5.12000	2.0269	3.0931	0.604121
3	1	10.42000	16.2761	-5.8561	-0.56201
4	1.5	20.15000	29.4401	-9.2901	-0.46105
5	2	30.05000	41.5188	-11.4688	-0.38166
6	2.5	40.52000	52.5124	-11.9924	-0.29596
7	3	60.31000	62.4208	-2.1108	-0.035
8	3.5	80.33000	71.2439	9.0861	0.11311
9	4	90.42000	78.9818	11.4382	0.126501
10	4.5	92.21000	85.6345	6.5755	0.07131
11	5	95.16000	91.2020	3.9580	0.041593
12	5.5	96.74000	95.6843	1.0557	0.010913
13	6	99.19000	99.0814	0.1086	0.001095
14	6.5	99.49000	101.3933	-1.9033	-0.01913
15	7	99.65000	102.6199	-2.9699	-0.0298
16	7.5	99.73000	102.7613	-3.0313	-0.0304

$$\text{COPPER} = -10.6012 + 29.4775*x - 1.9195*x^2$$

NO. (3)	MgO, g/l	Observed R.E. % (Cu)	Predicted R.E. % (Cu)	Residual	Relative error
1	0	0.00000	-10.6012	10.6012	
2	0.5	10.23000	3.6577	6.5723	0.64245
3	1	10.64000	16.9569	-6.3169	-0.59369
4	1.5	20.54000	29.2963	-8.7563	-0.4263
5	2	30.25000	40.6760	-10.4260	-0.34466
6	2.5	40.44000	51.0960	-10.6560	-0.26350
7	3	60.32000	60.5562	-0.2362	-0.00392
8	3.5	70.14000	69.0567	1.0833	0.01544
9	4	85.55000	76.5975	8.9525	0.10465
10	4.5	91.08000	83.1786	7.9014	0.08675
11	5	94.77000	88.7999	5.9701	0.06300
12	5.5	97.52000	93.4616	4.0584	0.04162
13	6	97.79000	97.1634	0.6266	0.00641
14	6.5	98.00000	99.9056	-1.9056	-0.01944
15	7	98.33000	101.6880	-3.3580	-0.0342
16	7.5	98.40000	102.5107	-4.1107	-0.04178

$$\text{LEAD} = -10.1992 + 20.1802 * x - 0.6221 * x^2$$

No. (4)	MgO, g/l	Observed R.E. % (Pb)	Predicted R.E. % (Pb)	Residual	Relative error
1	0	0.00000	-10.1992	10.1992	
2	0.5	0.00000	-0.2646	0.2646	
3	1	5.50000	9.3589	-3.8589	-0.70162
4	1.5	20.04000	18.6714	1.3686	0.068291
5	2	20.67000	27.6729	-7.0029	-0.3388
6	2.5	30.15000	36.3633	-6.2133	-0.20608
7	3	40.53000	44.7427	-4.2127	-0.10394
8	3.5	45.88000	52.8111	-6.9311	-0.15107
9	4	50.23000	60.5684	-10.3384	-0.20582
10	4.5	75.26000	68.0146	7.2454	0.09627
11	5	88.30000	75.1498	13.1502	0.148926
12	5.5	95.41000	81.9740	13.4360	0.140824
13	6	95.58000	88.4871	7.0929	0.074209
14	6.5	95.88000	94.6892	1.1908	0.01242
15	7	95.90000	100.5802	-4.6802	-0.0488
16	7.5	95.45000	106.1602	-10.7102	-0.11221

