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Flash furnace dust processing via roasting and acid leaching operation

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Abstract: Flue dusts accumulating within the gas cleaning units of copper smelting plants establish a critical recycling loop that cannot be directly reintegrated into the mainstream flash furnace due to capacity degradation and operational constraints. This study investigates the hydrometallurgical extraction of valuable base metals from cyclone (CD), boiler (BD), and electrostatic precipitator (ESP) dusts collected from an industrial smelting facility. Direct atmospheric sulfuric acid leaching tests conducted without prior thermal treatment yielded suboptimal zinc extractions of 40%–52%, and copper extractions ranging from 71% to 73%. These restricted dissolution rates are fundamentally attributed to the complex mineralogical nature of the feed material, which is dominated by amorphous phases and highly acid-resistant crystalline structures, such as franklinite, that act as a refractory barrier. To overcome these structural limitations, thermal roasting pretreatment was systematically executed on homogenized composite dust samples across a temperature spectrum of 600 °C to 900 °C. The experimental results revealed that increasing the roasting temperature above 600 °C induces thermal sintering and severe particle agglomeration, which substantially reduces the active surface area and degrades downstream leaching kinetics. Under leaching conditions of 90 °C, 8 hours and 1.0 M sulfuric acid, the optimum roasting pretreatment was determined to be 600 °C. This optimized route elevated copper and zinc extraction efficiencies to their peak values of 93.07% and 88.74%, respectively. Ultimately, this process demonstrates a viable industrial flowsheet for breaking the impurity accumulation cycle and shifting smelter waste into a sustainable circular economy model.

Keywords: acid leaching, roasting, smelting dust, ESP, circular economy

1. Introduction

Dusts generated as by-products in copper smelting processes contain significant amounts of valuable copper and zinc; however, they also inevitably incorporate critical penalizing impurities such as arsenic, bismuth, antimony, and iron. Directly recirculating these fine materials into the primary flash smelting furnace without chemical or thermal pretreatment increases the steady-state impurity concentration in the feed blend, significantly reducing total furnace capacity and operational throughput. These detrimental elements form a continuous cyclic accumulation within the metallurgical system, causing major operational challenges during subsequent electrolytic refining of copper anodes and directly degrading final commercial cathode quality by disrupting structural uniformity. Furthermore, volatile arsenic compounds entrained by high-velocity furnace gases chemically poison and deactivate vanadium-based catalysts (V_2O_5) in downstream sulfuric acid plants, significantly shortening their service life and increasing maintenance costs. To effectively minimize such interconnected environmental hazards and metallurgical risks, isolating these hazardous dusts from the main production line, selectively recovering high-value metallic components, and securely discharging harmful contaminants in strict compliance with rigorous ecological standards constitutes a modern, sustainable production model for the circular economy (Tan et al., 2012; Xu et al., 2010; Arslan & Arslan, 2002).

High temperatures and the highly dynamic presence of oxygen during flash smelting and converting processes prevent the rapidly cooling dust particles from forming a regular crystalline lattice structure, systematically leading to the development of complex amorphous phases. This structural disorder

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phenomenon significantly complicates the definitive mineralogical characterization and quantitative phase analysis of the material. According to advanced mineralogical investigations of Bottom-blown Bath Smelting (BBS) and Flash Smelting (FS)—the two dominant industrial copper smelting technologies globally—magnetite (Fe_3O_4) and copper sulfate ($CuSO_4$) are identified as the dominant crystalline phases in FS dusts. In contrast, magnetite, lead sulfate ($PbSO_4$), and complex copper-iron oxide ($CuFe_5O_8$) structures are prominent in BBS dusts (Chen et al., 2020). A comprehensive examination of the coexisting amorphous phases revealed multi-component amorphous Cu-Zn-FeOx matrix phases in FS samples, while amorphous Cu-Zn-S structures and complex copper-zinc-sulfur melts were readily detected in BBS samples. Furthermore, arsenic, a critical impurity in copper smelting infrastructure, was found to exist predominantly in an encapsulated amorphous form in both processes (Chen et al., 2020). Electric Arc Furnace (EAF) dusts are often selected as model materials for investigating complex zinc phases because they form under high-temperature, highly oxidative conditions similar to copper smelting flue gas environments and contain high concentrations of zinc compounds. In foundational studies on EAF dust characterization, the primary zinc-bearing phase was identified as franklinite ($ZnFe_2O_4$), a highly stable spinel structure that forms through the solid-state contact of vaporized zinc at high temperatures with iron oxide particles in an oxidizing atmosphere. The secondary zinc phase was determined to be zincite (ZnO), which exhibits a much more favorable dissolution behavior (Machado et al., 2006). Recent thermodynamic and phase-equilibrium assessments have shown that the highly refractory nature of this zinc-ferrite spinel matrix can be effectively overcome through caustic-roasting pretreatments using sodium hydroxide (NaOH) as an additive. Thermodynamic modeling utilizing thermochemical software indicated that operating above the melting point of NaOH (T > 318 °C) successfully shifts the reaction kinetics into a solid-liquid mode, promoting the complete structural decomposition of stable zinc-ferrite into readily leachable zinc oxide (ZnO) and sodium-ferrite ($NaFeO_2$) intermediate phases without requiring strict atmospheric controls (Ahmad et al., 2022).

