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Recovery of Refractory Metals from Steelmaking Dust using a Hydrometallurgical Approach

Bachelor's thesis in the Chemical Engineering program

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Cover: A sample of steelmaking dust used in this study

Abstract

Molybdenum is a valuable refractory metal that is widely used in the steel industry to reduce weight in automobiles and in the production of other chemical products. Due to its scarcity in primary sources, the need to develop technology that can effectively recover molybdenum from secondary sources has been of great interest for researchers. In this study, a hydrometallurgical method was used to recovery molybdenum from steelmaking dust using sodium hydroxide (alkaline leaching). Leaching was done with a constant solid/liquid ratio of 1:50. The optimum leaching conditions were found to be 0.5M sodium hydroxide, 25°C and 5 minutes. The leaching efficiencies obtained were 48% and 52% at 60°C and 90°C respectively. The leaching process was found to occur fast, with maximum efficiency being achieved within the first 5 minutes. The other elements such as zinc, vanadium, and iron were leached in small amounts, which confirmed that alkaline leaching is selective.

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1. Introduction

Refractory metals are metals that are used for various industrial applications due to their ability to resist high temperatures. The most common refractory metals include tungsten, rhenium, tantalum, and osmium. Molybdenum (Mo) and vanadium (V) are some of the rare refractory metals whose physical and chemical properties make them valuable elements for the steel industry [1]. These rare refractory metals occur in limited amounts in nature. Thus the need to develop technologies that can be used to recover such refractory metals from secondary sources has been of great interest for many researchers.

Although there are many refractory metals, this study will only focus on the recovery of molybdenum from secondary sources. With a melting point of 2622°C, molybdenum is used as a valuable additive in steel production. When molybdenum is combined with chromium and vanadium, the resulting alloy is used for hardening, tempering and hydrogen embrittlement of steel metal to achieve the desired resistance against high temperatures and heavy loads. Molybdenum is also used to promote green technology when it is used in various industrial processes for example as catalyst, corrosion inhibitors, smoke suppressants, and to reduce weight in automobiles. According to the International Molybdenum Association (IMO), the industrial application of molybdenum is as shown in Figure 1. [2]

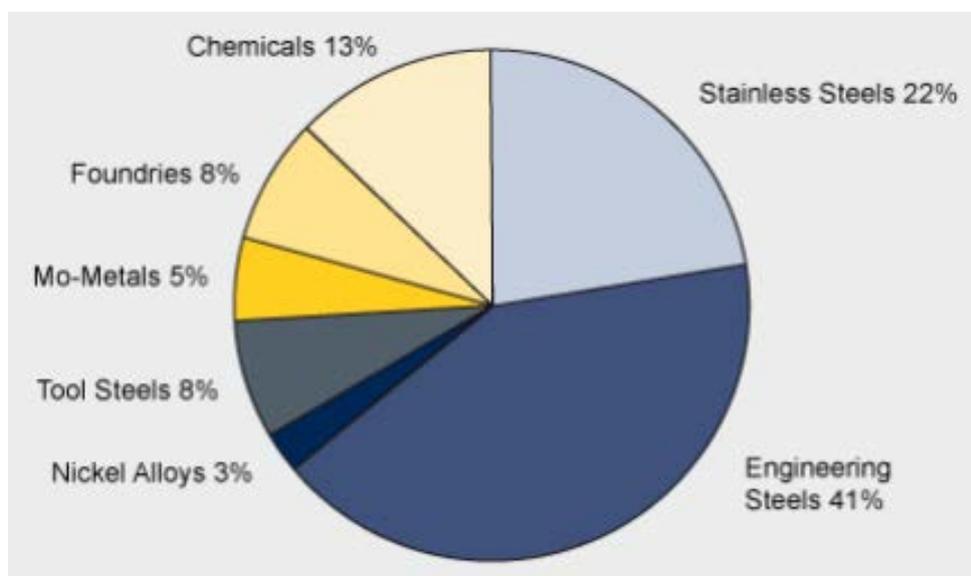


Figure 1. Application areas for molybdenum [2].

Although the application of molybdenum has increased over the last decades, its world production has been low with just a few countries being able to produce it from ores as shown

in figure 2. The global production of molybdenum as of 2014 was 266000 ton [3]. This low production of molybdenum from primary sources (ores) is mainly because molybdenum is limited in ores and only exists in combination with other elements, such as in MoS₂. In the ores, molybdenum content ranges between 0.01 and 0.25% [2].

Countries	Production (MT)
China	94000
US	56000
Chile	39000
Peru	12000
Canada	9100
Mexico	8000
Armenia	4200
Russia	3800
Iran	3700
Mongolia	3000
Uzbekistan	550
Kazakhstan	400
Kyrgyzstan	250

Figure 2. Major world producers of molybdenum [4].

However, molybdenum can also be produced from several secondary resources. These resources include Fly ash (from combustion of coal), mill scale, copper slag, radioactive wastes and steelmaking dust. In this study, steelmaking dust will be used as the source to recover molybdenum. It is estimated that 30-70 kg of steelmaking dust per ton of produced steel goes to waste [5]. Although steelmaking dust contains mainly iron and zinc, it also contains valuable elements that can be recovered and reused, such as chromium, magnesium, manganese, nickel, lead and molybdenum.

Within the European Union (EU), the production of molybdenum has been low mainly because of its low availability in nature. Thus, many countries within EU import molybdenum from other countries. This has led to an increase in costs and dependency on other molybdenum producing countries, such as China. A report issued in 2016 by PROMETIA stressed the need to develop technologies for recovery of refractory metals from secondary sources. [3] This approach will not only save the environment from waste dumping, but also save EU countries costs of importing such raw-material and reduce dependency on other countries.

2. Purpose

With increasing demand of molybdenum for industrial applications, the need to explore and utilize secondary resources of molybdenum is increasing. In this project, the recovery of molybdenum from steelmaking dust using alkaline leaching was examined. The investigation was carried out with the aim to study different factors that influence the leaching process, and examine the optimum leaching conditions for molybdenum. The study also aims to improve the leaching technology for molybdenum by separating it from zinc using sodium hydroxide (NaOH). Low concentration of NaOH and low temperatures was used, which a good approach for metal recovery.

The study also included measurements of the concentrations of vanadium, zinc, and iron in the dust samples.

3. Theory

The recovery of refractory metals such as molybdenum is becoming more essential within chemical industry. When recovering molybdenum, two main separation techniques can be used: pyrometallurgical and hydrometallurgical processes. Although the former is predominantly used today to recover metals, it presents more challenges both for the chemical processes and to the environment. Pyrometallurgical methods require high amounts of energy and a well-developed dust collecting system must be developed to render the method effective [6]. Hydrometallurgical methods, however, have more advantages than pyrometallurgical methods. For example, a hydrometallurgical process is more suitable for small scale metal recovery with a high purity final product, more environmentally friendly since it requires low energy and is suitable for recovery of industrial wastes with different metal compositions [7].

Although a hydrometallurgical process has more advantages, there has been only a little research done on the alkaline leaching of steelmaking dust. In most of the previous studies, hydrometallurgical processes have mainly been applied in recovery of zinc and iron from industrial waste. Both acidic and alkaline leaching have been studied, where zinc and iron have been recovered in high yields (85%-100%) [5,8]. The presence of significant amounts of molybdenum has also been reported in other studies. A report of an investigation done by the Bureau of Mines in the United States showed that there is a significant amount of molybdenum in steelmaking dust [9]. Another study found concentrations of molybdenum in two samples in the range of 0.075-1.4% [5]. Steelmaking dust is thus a potential secondary resource for recovery of molybdenum.

To determine the optimum conditions for the recovery of molybdenum from steelmaking dust in this study, the dust will undergo a leaching process using NaOH and then be filtrated. Molybdenum is mainly present in the steelmaking dust in the form of MoO₃. As shown in figure 3 below, molybdenum can be produced and recovered via different routes. During alkaline leaching, molybdenum reacts with NaOH to form sodium molybdate according to equation (1) [2]. The product formed (sodium molybdate) can then be used as raw material for production of other products. Molybdenum has been reported to form different species depending on the pH of the medium, with the main specie in alkaline solution being MoO₄²⁻ [10].