$$\text{NICKEL} = -8.1917 + 13.1949 * x + 0.3361 * x^2$$

No. (5)	MgO, g/l	Observed R.E. % (Ni)	Predicted R.E. % (Ni)	Residual	Relative error
1	0	0.00000	-8.1917	8.1917	
2	0.5	0.00000	-1.5102	1.5102	
3	1	5.32000	5.3393	-0.0193	-0.00363
4	1.5	10.23000	12.3569	-2.1269	-0.20791
5	2	12.46000	19.5425	-7.0825	-0.56842
6	2.5	15.22000	26.8962	-11.6762	-0.76716
7	3	35.33000	34.4180	0.9120	0.025815
8	3.5	38.64000	42.1078	-3.4678	-0.08975
9	4	50.53000	49.9656	0.5644	0.011169
10	4.5	55.56000	57.9915	-2.4315	-0.04376
11	5	70.16000	66.1855	3.9745	0.056649
12	5.5	85.74000	74.5475	11.1925	0.13054
13	6	95.31000	83.0776	12.2324	0.128344
14	6.5	96.35000	91.7757	4.5743	0.047476
15	7	96.75000	100.6419	-3.8919	-0.04023
16	7.5	97.22000	109.6761	-12.4561	-0.12812

$$\text{CADMIUM} = -8.9251 + 10.136 * x + 0.7789 * x^2$$

No. (6)	MgO, g/l	Observed R.E. % (Cd)	Predicted R.E. % (Cd)	Residual	Relative error
1	0	0.00000	-8.9251	8.9251	
2	0.5	0.00000	-3.6624	3.6624	
3	1	0.00000	1.9898	-1.9898	
4	1.5	5.32000	8.0314	-2.7114	-0.50967
5	2	7.34000	14.4625	-7.1225	-0.97037
6	2.5	10.52000	21.2831	-10.7631	-1.02311
7	3	25.24000	28.4931	-3.2531	-0.12889
8	3.5	35.26000	36.0925	-0.8325	-0.02361
9	4	40.63000	44.0814	-3.4514	-0.08495
10	4.5	45.61000	52.4598	-6.8498	-0.15018
11	5	76.12000	61.2276	14.8924	0.195643
12	5.5	80.74000	70.3849	10.3551	0.128252
13	6	93.18000	79.9316	13.2484	0.14218
14	6.5	94.53000	89.8678	4.6622	0.04932
15	7	95.67000	100.1934	-4.5234	-0.04728
16	7.5	96.66000	110.9085	-14.2485	-0.14741

