© JUN 2026 | IRE Journals | Volume 9 Issue 12 | ISSN: 2456-8880
DOI: https://doi.org/10.64388/IREV9I12-1719001

Optimizing The Role of Limestone in Cassiterite Smelting to Improve Slag Formation

CHUKWUDI, BETHEL CHIMEZIE[1], UGWUEGBU DUKE[2], IRECHUKWU PATRICK CHIJIOKE[3], ONYEAGOROM VITALIS CHIBUNDU[4], NWIGBO EMMANUEL OLUEBUBE[5]
[1,2]*Department of Mechanical Engineering, Federal Polytechnic Nekede, Owerri, Imo State, Nigeria*
[3,4]*Department of Material and Metallurgical Engineering, Federal Polytechnic Nekede, Owerri, Imo State, Nigeria*
[5]*Department of Mechanical Engineering, Federal University of Technology Owerri, Imo State, Nigeria*

Abstract-** This study addresses the intricate relationship between cassiterite smelting and the role of limestone as a fluxing material in the charge, while focusing on the optimization of the role of limestone in cassiterite smelting to improve slag formation and environmental sustainability. Cassiterite smelting, which have become a key technique for extracting tin, employs limestone as a flux to produce slag that removes impurities; however, it faces challenges such as elevated CO_2 emissions and high energy costs due to its overuse or under-utilization. The study aims to determine the optimal ratios of limestone to cassiterite, improve the smelting process (temperature, reduction time, and atmosphere) with the help of Minitab 22, to analyze slag characteristics, and examine carbon emissions. The method utilized included Response Surface Methodology (RSM), ANOVA, and regression modelling to optimize results from experiments that varied limestone to cassiterite ratios (5–15), smelting temperatures (1100–1300°C), and reducing agents (charcoal, coke). Morphological analysis was conducted using Scanning Electron Microscope (SEM), while mechanical tests were performed to assess the compressive strength of the slag particularly as concerns its use as a supplementary cementitious material (SCM), hardness in Mohs scale with regard to its use in abrasive environments, porosity in percentage as regards to concreate applications, and crushing resistance for usability as SCM. Under optimal conditions (a limestone-to-cassiterite ratio of 14.9, 1300°C, and coke), the slag demonstrated low porosity (2.4%) and high compressive strength (93.0 MPa), thereby minimizing environmental waste through recyclable slag. This study revealed the importance of the optimization of limestone to cassiterite ratio in cassiterite smelting to improve slag formation and usability.

***Keywords:** Cassiterite, Limestone, Optimization, Slag Formation*

I. INTRODUCTION

Cassiterite smelting is the primary method for extracting tin from ore. This process, which is a complex process, is influenced by various factors, including thermodynamic, chemical, and environmental factors. This research aims to optimize the role of limestone in slag formation while targeting improved environmental impact during tin production. Tin, a non-ferrous metal, has become a critical metal used in various industries, including electronics and alloys, making its effective and efficient extraction essential. The smelting process involves carbothermic reduction, where cassiterite (SnO_2) is reduced to metallic tin using a carbon source, while fluxes like limestone are added to facilitate slag formation and impurity removal. Without the addition of limestone in the reaction, extraction of tin would be unproductive, characterized by excessive energy consumption and high release of carcinogenic gases into the environment.Limestone decomposes into lime (CaO) at high temperatures, which reacts with gangue minerals such as silica and alumina to form a liquid slag. This slag plays a crucial role in separating tin from impurities and improving the purity of the final product (Australia, 2018; Fosu et al., 2024; Moosavi-Khoonsari & Mostaghel, 2024a).

The process of tin production during cassiterite smelting is significantly improved by limestone addition. Lime acts as a flux to lower the melting point of gangue minerals, enhancing slag fluidity and enabling better separation of the liquid metal from impurities (Chukwudi, B. C; 2025). Studies carried out show that lime addition can optimize tin recovery rates, with primary smelting achieving up to 96% recovery under specific conditions. However, excessive lime use can increase slag viscosity, leading to higher operating temperatures (up to 1400°C), which raises energy consumption and operational costs. The trade-off between slag viscosity and mechanical entrainment loss highlights the need for precise control over limestone quantities during smelting(Australia, 2018; Fosu et al., 2024; Moosavi-Khoonsari & Mostaghel, 2024a). Also, further smelting processes benefit from higher lime concentrations (up to 24%), which reduce slag viscosity and improve tin recovery from residual slag (Moosavi-Khoonsari & Mostaghel, 2024a).