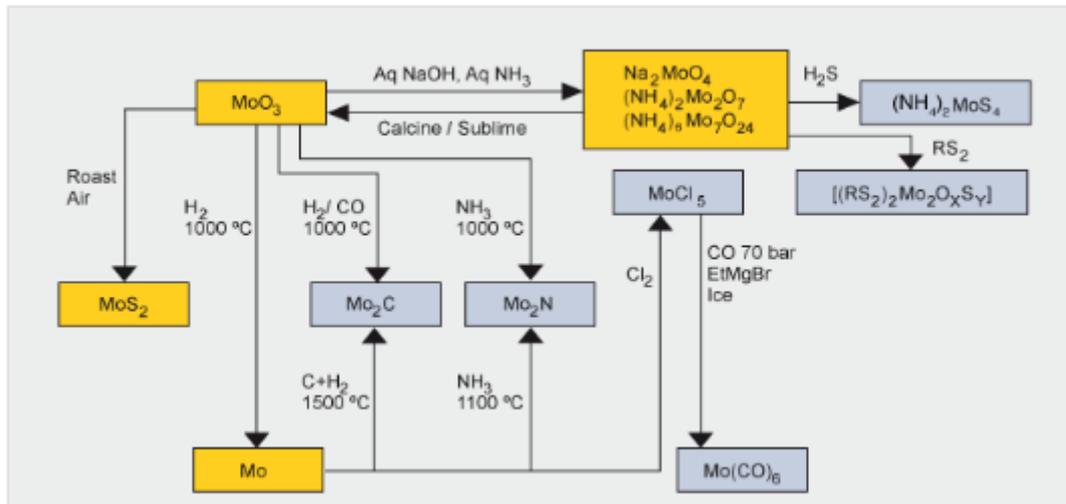


Figure 3. Different routes for production of molybdenum. [2]

3.1 Characterization of steelmaking dust

Material characterization gives insight into the chemical composition of the sample. By using different analytical techniques, it is possible to understand the chemical composition of the material, the size of particles and, the presence of crystal compounds. This is specifically important when determining which separation technique to use for the recovery of metals in sample.

In this study, the analytical techniques used to characterize the samples included: inductive coupled plasma optical emission spectrometry for element concentrations, X-ray powder diffractometry for identification of crystalline compounds, scanning electron microscopy with element identification by energy dispersive X-ray fluorescence spectroscopy and measurement of specific surface area by BET analysis [11].

3.2 Optimization of the leaching process

A leaching process involves removing chemical compounds from solid substances into a liquid solvent. It involves the chemical dissolution of the compounds as well as transport of the dissolved ions through the pore system of the solid to the bulk liquid solvent, i.e. the leachate. In this study, alkaline leaching was used with aqueous solution of NaOH as the solvent. Although there are several factors that influence both the leaching process and product quality, only three factors were investigated in this study. These factors include: NaOH concentration, leaching temperature and leaching time. Molybdenum has been reported to dissolve just as well as zinc in higher NaOH concentration [5]. The higher concentrations used for leaching molybdenum presents however a problem for the steel industry because zinc

is harmful for steel production. Thus the need to separate molybdenum from zinc in the leachate is vital in order to render the leachate more useful.

Recovery of refractory metals through acidic leaching has also been tested in many other studies, giving good yields of metal recovery [8,10]. Acidic leaching based on sulphuric acid and hydrochloric acid when used however brings unwanted constituents such as sulphur and chlorine to the steelmaking process. In this respect, alkaline leaching provides better selectivity leading to pure product.

4. Materials and method

4.1 Materials

The steelmaking dust samples used in this study were provided by Uddeholm AB. Different analytical techniques used for analysis of the samples included; inductive coupled plasma optical emission spectrometry ((ICP-OES, ICAP 6500, Thermo Fischer), energy dispersive spectroscopy (EDS), field emission scanning electron microscopy (FEI, Quanta 200 FEG ESEM), and BET analysis.

Reagents: 0.5M and 1M NaOH for leaching and 0.5M HNO₃ for dilution.

4.2 Characterization of the steelmaking dust samples

Characterization of the samples was already performed before I started with my project. The method and procedure used was as follows.

X-ray diffraction (XRD, Bruker D8 Advance) using Cu K α radiation was used to identify the crystalline compounds present in the samples. The conditions for XRD data collection were continuous scanning of a detector covering a 2Θ angular range from 10° to 90° with a step size of 0.04 and a wavelength of 1.541874 Å. The crystalline compounds in the samples were identified by comparison with standards in the Joint Committee for Powder Diffraction Standards database.

The chemical compositions of the samples were analyzed by inductive coupled plasma optical emission spectrometry after dissolution (ICP-OES, ICAP 6500, Thermo Fischer) and energy dispersive spectroscopy (EDS) coupled to a Scanning Electron Microscope (SEM). The particle size and morphology of the samples were investigated by field emission scanning electron microscopy (FEI, Quanta 200 FEG ESEM). The surface area of the samples was measured by BET analysis (Micromeritics ASAP 2020 Surface Area and Porosity Analyzer).

4.3 Leaching process

For the leaching process, different parameters were investigated to determine the optimum conditions for leaching. The investigated parameters were NaOH concentration, leaching temperature, and leaching time. The steelmaking dust sample provided by Uddeholm was used for the experiments. A constant low solid to liquid ratio of 1:50 was used to make it easy to observe the effect of the different parameters under investigation.

NaOH was used as leaching medium with concentrations of 0.5M and 1M. The 0.5M was provided by the supervisor and 1M of NaOH was calculated and prepared (see appendix A for calculations). 50 ml 0.5M NaOH was added to a plastic jar and placed on a heater. The temperature was then set to 25° C and the solution was stirred using a magnetic stirrer at a rate of 250 rpm. When the solution had reached the 25° C, 1g of sample was added and a timer started immediately. After 5 minutes, a sample was taken and transferred to a 10mm vial. The set up was shown in figure 4.



Figure 4. Experimental set up for the leaching process of molybdenum

4.3.1 Investigation of the effect of sodium hydroxide concentration on the leaching process.

To investigate the effect of the concentration of the leaching medium (NaOH) on leaching, the procedure above was done separately for 0.5M and 1M of NaOH. A summary of leaching conditions were as shown in table 1.

4.3.2 Investigation of the effect of temperature on the leaching process.

The effect of temperature on the leaching process was investigated by repeating the leaching process for temperatures of 25° C, 40° C and 60° C and taking samples for time intervals of 5, 15, 30, 60, 120 min.

4.3.3 Investigation of the effect of time on the leaching process.

To investigate the effect of time on the leaching process, samples were taken for time intervals of 5, 5, 15, 30, 60, 120 min.

Table 1. Leaching conditions for optimization of leaching process

Concentration of NaOH (M)	Temperature (°C)	Leaching time and sampling (min)	Solid to liquid ratio (g:ml)
0.5	25, 40, 60	5, 15, 30, 60, 120	1:50
1	25, 40, 60	5, 15, 30, 60, 120	1:50

4.3.4 Determining the actual concentrations of target elements in steelmaking dust

To determine the actual concentration of the steelmaking dust used in this study, aqua regia was used. Aqua regia is a solution mixture of nitric acid and hydrochloric acid in volume ratio of 1:3.

0.2g of the dust was dissolved in 50ml of aqua regia and then diluted 1000 times. A sample was then taken and analyzed using ICP-OES to determine the concentrations of the elements.

4.4 Filtration process

The leachate from section 4.3 was filtered using Lafil 400 vacuum filtration system with Whatman Grade GF/B filter paper (12.5 cm size). The mass of the filter paper was noted before filtration. After filtration, the filter paper and the filtrate were left to dry, and their masses determined afterwards.

5. Results and discussion

In this section, the results from characterization of samples and ICP analysis will be presented and discussed.