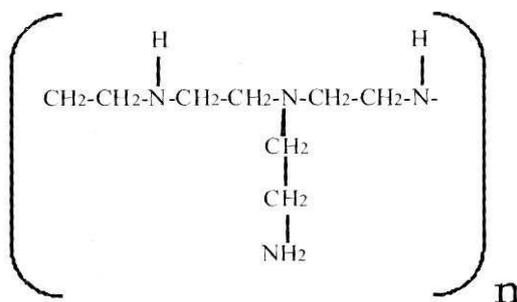


Figure 1 The polyelectrolyte used in the experiment

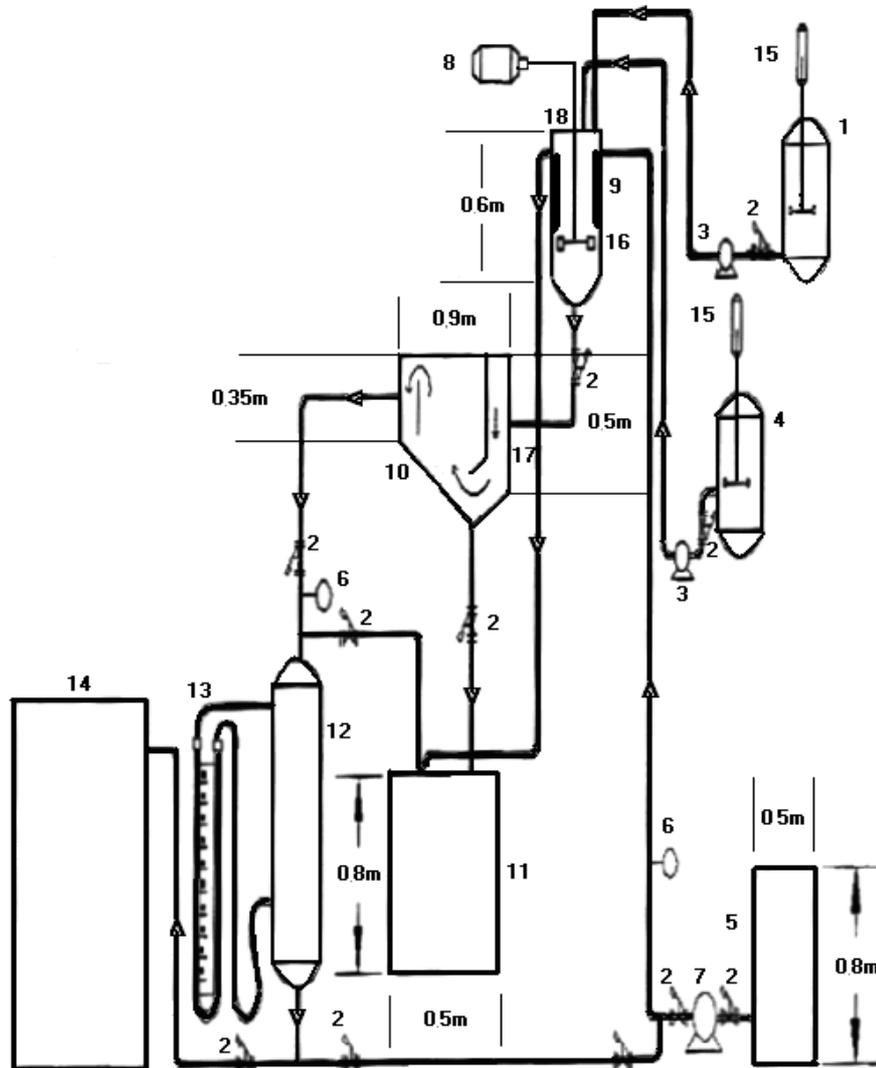


Figure 2 Schematic diagram of the wastewater treatment pilot plant

- |                         |                   |                         |
|-------------------------|-------------------|-------------------------|
| 1. MgO or CaO solutions | 7. Pump           | 13. Manometer           |
| 2. Valve                | 8. Motor          | 14. Storage tank        |
| 3. Dosing pump          | 9. Mixing tank    | 15. Mixer               |
| 4. Polyelectrolyte      | 10. Settling tank | 16. Six bladed Turbine  |
| 5. Feed tank            | 11. Sludge tank   | 17. Steel plates        |
| 6. Flowmeter            | 12. Sand filter   | 18. Rectangular baffles |

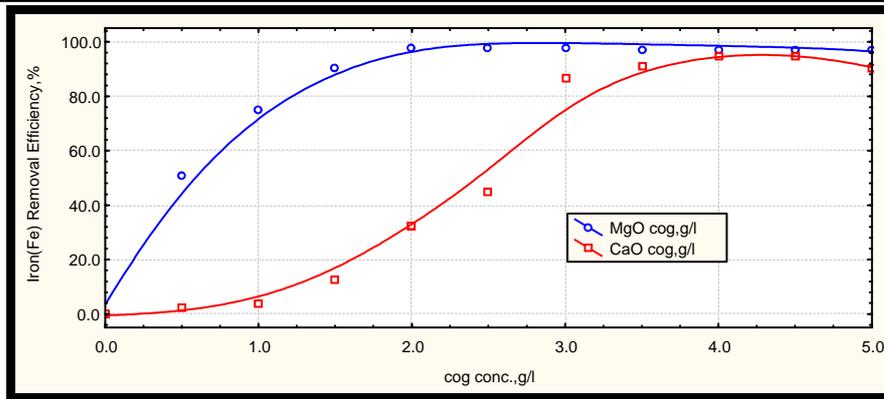


Figure 3 Effect of the precipitation agents type and dosage on the removal efficiency of iron ( $C_{initial} = 1100$  mg/l).