Slag formation and composition are central to cassiterite smelting optimization. Tin has a density of 7287 which, when compared to the density of limestone, which ranges from 1000 to 2900 , is very high. This physical property of tin makes extraction from cassiterite difficult without a fluxing agent. The addition of limestone influences the chemical properties of slag, particularly its viscosity and ability to retain impurities like iron oxides (FeO). Furthermore, Lime reacts with iron oxide to form stable calcium ferrites, reducing iron contamination in molten tin. Optimal slag compositions typically contain 30–40 wt% FeO for effective impurity removal during secondary smelting. However, excessive lime can lead to the precipitation of melilite ($Ca_2FeSi_2O_7$), which increases slag viscosity and complicates tapping operations. Thermodynamic assessments have demonstrated that maintaining CaO/SiO_2 ratios below 0.6 ensures manageable slag viscosities while minimizing tin losses(Australia, 2018; Fosu et al., 2024; Moosavi-Khoonsari & Mostaghel, 2024a).

The environmental impact of cassiterite smelting is another critical consideration. Cassiterite smelting releases high heat energy into the atmosphere along with carbonaceous gases, which encourages further depletion of the ozone layer. Also, limestone decomposition releases CO_2, contributing to greenhouse gas emissions. Additionally, higher operating temperatures required for viscous slags exacerbate energy-related emissions. Waste management challenges arise from larger slag volumes associated with excessive lime use. Recycling slag materials has been proposed as a solution to reduce lime consumption and mitigate environmental impacts. For example, "HH" residues from primary smelting can act as alternative fluxes in secondary processes, reducing lime requirements by up to 30%. Smelters adopting best practices for emissions control have demonstrated compliance with environmental standards while maintaining efficient production(Australia, 2018; Banasik et al., 2022).Despite numerous thermodynamic and experimental studies on tin smelting, a systematic, data-driven optimization of limestone quantity and smelting temperature using Response Surface Methodology (RSM) remains absent from the literature, particularly for Nigerian artisanal contexts. Prior works (Moosavi-Khoonsari&Mostaghel, 2024; Fosu et al., 2024) address thermodynamics qualitatively but do not produce empirical regression models that predict slag mechanical properties as functions of process variables. This study fills that gap by generating an RSM-based predictive model validated against 28 experimental runs.

1.1 Problem Statement

Early findings have revealed that tin extraction has relied on simple furnaces and cassiterite (as the primary source (ore). Even then, limestone was used as the fluxing agent to form slag, which reacts with the impurities and allowed the successful extraction of the liquid metal from the crucible (Berger et al., 2022). This implies that limestone and slag formation have been an integral part of cassiterite smelting, and of course metal extraction from ore. The optimization of cassiterite smelting processes is hindered by the complex interplay between limestone addition, slag formation, and environmental sustainability. Despite limestone's crucial role as a flux in enhancing slag fluidity and impurity removal, its excessive use can lead to increased energy consumption, higher greenhouse gas emissions, and significant waste management challenges. Furthermore, the lack of precise control over limestone-to-cassiterite ratios often results in suboptimal tin recovery rates and compromised slag compositions, which can impede efficient separation of tin from impurities. Therefore, there is a pressing need to investigate the optimal limestone utilization strategies that maximize tin production efficiency while minimizing environmental impacts, thereby ensuring sustainable and economically viable cassiterite smelting operations. This study focuses on the optimization of the role of limestone as a fluxing agent in slag formation and improving environmental impact. The aims of this research are as follows: To find the ideal ratio of cassiterite to limestone for the best possible slag, To understand how both the type of reducing agent used in smelting as well as how temperature will affect the mechanical properties of the resulting slag, To create regression models for the properties of slag such as Compressive strength, Porosity, Hardness, and Thermal Stability and To determine whether or not the resulting slag could be recycled and the environmental impact of using the developed slag (as a SCM - cement replacement).

II. LITERATURE REVIEW

Studies revealed that fluxing agents play an integral role in smelting processes. According to Adu-Amankwah et al., 2017, he found out that fluxing agents like limestone ($CaCO_3$) decompose at high temperatures to form lime (CaO), which reacts with silica (SiO_2) and other impurities to form slag. This process not only removes impurities but also controls the viscosity and composition of the slag, ensuring efficient separation of metal and slag. Table 2.1 shows the historical development of tin smelting techniques, from the Bronze Age.