5.1 Results from characterization of samples

Figure 5 shows EDS results from the steelmaking dust sample. The EDS analysis was performed to determine the general chemical composition of the sample to lead the detailed elemental characterization by ICP-OES. The major chemical compositions of the sample include iron, zinc and oxygen elements. Manganese, magnesium, nickel and calcium were observed in low amounts. Chromium was observed in high amount in the sample.

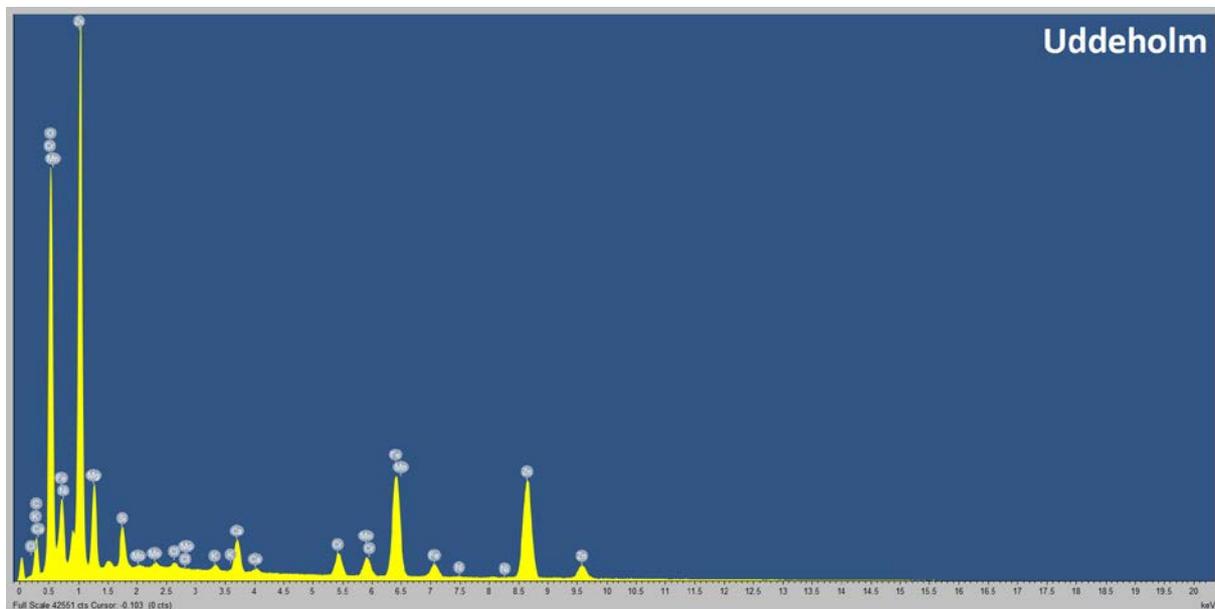


Figure 5: Chemical composition of steelmaking dust sample as obtained using EDS

Figure 2 shows the XRD pattern of the samples. Peaks observed at 18.3° , 30.1° , 35.5° , 37.1° , 42.1° , 53.5° , 56.7° , 62.3° , 73.5° and 89° 2theta values belong to franklinite ($\text{Zn}_{1.1}\text{Fe}_{1.9}\text{O}_4$) and manganese zinc iron oxide ($\text{Zn}_{0.7}\text{Mn}_{0.23}\text{Fe}_{1.89}\text{O}_4$) structures which are face centered cubic structured with Fd-3m space group. Hexagonal ZnO and zinc-iron oxide peaks (Space group: P63mc) are detected at 31.8° , 34.4° , 36.2° , 47.6° , 59.7° , 62.9° , 68° and 69.2° 2theta values. The main phase of the sample was Hexagonal ZnO and $\text{Zn}_{0.97}\text{Fe}_{0.03}\text{O}$ and second major phase

was franklinite structure.

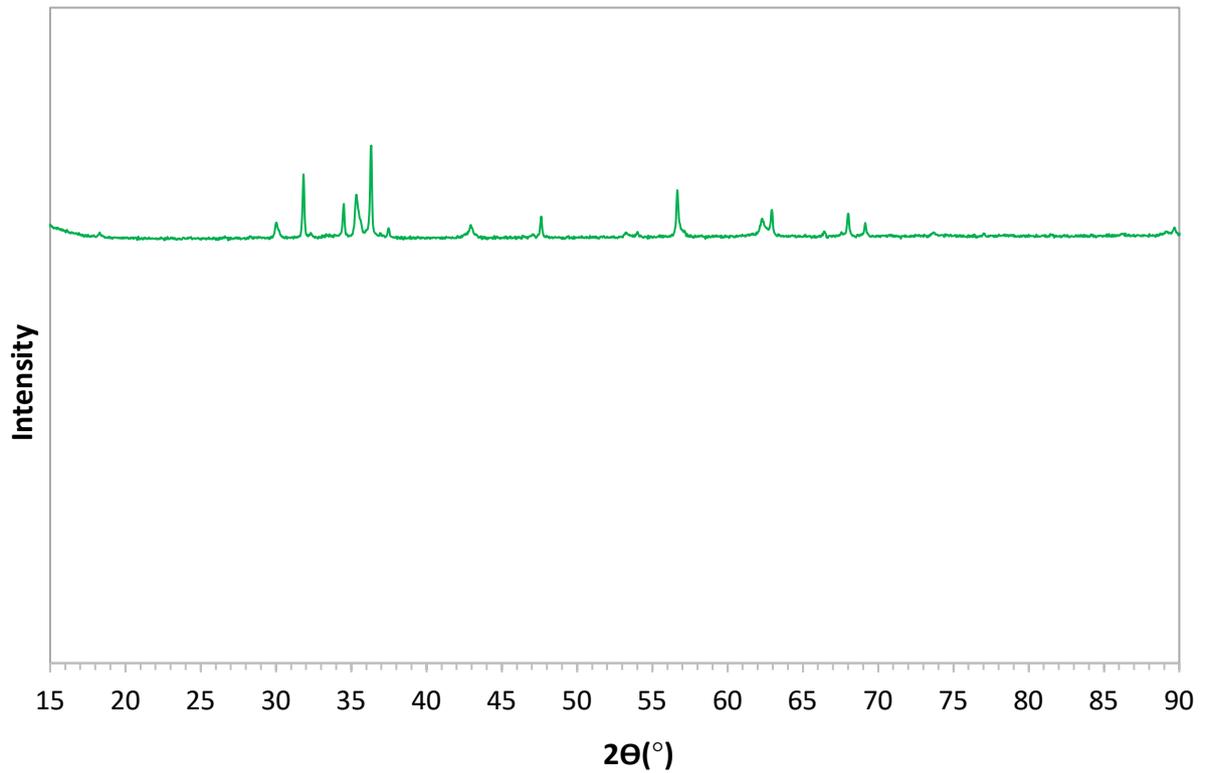


Figure 6: XRD patterns of steelmaking dust sample

The SEM images of the samples are shown in Figure 7. The samples have spherical particle morphology and their particle sizes are in the submicron range, but they are agglomerated. Although samples have some coarse particles around 5 μm , the average particle size was 360 nm. The BET surface area was $3.5477 \pm 0.0232 \text{ m}^2/\text{g}$. The results exhibit relatively high surface area, which support the determined average particle sizes from the SEM images.

