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Recovery of Silica from Steel Slag Waste Using Extraction and Acid Precipitation Methods

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ABSTRACT

Steelmaking processes generate large amounts of slag waste that contain silica, which can be recovered and converted into valuable products. In this study, silica (SiO_2) was extracted from steel slag waste through alkaline extraction using sodium hydroxide (NaOH) followed by acid precipitation. The experimental parameters included NaOH concentrations of 0.5, 1.0, 1.5, 2.0, and 2.5 M, and extraction temperatures of 60, 70, 80, 90, and 100 °C. Each extraction was carried out for 60 minutes with continuous stirring at 300 rpm. The X-ray diffraction (XRD) analysis confirmed that the product exhibited a broad peak at 2θ around 20–30°, which is characteristic of amorphous silica. The results indicated that both NaOH concentration and temperature had a positive correlation with silica yield. As the NaOH concentration and extraction temperature increased, the percentage of extracted silica also increased. The optimum condition was achieved at 100 °C and 2.5 M NaOH, yielding silica with a purity of 91.10%. These findings highlight the potential of utilising steel slag waste as a low-cost raw material for producing amorphous silica. Furthermore, the process demonstrates a sustainable approach to waste valorization while providing high-purity silica for potential applications in industrial materials, adsorbents, and nanotechnology.

Contribution to Sustainable Development Goals (SDGs):
SDG 12: Responsible Consumption and Production
SDG 13: Climate Action
SDG 15: Life on Land

1. INTRODUCTION

1.1. *Research Background*

Steelmaking industries generate large amounts of waste, including steel slag. This by-product primarily consists of metal oxides, including iron, calcium, magnesium, and silica. Traditionally, steel slag has been utilized as a construction material or disposed of as solid waste, which poses environmental concerns if not properly managed.

In steel production, silica (SiO_2) plays an important role in slag formation within the furnace. During smelting, silica reacts with calcium oxide (CaO) to capture impurities such as sulfur and phosphorus. While molten steel is separated, the slag composed of SiO_2 and CaO settles at the bottom of the furnace, effectively removing unwanted elements from the final product.

Although widely produced, steel slag remains underutilised, underscoring the need for innovative and environmentally friendly approaches to valorise this waste. One promising method is the recovery of silica from steel slag through alkaline extraction followed by acid precipitation. This technique has been shown to produce high-quality amorphous silica effectively. With its versatile applications in material science, catalysis, and energy-related technologies, the synthesis of silica from steel slag not only reduces environmental impact but also contributes to the development of sustainable value-added products.

1.2. *Literature Review*

Several studies have reported the synthesis of silica from various industrial wastes using alkaline extraction and acid precipitation. Research on nickel waste treatment employed acid leaching with H_2SO_4 to remove impurities such as Fe_2O_3, K_2O, and CaO, followed by NaOH extraction [10]. From 40 g of nickel waste, the process yielded 29.40 g of silica extract, indicating the effectiveness of NaOH in silica recovery. Similarly, [12] successfully synthesised silica from geothermal waste using a stepwise extraction process with KOH and subsequent acidification with citric acid. The study reported a silica content of 93% under optimum conditions of 2N KOH and 2.5N citric acid at pH 4, with denser silica gel morphology compared to humic acid particles.

Another study [8] investigated silica gel synthesis from glass waste using different HCl concentrations (0.5, 0.75, and 1 M). The results showed amorphous structures with silica contents of 96.1%, 92.1%, and 89.1%, respectively, and particle sizes in the nanometer range. In addition, [13] also explored silica precipitation from bagasse ash using NaOH (2N) extraction and CO_2 as a precipitant, yielding silica with a surface area ranging from 100 to 227 m^2/g and a purity above 80%. Furthermore, [10] examined mesoporous silica production under varying NaOH concentrations and pH conditions, showing that higher pH levels reduced the surface area, with the best results obtained at 1 M NaOH.

These studies demonstrate that silica recovery from diverse waste sources is feasible and can achieve high purity and surface area depending on extraction conditions. However, specific investigations into steel slag as a silica source remain limited, especially regarding the influence of NaOH concentration and extraction temperature on silica yield and purity. This study addresses this gap by synthesising silica from steelmaking slag via alkaline extraction and acid precipitation, aiming to optimize operating parameters and evaluate product characteristics.

Fig. 1. Pretreatment of steel slag: (A) Slag collection from the field, (B) Particle size reduction by crushing and grinding.