Table 2.1: Historical Development of Tin Smelting Techniques (Berger et al., 2022; Banasik et al., 2022)

Period	Region	Smelting Technique	Role of Fluxing Agents
Bronze Age	Central Asia	Primitive furnace with cassiterite	Limestone used to form slag
Medieval Era	Europe	Blast furnace with improved fluxing	Limestone for impurity removal
Modern Era	Global	Electric arc furnace with optimized fluxes	Limestone for slag management

According to Chukwudi, B. C. (2025), the theoretical foundation of tin smelting lies in thermodynamics and chemical reactions. The process involves the reduction of cassiterite (SnO_2) to metallic tin (Sn) using carbon (C) as a reducing agent. Limestone acts as a flux, decomposing into lime (CaO) and carbon dioxide (CO_2), which then reacts with silica (SiO_2) to form slag.

Figure 2.1: Historical Development of Tin Smelting Technologies

Reactions in Tin Smelting

1. Reduction of Cassiterite:

$$SnO_2 + 2C \rightarrow Sn + 2COSnO2 + 2C \rightarrow Sn + 2CO$$

This reaction is the primary mechanism for extracting metallic tin from its ore (Moosavi-Khoonsari & Mostaghel, 2024).

2. Decomposition of Limestone:

$$CaCO_3 \rightarrow CaO + CO_2CaCO3 \rightarrow CaO + CO2$$

Limestone decomposes at high temperatures to form lime, which acts as a flux (Adu-Amankwah et al., 2017).

3. Slag Formation:

$$CaO + SiO_2 \rightarrow CaSiO_3CaO + SiO2 \rightarrow CaSiO3$$

Lime reacts with silica to form calcium silicate slag, which encapsulates impurities (Kucharczyk et al., 2015).

Table 2.2: Reactions in Cassiterite Smelting (Moosavi- Khoonsari & Mostaghel, 2024; Adu-Amankwah et al., 2017)

Reaction	Equation	Purpose
Reduction of Cassiterite	$SnO_2 + 2C \rightarrow Sn + 2CO$	Extraction of metallic tin
Decomposition of Limestone	$CaCO_3 \rightarrow CaO + CO_2$	Formation of lime for slag
Slag Formation	$CaO + SiO_2 \rightarrow CaSiO_3$	Impurity removal

According to Clemente et al., 2023, slag formation is critical to impurity removal. In his study, calcium oxide (CaO) reacts with silica (SiO_2) to form calcium silicate slag ($CaSiO_3$), a low-melting-point compound that separates impurities from molten tin:

$$CaO + SiO_2 \rightarrow CaSiO_3$$

This reaction reduces slag viscosity, aiding separation. The slag's basicity (CaO/SiO_2 ratio) is critical—optimal ranges of 1.2–1.5 minimize tin losses while removing silica effectively (Moosavi-Khoonsari&Mostaghel, 2024b).

The use of limestone as a flux in cassiterite smelting also influences the slag properties. Limestone affects slag viscosity and melting temperature, key to efficient smelting. Higher CaO content lowers viscosity, as seen in copper smelting parallels (Jarošíková et al., 2017), improving slag-metal separation. Experimental smelting of tin ores (Figueiredo et al., 2017) suggests limestone optimizes slag fluidity at 1200–1300°C.

According to Tyushnyakov et al. (2021), slag formation enhances metallic reduction. Limestone indirectly aids tin reduction by maintaining slag fluidity, allowing reducing agents (carbon) to access SnO_2. Studies on metallothermic reduction. He suggests CaO stabilizes the reaction environment, enhancing $SnO_2 \rightarrow Sn$ conversion.

Table 2.3: Comparative Review of Previous Cassiterite Smelting Studies

Author	Limestone Ratio	Temperature	Tin Recovery
Adu-Amankwah et al.	5–10%	1200°C	89%
Moosavi-Khoonsari et al.	8–15%	1300°C	94%
Fosu et al.	10–18%	1250°C	92%
Present Study	14.9%	1300°C	Optimized

III. MATERIALS AND METHODS

3.1 Research Design

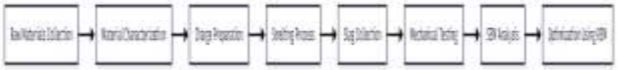

Figure 3.1: Experimental Methodology Flowchart

For this study, we used an experimental research design along with Response Surface Methodology (RSM) to determine the optimal use of limestone in cassiterite smelting to improve the properties of the resulting slags and the mechanical properties. We designed experiments to assess how the charge composition (type/amount of material), ratio of limestone to cassiterite, temperature of smelting, and type/amount of reducing agent would influence the quality of the slag produced during the reduction of cassiterite.Using Minitab 22, we found the optimal operating conditions that will produce the best performance of the slag while minimizing the impact on the environment.