The precise leaching methods used, based on the inherent mineralogical complexity of smelting dusts and the target metal yield, directly govern overall hydrometallurgical process efficiency and reagent consumption rates. Atmospheric sulfuric acid leaching at 60–95 °C is a common industrial method for dissolving readily accessible copper oxides and sulfates; however, pressure oxidation leaching under elevated oxygen overpressures provides substantially higher yields, particularly for dissolving highly stable sulfidic mineral matrices. As an alternative sequential strategy, neutral water leaching applied to selectively recover highly soluble metal sulfates not only significantly reduces total acid consumption by providing initial mass loss but also inherently assists in early-stage impurity control. Additionally, caustic (alkaline) leaching, which selectively extracts problematic arsenic into the liquid phase while preventing any undesirable copper dissolution, is among the specialized options evaluated depending on the precise mineralogical profile of the byproduct. In this study, direct atmospheric leaching processes were systematically applied to dust samples collected from various units of the smelting plant, and the metal extraction efficiencies of the furnace dusts were investigated. To optimize the downstream dissolution kinetics and decompose refractory mineral phases, an optimized roasting step as a thermal pretreatment was integrated into the hydrometallurgical flowsheet. The resulting comparative analyses revealed that combining aggressive leaching conditions with the thermal roasting process successfully transformed the refractory amorphous and spinel structures into a more leachable mineralogical phase, thereby unlocking high extraction yields for both copper and zinc.

Although the hydrometallurgical extraction of valuable metals from smelting residues has been extensively explored, current literature often lacks a comprehensive integration of roasting pretreatments tailored specifically to overcome the refractory $ZnFe_2O_4$ and amorphous matrices characteristic of flash furnace dusts. This study bridges this critical research gap by optimizing a controlled roasting-leaching sequence at 600 °C under an oxygen flow of 220 dm^3/min, effectively inducing in-situ sulfation while avoiding the severe structural sintering observed at elevated temperatures. By systematically evaluating the dissolution kinetics of CD, BD, and ESP dusts, this work provides a sustainable, industrially scalable flowsheet that successfully mitigates impurity

accumulation cycles and advances the circular economy framework in copper smelting operations (Ahmad et al., 2022; Chen et al., 2020; Xia et al., 2021).

2. Materials and methods

The feed materials utilized in this investigative study comprise CD, BD, and ESP dusts. These secondary by-products were systematically collected from the respective gas purification and heat recovery units of the flash smelting furnace operation at the Eti Bakır Co. Smelting Plant located in Tekkeköy, Samsun, Türkiye. Volatilization occurs due to the high-temperature, strongly oxidative atmosphere inside the flash furnace; consequently, these fine particulates are entrained in the flue gases, carrying high concentrations of base metals alongside complex heavy-metal impurities.

To evaluate individual and synergistic behaviors, the raw dusts from the CD, BD, and ESP units were first tested independently and then blended via mechanical homogenization to generate a representative composite sample. The raw composite material exhibited a heterogeneous particle-size distribution with a coarse fraction. Therefore, to ensure experimental and analytical uniformity, the material stream exceeding 500 μm was isolated and subjected to size reduction using a laboratory-scale cone crusher. After crushing, the resulting fractions were recombined with the undersize material, thoroughly homogenized, and split into equal representative aliquots for subsequent chemical, physical, and mineralogical characterization. Detailed sieve analysis of the final composite feed revealed a fine particulate nature, with a characteristic d_{80} value of 33.5 μm.

