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Feasibility Study of Vanadium Extraction from Steelmaking Slag of Mobarakeh Steel Company at laboratory and semi-Industrial Scales

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Abstract

In our country, a massive volume of slag is generated annually from steel production facilities, amounting to about 20 percent of the total steel produced. This slag is an important and valuable source for extracting vanadium, with 67 percent of the world's vanadium production sourced from slag. Iran ranks among the top five countries that possess this vital metal; however, vanadium extraction from slag has not been carried out to date. Moreover, due to the unstable quality of the slag, its utilization in other industries has not been feasible. To prevent the environmentally harmful effects of accumulating slag and the inability to utilize it in various industries, it is essential to implement an economic solution for recovering the components present in steel-making slag. In the present project, after sampling from the stored slag deposits at Mobarakeh Steel Company, comprehensive laboratory and pilot-scale studies were conducted on the representative samples. Through processes involving roasting with sodium carbonate, acid leaching with 2 M sulfuric acid, iron cementation, solvent extraction using DEHPA, stripping, and scrubbing, we successfully extracted pentoxide vanadium with high purity suitable for producing ferrovanadium.

1. Introduction

Vanadium holds significant importance in the steel manufacturing industry. It is a crucial alloying element in many types of steel, particularly in high-strength low-alloy steels. The impact of increasing vanadium content leads to improved hardness and wear resistance. Iron alloys containing vanadium are harder and stronger than regular iron, exhibiting greater resistance to rust and corrosion. Furthermore, vanadium is utilized in non-ferrous alloys, especially in titanium-vanadium alloys and nickel-based superalloys, which are essential for the aerospace industry. Another application of vanadium is its role as a catalyst, which plays a special position in the chemical industries. One of the compounds used for this purpose is vanadium pentoxide (V_2O_5), which is employed in processes such as the oxidation of SO_2 to SO_3 in sulfuric acid production, the removal of sulfur from crude oil, and in the dye and ink manufacturing industries [1,2,3,4].

Vanadium extraction from steel plant slag is generally carried out by two methods: hydrometallurgy and pyrometallurgy. The pyrometallurgical method typically has higher energy consumption and economic capacity compared to the hydrometallurgical method. In this process, ferrovanadium (FeV) is produced directly through smelting. However, the ferrovanadium produced by this method has a lower grade (40 to 50 percent), resulting in a lower vanadium recovery rate compared to hydrometallurgy. Additionally, the pyrometallurgical method requires higher investment than hydrometallurgy and is less environmentally friendly due to the generation of toxic gases as byproducts [5,6].

The hydrometallurgical method is more environmentally friendly with lower investment costs. One advantage of the hydrometallurgical method for extracting vanadium from slag is that it allows for the production of high-grade vanadium

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pentoxide, which can then be reduced with aluminum in combination with scrap and lime to obtain high-grade ferrovanadium (around 80 percent). In hydrometallurgy, if the vanadium content in the slag changes, it offers better flexibility compared to pyrometallurgy. Hydrometallurgical methods include salt roasting and aqueous, acidic, or alkaline leaching. The elements constituting the slag content from steel plants determine the effective hydrometallurgical method for extracting vanadium from iron slag [7, 8].

The calcium content present in the iron slag plays a significant role in process selection [9]. The salt roasting-leaching with water method is applicable when the calcium content in the slag is very low. For every one percent increase in CaO, the percentage of V_2O_5 extraction significantly decreases. In 2012, Mr. Sheng Li and Bing Zhi, and also in 2015, Mr. Zhao Manyan and colleagues conducted hydrometallurgical studies to extract vanadium from iron slag. The slag contained a lot of calcium, so they recovered vanadium in the leaching solution by direct roasting without adding salt and then alkaline leaching [10, 11].

As mentioned, depending on the elements in the vanadium feed, either acidic or alkaline leaching can be used to extract vanadium. Mr. Deng studied the sample in the year of 2010 which used acidic leaching applying sulfuric acid [12].

Furthermore, In 2017, research by Mr. Jiang et al. focused on recovering vanadium using acid leaching after the roasting process. Acid leaching dissolves complex vanadium compounds formed during roasting, improving leaching efficiency. The research optimized the parameters of this acid leaching process to enhance vanadium recovery from the leaching solution, as also supported by other studies involving acid leaching and solvent extraction for vanadium recovery from various sources like clay vanadium ore and oil-fired boiler slag. This approach addresses the challenge of extracting valuable vanadium from complex matrices [13].

Following the leaching process, solvent extraction process is vital to transfer vanadium from aqueous phase to organic phase. Depending on the associated elements and primary leaching, various types of solvent extractors can be used [14,15,16,17].

In 2021, Liu Y. and his colleagues obtained a new approach of stripping process via transferring vanadium from the organic phase to the aqueous phase using only the vanadium oxidation method [18].

In our country, a huge volume of slag is obtained annually from steel manufacturing plants. The amount of slag is approximately 20 percent of the steel produced and is the most important valuable source for the extraction of vanadium, accounting for 67 percent of the world's vanadium production. Despite having significant vanadium reserves, Iran is classified among the top five countries possessing this vital metal; however, vanadium extraction has not been carried out so far. Furthermore, due to the unstable quality of the slag, its use in other industries has not been feasible. Therefore, the aim of this project is to enable the production of vanadium pentoxide from slag as a valuable source of vanadium under optimal technical and economic conditions. Additionally, the waste generated from the processes of this project contains minimal harmful materials and can be utilized in other industries.