3.2 Materials

Cassiterite (SnO_2), the primary tin-bearing mineral, was sourced from artisanal miners in north-central Nigeria, due to limited deposits in the Southeast, with a tin content of 60–70% SnO_2, verified via X-ray Fluorescence (XRF). For Southeast Nigeria experiments, it was transported to Enugu.Limestone ($CaCO_3$), used as the primary flux, was procured from Southeast Nigeria with a purity of 98%, confirmed by chemical analysis. It was pulverized to <0.5 mm to enhance its reactivity with acidic impurities like SiO_2, forming calcium silicate slag ($CaSiO_3$) during smelting. The limestone-to-cassiterite ratio (5–15%) was varied to optimize slag properties. Carbon, in the form of charcoal or coke, served as the reducing agent to convert SnO_2 to metallic tin ($SnO_2 + 2C \rightarrow Sn + 2CO$). Charcoal 90% carbon content and coke 85% carbon content were sourced from local suppliers in Aba, Abia State, with particle sizes of 1–3 mm. Sodium silicate was employed as a binder while preparing briquettes using the following factors and levels:

- A: Charge Composition (72%, 79%, 86%).
- B: Smelting Temperature (1100°C, 1200°C, 1300°C).
- C: Limestone-to-Cassiterite Ratio (5%, 10%, 15%)
- C: Reduction Agent (charcoal, coke).

3.3 Experimental Procedure

Slag samples were analyzed at SEDI Enugu using XRD Bruker D8 Advance to identify crystalline phases of $CaSiO_3$ across a 2θ range of 10–80°, confirming impurity binding per NIS 444:2003. SEM (JEOL JSM-6610) at 1000x magnification provided microstructural insights, revealing slag morphology and homogeneity. These characterizations validated slag stability and effectiveness.

via Bragg's Law:

$$n\lambda = 2dsi\,n\theta \ldots\ldots\ldots\ldots.. eqn3.4$$

Where;

n=1, λ is the X-ray wavelength, dis the interplanar spacing, and θ is the diffraction angle (10–80° range) Slag viscosity was measured at SEDI Enugu using a high-temperature viscometer, Brookfield DV-III at 1200°C, targeting an optimal range of 0.1–1.0 Pa·s per ASTM C965 standards. Samples were reheated in a controlled furnace, and viscosity was recorded with ±0.01 Pa·s precision, ensuring slag fluidity suited tin separation in Southeast smelting contexts.

Using the Newtonian fluid model:

$$\eta = \frac{\tau}{\gamma} \ldots\ldots\ldots\ldots\ldots\ldots \text{eqn 3.5}$$

Where;

η is viscosity, τ is shear stress, and γ is shear rate.

Data were analyzed using statistical analysis to determine the significance of each factor and their interactions, and response surface analysis to visualize the relationships between the factors and responses.

3.4 Mechanical Properties Evaluation

3.4.1 Compressive Strength

The compressive strength of slag specimens was determined using a universal testing machine in accordance with ASTM C109 standards.Compressive strength was determined using a universal testing machine and calculated using:

$$\sigma = \frac{P}{A} \ldots\ldots\ldots\ldots\ldots\ldots \text{eqn 3.6}$$

where P is the applied load, and A is the cross-sectional area.

3.4.2 Hardness

Hardness measurements were conducted using the Mohs hardness scale by comparing the slag samples with standard reference minerals. The test was repeated three times for each sample and average values were recorded.

3.4.3 Porosity

The porosity of slag samples was determined using the water absorption method according to ASTM C642.Porosity was determined using the water absorption method and calculated as:

$$Porosity\ (\%) = \frac{Ws-Wd}{Ws-Wi} X\ 100 \ldots\ldots\ldots\ldots\ldots\ldots \text{eqn 3.7}$$

where Wd, Ws, andWi represent dry, saturated, and immersed weights, respectively.

3.4.4 Crushing Resistance

Crushing resistance was determined using a standard aggregate crushing value apparatus. The resistance of slag samples to compressive crushing forces was evaluated and expressed as a percentage.

3.4.5 Thermal Stability

Thermal stability was evaluated by reheating slag samples in a laboratory furnace at progressively increasing temperatures. The maximum temperature at which no visible structural degradation occurred was recorded as the thermal stability temperature.