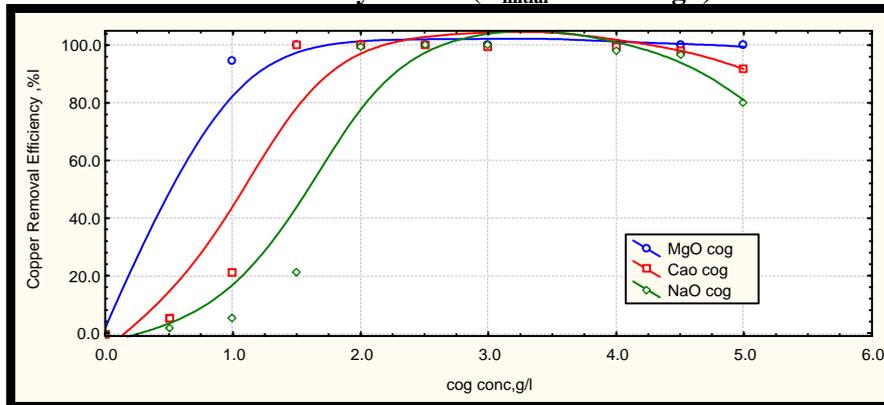


Figure 4 Effect of the agent type and dosage on the removal efficiency of copper (initial concentration ( $C_{initial} = 1300$  mg/l)).

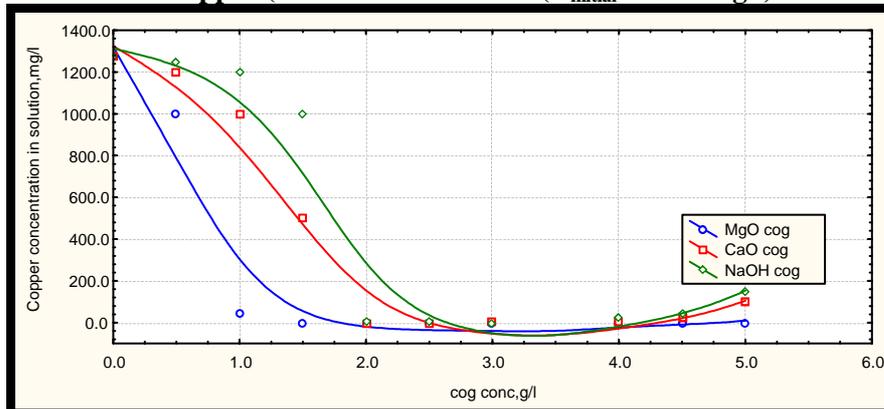


Figure 5 Effect of the precipitation agents on the concentration reduction of copper in the solution ( $C_{initial} = 1300$  mg/l).

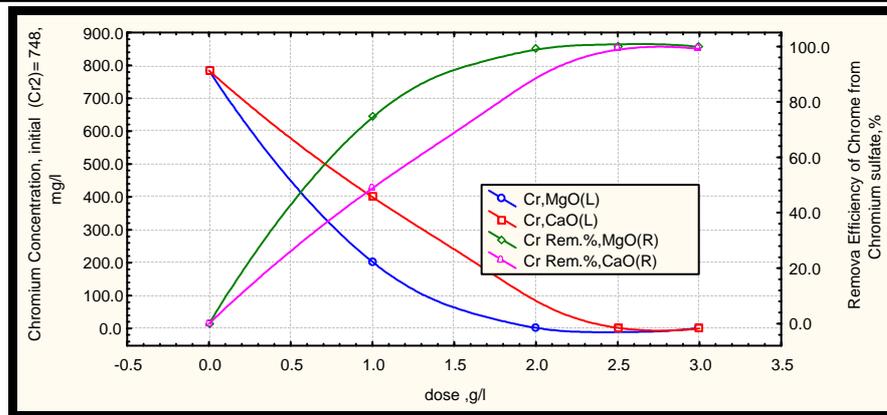


Figure 6 Effect of magnesia and lime doses on the removal efficiency and concentration decay of chromium ( $C_{initial} = 748$  mg/l).