2. Methods

To study on the slag of steel plants, first of all it is necessary to take sample carefully from the huge amount of depot. After that sample preparation through several crushing and milling processes was done to prepare representative sample. Based on sample identification results, roasting with salt and acid or alkaline leaching are performed to evaluate how the vanadium content is recovered and extracted. following, for more vanadium purification, solvent extraction process and stripping process are done on leach solution.

3. Case study

3.1. Sample preparation and comminution

In order to study the slag of the Isfahan Steel Plant, samples were first taken from the slag depot. The slag generated from several years of steel production has been collected in multiple depots at the Mobarakeh Steel Company site. Sampling from the depots was carried out to select a representative sample, in consultation with colleagues from Mobarakeh Steel Company, as follows: Initially, three samples, each weighing approximately 100 tons on average, were selected under the careful supervision of IMPRC experts from different points within the new slag depots. These samples were then transferred to another location using specialized machinery. After several rounds of division and homogenization of the samples, approximately 15 tons of the sample were sent to the Iran Mineral Processing Research Center as the representative sample.

The sent slag sample was crushed to under one inch using a jaw crusher. After homogenizing the sample manually, a control sample was selected and stored using a conical method in a single step. The remaining sample was crushed using a cone crusher with an output aperture size of 3 millimeters in a closed circuit with a 3-millimeter sieve for control. The sample was then divided into 1-kilogram representative sample packages using a rotary splitter.

3.2. Sample identification

Complete chemical analysis and XRF studies were conducted on the representative sample. Mineralogical studies were also performed on it. These mineralogical studies included X-ray diffraction (XRD), microscopic studies, and SEM. The results of the complete chemical analysis are presented in Table 1. Additionally, the results of the XRF studies are provided in Table 2.

Table 1. Results of the full Chemical Analysis of the Mobarakeh steel slag sample.

Ag (ppm)	**Al (%)**	**As (ppm)**	**Be (ppm)**	**Bi (ppm)**	**Ca (%)**	**Cd (ppm)**	**Ce (ppm)**	**Co (ppm)**	**Cr (ppm)**
<1	1.51	<10	<2	<20	14.93	<1	101	8	119
Cu (ppm)	**Fe (%)**	**K (%)**	**La (ppm)**	**Mg (%)**	**Mn (ppm)**	**Mo (ppm)**	**Na (%)**	**Ni (ppm)**	**P (%)**
8	27.93	0.16	71	4.41	1325	<2	0.47	<10	0.2
Pb (ppm)	**S (%)**	**Sb (ppm)**	**Sc (ppm)**	**Sr (ppm)**	**Ti (%)**	**V (ppm)**	**Y (ppm)**	**Zn (ppm)**	
36	<0.1	<20	<5	86	0.47	6037	27	39	

Table 2. XRF study results of the Mobarakeh steel slag sample.

SiO2 (%)	**Al2O3 (%)**	**CaO (%)**	**MgO (%)**	**TiO2 (%)**	**Fe2O3 (%)**	**MnO (%)**	**SO3 (%)**
17.03	3.65	27.65	5.49	.78	39.93	0.32	0.06
P2O5 (%)	**Na2O (%)**	**K2O (%)**	**V2O5 (%)**	**SrO (%)**	**Cl (%)**	**L.O.I (%)**	
0.32	0.59	0.18	1.08	<.1	<.1	-	

3.2.1. XRD studies result

XRD studies were conducted on several different samples taken from various slag deposition areas, and it was determined that the majority of the contained minerals include merwinite, wuestite, fayalite, gehlenite, perovskite, and magnetite. Quartz, calcite, hedenbergite, monticellite, dolomite, grossular, diopside, anorthite, hematite, and akermanite were identified as minor minerals in some samples. Figure 1 shows the results of the XRD study.

3.2.2. Microscopic studies result

The results of microscopic studies on the reference sample also indicated that the sample is composed of two phases: metallic and silicate. The metallic phase of the sample is predominantly made up of iron metal and both divalent and trivalent iron oxides. The silicate phase consists mainly of quartz (high-temperature silica), cristobalite, fayalite, which is the most significant constituent of the silicate in the slag, and pyroxene (mainly diopside). The texture of most slag particles is flow-like, sometimes displaying a glassy and shiny texture. Porosity is observed on the surface of most grains. The iron present in the sample is seen in the form of wuestite, a divalent iron oxide, which is the final reduction product of iron. However, in most cases, trivalent iron (magnetite) is also observed, exhibiting idiomorphic and dendritic textures. The approximate abundance of magnetite can be estimated at 10 to 15 percent. Magnetite is fully embedded within the silicate phases (quartz, fayalite, and pyroxene). Magnetite has been oxidized to hematite and, in some cases, to goethite, which is observed in the sample. Other minerals present in the sample, estimated at approximately 3 to 5 percent in crystalline form, include calcite and dolomite.

