

## APPLICATION OF QUARRY DUST AND CONCRETE RECYCLING DUST IN PYROMETALLURGICAL TREATMENT OF WAEZ SLAG TO ENABLE THE RECOVERY OF VALUABLE MATERIALS

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### Abstract

Quarry dust and concrete recycling dust, generated as solid waste during rock and concrete crushing operations, poses a significant environmental challenge. Rich in SiO<sub>2</sub>, these fine-grained materials hold potential as fluxing agents in pyrometallurgical processes, yet their metallurgical applications remain underexplored due to the complexity of such waste streams. Within the FINEST project (<https://finest-project.de/>), subproject 3: FINEST Disperse Metals, investigates the safe blending of multiple fine and ultra-fine grained industrial waste streams and their subsequent multi-stage pyrometallurgical processing for metal extraction and inert disposal. Furthermore, the Waelue project (<https://www.recomine.de/en/project/waelue/>) aims to valorize Waelz slag, a by-product of the well-established Waelz process for zinc extraction. Present study explores the feasibility of using quarry and concrete recycling dust as flux materials for the pyrometallurgical processing of Waelz slag. A carbothermic reduction process was designed and subjected to experimental testing. The process incorporated the dusts with the objective of extracting metals (Fe and Zn) and producing a non-hazardous slag suitable for use as a construction material. The FactSage™ software was employed to calculate the most suitable proportion between the dusts and Waelz slag, and reducing agent to ensure optimal smelting conditions. The results indicate that the incorporation of these dusts reduces the melting point and viscosity of the slag, facilitating efficient slag - metal separation along with valorization of the fine particulate waste. These findings highlight the potential of integrating quarry and concrete recycling dust in pyrometallurgical processes, advancing waste valorization and aligning with circular economy principles for sustainable industrial by-product recycling.

**Keywords:** Quarry dust, concrete recycling dust, Waelz slag, circular economy, waste valorization

### 1. INTRODUCTION

Quarry dust and concrete recycling dust are two industrial by-products with growing environmental and operational implications, yet they offer significant potential for sustainable reuse in pyrometallurgical processes. During mechanical breakdown and transportation of rocks through conveyor systems, substantial amounts of fine particulate matters are released. These fine dusts pose operational challenges by accumulating on and in the equipment and creating air quality concerns, prompting the installation of dedusting plants to capture and manage these fine dusts [1]. Similarly, concrete recycling dust originates from the crushing and separation of construction and demolition waste. This residue is often rich in fine silicate particles, cement paste, and carbonates [2, 3]. Both quarry and concrete recycling dusts are produced in significant

quantities but remain underutilized presenting opportunities for integration into high-temperature processes as flux materials.

The Waelz process is a widely adopted pyrometallurgical method used to recover zinc and other volatile metals from electric arc furnace (EAF) dust and other zinc (Zn) containing by-products [4–6]. Operating in a rotary kiln at temperatures between 1000–1200 °C, the process enables the selective volatilization of Zn, which subsequently condenses as Waelz oxide in the off-gas system. The remaining non-volatile residue, Waelz slag, primarily contains Fe, Ca, Si, as well as minor quantities of unrecovered Zn and other metals [7, 8]. While Waelz oxide is refined for Zn recovery, Waelz slag is often considered a low-value by-product, commonly disposed of in landfills [9]. Its relatively high melting point and viscosity pose barriers to direct reuse in metallurgical operations, necessitating process modifications or additives for effective slag conditioning.

The global availability of Waelz slag is on the rise, driven by increasing volumes of EAF dust and tighter environmental regulations on hazardous waste disposal. Concurrently, the demand for Zn has been rising at an average annual rate of 4.7% since 2012. In Europe alone, several hundred thousand tons of Waelz slag are produced annually [10]. Despite their chemical stability, these slags represent an untapped resource stream. If optimized for further metal recovery or slag valorization, they could enhance the circularity of the Fe and Zn. The addition of flux material such as quarry dust and recycled concrete dust holds promise in lowering the melting temperature and reducing the viscosity of Waelz slag, improving the overall efficiency and sustainability of secondary metal extraction processes [11, 12]. This study aligns with circular economy approach by closing material loops and reducing the environmental impact of both metallurgical and construction waste streams.