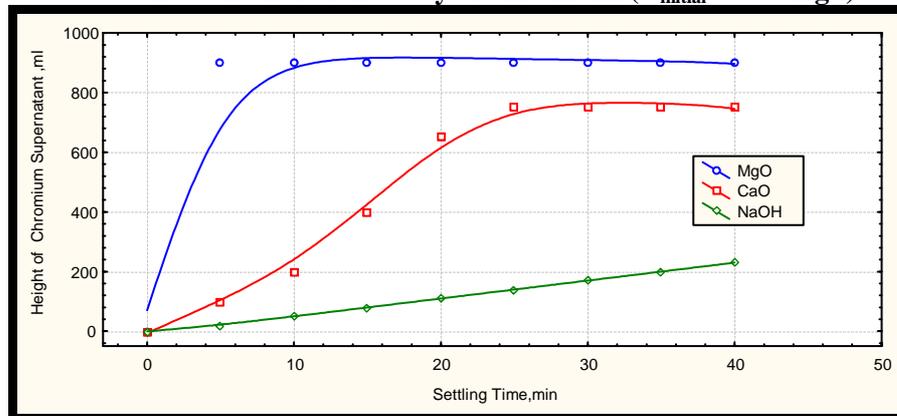


Figure 7 Cr precipitation settling rate by MgO, CaO, and NaOH agents

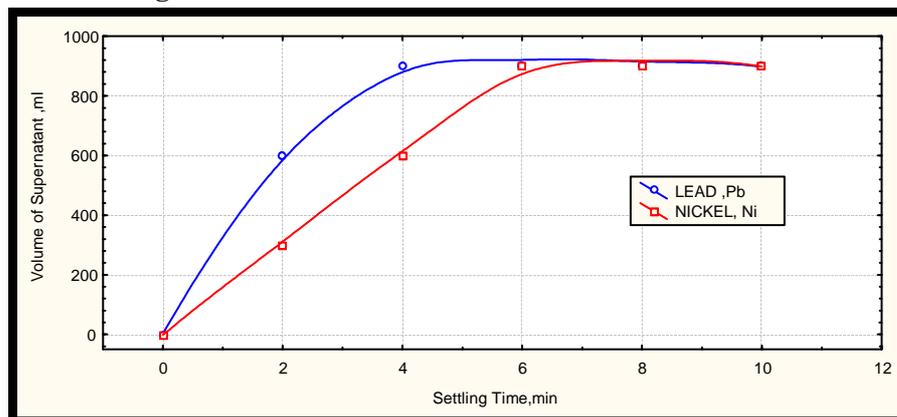


Figure 8 Nickel and lead precipitation settling rate by magnesia with polyelectrolyte.

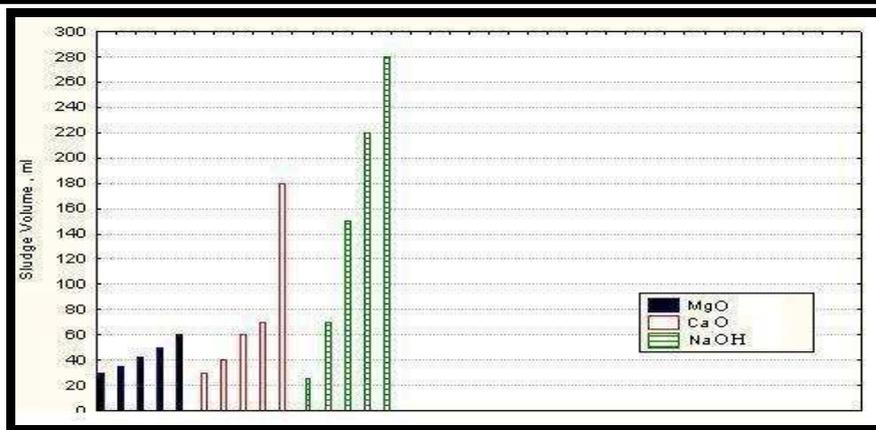


Figure 9 Sludge volumes of chromium for the three precipitating agents (settling time 3 hrs)