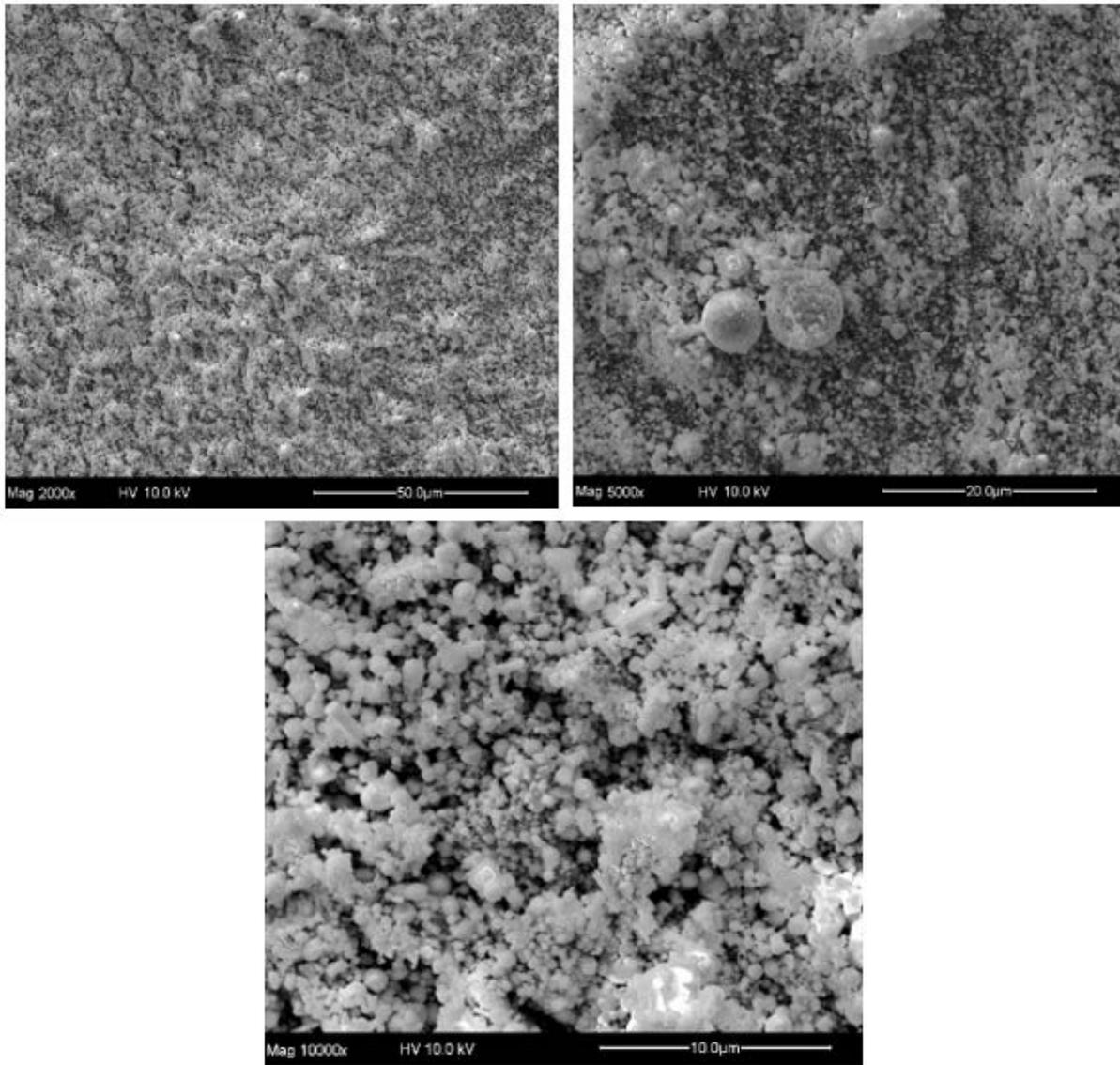


Figure 7: SEM images of the sample

5.2 Results from ICP-OES analysis

The actual concentrations of the target elements in the dust as leached with aqua regia were as shown in table 2. Zinc was found to be present in twice as high concentration as iron.

Molybdenum and vanadium content was found to be less than 1% in the dust. These metal compositions were later used in calculating the amount of leached content during the alkaline leaching process, as will be discussed in the next section.

Table 2. Composition of the steelmaking dust as leached with aqua regia.

Element	Concentration (%)
Mo	0.61
V	0.07
Zn	33.0
Fe	15.4

The metal concentrations obtained from the ICP-OES can be found in appendix B. The discussion of results mainly focuses on molybdenum since it is the target element for this study.

5.2.1 Effect of NaOH concentration

The effect of concentration of NaOH on the leaching process for molybdenum was as shown in figure 9 below. When the concentration was increased from 0.5M to 1M, no significant increase in leaching efficiency was observed. For both concentrations, the leaching efficiencies obtained were 45% after 5 minutes and 47% after 120 minutes. This indicates that the concentration of NaOH does not have a significant effect on the leaching process of molybdenum.

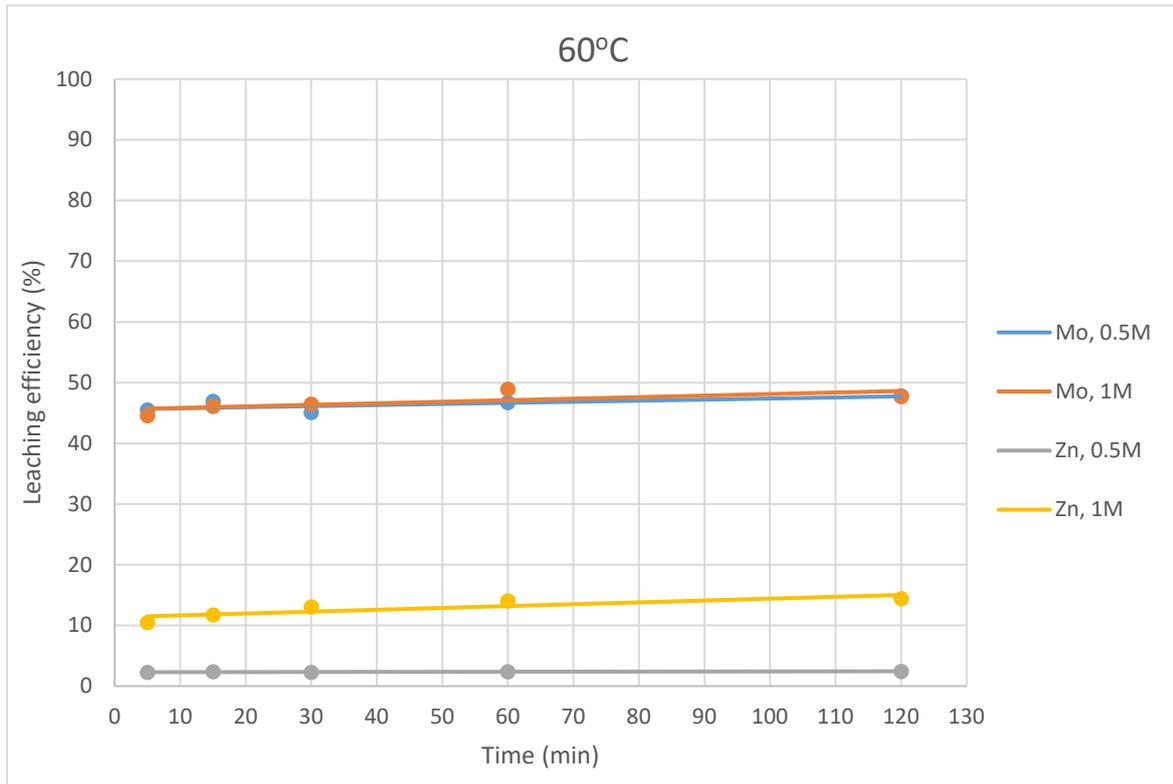


Figure 9. The effect of concentration of NaOH on leaching process of molybdenum and zinc

Figure 9 also shows how zinc was leached in comparison to molybdenum. It can be seen that zinc had leaching efficiencies of 2% and 14% for 0,5M and 1M respectively. The leaching of zinc is seen to increase with increasing concentration of NaOH. Thus to separate molybdenum from zinc, low concentration of NaOH (0.5M) is preferable since less zinc is leached out.

5.2.2 Effect of leaching temperature

Leaching temperature can be observed in figure 10. It can be seen that more molybdenum was recovered as the temperature was increased. The leaching efficiencies achieved with 0.5M NaOH were 42% and 48% for 25°C and 60°C respectively. It can be seen that the increase in molybdenum recovery with increasing temperature is not high. This can also be observed in the free Gibbs energy diagram (see appendix D) that the change in Gibbs free energy with increasing temperature is very small. Zinc recovery was low (2%) for all the temperatures, as seen in figure 10.