## 2. MATERIALS AND METHODS

In this study, four primary material groups were utilized: Waelz slag, fluxing agents (quarry dust and recycled concrete dust), and a reducing agent. All materials were characterized to determine their chemical compositions prior to thermochemical modelling and experimentation. Two types of quarry dust were sourced from active quarrying operations in the Free State of Saxony, Germany. One concrete recycling dust was collected from an extensive demolition project in Dresden, Germany. The investigated dusts are fine grained materials with particle size below 250µm. Bulk chemical compositions were determined using X-ray fluorescence (XRF) as illustrated in **Table 1**. Henceforth, the quarry dust samples will be designated QD1 and QD2, whereas the recycled concrete dust samples will be labeled RCD1.

**Table 1** Chemical composition of the flux materials (wt%)

| Sample      | SiO <sub>2</sub> | CaO   | Al <sub>2</sub> O <sub>3</sub> | Fe <sub>2</sub> O <sub>3</sub> | MgO  | Mn <sub>3</sub> O <sub>4</sub> | Na <sub>2</sub> O | K <sub>2</sub> O | SO <sub>3</sub> |
|-------------|------------------|-------|--------------------------------|--------------------------------|------|--------------------------------|-------------------|------------------|-----------------|
| <b>QD1</b>  | 65.94            | 2.98  | 13.94                          | 4.99                           | 2.36 | 0.07                           | 2.84              | 3.00             | 0.02            |
| <b>QD2</b>  | 41.54            | 10.61 | 13.40                          | 13.65                          | 9.47 | 0.13                           | 1.82              | 0.89             | 0.07            |
| <b>RCD1</b> | 61.62            | 19.93 | 8.14                           | 3.03                           | 2.02 | 0.09                           | 0.74              | 1.61             | 1.49            |

The Waelz slag was provided by BEFESA Zinc Freiberg GmbH and represents the non-volatile residue from Waelz process. The Waelz slag sample is designated as WS1 in this study. Its chemical composition was determined using X-ray fluorescence (XRF) analysis. The distribution of iron phases Fe<sub>2</sub>O<sub>3</sub>, FeO, and metallic Fe was quantified through Mössbauer spectroscopy which is presented in **Table 2**. Additionally, a CHNS elemental analysis was performed to quantify the residual carbon content in WS1.

**Table 2** The chemical composition of Waelz slag (wt%)

| Sample | Fe <sub>2</sub> O <sub>3</sub> | FeO  | Fe   | ZnO  | SiO <sub>2</sub> | CaO   | Al <sub>2</sub> O <sub>3</sub> | MgO  | MnO  | K <sub>2</sub> O | Na <sub>2</sub> O | S    | C    |
|--------|--------------------------------|------|------|------|------------------|-------|--------------------------------|------|------|------------------|-------------------|------|------|
| WS1    | 37.78                          | 0.60 | 9.26 | 3.54 | 10.00            | 15.67 | 1.50                           | 1.87 | 7.76 | 1.54             | 0.84              | 1.54 | 8.09 |

Petroleum coke (pet coke) was used as the reducing agent in all experimental trials due to its high fixed carbon content and stability at high temperatures. The pet coke was milled and sieved to a particle size below 250 µm to promote uniform reactivity during high-temperature reduction processes.

Carbothermic reduction experiments were conducted at 1450 °C using a high-temperature laboratory-scale muffle furnace (Linn High Therm VMK 1800-G). A fixed 25 g and 10g of WS1 was thoroughly mixed with one of the selected fluxing agents (QD1, QD2, or RCD1) and petcoke as the reducing agent. The prepared mixture was placed in a graphite crucible, which was then inserted into a larger alumina crucible fitted with a lid containing an opening for an alumina gas lance. An argon flow of 60 L/h was continuously introduced through the lance to maintain an inert atmosphere, preventing oxidation. The crucible assembly was heated at a controlled rate of 10 K/min, kept at 1450 °C for 4 hours, and subsequently allowed to cool within the furnace to room temperature under the same inert conditions.