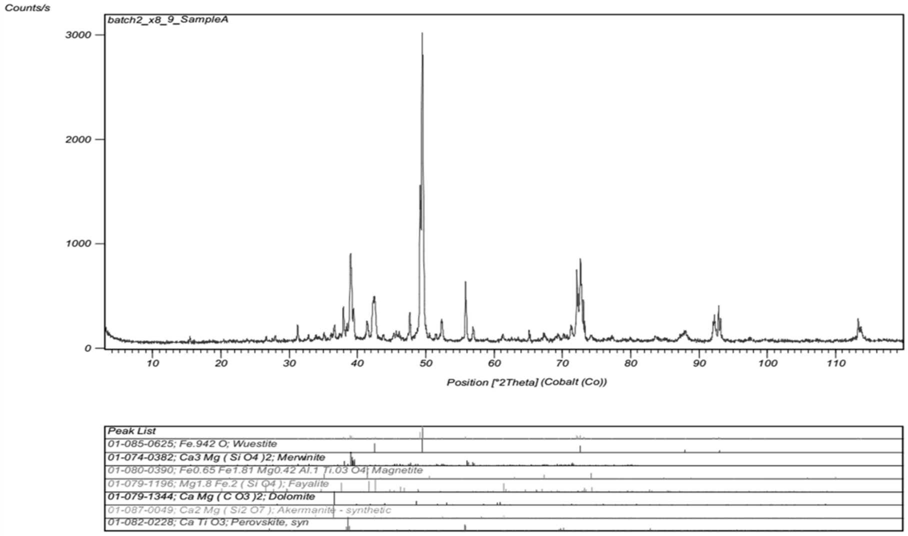

Figure 1. XRD studies on the slag sample

3.2.3. SEM studies result

SEM studies were conducted on samples with fractionation (0.106+0.031-), (0.038+0.075-), and (0.075+0.106-). The results of the SEM studies indicated a significant amount of iron oxides (primarily magnetite and occasionally hematite) present in the sample, with the interaction of magnetite with perovskite and pyroxene observable in various parts of the sample. The ragged texture of magnetite is evident in the sample. Some dendritic iron formations are also present in the sample, which are, in some areas, associated with magnetite and pyroxene. Additionally, several phases containing iron, titanium, vanadium, and aluminum were identified. The identified minerals in the sample include some calcite, minor chalcopyrite, chlorite, quartz, albite, and diaspor.

3.3. Processing studies

The following processes were carried out to extract vanadium from slag; which includes roasting with sault, Acid Leaching, solvent extraction, stripping and precipitation.

3.3.1. Roasting and acid leaching

In the roasting processes, sodium carbonate (Na_2CO_3) was used. It is worth mentioning that, in addition to this salt, other salts such as sodium sulfate (Na_2SO_4) and sodium chloride (NaCl) were also tested. However, nowadays, the use of sodium carbonate is more common due to its environmental compatibility, and the recovery of vanadium using sodium carbonate is greater than that achieved with the other mentioned salts.

Roasting with salt leads to the formation of sodium vanadate ($NaVO_3$), which is soluble in water. In the next stage, the sodium vanadate obtained from the roasting process can be recovered using a leaching process. Leaching has been studied in both acidic and alkaline forms. In both cases, the investigated parameters were optimized, and it was found that the vanadium recovery from the roasting and alkaline leaching process was lower than that from the roasting and acidic leaching process. Therefore, acidic leaching was selected, and the factors under investigation and optimization will be described further.

-The Effect of Salt Weight Percentage in the Roasting Process on Vanadium Recovery

The effect of Na_2CO_3 salt at weight percentages of 0, 10, 15, 20 and 30 on vanadium extraction from slag was evaluated during the roasting process. Since sodium vanadate begins to form at temperatures above 500 degrees, the initial roasting temperature was set at 600 degrees for 150 minutes for all experiments. The conditions for the roasting and acidic leaching processes are presented in Table 3. Except for the weight percentage, the other parameters were kept constant. Figure 2 illustrates the vanadium recovery as a function of the salt weight percentage in the roasting process. It can be observed that as the percentage of sodium carbonate salt increases from 0 to 15 percent during the roasting process, the percentage of vanadium recovery in the leaching solution increases from 86.4 percent to 95.6 percent. However, when the weight percentage of sodium carbonate salt in the roasting process was raised to 30%, the vanadium recovery stabilized and even experienced a slight decrease. Therefore, a weight percentage of 15 percent was selected as the optimal percentage for subsequent stages. Additionally, in examining the effect of Na_2CO_3 salt in the roasting and acidic leaching processes on iron dissolution, it was observed that at a salt weight percentage of 15 percent, the maximum iron dissolution reached 87.6%.

Table 3. Conditions of conducted experiments to evaluate the effect of sault additive.

Particle size (d_{80} µm)	Roasting Condition			Leaching Condition				
	Additive (%W)	Temp (°C)	Time (min)	Agent Name	Agent (Molarity)	S/L	Time (min)	Temp (°C)
75	0,10,15,20	600	150	H_2SO_4	2	1/10	150	90

-The effect of roasting temperature on vanadium recovery

The roasting temperature was evaluated at four levels: 600, 800, 1000, and 1100 degrees Celsius for vanadium extraction from slag, according to the experimental conditions outlined in Table 4. Figure 3 shows the vanadium recovery as a function of roasting temperature. It can be observed that as the roasting temperature increases from 600 degrees Celsius to 1000 degrees Celsius, the percentage of vanadium recovery in the leaching solution increases; however, beyond this, at 1100 ºC, it decreases from 95 percent to 88 percent. Therefore, a roasting temperature of 1000 ºC was selected as the optimal roasting temperature for subsequent stages. It is noting that at the roasting temperature of 1000 ºC, where vanadium recovery is maximized, the iron dissolution is also maximized.