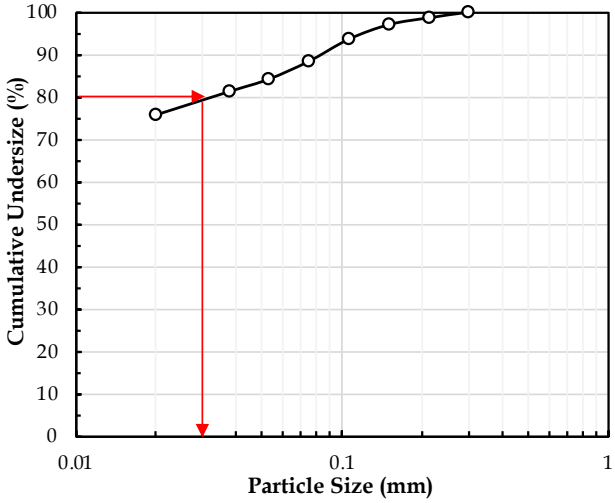

Fig. 1. Particle size distribution of the representative sample (d_{80} = 33.5 μm)

2.1. Characteristics of the experimental sample

2.1.1. Chemical analysis

Representative samples collected from the CD, BD, and ESP units, along with the systematically homogenized composite blend, were subjected to elemental quantification via Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Table 1 presents the comprehensive chemical profiles, showing the mass fractions of key base metals and penalizing impurities. Chemical characterization reveals that while the streams are heavily enriched in valuable components such as copper and zinc, they concurrently carry critical structural impurities, most notably iron and arsenic, emphasizing the necessity of targeted metallurgical extraction.

2.1.2. Mineralogical analysis

X-ray Diffraction (XRD) analyses of the combined CD, BD, and ESP dust samples revealed a distinctly amorphous character of the material. This glassy and disordered structure complicates the clear identification of mineral phases and hinders the precise calculation of their quantitative ratios. Nevertheless, mineralogical characterization studies identified zinc-iron oxide and complex iron oxide formations as the predominant mineral phases within the matrix. In particular, identifying franklinite—

an acid-resistant spinel structure—as the dominant phase confirms that zinc and iron are chemically bound within the material, posing a significant thermodynamic barrier to direct hydrometallurgical dissolution.

Table 1. Chemical analysis results of samples (mass fraction, %)

Product	Fe (%)	Cu (%)	Zn (%)	As (%)	Bi (%)
CD	25.12	13.95	9.08	3.46	0.11
BD	28.64	15.14	8.10	2.06	0.08
ESP	22.05	14.39	7.81	4.20	0.11
Composite	26.41	14.66	8.25	2.35	0.08