Subsequent to the carbothermic reduction, the smelting samples were subjected to further analysis. Micro-XRF mapping (Bruker M4+ Tornado) was utilized to examine the elemental distribution in both phases, while X-ray computed tomography (XCT) provided insight into the internal structure and phase distribution of the metal–slag samples

### 3. RESULTS AND DISCUSSION

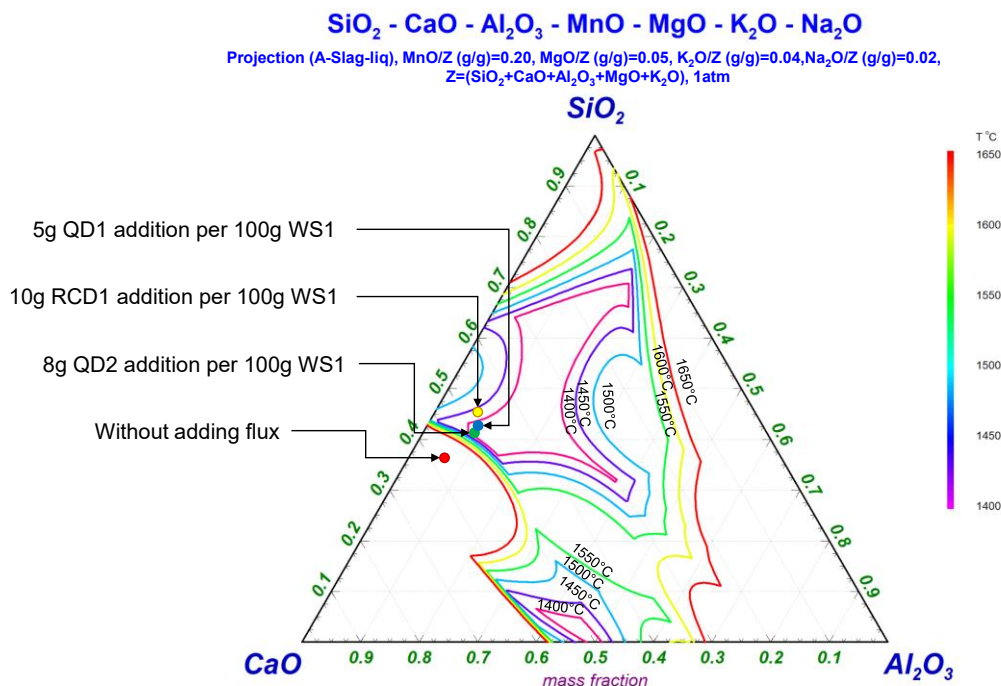
#### 3.1 Thermochemical modelling

The slag composition (**Table 3**) was estimated based on the chemical composition of WS1, under the assumption that all Fe would be reduced to the metallic phase and Zn would volatilize into the gas phase during carbothermic reduction. Although manganese should ideally be reduced to the metal phase to produce a non-hazardous slag suitable for use in construction materials, this preliminary study focuses primarily on Zn and Fe removal from the feed. Accordingly, Mn is considered as MnO in the slag phase for the purposes of the modelling. The relative proportions of the remaining slag-forming oxides were adjusted to optimize process conditions. Specifically, the SiO<sub>2</sub>–CaO–Al<sub>2</sub>O<sub>3</sub> ternary phase diagram (**Figure 1**) was constructed using FactSage™ 8.2 (database: FToxid) to achieve the following targets:

- A adequately low liquidus temperature to ensure complete slag melting and prevent premature solidification during tapping.
- A slag viscosity in the range of approximately 0.1 – 0.2 Pa·s to promote efficient mass transfer and separation between the slag and metallic phases.