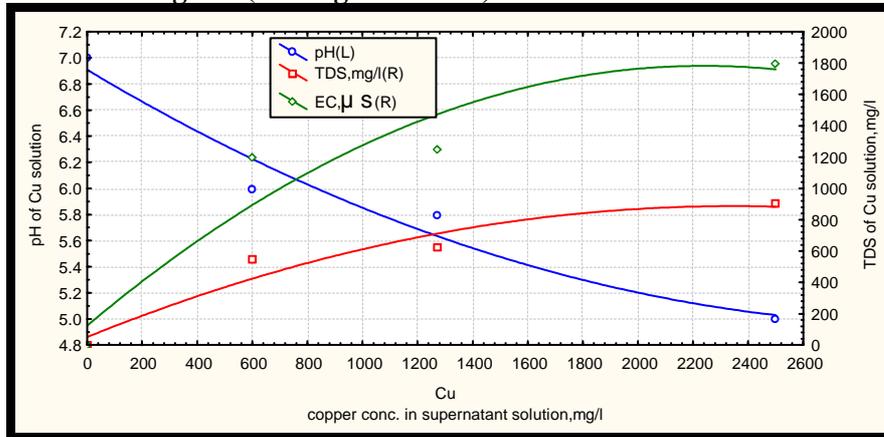


Figure 10 Effect of the concentration changes of copper on the pH and TDS in the solution before adding the agent.

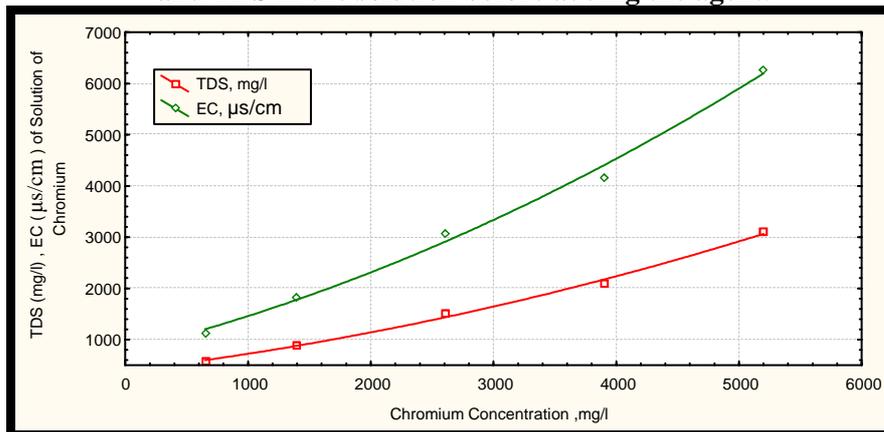


Figure 11 Effect of the concentration changes of chromium on the TDS and EC in the solution before adding the coagulant.