1.1.1. *Extraction*

Previous studies have highlighted the importance of alkaline extraction in recovering silica from solid wastes, as silica is highly stable and insoluble in conventional solvents [3]. Sodium hydroxide (NaOH) has been widely applied due to its ability to convert silica (SiO_2) into soluble sodium silicate (Na_2SiO_3). In this research, steel slag was treated with NaOH solutions of varying concentrations (0.5–2.5 M) under controlled temperatures (60–100 °C) with constant stirring. Silica extraction occurs according to the reaction :

$$SiO_2 + 2NaOH \rightarrow Na_2SiO_3 + H_2O$$

While other oxides present in slag, such as CaO, MgO, Fe_2O_3, and Al_2O_3, may undergo secondary reactions. Filtration after cooling enables the separation of insoluble residues from sodium silicate solution. This approach provides a systematic evaluation of solvent concentration and thermal conditions to optimize silica extraction efficiency from steelmaking slag.

1.1.2. *Precipitation*

Precipitation is a widely used technique for recovering silica (SiO_2) from sodium silicate (Na_2SiO_3) solutions by inducing insolubility through changes in solution conditions, such as pH, temperature, or chemical reactions [7]. In the context of silica synthesis from industrial wastes, precipitation is typically performed by acidifying a sodium silicate solution, which converts dissolved silicate ions into amorphous silica.

Sodium hydroxide (NaOH) plays a crucial role in this process, as it dissolves silica from raw materials, such as iron slag, to form soluble sodium silicate. The addition of an acid, usually HCl, gradually lowers the pH of the solution, causing the formation of amorphous silica according to the reaction:

$$Na_2SiO_3 + 2HCl \rightarrow SiO_2\downarrow + 2NaCl + H_2O$$

Other residual metal hydroxides present in slag, such as calcium, magnesium, aluminium, or iron compounds, may also react with HCl during precipitation:

- $Ca(OH)_2 + 2HCl \rightarrow CaCl_2 + 2H_2O$
- $Mg(OH)_2 + 2HCl \rightarrow MgCl_2 + 2H_2O$
- $NaAl(OH)_4 + HCl \rightarrow Al(OH)_3 + NaCl + H_2O$
- $Na_3FeO_3 + 3HCl \rightarrow Fe(OH)_3 + 3NaCl$

The morphology and particle size of the precipitated silica are influenced by the pH, temperature, and stirring rate. Lowering the pH further (to 3–4) can accelerate precipitation and improve silica recovery. Previous studies have demonstrated that controlled precipitation yields high-purity amorphous silica suitable for both industrial and research applications [7].

1.3. *Research Objective*

This study aims to recover and purify amorphous silica from steel slag through alkaline extraction followed by acid precipitation. It also examines the influence of extraction temperature and NaOH concentration on the purity and yield of the recovered silica.

2. MATERIALS AND METHODS

2.1. *Materials and Equipment*

The primary material used in this study was steel slag waste, obtained from PT. Ispat Indo in Sidoarjo Regency. The slag contains approximately 35% silica, making it a suitable raw material for silica recovery. For the extraction and precipitation processes, hydrochloric acid (HCl, 37%) and sodium hydroxide (NaOH) were used as reagents. Both chemicals were purchased from the local supplier “BERKAT KIMIA” on Jl. Tidar, Surabaya. These materials were handled following standard laboratory procedures to ensure safety and consistency in the experiments.

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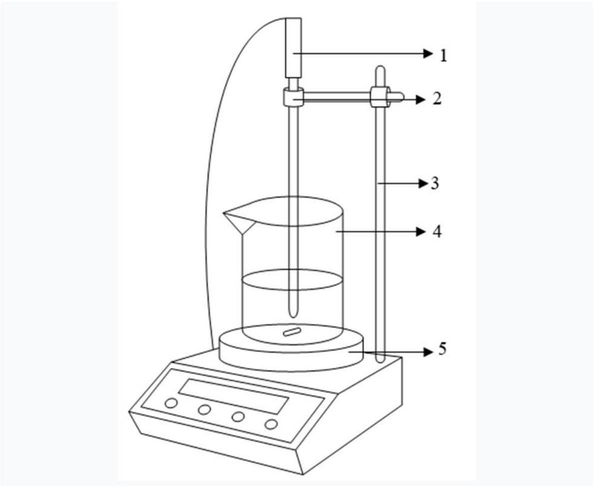