**Table 3** Estimated slag composition for modelling the carbothermic reduction (wt%)

| Slag composition | SiO <sub>2</sub> | CaO   | Al <sub>2</sub> O <sub>3</sub> | MgO  | MnO   | K <sub>2</sub> O | Na <sub>2</sub> O |
|------------------|------------------|-------|--------------------------------|------|-------|------------------|-------------------|
|                  | 25.52            | 39.98 | 3.84                           | 4.78 | 19.80 | 3.93             | 2.15              |



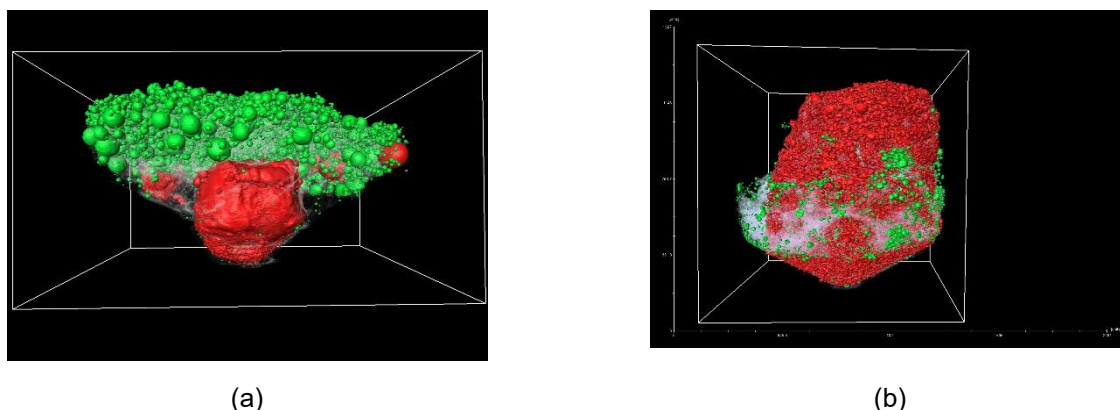
**Figure 1** Phase diagram for the SiO<sub>2</sub>-CaO-Al<sub>2</sub>O<sub>3</sub> slag system for carbothermic reduction with addition of different flux materials for 100 g WS1 feed (created using FactSage™ 8.2 software)

As shown in **Figure 1**, the addition of quarry dust (QD1, QD2) and recycled concrete dust (RCD1) to Waelz slag significantly reduces the liquidus temperature of the slag system, bringing it within the target processing range of 1450 °C. In contrast, the unmodified slag composition exhibits a liquidus temperature exceeding 1650 °C, rendering it less suitable for efficient reduction and slag-metal separation.

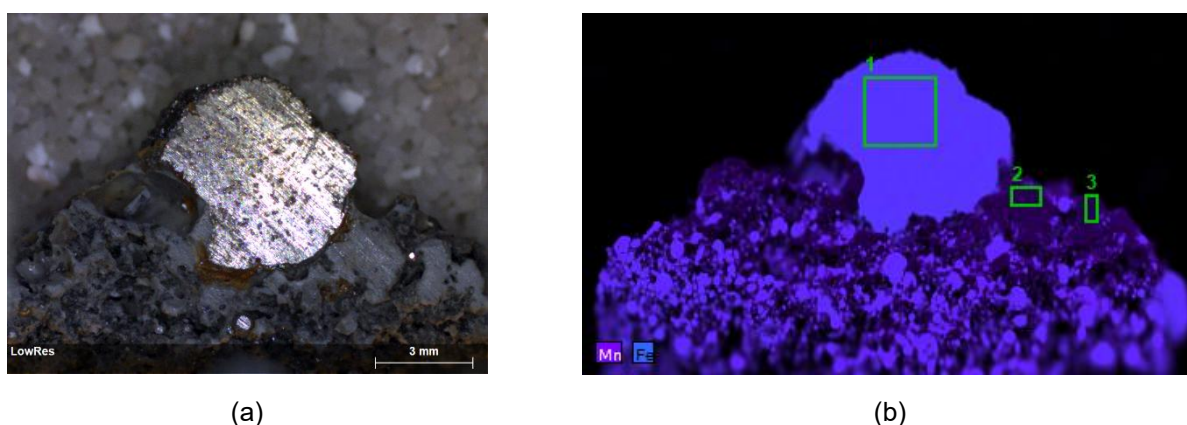
Although increasing the amount of flux materials could reduce the melting temperature of the slag, The high SiO<sub>2</sub> content significantly increases the polymerization of the (slag) melt and thus the viscosity. This effect is further compounded by a decrease in the slag basicity index (CaO/SiO<sub>2</sub> ratio), as excessive SiO<sub>2</sub> shifts the slag composition toward a more acidic nature. The combination of high viscosity and low basicity adversely affects mass transfer and impairs efficient metal–slag phase separation, ultimately reducing metal recovery efficiency during the smelting process [13, 14]. Therefore, an optimal flux ratio must balance melting temperature, viscosity, and slag basicity to ensure process efficiency and equipment longevity.