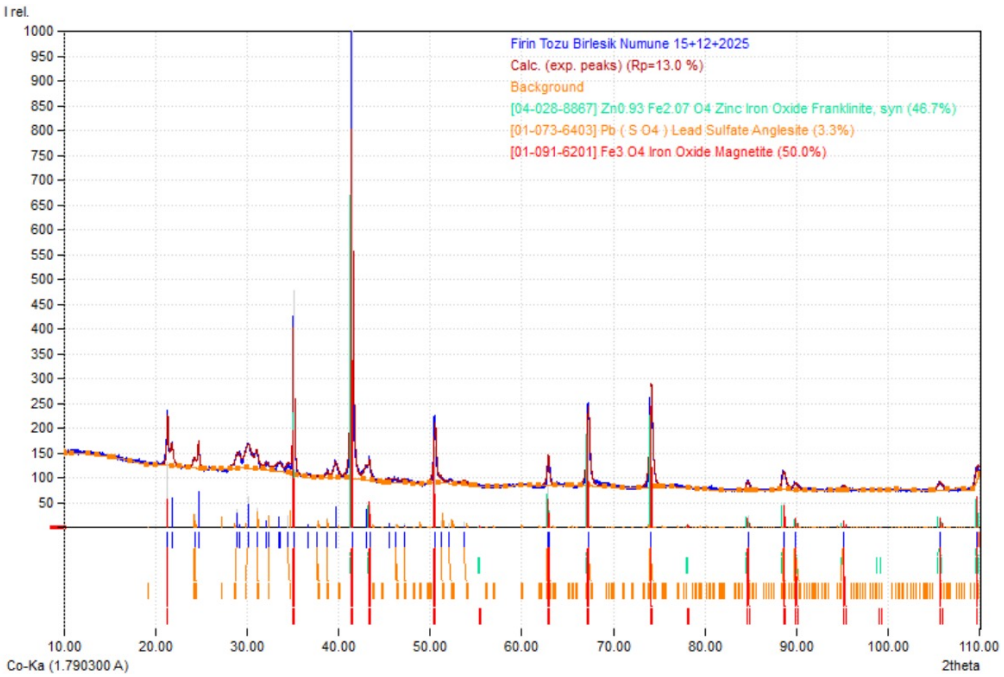

Fig. 2. X-ray diffraction analysis of blended furnace dust sample

2.2. Test conditions

The experimental methodology was divided into two primary phases: the direct leaching of raw materials and the leaching of thermally pretreated composite dusts. While the raw CD, BD, and ESP dusts were leached individually as non-roasted control samples, the combined dust stream was thoroughly homogenized to prepare a representative composite sample for the roasting stage. The roasting step, acting as a critical thermal pretreatment to disrupt the refractory mineralogical matrix, was performed in a laboratory-scale rotary kiln. This thermal treatment was carried out at 600-900 °C in 50 °C increments, with a regulated oxygen flow rate of 220 dm^3/min and a constant rotation speed of 3 rpm for 8 hours. After the roasting cycles and subsequent cooling, the roasted products were split into equal, representative portions using a mechanical sample splitter to ensure uniform sampling for the downstream hydrometallurgical stages. To overcome the highly refractory nature and chemical stability of the non-roasted samples, aggressive direct leaching conditions were employed at 90 °C with a 1.0 mol/dm^3 sulfuric acid (H_2SO_4) concentration and a 1/8 solid-to-liquid ratio (w/v) for a constant period of 8 hours. Conversely, the roasted composite samples were subjected to comparative leaching tests for the same 8-hour duration under two distinct regimes while maintaining the identical 1/8 solid-to-liquid ratio: a mild digestion path at ambient temperature with 0.15 mol/dm^3 H_2SO_4, and an aggressive extraction path at 90 °C with 1.0 mol/dm^3 H_2SO_4. Following the completion of the leaching intervals, the resulting slurries underwent vacuum filtration to achieve efficient solid-liquid separation. The final pregnant leach solutions were then analyzed, and the precise concentrations of dissolved base metals and impurities were quantified using ICP-OES.

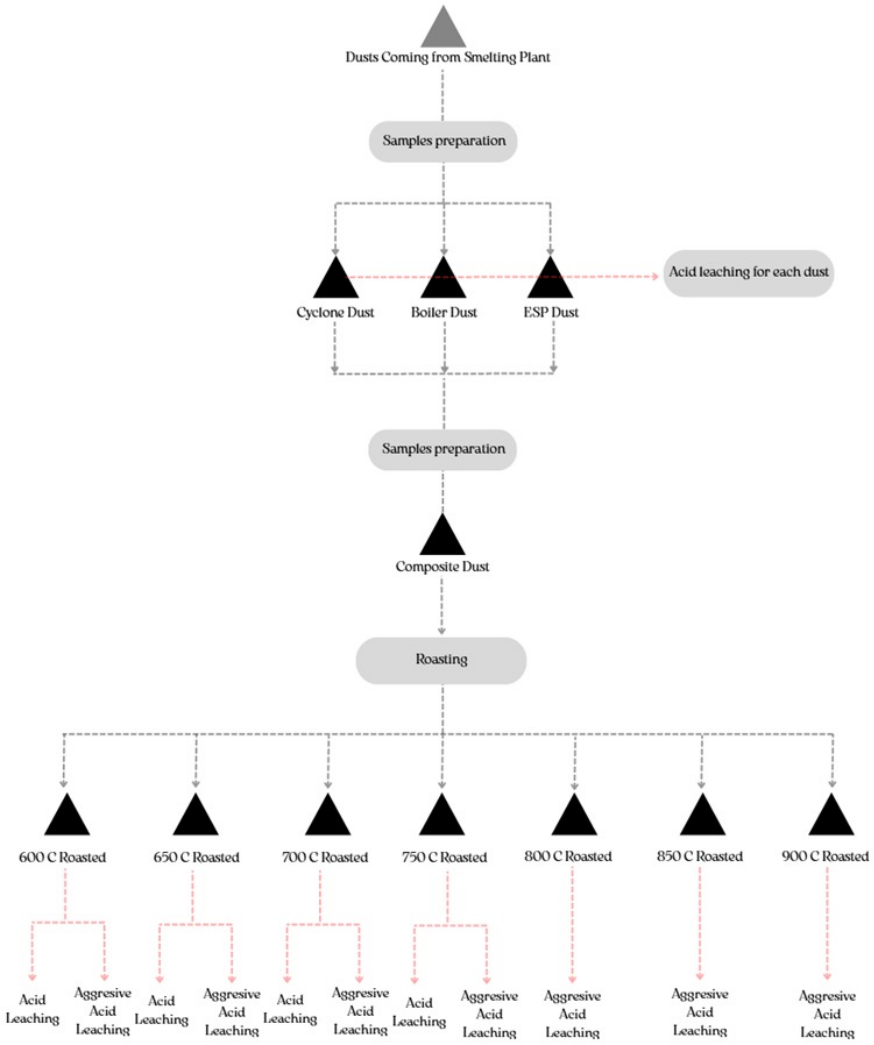

Fig. 3. Experimental flowsheet of the roasting and acid leaching tests for copper smelting dusts