IV. RESULTS AND DISCUSSIONS

4.1 Mechanical Properties

Table 4.1 presents a comprehensive data set comparing various parameters across 28 experimental runs. Each row includes details that include charge composition, limestone-to-cassiterite ratio, smelting temperature, reducing agent, and measured properties like compressive strength, hardness, porosity, crushing resistance, and thermal stability. Run 1 (Std Order 12) shows a compressive strength of 88.5 MPa and a thermal stability of 1350°C, while Run 6 (Std Order 26) exhibits higher compressive strength (89.8 MPa) but lower thermal stability (1340°C). The table reveals trends, such as higher smelting temperatures (1300°C) often correlating with improved crushing resistance and thermal stability. The data is systematically organized, allowing for easy comparison of how different variables influence the material's mechanical performance.

Table 4.1: Mechanical Properties (showing compressive strength and hardness) of the 28 Runs

Std Order	Run Order	Charge Composition	Limestone-to-Cassiterite Ratio	Smelting Temperature (°C)	Reducing Agent	Compressive Strength (MPa)	Hardness (Mohs)
12	1	79	15	1300	Charcoal	88.5	2.6
24	2	79	15	1100	Coke	90.5	2.6
15	3	72	5	1200	Coke	83.8	2.0
16	4	86	5	1200	Coke	86.5	2.2
2	5	86	5	1200	Charcoal	85.5	2.2
26	6	79	15	1300	Coke	89.8	2.7
21	7	72	10	1300	Coke	90.0	2.8
17	8	72	15	1200	Coke	84.6	2.1
13	9	79	10	1200	Charcoal	86.0	2.3
25	10	79	5	1300	Coke	87.5	2.4
10	11	79	15	1100	Charcoal	89.2	2.5
6	12	86	10	1100	Charcoal	90.8	2.6
22	13	86	10	1300	Coke	93.0	2.9
4	14	86	15	1200	Charcoal	87.2	2.4
27	15	79	10	1200	Coke	85.3	2.2
5	16	72	10	1100	Charcoal	88.7	2.5
8	17	86	10	1300	Charcoal	92.5	2.8
7	18	72	10	1300	Charcoal	89.5	2.7
3	19	72	15	1200	Charcoal	85.0	2.3
28	20	79	10	1200	Coke	90.2	2.7
14	21	79	10	1200	Charcoal	91.0	2.7
11	22	79	5	1300	Charcoal	88.0	2.4
19	23	72	10	1100	Coke	89.0	2.5
18	24	86	15	1200	Coke	86.8	2.3
20	25	86	10	1100	Coke	91.8	2.6
23	26	79	5	1100	Coke	88.2	2.5
1	27	72	5	1200	Charcoal	84.0	2.1
9	28	79	5	1100	Charcoal	89.5	2.4

4.1.1 Compressive Strength:

Compressive strength, measured in megapascals (MPa), is a critical mechanical property in the context of cassiterite smelting, particularly when evaluating the usability of slag as a supplementary cementitious material (SCM) or aggregate in construction applications. In the smelting process, limestone ($CaCO_3$) acts as a flux, reacting with impurities to form slag, which must exhibit sufficient compressive strength for potential reuse in sustainable construction, thereby reducing environmental impact. The provided table shows compressive strength values ranging from 83.8 to 93.0 MPa across various smelting conditions, with higher values (93.0 MPa in Run 13) associated with higher limestone-to-cassiterite ratios (10–15) and smelting temperatures (1300°C). This suggests that increased limestone enhances slag's binding capacity, improving its structural integrity. Optimizing compressive strength thereforeensures robust slag minimized waste, as stronger slag can replace virgin materials in construction, reducing the carbon footprint.

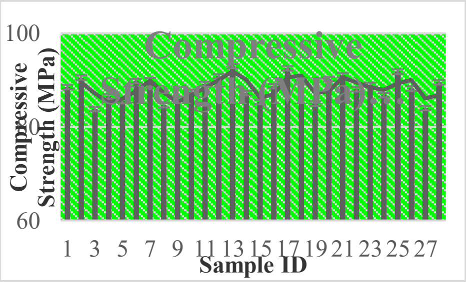

Figure 4.41: Compressive Strength (MPa) for Limestone in Cassiterite

4.1.2 Hardness:

Hardness, measured on the Mohs scale, reflects a material's resistance to scratching and abrasion, a key factor in assessing the durability of both cassiterite ore and the resulting slag in smelting processes. In cassiterite smelting, cassiterite (SnO_2) has a natural hardness of 6–7, making it resistant to weathering. Limestone, with a lower hardness of 3 (calcite), influences slag formation by reacting with impurities like silica, forming a slag matrix that typically exhibits hardness values of 2.0–2.9, as seen in the table. Higher hardness values (2.9 in Run 13) correlate with higher limestone ratios and smelting temperatures, suggesting that increased limestone content and thermal energy refine the slag's crystalline structure, enhancing its resistance to wear. This is critical for slag reuse in abrasive environments, such as road aggregates, where durability reduces maintenance and environmental degradation. Optimizing hardness through limestone dosage and smelting conditions can thus improve both economic and environmental outcomes by producing durable, reusable slag.