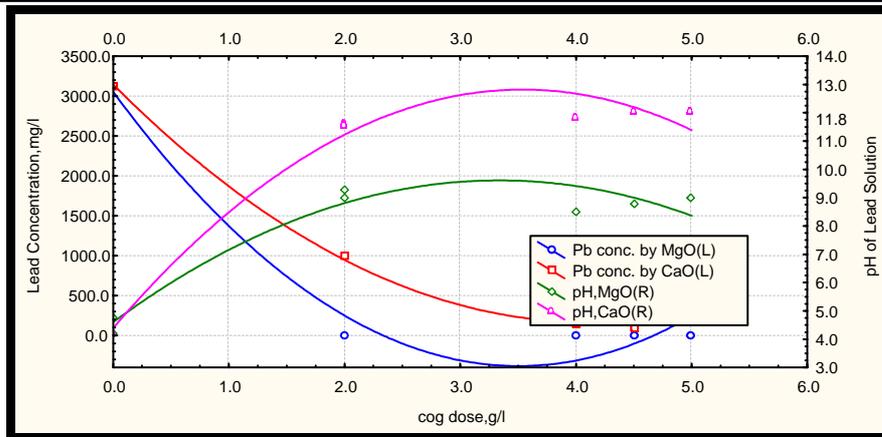


Figure 12 Effect of the agent type and its concentration on the residual concentration and pH values of lead in solution ( $C_0 = 3120$  mg/l).

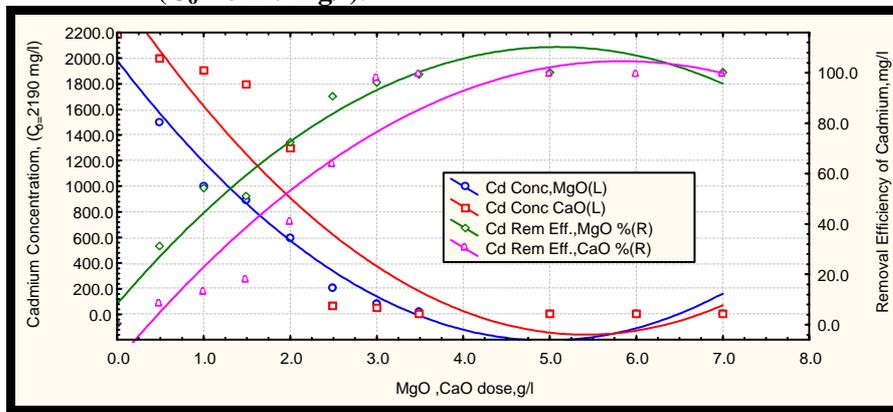


Figure 13 Effect of the precipitation agent type and doses on residual concentration and removal efficiency of Cd ( $C_0=2190$ ).

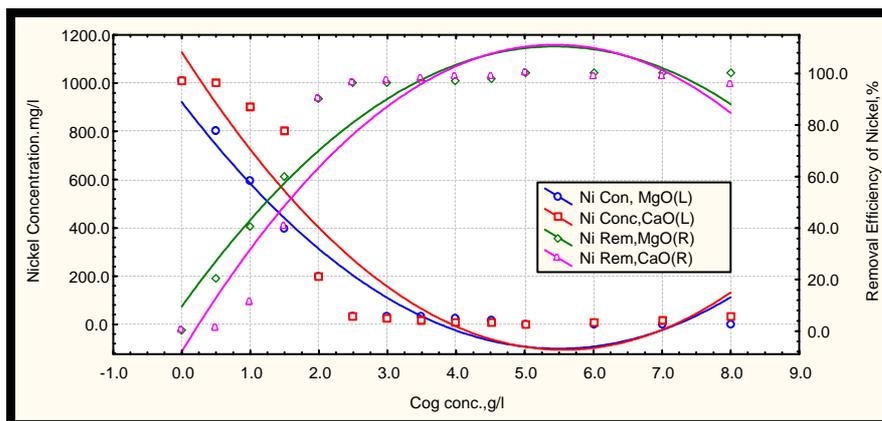


Figure 14 Effect of the precipitation agent type and doses on residual concentration and removal efficiency of the Ni ( $C_0=1000$ ).