Table 4. The conditions of conducted experiments to evaluate the effect of roasting temperature.

Particle size (d_{80} µm)	Roasting condition			Leaching condition				
	Additive (%W)	Temp (°C)	Time (min)	Agent Name	Agent (Molarity)	S/L	Time (min)	Temp (°C)
75	15	600,800,1000,1100	150	H_2SO_4	2	1/10	150	90

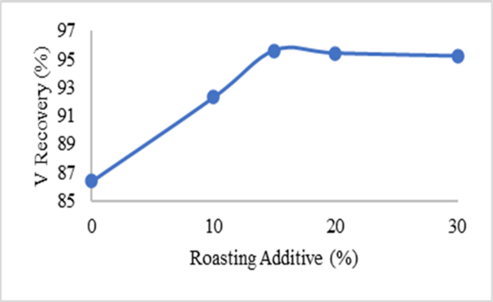

Figure 2. The effect of sault additive on vanadium recovery

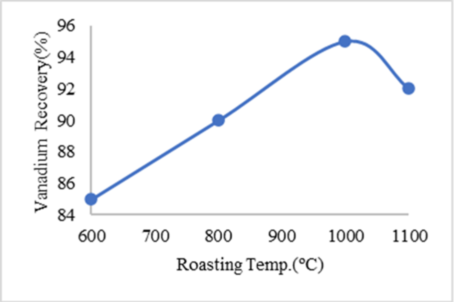

Figure 3. The effect of roasting temperature on vanadium recovery

-The effect of roasting time on vanadium recovery

The effect of roasting time on vanadium extraction from slag was evaluated according to the experimental conditions outlined in Table 5. Figure 4 illustrates the vanadium recovery as a function of roasting time. In Figure 4, it can be observed that as the roasting time increases from 45 minutes to 90 minutes, the percentage of vanadium recovery in the leaching solution remains relatively stable at about 92 percent. However, as the roasting time increases from 90 minutes to 150 minutes, the percentage of vanadium recovery in the leaching solution increases from 92 percent to 95.73 percent. Therefore, a roasting time of 150 minutes was selected as the optimal roasting time for subsequent stages.

Table 5. The condition of conducted experiments to evaluate the effect of the roasting time.

Particle size (d_{80} µm)	Roasting Condition			Leaching Condition				
	Additive (%W)	Temp (°C)	Time (min)	Agent Name	Agent (Molarity)	S/L	Time (min)	Temp (°C)
75	15	1000	45,90,150	H_2SO_4	2	1/10	150	90

-The effect of sulfuric acid concentration on vanadium extraction

The effect of sulfuric acid concentration on the extraction of vanadium from slag was evaluated according to the experimental conditions stated in Table 6. Figure 5 shows the vanadium recovery curve relative to acid concentration. It can be observed that as the concentration of sulfuric acid increases from 1 molar to 2 molar, the percentage of vanadium extraction in the leaching pregnant solution increases from 62% to 95.6%. However, with a further increase in acid concentration from 2 molar to 3 molar, the percentage of vanadium extraction in the leaching pregnant solution remains almost constant, with only a slight increase from 95.73% to 96%. Therefore, the 2-molar acid concentration was selected as the optimal concentration for subsequent stages. Additionally, at a 3 molar sulfuric acid concentration, where the dissolution of vanadium is maximized, the dissolution of iron is also at its maximum, equal to 93.83%. In contrast, at a 2-molar sulfuric acid concentration, the dissolution of iron is lower, at 87.7%.

Table 6. The condition of conducted experiments to evaluate the effect of acid molarity in leaching process.

Particle size (d_{80} µm)	Roasting Condition			Leaching Condition				
	Additive (%W)	Temp (°C)	Time (min)	Agent Name	Agent (Molarity)	S/L	Time (min)	Temp (°C)
75	15	1000	150	H_2SO_4	1,2,3	1/10	150	90

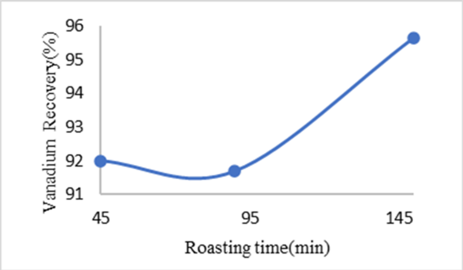

Figure 4. The effect of roasting time duration on vanadium recovery

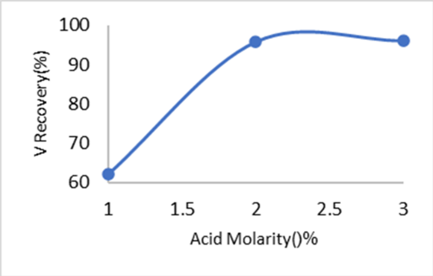

Figure 5. The effect of acid molarity in leaching process on vanadium recovery.