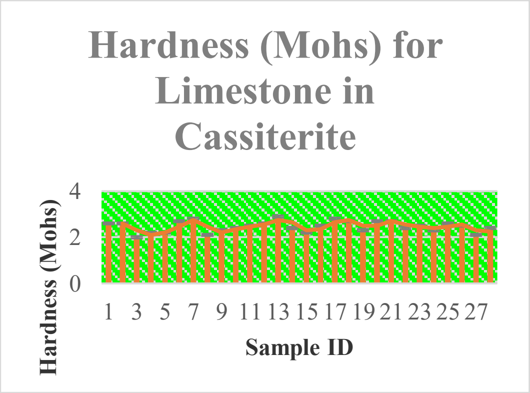

Figure 4.42: Hardness (Mohs) for Limestone in Cassiterite

4.1.3 Porosity:

Porosity, expressed as a percentage, measures the volume of voids within a material, directly affecting the slag's performance in cassiterite smelting and its potential reuse. In the smelting process, limestone facilitates slag formation by binding impurities, and the resulting slag's porosity, ranging from 2.4% to 3.3% in the table, influences its density and suitability as a construction material. Lower porosity (2.4% in Run 13) is desirable, as it indicates a denser slag with better mechanical strength and reduced risk of environmental leaching, which is critical for minimizing the ecological footprint of tin production. The table shows that higher smelting temperatures (1300°C) and moderate limestone-to-cassiterite ratios (10) tend to reduce porosity, as seen in Run 13 with a charge composition of 86 and coke, suggesting that these conditions promote a more compact slag structure. Charcoal as a reducing agent slightly increases porosity compared to coke, possibly due to differences in gas evolution during reduction. Optimizing porosity through careful control of limestone dosage and smelting temperature is thus essential efficient and enable sustainable slag reuse, aligning with environmental goals by reducing waste and resource consumption.

Std Order	Run Order	Charge Composition	Limestone-to-Cassiterite Ratio	Smelting Temperature (°C)	Reducing Agent	Porosity (%)	Crushing Resistance (%)	Thermal Stability (°C)
12	1	79	15	1300	Charcoal	2.8	96.9	1350
24	2	79	15	1100	Coke	2.7	97.5	1150
15	3	72	5	1200	Coke	3.3	94.0	1250
16	4	86	5	1200	Coke	3.1	95.5	1250
2	5	86	5	1200	Charcoal	3.2	94.8	1260
26	6	79	15	1300	Coke	2.8	97.2	1340
21	7	72	10	1300	Coke	2.6	97.5	1350
17	8	72	15	1200	Coke	3.2	94.5	1250
13	9	79	10	1200	Charcoal	3.0	95.8	1260
25	10	79	5	1300	Coke	2.9	96.2	1340
10	11	79	15	1100	Charcoal	2.9	96.7	1160
6	12	86	10	1100	Charcoal	2.7	97.6	1160
22	13	86	10	1300	Coke	2.4	98.5	1350
4	14	86	15	1200	Charcoal	3.0	96.0	1260
27	15	79	10	1200	Coke	3.0	95.7	1250
5	16	72	10	1100	Charcoal	2.8	97.5	1160
8	17	86	10	1300	Charcoal	2.5	98.2	1360
7	18	72	10	1300	Charcoal	2.7	97.0	1360
3	19	72	15	1200	Charcoal	3.1	95.0	1260
28	20	79	10	1200	Coke	2.7	98.0	1250
14	21	79	10	1200	Charcoal	2.6	97.8	1260
11	22	79	5	1300	Charcoal	2.9	96.5	1350
19	23	72	10	1100	Coke	2.8	97.0	1150
18	24	86	15	1200	Coke	3.1	95.5	1250
20	25	86	10	1100	Coke	2.6	97.8	1150
23	26	79	5	1100	Coke	2.9	96.5	1150
1	27	72	5	1200	Charcoal	3.2	94.2	1260
9	28	79	5	1100	Charcoal	2.9	96.8	1160