Fig. 2. Equipment for Extraction and precipitation

Description :

1. Thermometer
2. Clamp
3. Retort stand
4. Erlenmeyer flask
5. Magnetic stirrer

2.2. *Methods*

2.2.1. Silica Extraction

The extraction of silica from steel slag began with the preparation of the raw material. The slag was ground to a particle size smaller than 100 µm to increase the surface area for the reaction. For the extraction process, 100 grams of the prepared slag were mixed with sodium hydroxide (NaOH) solutions of varying concentrations (0.5, 1.0, 1.5, 2.0, and 2.5 M) in a glass beaker. The mixture was then heated at different temperatures (60, 70, 80, 90, and 100 °C) for 1 hour under constant stirring at 300 rpm using a hot plate with a magnetic stirrer. After heating, the solution was allowed to cool to room temperature and then filtered using filter paper to separate the insoluble residues from the sodium silicate solution.

The filtrate, containing dissolved silica, was subsequently titrated with 2 M hydrochloric acid (HCl) to lower the pH to 6–7. Once precipitation began, the pH was further reduced to 3–4 to accelerate the formation of amorphous silica. The resulting precipitate was left to age for 24 hours to ensure optimal crystal growth.

2.2.2. Silica Washing and Drying

The silica precipitate was washed 5–10 times with deionized water until a neutral pH was reached. During washing, the precipitate was gently stirred for 5–10 minutes to ensure thorough removal of impurities. The washing solution containing residual impurities was removed by repeated filtration. Finally, the purified silica was dried in an oven at 100 °C for 6 hours, yielding a fine, white powder. The resulting silica powder was weighed and analyzed to determine its purity.

3. RESULT AND DISCUSSION

3.1. Analysis of Slag

This study analyzed the raw material, which consisted of steel slag waste. The slag was characterized using X-ray fluorescence (XRF) analysis to determine its chemical composition. The results of the analysis are presented in the following table:

Table 2. Analysis of Slag

Element	Concentration
(MgO) Magnesium oxide	4.552 %
(Al_2O_3) Aluminium oxide	2.809 %
(SiO_2) Silicon dioxide	35.340 %
(S) Sulfur	11.690 %
(CaO) Calcium oxide	14.519 %
(MnO) Manganese (II) oxide	5.000 %
(FeO) Iron (II) oxide	26.090 %

(Laboratory Qc P.T Ispat Indo, 2024)

3.2. Analysis of Extracted Silica

Table 2. Analysis of Extracted Silica

Suhu (ºC)	Konsentrasi NaOH (M)	Konsentrasi Silika (%)
60	0.5	52.90
	1	55.83
	1.5	58.75
	2	61.68
	2.5	64.60
70	0.5	58.55
	1	61.85
	1.5	65.15
	2	68.45
	2.5	71.75
80	0.5	64.20
	1	68.50
	1.5	72.80
	2	77.10
	2.5	78.90
90	0.5	70.15
	1	73.86
	1.5	77.58
	2	81.29
	2.5	89.50
100	0.5	71.30
	1	73.70
	1.5	76.10
	2	81.20
	2.5	91.10

(Source: Integrated Research and Testing Laboratory, UGM)

The extracted samples were analysed for silica (SiO_2) content using X-ray fluorescence (XRF) spectroscopy. The results, summarised in Table 2, show that increasing the NaOH concentration from 0.5 M to 2.5 M enhanced silica recovery across all tested temperatures. At 0.5 M, the silica yield ranged from 52.9% to 71.3%, indicating that low OH^- availability limited the breakdown of Si–O–Si bonds in the slag matrix.

An increase in NaOH concentration from 1 M to 1.5 M resulted in a notable improvement in silica yield, indicating that higher alkali concentrations facilitate the dissolution of silica into sodium silicate. This aligns with the findings [5], which reported that a higher OH^- ion concentration accelerates silicate network depolymerisation, thereby increasing soluble silica. However, excessive NaOH levels may promote the dissolution of impurities such as Al, Fe, and Ca, which can co-precipitate and reduce the overall silica purity [9]. Consequently, although 2.5 M NaOH provided the highest yield, concentrations of 1.5–2 M are recommended to optimize yield while minimizing impurity incorporation.

Temperature also played a crucial role in the extraction of silica. Increasing the reaction temperature from 60 °C to 90 °C enhanced the diffusion of OH^- ions into the slag matrix, resulting in higher silica recovery [4]. Overall, these results demonstrate that both NaOH concentration and extraction temperature are key factors influencing the efficiency and quality of silica recovery from steel slag.