-The effect of the liquid-to-solid ratio on vanadium extraction

The effect of the liquid-to-solid ratio at ratios of (5, 10, 15) in the leaching process on the extraction of vanadium from slag was evaluated according to the experimental conditions stated in Table 7. Figure 6 shows the vanadium recovery curve relative to the liquid-to-solid ratio in the leaching process. As seen in Figure 6, with an increase in the liquid-to-solid ratio from 5 to 10, the percentage of vanadium extraction in the leaching pregnant solution increases from 68% to 95.6%. However, with a further increase in the liquid-to-solid ratio from 10 to 15, the percentage of vanadium extraction in the leaching pregnant solution remains constant. Therefore, a liquid-to-solid ratio of 10 was selected as the optimal ratio for subsequent stages.

Table 7. The condition of conducted experiments to evaluate the effect of L/S in leaching process.

Particle size (d_{80} µm)	Roasting condition			Leaching condition				
	Additive (%W)	Temp (°C)	Time (min)	Agent Name	Agent (Molarity)	L/S	Time (min)	Temp (°C)
75	15	1000	150	H_2SO_4	2	5,10,15	150	90

- The effect of acid leaching time on vanadium recovery

The effect of acid leaching time on vanadium recovery was examined according to Table 8. The results are presented in Figure 7. As shown in Figure 7, with an increase in leaching time from 60 to 90 minutes, the vanadium extraction in the leaching pregnant solution increases from 89.79% to 92%. Furthermore, with an increase in leaching time from 90 to 150 minutes, the percentage of vanadium extraction in the leaching pregnant solution rises from 92% to 95.6%. Furthermore, at a leaching time of 150 minutes, where the dissolution of vanadium is maximized, the dissolution of iron is also at its maximum, equal to 87.87%.

Table 8. The condition of conducted experiments to evaluate the effect of leaching time duration.

Particle size (d_{80} μm)	Roasting condition			Leaching condition				
	Additive (%W)	Temp (°C)	Time (min)	Agent Name	Agent (Molarity)	S/L	Time (min)	Temp (°C)
75	15	1000	150	H_2SO_4	2	1/10	60,90,150	90

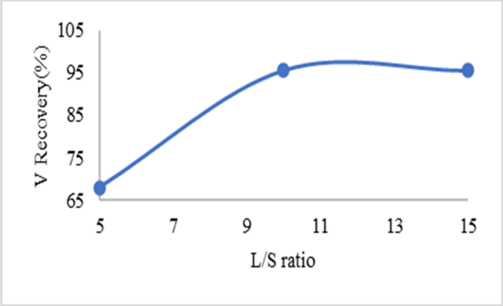

Figure 6. The effect of L/S ratio in leaching process on vanadium recovery

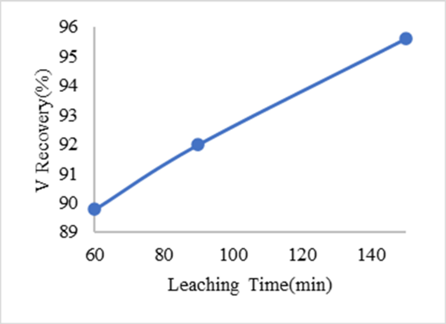

Figure 7. The effect of leaching time duration on vanadium recovery

-Optimized condition

The optimal conditions for roasting with sodium carbonate and leaching with sulfuric acid, as well as the amount of vanadium recovery in the leaching solution, are shown in Table 9.

After vanadium has entered the leaching solution, it must be transferred from the aqueous phase to the organic phase using a solvent extraction process.

Table 9. The optimized condition of roasting and leaching processes.

Particle size (d_{80} μm)	Roasting condition			Leaching Condition					V-Recovery (%)
	Additive (%W)	Temp (°C)	Time (min)	Agent Name	Agent (Mollar)	S/L	Time (min)	Temp (°C)	
75	15	1000	150	H_2SO_4	2	1/10	150	90	95.6

3.3.2. Iron cementation process and its necessity before solvent extraction with D2EHPA

The leaching solution content is mostly in the form of ferric ions (Fe^{3+}), which compete with vanadium for transfer to the organic phase. To prevent iron from entering the organic phase, Fe^{3+} should be converted to Fe^{2+} as much as possible. Using the cementation process, ferric iron can be converted to ferrous iron by adding iron powder (reaction 1) under the following conditions as shown in Table 10.

$$Fe^0 + 2Fe^{3+} = 3Fe^{2+} \quad (1)$$

Where are:

Fe^0 - Fe powder,

Fe^{3+} - Ferric ion

Fe^{2+} - Ferrous ion.

3.3.3. Solvent extraction process.

After the cementation process and the conversion of ferric ions to ferrous, the solvent extraction process was carried out with a ratio of organic phase to aqueous phase of one to one under optimal conditions. By using an organic phase containing 10% D2EHPA and a kerosene diluent, it was possible to transfer about 96% of the vanadium content to the organic phase and only 2% of the iron to the organic phase. It is noted that the suitable pH for leach solution in solvent extraction is 1; therefore, some amount of NaOH was added before that.

Table 10. condition of Fe cementation process.