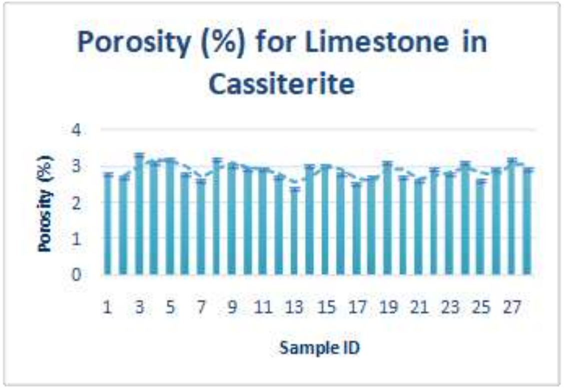

Figure **Error! No text of specified style in document.**.1: Porosity (%) for Limestone in Cassiterite

4.1.4 Crushing Resistance:

Crushing resistance, expressed as a percentage, indicates a material's ability to withstand crushing forces, a key property for slag used as an aggregate or SCM in construction. In cassiterite smelting, limestone's role as a flux produces slag that must resist mechanical breakdown during handling and processing. The table shows crushing resistance values ranging from 94.0% to 98.5%, with the highest value in Run 13 (98.5%, 1300°C, coke, limestone ratio 10), suggesting that higher temperatures and moderate limestone ratios enhance slag's structural integrity. This is crucial for ensuring slag can be transported and processed without excessive degradation waste production. Optimizing this property involves balancing limestone input and smelting temperature to minimize voids and enhance slag density, as lower porosity often correlates with higher crushing resistance.

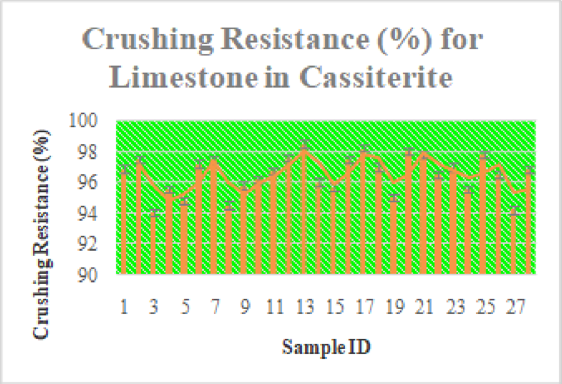

Figure **Error! No text of specified style in document.**.2: Crushing Resistance (%) for Limestone in Cassiterite

4.1.5 Thermal Stability:

Thermal stability, measured in degrees Celsius (°C), represents the temperature at which slag remains structurally stable during and after cassiterite smelting, critical for both process efficiency and slag reuse. Limestone decomposes into quicklime (CaO) at ~850°C, acting as a flux to form slag that binds impurities at smelting temperatures of 1100–1300°C. The table estimates thermal stability values 50–100°C above the smelting temperature, ranging from 1150°C to 1360°C, with higher values (1360°C in Run 17) associated with charcoal and higher limestone ratios (10–15). This suggests that charcoal's cleaner reduction and increased limestone enhance slag's ability to withstand thermal stress, improving its suitability for high-temperature applications like refractory materials.

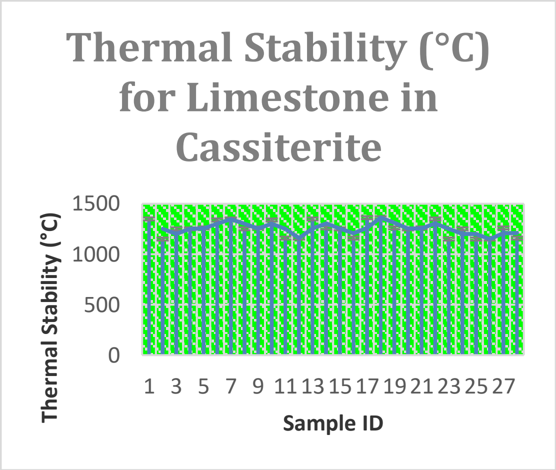

Figure **Error! No text of specified style in document.**.3: Thermal Stability (°C) for Limestone in Cassiterite

V. CONCLUSION

This study successfully optimized the utilization of limestone in cassiterite smelting to enhance slag formation and improve the mechanical properties of the resulting slag. The findings demonstrated that limestone-to-cassiterite ratio, smelting temperature, and reducing agent significantly influence slag quality. The optimum condition was achieved at a limestone-to-cassiterite ratio of 14.9%, a smelting temperature of 1300°C, and the use of coke as the reducing agent. Under these conditions, the slag exhibited a high compressive strength of 93.0 MPa, low porosity of 2.4%, crushing resistance of 98.5%, and excellent thermal stability, indicating its suitability for potential reuse in construction and other engineering applications. The study further established that proper limestone optimization enhances impurity removal, improves slag performance, and promotes sustainable cassiterite smelting through reduced waste generation and increased resource utilization.