3. Results and discussion

3.1. Leach tests of CD, BD and ESP dusts

To establish a baseline for metal extraction following operational adjustments that increased oxygen partial pressure within the industrial flash furnace, direct atmospheric sulfuric acid leaching was initially performed on the raw dust samples collected from the CD, BD, and ESP units. These baseline tests were conducted under intensive conditions: 90 °C, 8 hours of leaching, and 1.0 mol/dm^3 H_2SO_4. However, despite these aggressive parameters, the experiments yielded limited metal extractions. These suboptimal dissolution rates, particularly for zinc (40.34%–51.69%), align closely with the findings of Ruiz et al. (2007) and Gonzalez-Montero et al. (2020), who similarly reported that direct atmospheric leaching of untreated copper smelter dusts yields restricted metal extractions due to the encapsulation of valuable metals within refractory oxide and ferrite matrices. This comparative limitation clearly underscores the necessity of a thermal pretreatment stage prior to hydrometallurgical processing. Table 2 presents the resulting base metal extraction efficiencies.

3.2. Roasting process of composite dust

To improve downstream dissolution yields and decompose the refractory phases identified in the raw dusts, the materials collected from the distinct units were systematically homogenized to form a composite dust sample and subjected to an optimized roasting pretreatment before leaching. Table 3 details the physical properties, chemical shifts, and progressive mass reductions of the composite matrix as a function of calcination temperature.

Table 2. Extraction results of individual dust samples (90 °C, 1.0 mol/dm^3 H_2SO_4, 8 h)

Product	Extraction (%)				
	Fe (%)	Cu (%)	Zn (%)	As (%)	Bi (%)
CD	17.77	70.71	40.34	90.71	55.42
BD	21.30	73.35	44.51	82.66	62.23
ESP	15.01	73.46	51.69	37.43	31.99

Table 3. Chemical analysis, density, and weight loss results of roasted composite sample.

Roasting Temperature (°C)	Fe (%)	Cu (%)	Zn (%)	As (%)	Bi (%)	S (%)	Density (g/cm^3)	Weight Loss (%)
600	26.99	15.01	8.01	2.33	0.11	5.91	6.21	8.01
650	27.43	15.42	8.23	2.34	0.11	5.72	6.66	9.71
700	30.21	16.67	8.73	2.41	0.12	3.91	5.83	18.76
750	30.37	17.11	8.41	2.45	0.12	2.12	5.21	20.51
800	31.22	17.85	8.17	2.74	0.12	1.97	4.98	21.12
850	31.01	17.88	7.85	2.80	0.13	1.00	4.81	22.33
900	30.91	17.43	8.42	4.42	0.13	1.27	4.80	23.25

High-temperature combustion carbon analysis (CS844, LECO Corp., USA) confirmed the complete absence of carbon in the samples. As detailed in Table 3, the bulk density of the roasted composite steadily decreased from 6.21 g/cm^3 to 4.80 g/cm^3 as the roasting temperature rose from 600 °C to 900 °C. Although thermal treatments typically promote sintering and densification, the density reduction observed here was primarily driven by substantial mass loss (increasing from 8.01% to 23.25%) due to the thermal decomposition and volatilization of sulfur and gaseous species. Concurrently, continuous gas evolution induced particle coalescence and bridging, resulting in porous, sponge-like macro-agglomerates with entrapped internal voids (Fig. 4). This substantial volatile release and the resulting void entrapment clearly outweighed localized sintering effects, leading to an overall decline in bulk density.

Regarding phase transformations, although initial feed analysis revealed no distinct sulfate phases, the moderate-to-high copper and zinc extraction yields at 600 °C strongly indicate in situ sulfation under regulated oxygen flow (220 dm^3/min). In this stage, target metals reacted with SO_2 and O_2 species to form readily soluble metal sulfates. Beyond 600 °C, however, these sulfates thermally decomposed into refractory oxide and ferrite matrices, directly causing the lower extraction yields observed at higher temperatures (Peng et al., 2018).

These chemical transformations correlate well with the microstructural evolution shown in Fig. 5. The sample roasted at 600 °C maintained a fine, homogeneous particle distribution and a high active surface area, fostering favorable reaction kinetics during downstream leaching. Conversely, raising the temperature to 900 °C caused significant morphological degradation and pronounced sintering that hindered leaching performance.