Although molybdenum recovery has been reported to increase with increasing temperature [12], in this study the increase in temperature had little effect on the leaching efficiency when low concentration of sodium hydroxide was used. From an economical point of view, it would be more sustainable to leach at 25°C than at higher temperatures.

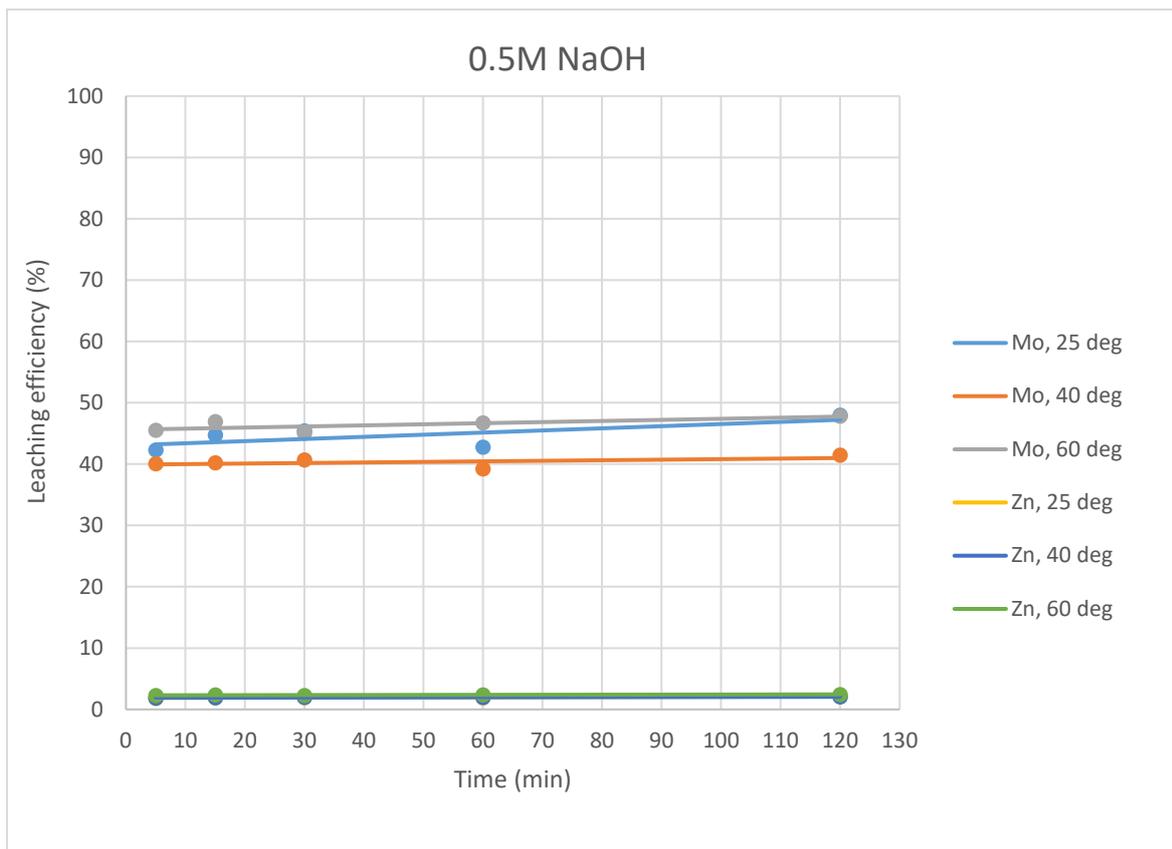


Table 10. The effect of temperature on the leaching process of molybdenum

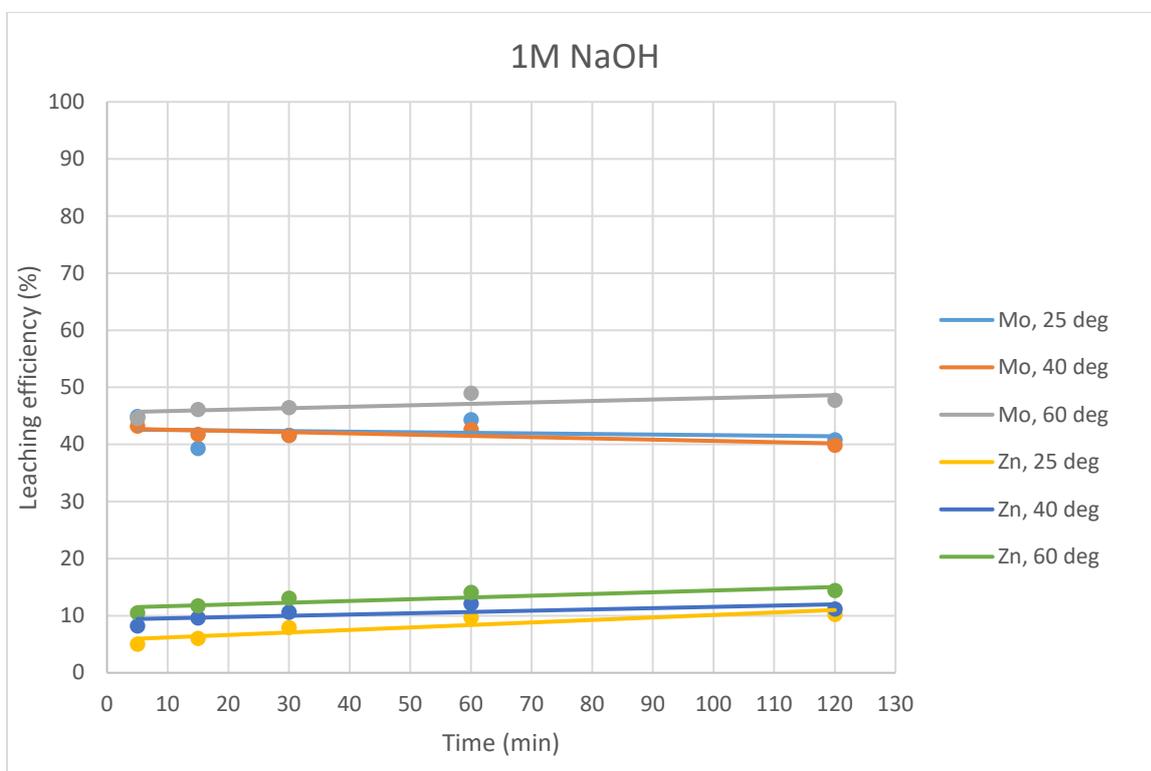


Figure 11. Effect of temperature on the leaching process of molybdenum

When the concentration of NaOH was increased to 1M, the effect of temperature on molybdenum recovery was observed to be small as well. On the other hand, zinc recovery was observed to increase up to 14% at 60°C, see figure 11. Molybdenum can thus be separated better from zinc by leaching at low temperature. Besides, leaching at 25°C is more environmentally friendly since less energy is consumed.

5.2.3 Effect of leaching time

The effect of time on the recovery of molybdenum was as observed in figures 10 and 11 above. Both figures show a small positive effect of time on the recovery of molybdenum. In both figures, the maximum leaching efficiency is reached within the first 5 minutes. This shows that alkaline leaching with low concentration is fast for recovery of molybdenum. This result agrees with the previous study that also found maximum leaching of molybdenum with NaOH to occur within the first minutes of leaching [12].

5.2.2. Leaching at 90°C

Leaching of molybdenum was tested at 90°C to understand the effect of higher leaching temperature on the leaching process and to increase molybdenum recovery rate if possible. And as seen in table 3 below, the highest achieved leaching efficiency was 52%, which was obtained within the first 5 minutes of leaching. When compared with leaching at 60°C (48%), the recovery only increased by 4%. This small increase in leaching efficiency for 60°C respective 90°C could indicate that most of the soluble and accessible molybdenum has already been leached out. However, to make sure of this, solid residues could be dissolved in aqua regia after 60 °C respective 90 °C and analyzed for residual molybdenum content.