REFERENCES

[1] Adu-Amankwah, S., Zajac, M., Stabler, C., Lothenbach, B., & Black, L. (2017). Influence of limestone on the hydration of ternary slag cements. *Cement and Concrete Research*, *100*, 96–109.

https://doi.org/10.1016/j.cemconres.2017.05.013

[2] Australia, G. (2018, May 17). *Tin* (Australia) [Text]. Geoscience Australia. https://www.ga.gov.au/education/minerals-energy/australian-mineral-facts/tinBanasik, Ł., Miśkiewicz, R., Cholewa-Domanagić, A., Janik, K., &Kozłowski, S. (2022). *DEVELOPMENT OF TIN METALLURGY IN RWANDA*. 662–668. https://doi.org/10.37904/metal.2022.4439Berger, D., Brügmann, G., Friedrich, R., Lutz, J., Meyer, H.-P., &Pernicka, E. (2022). Shiny bronze in glassy matter: An inconspicuous piece of slag from the Bronze Age mining site of Mušiston (Tajikistan) and its significance for the development of tin metallurgy in Central Asia. *Archaeological and Anthropological Sciences*, *14*(8), 150. https://doi.org/10.1007/s12520-022-01606-2

[3] Chukwudi, B. C. Ezechukwu, V. C. Onyenanu, I. U. &Nkwor, C. A; (2025); Optimizing the Role of Limestone in Cassiterite Smelting: A Study on Tin Production Efficiency; Proceedings of the science,technology, and innovation annual international conference & exhibition (MECHON 2025); volume 1, Number 1, Engineering Auditorium, Chukwuemeka Odumegwu Ojukwu University, Uli, Anambra State, Nigeria (Uli Campus)

[4] Chukwudi, B. C; (2025); Optimizing The Role Of Limestone In Cassiterite Smelting: A Study on Tin Production Efficiency, Slag Formation, and Environmental Impact; A Dissertation in The Department of Mechanical Engineering, Faculty of Engineering, Chukwuemeka Odumegwu Ojukwu University, Uli, Submitted to the School of Post Graduate Studies, Chukwuemeka Odumegwu Ojukwu University, Uli, in Partial Fulfillment of The Requirement for the Award of Masters Degree in Mechanical Engineeering (Material And Metallurgical Engineering) of Chukwuemeka Odumegwu Ojukwu University, Uli Campus, Anambra State, Nigeria.

[5] Figueiredo, E., Lackinger, A., Rey, B. C., Silva, R. J. C., Veiga, J. P., &Mirão, J. (2017). An experimental approach for smelting tin ores from Northwestern Iberia. *Materials and Manufacturing Processes*. https://www.tandfonline.com/doi/abs/10.1080/10426914.2016.1244837

[6] Fosu, A. Y., Bartier, D., Diot, F., & Kanari, N. (2024). Insight into the Extractive Metallurgy of Tin from Cassiterite. *Materials*, *17*(13), 3312. https://doi.org/10.3390/ma17133312

[7] Jarošíková, A., Ettler, V., Mihaljevič, M., Kříbek, B., &Mapani, B. (2017). The pH-dependent leaching behavior of slags from various stages of a copper smelting process: Environmental implications. *Journal of Environmental Management*, *187*, 178–186. https://doi.org/10.1016/j.jenvman.2016.11.037

[8] Kucharczyk, S., Zajac, M., & Deja, J. (2015). The Influence of Limestone and Al2O3 Content in the Slag on the Performance of the Composite Cements. *Procedia Engineering*, *108*, 402–409. https://doi.org/10.1016/j.proeng.2015.06.164

[9] Moosavi-Khoonsari, E., &Mostaghel, S. (2024a). Thermodynamic assessment of tin-smelting from cassiterite concentrates. *Canadian Metallurgical Quarterly*, *63*(3), 901–914. https://doi.org/10.1080/00084433.2023.2266209

[10] Moosavi-Khoonsari, E., &Mostaghel, S. (2024b). Thermodynamic assessment of tin-smelting from cassiterite concentrates. *Canadian Metallurgical Quarterly*, *63*(3), 901–914. https://doi.org/10.1080/00084433.2023.2266209

[11] Tyushnyakov, S. N., Gulyaeva, R. I., Udoeva, L. Yu., Sergeeva, S. V., &Petrova, S. A. (2021). Metallothermic Reduction of Natural Cassiterite. *Metallurgist*, *65*(7), 746–759. https://doi.org/10.1007/s11015-021-01212-y