The sample treated at 900 °C demonstrates substantial structural alterations dominated by thermal sintering and severe particle agglomeration. At this elevated temperature, individual fine grains undergo high-temperature fusion, forming drastically coarsened, surface-sealed macro-agglomerates. This distinctive sintering mechanism closes the open porosity and encapsulates the target copper and zinc metallic phases, drastically reducing the active surface area accessible to the fluid medium and consequently retarding the downstream hydrometallurgical leaching kinetics. To quantitatively validate these sintering dynamics, sieve analyses were performed across the roasting temperature spectrum. In agreement with the microscopic findings, higher temperatures promoted substantial grain coarsening. The sample roasted at the optimum temperature of 600 °C retained a fine particle size (d_{80} = 25.6 μm), whereas the d_{80} value surged to 175.3 μm at 850 °C and peaked at 388.2 μm at 900 °C. This significant grain growth confirms extensive solid-state fusion at elevated temperatures, providing a physical explanation for the impaired hydrometallurgical leaching kinetics.

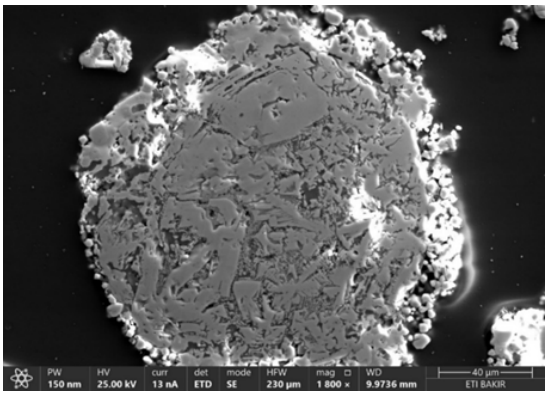

Fig. 4. SEM micrograph of the composite dust roasted at 850 °C

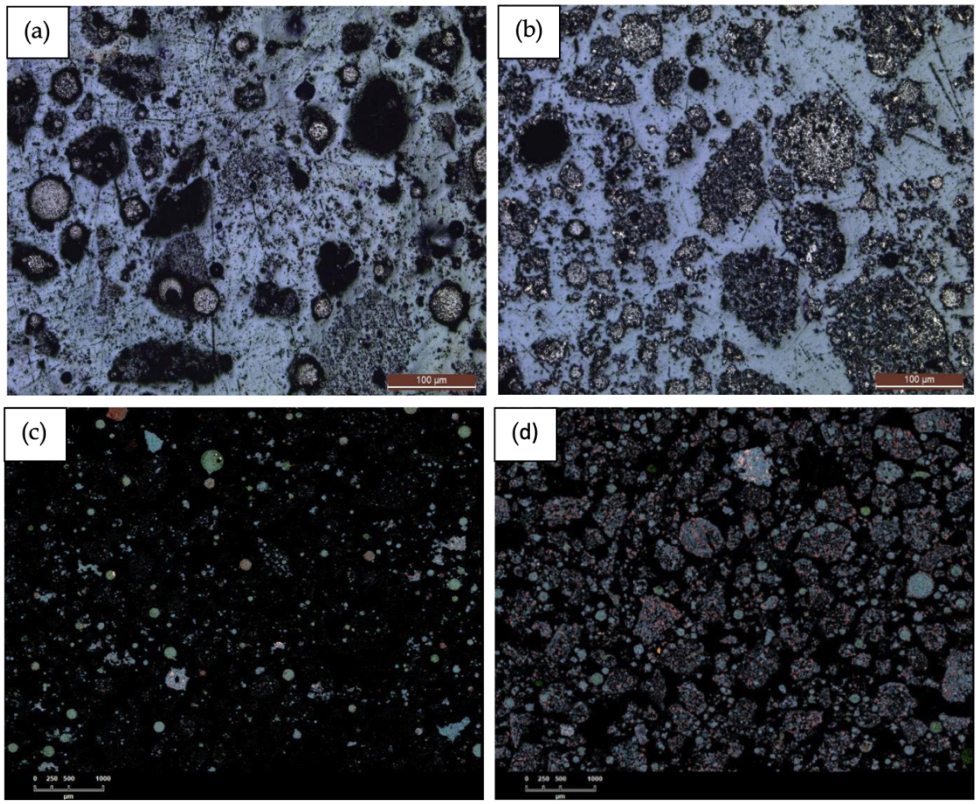

Fig. 5. SEM images of roasted dust (a) and (c) at 600 °C; (b) and (d) at 900 °C

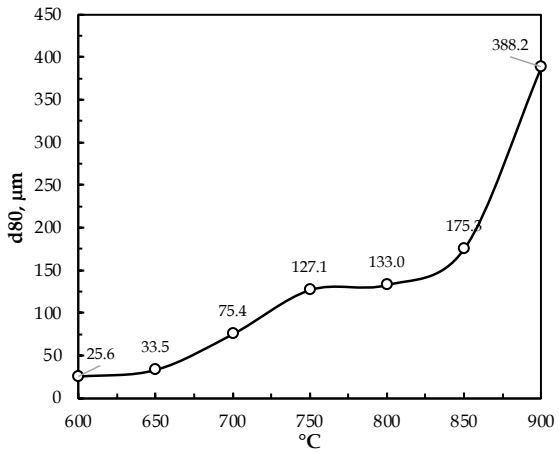

Fig. 6. Sieve analyses of roasted dusts

3.3. Leach tests of roasted dusts

Systematic sulfuric acid leaching trials were performed on the roasted composite dust samples to evaluate the effect of calcination temperature on metal dissolution kinetics. Throughout these investigative acid digestion tests, the solid-to-liquid ratio was strictly maintained at a constant 1/8 ratio, and the total leaching duration was fixed at a constant period of 8 hours under steady agitation. To compare metallurgical extraction yields, the acid leaching variants were conducted under two regimes: a non-aggressive (mild) path using 0.15 mol/dm^3 sulfuric acid at 25 °C, and an aggressive (intensive) path using 1.0 mol/dm^3 sulfuric acid at 90 °C. Additionally, neutral water leaching tests were conducted on both the raw non-roasted dust and the 600 °C roasted sample to quantify the extraction potential of readily soluble sulfate phases.