Table 3. Leaching of Molybdenum at 90°C

NaOH concentration	Temperature, 90°C				
	Time (min)	Leaching efficiency (%)			
0.5M		Mo	V	Zn	Fe
	5	52.24	1.53	2.57	0.75
	15	52.59	7.03	2.56	0.71
	30	52.59	6.89	2.56	0.72
	60	52.02	2.88	2.59	0.72
	120	52.50	8.45	2.64	0.73
1M	5	52.17	3.86	13.57	0.78
	15	52.04	1.15	14.29	0.72
	30	51.57	1.83	14.58	0.68
	60	51.44	3.72	14.85	0.67
	120	51.92	2.25	14.90	0.65

5.3 Leaching of other elements

The other elements measured in this study were vanadium, zinc and iron. Vanadium had a low leaching efficiency, with only up to 5% being leached out. Zinc showed a positive response to all the parameters under study, with leaching efficiencies of 2% and 14% for 0.5M and 1M NaOH respectively. Zinc becomes more soluble in sodium hydroxide as the concentration increases. From the potential/pH diagram in appendix E2, it is seen that when pH is below 13, the most common zinc specie is $Zn(OH)_2$, which hardly dissolves in sodium hydroxide. However, as the pH of the solution increases, a more soluble specie of zinc ($Zn(OH)_4$) is formed. When the leaching was tested at 90°C for both 0.5M and 1M NaOH, the same leaching efficiency was obtained for zinc (see table 2). It has also been reported in other studies that zinc dissolves well in higher concentrations of NaOH [3,10]. Thus, in order to recover molybdenum from secondary sources that contain high amount of zinc, alkaline leaching with low concentrations of alkaline substance is recommended.

Iron had very low leaching efficiency of less than 1%. In alkaline solution, iron forms precipitate which is insoluble in solution, see appendix E3. This confirms that alkaline leaching is selective for certain metals.

From filtration, it was found that little of the constituents of the dust was dissolved in sodium hydroxide (see appendix F). This is because only those metals with high solubility in sodium hydroxide could dissolve during leaching. The color of the filtrate was also observed to be light green, indicating the presence of chromium ions. It is recommended that the leachate undergoes further treatment to recover chromium and other heavy metals that are soluble in sodium hydroxide during leaching of steelmaking dust.

6. Conclusion

The aim of this study was to investigate the effect of selected parameters on molybdenum leaching from steelmaking dust using a hydrometallurgical approach. The hydrometallurgical methods used in this study were alkaline leaching using NaOH and filtration. The parameters investigated were concentration of leaching medium, leaching temperature and time for leaching. All these factors are considered important for the effective recovery of molybdenum in steelmaking dust.

The steelmaking dust used in this study was provided by Uddeholm AB. Through sample characterization, it was found that the dust contained different elements including refractory metals such as molybdenum and vanadium. Other important elements such as zinc and chromium and iron were also found to be main components of the dust in the form of oxides and metal complexes.

From this study, it has been found that the concentration of sodium hydroxide does not have much effect on the leaching process of molybdenum. Similarly, the leaching temperature was found to have little effect on the leaching process. The maximum leaching efficiency obtained for molybdenum was 48%, which was reached within the first 5 minutes of leaching with temperature of 25°C and 0.5M NaOH.

The other elements had low leaching efficiencies: zinc (2-14%), vanadium (5%) and iron was almost not leached out (<1%). This confirmed that alkaline leaching is selective for molybdenum leaching and could further be optimized to selectively leach out more molybdenum from steelmaking dust. When leaching with low concentration of NaOH (0.5M) and low temperature (25°C), the process becomes more economical and environmentally friendly since less energy is consumed in the process.

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Appendix

Appendix A. Formulas and calculations used in the study

Calculating mass for obtaining 1M NaOH

NaOH pellets of 97.0% purity were provided by the supervisor. To prepare 1M, the following calculations were done.

$n = C \cdot V$ where C is the concentration, n is number of moles, V is volume

$$n = 1 \text{ (mol/liter)} \cdot 0.5 \text{ (liter)} = 0.5 \text{ mol}$$

$m = n \cdot M$ where m is mass, M is molar mass of NaOH

$$m = 0.5 \text{ (mol)} \cdot 39.997 \text{ (g/mol)} = 19.9985 \text{ g.}$$

Assumption: The calculations were based on 100% purity

Calculating volume for obtaining 0.5M HNO₃

HNO₃ was provided with 65% purity and density of 1.39 g/ml. The calculations for preparing 0.5M were as shown below.

Assuming 100 gram of solution

$$\text{Moles of HNO}_3 \text{ present in solution, } n = 65 \text{ (g)} / 63.01 \text{ (g/mol)} = 1.032 \text{ mol}$$

$$\text{Volume of HNO}_3 \text{ in 100g of solution, } V = 100 \text{ (g)} / 1.39 \text{ (g/ml)} = 71.94 \text{ ml}$$

$$\text{Molarity, } M = 1.032 \text{ mol} / (71.94/1000) \text{ lit} = 14.34 \text{ M}$$

Volume to be obtained is calculated by:

$$V_1 = \frac{C_2 V_2}{C_1} = \frac{0.5 \cdot 1}{14.34} = 0.03487 \text{ lit} = 34.87 \text{ ml.}$$

Calculating leaching efficiency

Both metal content in the sample and leaching efficiency can be calculated using equations 1 and 2.

$$Y = \frac{\text{metal content in steelmaking dust}}{100} * 100 \quad (1)$$

Where; Y = metal content in sample

$$\text{Leaching efficiency} = \frac{\text{ICP-OES value} * V * X}{Y} * 100 \quad (2)$$

Where; v = volume (l)

X = dilution factor

Appendix B. Raw data from analysis with ICP-OES

Temperature (°C)	0.5M NaOH				
25 °C	Time (min)	Concentration (ppm)			
		Mo	V	Zn	Fe
25 °C	5	0.596	0.004	1.429	0.186
	15	0.528	0.000	1.291	0.179
	30	0.558	0.010	1.321	0.179
	60	0.546	0.002	1.283	0.167
	120	0.513	0.002	1.204	0.306
40 °C	5	0.544	0.001	3.299	0.220
	15	0.479	0.001	3.989	0.236
	30	0.511	0.005	5.278	0.209
	60	0.547	0.006	6.516	0.199
	120	0.507	0.004	6.918	0.198
60 °C	5	0.515	0.004	1.388	0.193
	15	0.484	0.009	1.307	0.193
	30	0.499	0.003	1.314	0.190
	60	0.490	0.005	1.276	0.182
	120	0.485	0.002	1.236	0.189
Temperature (°C)	1M NaOH				
25 °C	5	0.594	0.003	1.654	0.236
	15	0.577	0.008	1.603	0.227
	30	0.553	0.010	1.526	0.225
	60	0.572	0.001	1.579	0.317
	120	0.551	0.008	1.505	0.305

40 °C	5	0.524	0.003	5.426	0.227
	15	0.509	0.002	6.366	0.224
	30	0.511	0.005	7.096	0.220
	60	0.526	0.001	8.143	0.209
	120	0.495	0.007	7.546	0.219
60 °C	5	0.540	0.004	6.924	0.257
	15	0.562	0.007	7.791	0.230
	30	0.570	0.004	8.727	0.227
	60	0.604	0.010	9.462	0.278
	120	0.592	0.008	9.754	0.219

Appendix C. Leaching efficiencies for different elements in percentage

C1. Leaching efficiency for Zinc

Leaching conditions	Time (min)				
	5	15	30	60	120
0.5M, 25°C	1.82	1.93	1.98	1.92	2.11
0.5M, 40°C	1.87	1.92	1.97	1.95	2.05
0.5M, 60°C	2.28	2.38	2.29	2.39	2.45
1M, 25°C	5.00	6.01	7.90	9.69	10.23
1M, 40°C	8.22	9.59	10.63	12.12	11.16
1M, 60°C	10.50	11.74	13.07	14.09	14.43

C2. Leaching efficiency for Molybdenum

Leaching conditions	Time (min)				
	5	15	30	60	120
0.5M, 25°C	42.31	44.76	45.44	42.76	47.96
0.5M, 40°C	40.05	40.21	40.66	39.21	41.45
0.5M, 60°C	45.52	46.91	45.07	46.74	47.84
1M, 25°C	44.90	39.28	41.61	44.33	40.77
1M, 40°C	43.19	41.75	41.61	42.62	39.82
1M, 60°C	44.56	46.10	46.44	48.95	47.72