3.3. Effect of Extraction Temperature and NaOH Concentration on Silica Concentration

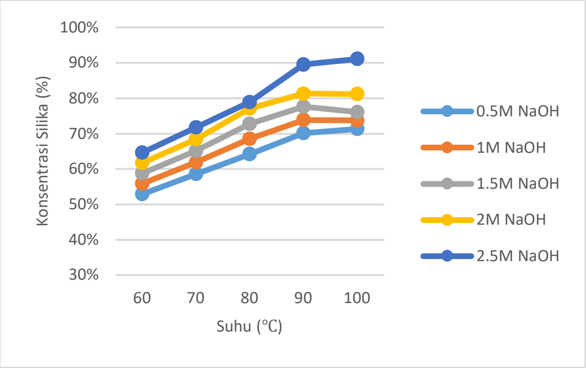

Fig. 3. Relation Between NaOH Concentration and Extracted Silica Concentration (%) at Various Temperatures (°C)

Variation in temperature accelerates the diffusion of OH^- ions into the pores of steel slag, promoting the breakdown of Si–O–Si bonds and increasing the dissolution of silica in the alkaline solution. Consequently, the silica yield rises with increasing temperature. As shown in **Figure 3**, the percentage of extracted silica increased as the temperature increased. At a NaOH concentration of 2.5 M, the lowest yield was observed at 60 °C, at 64.60%, while the yield increased steadily with temperature, reaching 91.10% at 100 °C.

These results are consistent with previous studies by [4], who reported a similar effect of extraction temperature on silica recovery from rice husk ash using 2 M NaOH. The study demonstrated that higher extraction temperatures enhance silica recovery until a saturation point is reached. At this point, the reaction rate stabilises due to the limitation of available reactants, and further temperature increases do not significantly improve silica recovery. This suggests that temperature is a crucial factor in maximising the extraction efficiency of silica from industrial waste materials.

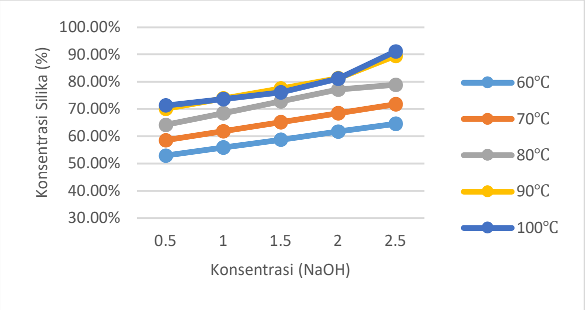

Fig. 4. Relation Between Temperature (ºC) and Extracted Silica Concentration (%) at Various NaOH Concentrations (M)

Based on the results, it was observed that increasing the NaOH concentration resulted in a higher percentage of silica being extracted. As shown in **Figure 4**, at 60 °C, the lowest silica yield was obtained with 0.5 M NaOH, at 52.90%. The silica recovery increased steadily with higher NaOH concentrations, reaching 71.03% at 2.5 M. This finding aligns with the study [5], which reported that higher NaOH concentrations enhance the ability of the alkaline solution to dissolve silica into sodium silicate. An increased number of OH^- ions accelerates the depolymerisation of the silicate network, thereby increasing the amount of silica that is extracted.

However, excessively high NaOH concentrations may also increase the solubility of impurities such as Al, Fe, and Ca, which can co-precipitate and reduce the overall purity, despite the high yield [9]. Therefore, although 2.5 M NaOH produced the highest yield, a practical recommendation is to use NaOH concentrations of 1.5–2 M, which provide a high recovery while minimizing the risk of impurity incorporation.