3.3.1. Sulfuric acid leaching of roasted dusts under non-aggressive conditions (0.15 mol/dm^3 H_2SO_4, 25 °C)

The experimental results demonstrate that even after thermal roasting, satisfactory extraction yields could not be achieved under non-aggressive conditions. Since the application of a mild chemical driving force remained fundamentally insufficient to disintegrate the stable mineral matrices, further tests were not conducted at higher temperatures. Table 4 summarizes the detailed extraction efficiencies.

Table 4. Extraction results of roasted dusts under non-aggressive conditions (25 °C, 0.15 mol/dm^3 H_2SO_4, 8 h)

Roasting Temperature	Extraction (%)				
(°C)	Fe (%)	Cu (%)	Zn (%)	As (%)	Bi (%)
600 °C	5.32	57.25	54.52	51.62	32.35
650 °C	5.74	58.90	54.09	88.64	32.05
700 °C	10.14	49.37	52.20	81.94	26.93
750 °C	2.08	21.14	34.40	91.61	29.10

3.3.2. Sulfuric acid leaching of roasted dusts under aggressive conditions (1.0 mol/dm^3 H_2SO_4, 90 °C)

Under aggressive conditions, the highest yields were achieved at the optimum roasting temperature of 600 °C, where copper and zinc extractions reached 93.07% and 88.74%, respectively. These findings substantiate that the 600 °C pretreatment effectively disrupts the refractory mineral lattice without inducing the severe sintering and surface sealing observed at elevated temperatures, thereby preserving sufficient active surface area for acid digestion. Furthermore, reaching a peak zinc extraction of 88.74% at 600 °C is highly consistent with the mechanisms described by Langová and Matýsek (2010), demonstrating that the acid-resistant $ZnFe_2O_4$ phase begins to thermally decompose into more soluble forms under these specific oxidative roasting conditions, thereby significantly enhancing the leaching kinetics compared to the raw dusts. The selection of 600 °C as the initial roasting temperature was based on existing literature on the thermal stability of zinc-ferrite spinels (Langová and Matýsek, 2010). Prior studies show that the robust franklinite phase remains thermodynamically stable and highly resistant to decomposition below 600 °C (Peng et al., 2018; Xia et al., 2021). Consequently, to effectively disrupt this refractory matrix and optimize hydrometallurgical efficiency, 600 °C was set as the operational baseline, leaving the effects of lower thermal regimes for future studies. Table 5 details the experimental values across the entire thermal profile.