C3. Leaching efficiency for Iron

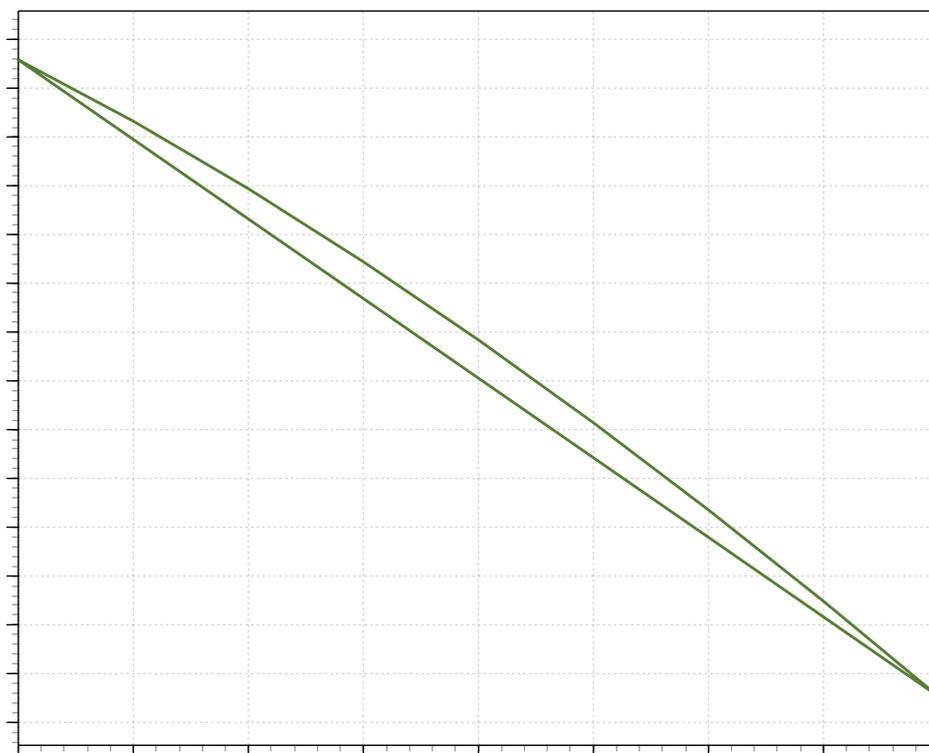
Leaching conditions	Time (min)				
	5	15	30	60	120
0.5M, 25°C	0.99	0.54	0.57	0.57	0.59
0.5M, 40°C	0.61	0.59	0.61	0.62	0.61
0.5M, 60°C	0.99	1.02	0.72	0.72	0.75
1M, 25°C	0.71	0.76	0.67	0.63	0.63
1M, 40°C	0.74	0.72	0.71	0.67	0.69
1M, 60°C	0.84	0.74	0.73	0.89	0.70

C4. Leaching efficiency for Vanadium

Leaching conditions	Time (min)				
	5	15	30	60	120
0.5M, 25°C	3.02	0.00	6.23	1.04	1.26
0.5M, 40°C	2.76	6.30	1.84	2.78	1.13
0.5M, 60°C	1.83	5.26	6.47	0.35	4.22
1M, 25°C	0.48	0.97	3.23	3.60	2.21
1M, 40°C	1.90	1.58	3.34	0.55	4.14
1M, 60°C	3.05	4.79	2.85	5.79	4.40

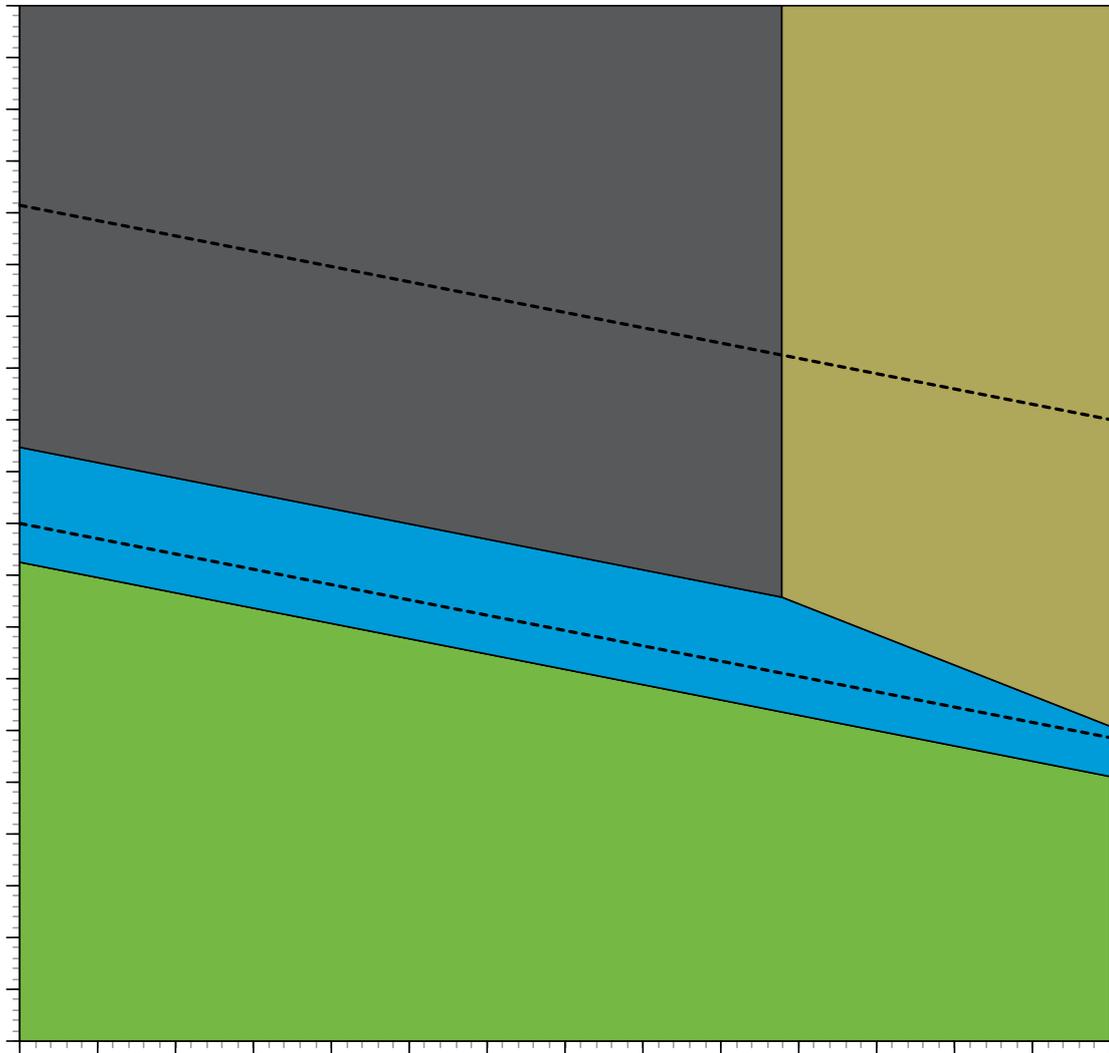
Appendix D. Gibbs free energy for the reaction.

The graph was drawn using HSC chemistry 9 software.