### 3.2 Experimental results

An initial evaluation of the smelting products was performed using X-ray computed tomography (XCT) to visualize the 3D distribution of metal (with red and green color) and slag (with transparent white color) phases within the experimental products (**Figure 2**). Detailed characterization of the products generated from the smelting of WS1 and QD1 is presented in this study. Micro XRF (μXRF) was performed to characterize the samples, which is presented as **Figure 3** and **Table 4**.



**Figure 2** XCT of (a) 10 g WS1 with 0.5 g QD1 (b) 25 g WS1 with 2 g QD1



**Figure 3** (a) Mosaic picture of the scanned sample of 10 g WS1 feed; (b) selected area for characterization

**Table 4** Characterization of metal and slag of sample of 10 g WS1 with 0.5 g QD1 (wt%)

| Elements       | Fe               | Mn    | Zn                             | Si               | Ca   | Al                             | S    | K               |
|----------------|------------------|-------|--------------------------------|------------------|------|--------------------------------|------|-----------------|
| Area 1 (metal) | 91.67            | 6.67  | 0.01                           | 1.07             | 0.12 | 0.09                           | 0.17 | 0.2             |
| Compounds      | SiO <sub>2</sub> | CaO   | Al <sub>2</sub> O <sub>3</sub> | K <sub>2</sub> O | MnO  | Fe <sub>2</sub> O <sub>3</sub> | ZnO  | SO <sub>3</sub> |
| Area 2 (Slag)  | 29.09            | 50.83 | 4.63                           | 0.12             | 2.55 | 0.32                           | 0.01 | 12.47           |
| Area 3 (Slag)  | 31.59            | 51.98 | 5.15                           | 0.06             | 2.54 | 0.3                            | 0.01 | 8.38            |

Characterization results indicate that the Zn content in both the metal and slag phases is negligible; suggesting that approximately, 99% of the Zn was volatilized into the gas phase during the smelting process. Residual Fe and Mn were detected in the slag phase, indicating incomplete reduction under the current process conditions.

#### 4. CONCLUSION AND OUTLOOK

This study demonstrates that quarry dust (QD1, QD2) and recycled concrete dust (RCD1), though not conventionally used in metallurgical processes, can act as effective flux material in the carbothermic reduction of Waelz slag. Their addition contributes to optimizing slag melting temperature and viscosity, enhancing metal recovery and supporting circular economy principles through the valorization of industrial residues.

However, the process remains at an early developmental stage and requires further optimization. Key areas include the adjustment of reducing agent dosage for complete Fe and Mn reduction, improvement of metal–slag separation, and reduction of MnO content in the slag to ensure its safe reuse. Due to the fine nature of

the feed materials, pelletizing is recommended to minimize losses to the off-gas system. Future work should also include a comprehensive Life Cycle Assessment (LCA) to evaluate the environmental and energy performance of the process.