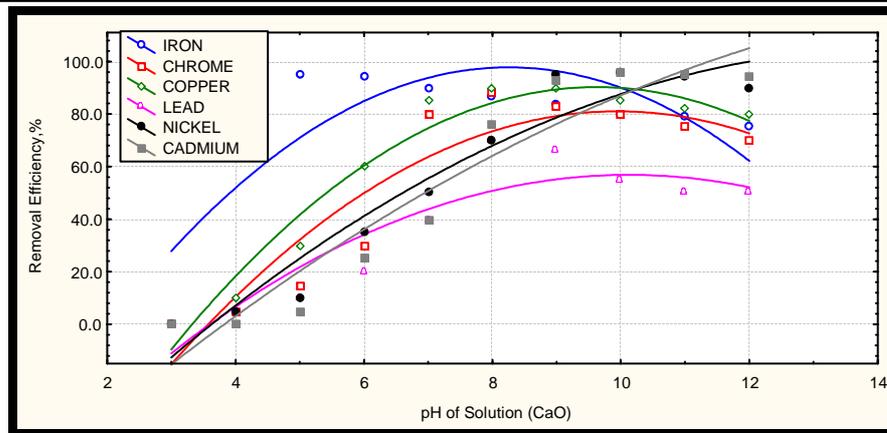


Figure 15 Effect of the pH values on the removal efficiency of the various metals used by using CaO.

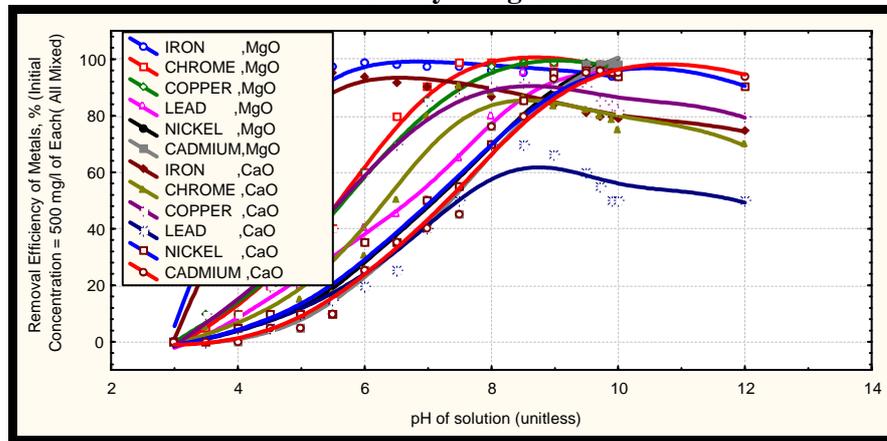


Figure 16 Effect of the pH values on the removal efficiency of the various metals used by using MgO, CaO

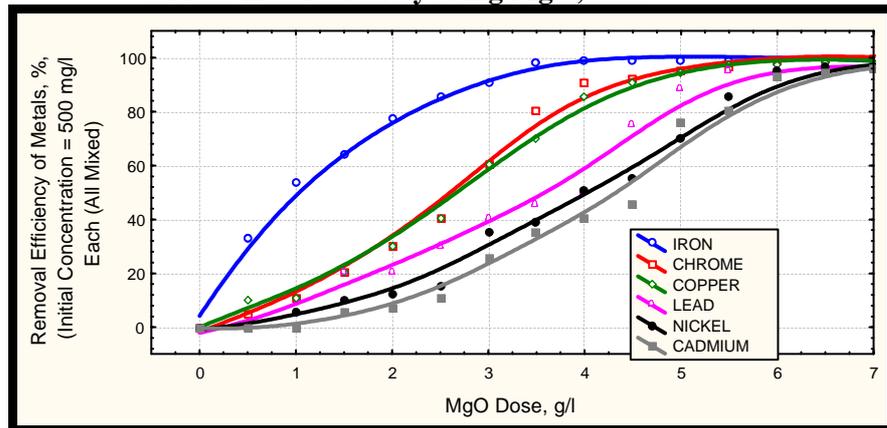


Figure 17 Effect of MgO doses on the removal efficiency of various metals used ( $C_0=500$  mg/l of Each (All Mixed Together))