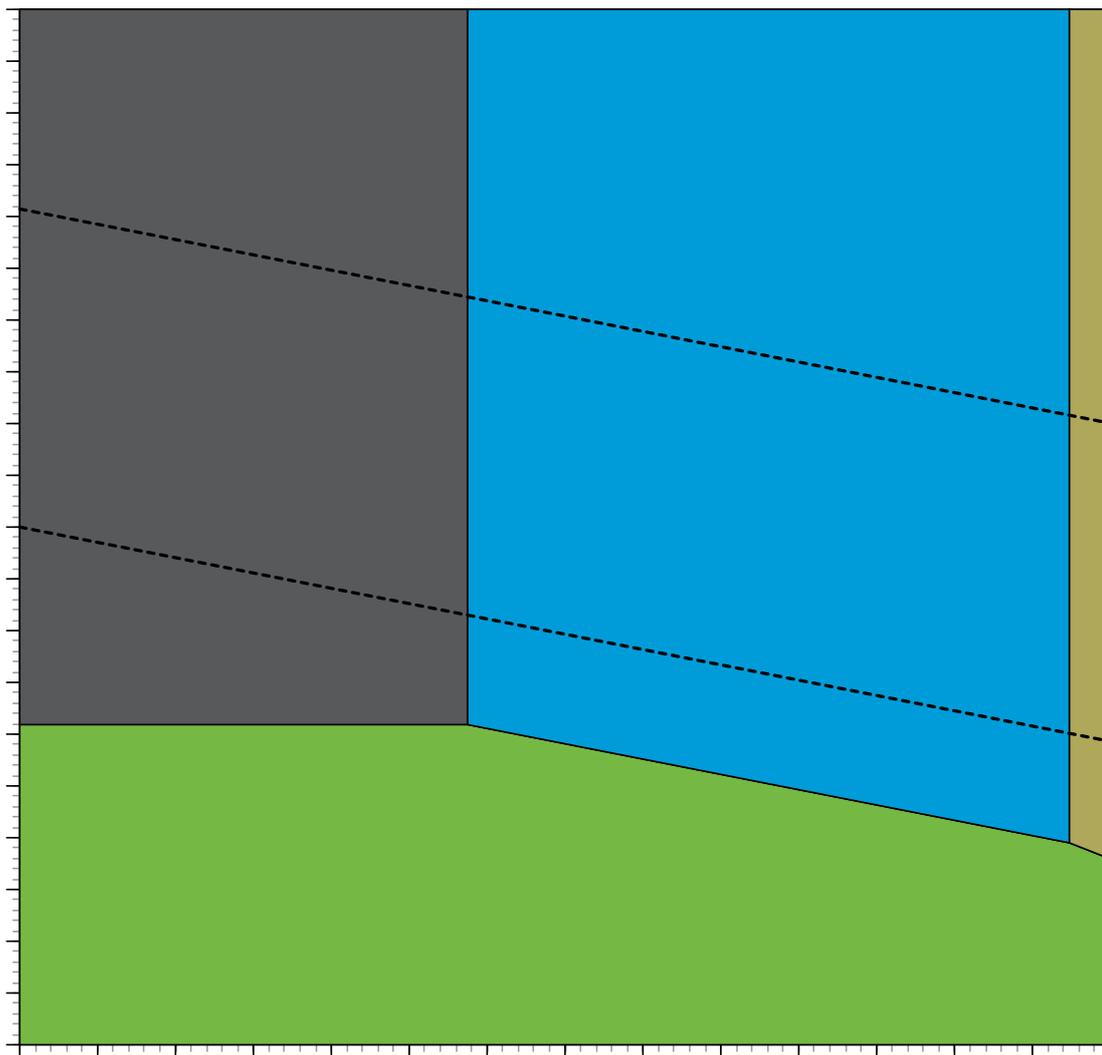


Appendix E. Potential/pH diagram for different systems

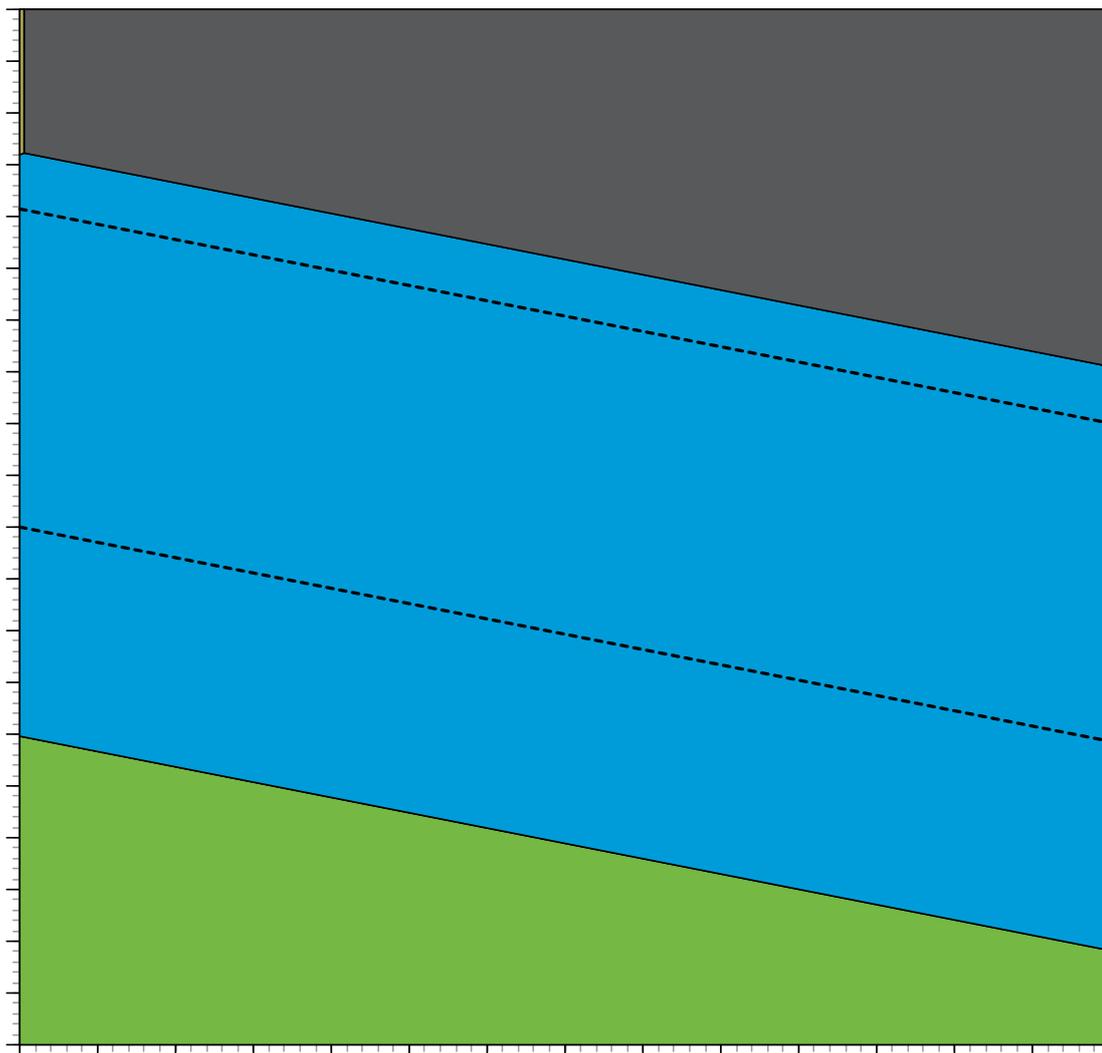
E1. Potential/pH diagram for molybdenum at 25°C. The graph was drawn using HSC chemistry 9 software.



E2. Potential/pH diagram for zinc at 25°C. The graph was drawn using HSC chemistry 9 software.



E3. Potential/pH diagram for iron at 25°C. The graph was drawn using HSC chemistry 9 software.



Appendix F. Percentage of leached material

Leaching conditions	Weight of sample before leaching (g)	Weight of sample after leaching (g)	Leached material (%)
0.5M NaOH, 25 °C, 120 min, S/L=1:50	1.0024	0.9635	3.8900
0.5M NaOH, 40 °C, 120 min, S/L=1:50	1.0007	0.9348	6.5900
0.5M NaOH, 60 °C, 120 min, S/L=1:50	1.0006	0.9564	4.4200
1M NaOH, 25 °C, 120 min, S/L=1:50	1.0016	0.9795	2.2100
1M NaOH, 40 °C, 120 min, S/L=1:50	1.0013	0.8629	13.8400
1M NaOH, 60°C, 120 min, S/L=1:50	1.0009	0.8971	10.3800