Temperature	Ambient Temp.
Time duration	1 hour
Deoxygenation	15 minutes of argon gas blowing into the solution before adding metallic iron – 0.5 liters/minute of argon gas blowing during the test
The amount of Fe powder	Iron powder – 1.2 times the stoichiometric amount of total iron in the leaching solution

3.3.4. Investigation of the effect of vanadium concentration in the organic phase on the extraction rate of vanadium.

In order to investigate the effect of vanadium concentration in the organic phase on the extraction rate of vanadium, solvent extraction experiments were conducted in several stages. In the first stage, the leaching solution after cementation was contacted with the fresh organic phase (Step1). In the second stage, the leaching solution after cementation was contacted with the fresh organic phase of the first stage (Step2). These stages continue until the crud is formed. The experiments showed that the crud was formed after three stages. In the first stage, 95% of vanadium was extracted from the leaching solution; in the second stage, 56%; and finally, in the third stage, only 11% of vanadium was extracted (Fig8).

Since it is difficult to separate the valuable material from the organic phase, it is necessary to transfer the valuable material back to the aqueous phase. Therefore, in the stripping process, the aqueous phase is contacted with a charged organic phase to allow the transfer of vanadium metal from the organic phase to the aqueous phase.

3.3.5. Stripping process

The stripping process often takes longer than the solvent extraction process because the kinetics of the stripping process are slower than that of solvent extraction.

Different aqueous phases were evaluated for the stripping process. First, acid was used in the aqueous phase. The recovery of vanadium was very low when using hydrochloric and sulfuric acids. In the case of nitric acid (in aqueous phase conditions of 4M, $V_O/V_A = 4.1$), the recovery was about 50%, and in the saturated state, the vanadium content was only 1 g/l, and during the precipitation stage, vanadium was not precipitated.

In the second study, alkali was also used in the organic phase. In the first stage (in aqueous phase conditions of 4M, $V_O/V_A = 4.1$), the recovery was about 50%, but in the concentration stage, a huge volume of viscous precipitate was formed in the aqueous phase, which could not be separated.

Direct precipitation from the organic phase was also investigated. In this method, a solution of ammonium sulfate in water is selected as the aqueous phase. The amount of ammonium sulfate is 2 times the stoichiometry of the vanadium content in the organic phase. The stripping process was carried out for 4 hours at a temperature of 50 ° C with a ratio of organic phase to aqueous phase of 3 to 1. After separating the two phases from each other, it was determined that no precipitation had occurred.

But in the end, the solution to the vanadium stripping process was obtained; That was the oxidation of vanadium. In this way, the aqueous phase consists of water with a pH of about 6.5 to 8 and 2% by volume of hydrogen peroxide. The ratio of organic phase to aqueous phase is 3 to 1 and the duration of its execution is less than 2 minutes. In order to concentrate vanadium in the aqueous phase, a three-step stripping process is performed with fresh organic phase. Then, the color of the aqueous phase solution becomes ochre, containing 8 g/L of vanadium (Figure 9).

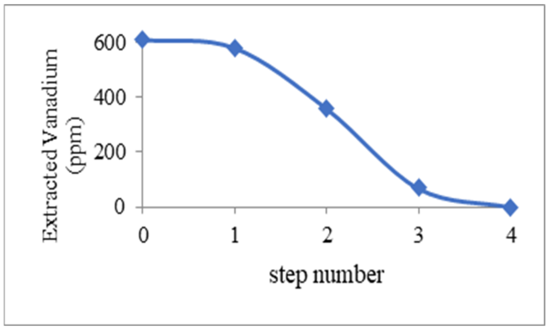

Figure. 8. the effect of vanadium concentration in the organic phase on the extraction rate of vanadium

Figure 9. the aqueous phase containing 8 g/L vanadium

3.3.6. Precipitation process

At this stage, the stripped solution is kept around 90°C for 6 hours and then under 60°C for 24 hours with a condenser. After filtering, 75% of the vanadium in the solution has precipitated. The results of this experiment show that heat and time duration of heating are an important and effective factor in the precipitation of vanadium. After calcination at 550°C for 2 hours, V_2O_5 containing

75% vanadium with the purity of 86.2% was obtained

4. Results

4.1. Operational flowsheet

After doing full study at laboratory scale, the flowsheet for the process of extracting vanadium from steel plant slag is obtained which is shown in the figure 10. By performing a set of effective technical processes, vanadium extraction from steel plant slag under optimal conditions has become possible which leads to vanadium pentoxide production with a grade of 86.2%.

4.2. Semi-industrial implementation

Vanadium pentoxide flowsheet was also implemented at semi-industrial scale thorough these processes:

- 100 kg of steel slag sample was crushed to less than one inch by jaw crusher. It was then crushed by a cone crusher with an outlet size of 3 mm in a closed circuit with a 3 mm control screen. Then it was milled in a closed circuit to a size of d80=75 mμ.
- Roasting and acid leaching process was performed on 100 kg of material. To avoid adding NaOH solution to adjust pH, the sodium carbonate salt was increased by 30% in the roasting process to bring the pH of the leaching solution to approximately 1, thus preventing its dilution. Roasting conditions included temperature of 1000 degrees for 150 minutes with addition of 30% by weight of sodium carbonate salt. Acid leaching was also performed under temperature conditions of 90 ºC, solid to liquid ratio of 1 to 10, for 150 minutes with 2 molar sulfuric acid.