## ACKNOWLEDGEMENTS

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## REFERENCES

- [1] SAKA, M.B., HASHIM, M. H. B. M. Critical assessment of the effectiveness of different dust control measures in a granite quarry. *Journal of public health policy*. 2024, vol. 45, no. 2, pp. 212–233. doi: 10.1057/s41271-024-00481-6.
- [2] MCNEIL, K., KANG, T. H.-K. Recycled concrete aggregates: A review. *International Journal of Concrete Structures and Materials*. 2013, vol. 7, no. 1, pp. 61–69. doi: 10.1007/s40069-013-0032-5.
- [3] SILVA, R.V., DE BRITO, J., DHIR, R.K. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Construction and Building Materials*. 2014, vol. 65, pp. 201–217. doi: 10.1016/j.conbuildmat.2014.04.117.
- [4] XUE, Y., HAO, X. LIU, X., ZHANG, N. Recovery of zinc and iron from steel mill dust. An overview of available technologies. *Materials*. 2022, vol. 15, no. 12. doi: 10.3390/ma15124127.
- [5] KOLESNIKOV, A.S. et al. Thermodynamic modeling of chemical and phase transformations in a Waelz process-slag – carbon system. *Refractories and Industrial Ceramics*. 2020, vol. 61, no. 3, pp. 289–292. doi: 10.1007/s11148-020-00474-4.
- [6] ANTREKOWITSCH, J., RÖSLER, G., STEINACKER, S. State of the art in steel mill dust recycling. *Chemie Ingenieur Technik*. 2015, vol. 87, no. 11, pp. 1498–1503. doi: 10.1002/cite.201500073.
- [7] GRUDINSKY, P.I., ZINOVEEV, D.V., DYUBANOV, V.G., KOZLOV, P.A. State of the art and prospect for recycling of Waelz slag from electric arc furnace dust processing. *Inorg. Mater. Appl. Res.* 2019, vol. 10, no. 5, pp. 1220–1226. doi: 10.1134/S2075113319050071.
- [8] MOMBELLI, D., MAPELLI, C., BARELLA, S., GRUTTADAURIA, A., DI LANDRO, U. Laboratory investigation of Waelz slag stabilization. *Process Safety and Environmental Protection*. 2015, vol. 94, pp. 227–238. doi: 10.1016/j.psep.2014.06.015.
- [9] KOLESNIKOV, A.S. et al. Processing of non-ferrous metallurgy waste slag for its complex recovery as a secondary mineral raw material. *Refract Ind Ceram*. 2021, vol. 62, no. 4, pp. 375–380. doi: 10.1007/s11148-021-00611-7.
- [10] GRUDINSKY, P., YURTAEVA, A., PANKRATOV, D., PASECHNIK, L., MUSAELIAN, R., DYUBANOV, V. The Waelz slag from electric arc furnace dust processing: Characterization and magnetic separation studies. *Materials (Basel, Switzerland)*. 2024, vol. 17, no. 10. doi: 10.3390/ma17102224.
- [11] HOLAPPA, L., KACAR, Y. Slag formation – Thermodynamic aspects and experimental observations. *Journal for Manufacturing Science and Production*. 2016, vol. 16, no. 4, pp. 227–232. doi: 10.1515/jmsp-2016-0028.
- [12] BRYANT, G.W., LUCAS, J.A., GUPTA, S.K., WALL, T.F. Use of thermomechanical analysis to quantify the flux additions necessary for slag flow in slagging gasifiers fired with coal. *Energy Fuels*, 1998, vol. 12, no. 2, pp. 257–261. doi: 10.1021/ef9700846.
- [13] LU, Z. et al. Effect of SiO<sub>2</sub>/CaO on the viscosity and structure of yellow phosphorus slag in the electric furnace. *Fuel*. 2024, vol. 358, p. 130214. doi: 10.1016/j.fuel.2023.130214.
- [14] KOVTUN, O., KOROBENNIKOV, I., SHUKLA, A.K., VOLKOVA, O. Viscosity of BOF slag. *Metals*. 2020, vol. 10, no. 7, p. 982. doi: 10.3390/met10070982.