Although the optimum roasting pretreatment at 600 °C maximized copper and zinc extractions, the final pregnant leach solution (PLS) evaluation indicates significant co-dissolution of structural impurities. As detailed in Table 5, under aggressive leaching conditions (90 °C, 1.0 mol/dm^3 H_2SO_4), the extraction rates of iron, arsenic, and bismuth reached 63.28%, 98.57%, and 79.20%, respectively. The intense chemical driving force provided by the high acid concentration and elevated temperature unselectively dissolves not only the base metals but also the impurity-bearing oxide and amorphous matrices. From an industrial flowsheet perspective, although this extraction stage successfully unlocks Cu and Zn, the resulting PLS carries a high contaminant load. Consequently, the industrial implementation of this process strictly requires the integration of robust downstream solution

purification stages, such as solvent extraction (SX) for selective copper extraction, alongside targeted precipitation circuits (e.g., jarosite or goethite precipitation for iron removal, and scorodite formation for arsenic stabilization) prior to the final electrowinning process.

Table 5. Extraction results of roasted dusts under aggressive conditions (90 °C, 1.0 mol/dm³ H_2SO_4, 8 h)

Roasting Temperature (°C)	Extraction (%)				
	Fe (%)	Cu (%)	Zn (%)	As (%)	Bi (%)
600 °C	63.28	93.07	88.74	98.57	79.20
650 °C	60.08	92.28	87.86	98.68	85.18
700 °C	44.46	74.84	70.82	97.64	78.46
750 °C	56.05	77.08	70.83	98.30	79.84
800 °C	47.90	71.56	57.53	97.88	79.19
850 °C	73.67	73.67	55.90	97.98	73.32
900 °C	68.54	68.54	54.81	98.03	72.48

3.3.3. Water leaching of roasted dusts

The dust sample roasted at 600 °C was subjected to water leaching for 30 min at room temperature (25 °C) to determine the extraction potential of the water-soluble sulfate phases in its structure. The resulting metal extraction efficiencies are presented in Table 6.

Table 6. Extraction results of 600°C roasted dusts during water leaching (25 °C, 30 min)

Product	Extraction (%)				
	Fe (%)	Cu (%)	Zn (%)	As (%)	Bi (%)
Roasted Dust (600 °C)	5.35	45.91	33.84	5.83	1.24

Evaluation of the aqueous extraction data reveals that zinc solubility remained constrained at 33.84%. This limited dissolution implies that while roasting at 600 °C successfully breaks down the refractory franklinite phase, a substantial fraction of the liberated zinc converts into acid-soluble ZnO rather than forming highly water-soluble zinc sulfates. Conversely, the 45.91% extraction rate for copper suggests the partial formation of water-soluble copper sulfate ($CuSO_4$) phases during the thermal pretreatment. In contrast, the highly restricted transition of contaminating elements such as iron (5.35%), arsenic (5.83%), and bismuth (1.24%) into the liquid phase represents a significant metallurgical advantage. These results demonstrate that water leaching can be implemented as a low-cost, selective pre-leaching step that minimizes the impurity load and iron contamination prior to the main acid leaching stage.

4. Conclusions

This study demonstrates the effects of roasting as a thermal pretreatment for extracting copper and zinc from flash smelting furnace dusts. The experimental findings indicate that under direct atmospheric sulfuric acid leaching, zinc extractions for CD, BD, and ESP dusts were determined as 40.34%, 44.51%, and 51.69%, respectively, while copper extractions were found to be 70.71%, 73.35%, and 73.46%, respectively. Implementing a controlled roasting pretreatment at 600 °C under an oxygen flow rate of 220 L/min on the composite mixture of CD, BD, and ESP dusts proved to maximize process efficiency by increasing these extractions to 93.07% Cu and 88.74% Zn. Characterization studies revealed that acid-resistant amorphous phases, such as $ZnFe_2O_4$, severely restricted metal extraction, whereas thermal treatment improved leaching kinetics by breaking down these mineralogical barriers. Conversely, sintering and subsequent grain coarsening above 600 °C reduced particle surface area, leading to a gradual decline in dissolution yields. Consequently, although 600 °C provided sufficient thermal energy for the formation of readily leachable new phases and stood out as the most favorable among the tested parameters, evaluating temperatures below 600 °C remains essential in future studies to fully establish

the lower thermodynamic and kinetic boundaries. Furthermore, it was established that increases in leaching temperature and acid concentration play a critical role in transferring metallic values into the sulfuric acid medium. However, the aggressive acidic environment required to maximize base metal extraction also triggers the significant co-dissolution of structural impurities, particularly iron, arsenic, and bismuth. Therefore, for this hydrometallurgical flowsheet to be industrially viable, the extraction stage must be strictly coupled with robust downstream solution purification and selective precipitation circuits prior to final metal recovery.

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