-The solvent extraction, stripping and scrubbing processes were carried out in a continuous circuit as follows:

The organic phase consists of 10% D2EHPA and kerosene diluent. The solvent extraction process was carried out with a ratio of aqueous to organic phase of 1:1 for 40 minutes. After the solvent extraction process was completed and stabilized, the stripping process was carried out. In the stripping process, the aqueous phase consists of water (pH=6-8) and 2% by volume of H_2O_2. The stripping process was performed in 6 steps with a ratio of aqueous to organic phase of 1:1 for 2 minutes. The organic phase was scrubbed with 2 molar sulfuric acid for 20 minutes after loading, and then 70% of it was mixed with 30% of the organic phase of the carpet and returned to the beginning of the circuit.

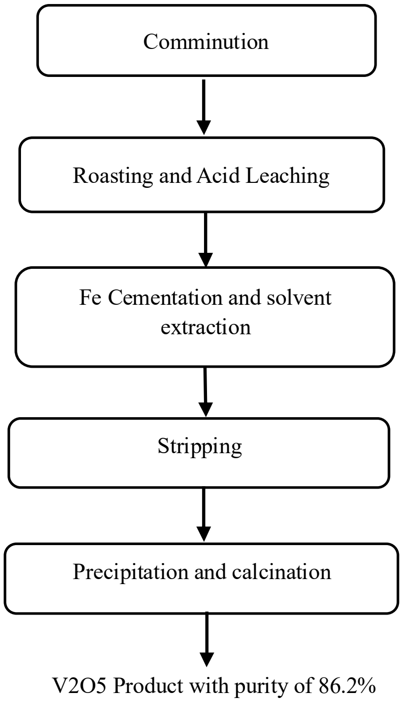

Figure 10. flowsheet of processes to product V2O5 from slag.

5. Discussion

5.1. Product identification

The final product of vanadium pentoxide is shown in Figure 11, and its full analysis is also given in Table 11. As it is shown in the table, the percentage of vanadium content is obtained 48.29% which it is suitable for ferrovanadium production industry.

Figure 11. Pentaoxide vanadium product

Table 11. Full analysis of Pentaoxide vanadium product.

Ag (ppm)	**Al (%)**	**As (ppm)**	**Be (ppm)**	**Bi (ppm)**	**Ca (%)**	**Cd (ppm)**	**Ce (ppm)**	**Co (ppm)**	**Cr (ppm)**
<1	0.09	15	<1	<20	0.62	<1	31	15	16
Cu (ppm)	**Fe (%)**	**K (%)**	**La (ppm)**	**Mg (%)**	**Mn (ppm)**	**Mo (ppm)**	**Na (%)**	**Ni (ppm)**	**P (%)**
779	0.26	0.08	11	0.23	85	498	1.2	116	2.01
Pb (ppm)	**S (%)**	**Sb (ppm)**	**Sc (ppm)**	**Sr (ppm)**	**Ti (%)**	**V (%)**	**Y (ppm)**	**Zn (ppm)**	
80	<0.1	<20	<5	106	0.1	48.29	7	526	

5.2. Semi-industrial scale flowsheet

The semi-industrial scale operational flowsheet along with a mass balance is illustrated in figure 12. By implementing the flowsheet on a semi-industrial scale, it was proven that this is technically feasible.

5.3. Environmental study on leaching waste

After acid leaching and filtering, leaching cake (waste) is produced. (About 900 grams of waste per kilogram of leaching feed). According to the information of Table12, the levels of iron, magnesium, and other interfering elements in the leach cake are minimized [19]. Consequently, the waste is free of harmful heavy metal elements in nature and it is unobstructed in terms of water pollution standards.

By adding appropriate additives and without the need for crushing, it is possible to use the waste in the cement and road construction industries.

6. Conclusions

The extraction of vanadium from the steelmaking slag of the Isfahan Steel Company has been studied at laboratory and semi-industrial scales under optimized conditions. The slag from the Isfahan Steel Company contains 0.6% vanadium and 28% iron. In this study, a combination of mineral processing methods such as roasting with salt, acid leaching, solvent extraction, stripping, and precipitation was employed to obtain vanadium pentoxide (V_2O_5) concentrate with a grade of 86.2%. Furthermore, the vanadium recovery after the entire process was 70%.

It is noteworthy that in the stripping stage, nearly complete extraction of vanadium from the organic phase was achieved solely using an oxidation process in a neutral pH aqueous phase. Another important point is that after acid leaching in this process, the levels of iron, magnesium, and other interfering elements in the leach cake are minimized, allowing for its utilization in other industries, such as the cement industry.

Table 12. Environmental study of waste generated from the acid leaching process.

Elements(ppm)	Ag	As	Cd	Co	Cr	Cu	Mo	Ni	Pb	Sb	V	Zn
Leaching waste	2	14	1>	5	76	157	28	38	32	20	208	19
Soil Pollution Standard Values - Environmental Protection	20	17	3.9	20	64	63	4	50	300	20	130	200
Soil Contamination Standard Values - Groundwater Protection	100	100	20	1000	3000	1500	100	600	300	12	500	3000