3.4. Analysis of XRD Results

To further characterize the structural properties of the extracted silica, X-ray diffraction (XRD) analysis was performed. This analysis provides insight into the crystallinity and phase composition of the material, allowing differentiation between amorphous and crystalline phases. The resulting diffractogram is presented :

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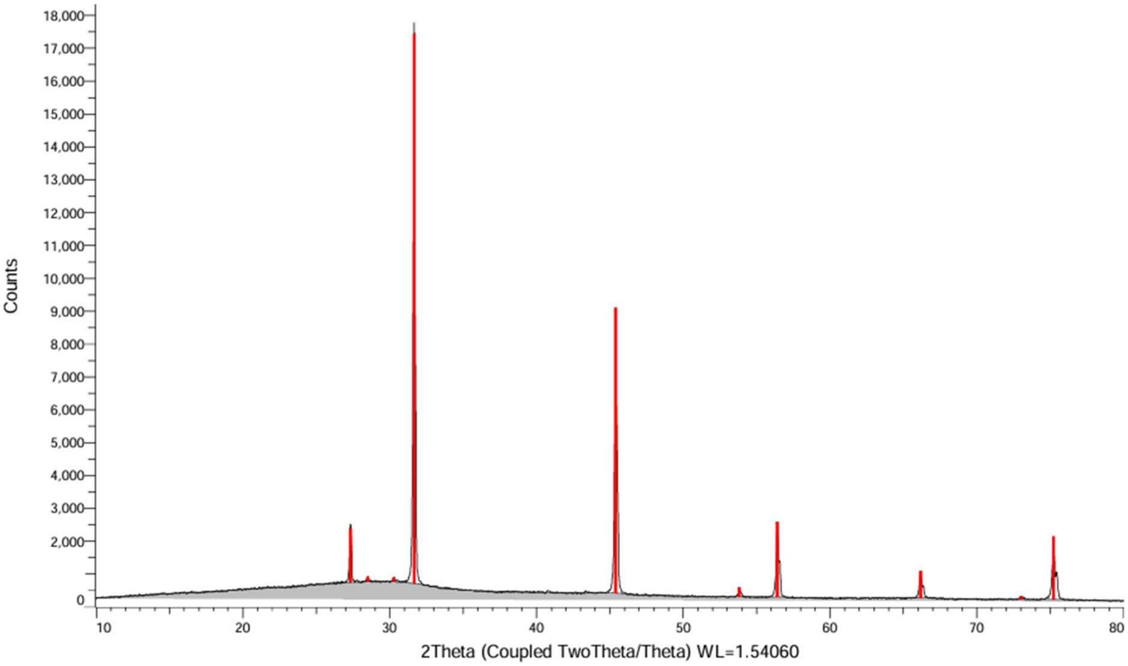

Fig. 5. Analysis Results of Silica from Steel Smelting Waste Using XRD

Figure 5. shows the XRD pattern of silica obtained from steel slag after alkaline extraction with NaOH. The diffractogram indicates that the sample is predominantly amorphous, as evidenced by a broad hump in the 2θ range of approximately 20–30°, without sharp diffraction peaks. This characteristic is consistent with the description [2], who noted that amorphous silica exhibits broad peaks due to its non-crystalline structure and atomic disorder. Similarly, [3] reported that silica precipitated from sodium silicate solutions shows a broad diffraction pattern around 20–30°.

Although the broad amorphous peak dominates, the diffractogram also displays minor sharp peaks at 2θ values of approximately 27.3°, 31.6°, 45.4°, 56.4°, and 75.2°, indicating the presence of residual crystalline fractions. Steel slag contains various metal oxides such as CaO, Fe_2O_3, Al_2O_3, and MgO, which are not completely dissolved during alkaline extraction. These oxides can form stable crystalline mineral phases that co-precipitate with silica [6].

Similar findings were reported in the conversion of rice husk ash to silica, where low calcination temperatures produced amorphous silica, but higher temperatures or the presence of mineral impurities resulted in minor crystalline peaks (tridymite, cristobalite) [1]. Therefore, the minor peaks observed in this study can be attributed to impurity phases rather than a dominant crystalline structure.

4. CONCLUSION

This study successfully demonstrated the recovery of silica from steel slag using an extraction and acid precipitation method. The resulting silica exhibited characteristics of amorphous silica, as indicated by a broad hump in the XRD pattern within the 2θ range of 20–30°. Under optimal conditions of 2.5 M NaOH and a temperature of 100 °C, the highest silica content of 91.10% was achieved.

Both extraction temperature and NaOH concentration were found to significantly influence the silica yield. Higher temperatures enhanced the diffusion of OH^- ions into the slag, promoting the breakdown of Si–O–Si bonds and increasing silica dissolution. Similarly, increasing the NaOH concentration improved the dissolution capacity of the alkaline solution, further increasing the extracted silica.

Overall, the study suggests that careful control of temperature and NaOH concentration is crucial for maximising silica recovery while maintaining high purity, offering valuable insights into the utilisation of steel slag as a sustainable silica source.

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