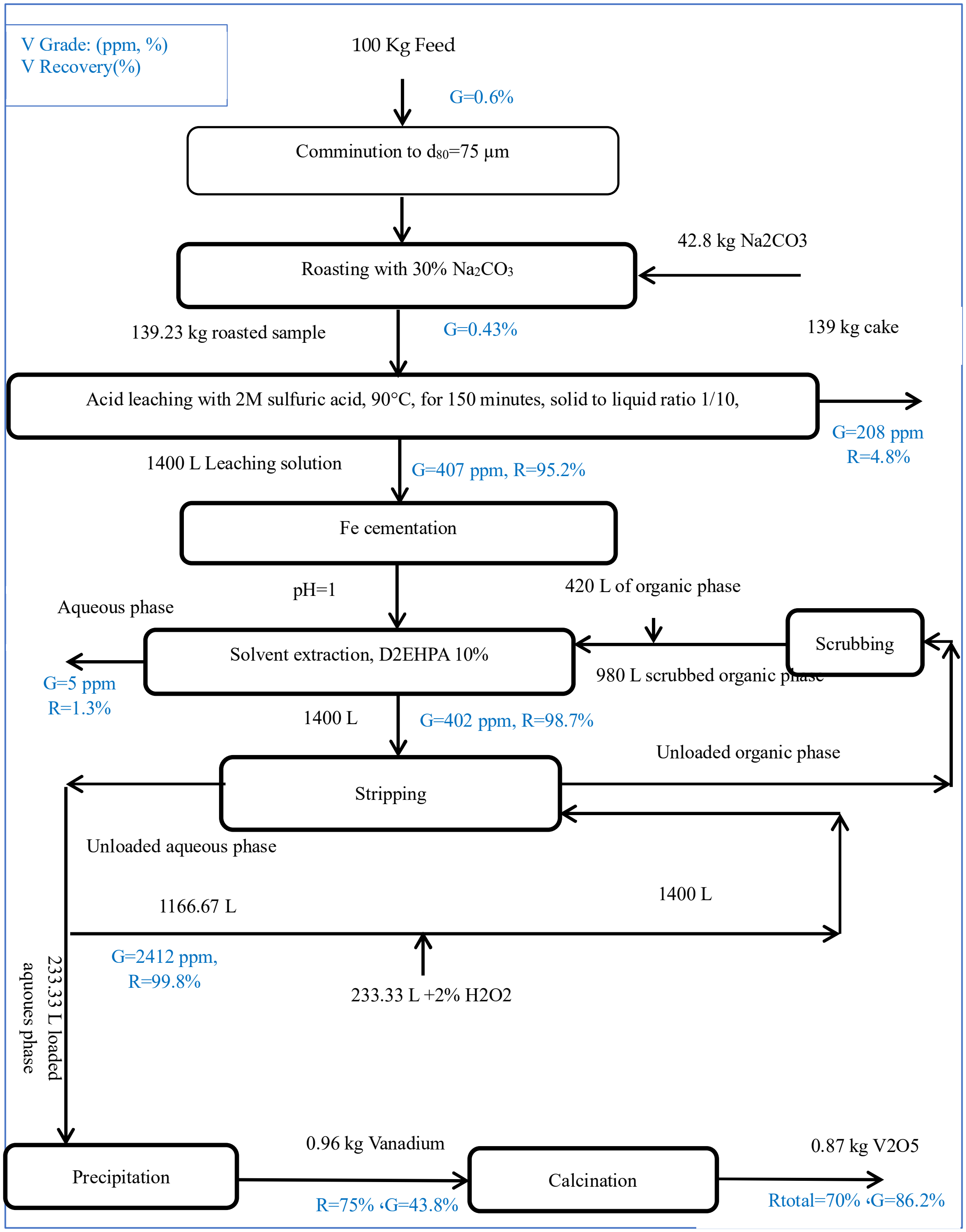

Figure 12. Semi-industrial implementation with mass balance.

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دانشگاه صنعتی شاهرود

امکان سنجی استحصال وانادیم از سرباره فولادسازی شرکت فولاد مبارکه در مقیاس آزمایشگاهی و نیمه صنعتی

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کلمات کلیدی

سرباره تولید فولاد
استخراج با حلال
اکسیداسیون وانادیوم
عاری سازی
پنتوکسید وانادیوم

چکیده

در کشور ما سالانه حجم انبوهی سرباره از کارخانه های تولید فولاد تولید می شود که حدود ۲۰ درصد کل فولاد تولیدی را شامل می شود. این سرباره منبع مهم و با ارزشی برای استخراج وانادیوم است به طوری که ۶۷ درصد از تولید وانادیوم جهان از سرباره تامین می شود. ایران در بین پنج کشور برتر دارای این فلز حیاتی قرار دارد. با این حال، استخراج وانادیم از سرباره تا به امروز انجام نشده است. همچنین به دلیل کیفیت ناپایدار سرباره، استفاده از آن در سایر صنایع امکان پذیر نبوده است. برای جلوگیری از اثرات مخرب زیست محیطی انباشته شدن سرباره و عدم امکان استفاده از آن در صنایع مختلف، اجرای یک راه حل اقتصادی برای استحصال عناصر باارزش موجود در سرباره فولادسازی ضروری است. در این مقاله ، پس از نمونه برداری از ذخایر سرباره ذخیره شده در شرکت فولاد مبارکه، مطالعات آزمایشگاهی جامعی بر روی نمونه های معرف انجام شد و مشخص گردید که با انجام فرآیندهای موثر شامل تشویه با کربنات سدیم، لیچینگ اسیدی با اسید سولفوریک ۲ مولار، سمنتاسیون آهن محتوا، استخراج حلالی با استفاده از D2EHPA، استریپینگ و اسکرابینگ، می توان پنتاکسید وانادیوم با خلوص بالا و مناسب برای تولید فرووانادیوم استحصال کرد..

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