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Utilization of Copper Slag as a Partial Clinker Replacement Material in Cement Production

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Abstract

The increasing demand for cement leads to higher global CO_2 emissions from heating limestone to produce clinker. Researchers and plant managers are seeking to overcome this challenge by reducing clinker content through alternative materials, which could lower environmental impact and improve cement properties. This study investigates the potential of using copper slag as a partial replacement for clinker in cement production. Five mixtures of clinker-copper slag ratios were prepared, mixed, cured, and then tested to evaluate the effects of adding the copper slag at the expense of clinker. These include compressive strength, flexural, tensile, and elastic modulus tests, as well as setting time measurements. The results were then compared with a baseline mixture that was prepared to represent a standard cement composition. The results show that 10% copper slag, at the expense of clinker, increases the cement compressive strength by +4 MPa compared to the baseline in the long-term test. Other mechanical properties results show an improvement in the cement production. As an example, flexural strength increased to 6.5 MPa, tensile strength increased to 4.4 MPa, and elastic modulus increased to 29.5 GPa compared to 6.2 MPa, 4.1 MPa, and 28.5 GPa in the baseline mixture, respectively.

Paper type: Research Paper

Keywords: Copper slag, CO_2 reduction, Cement, Clinker replacement

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1. Introduction

Cement manufacturing is one of the most carbon-intensive industrial processes, primarily due to the high temperatures required for clinker formation and calcination. When basic raw materials, such as clay and limestone, are heated to 1400-1500 °C, significant amounts of carbon dioxide are released (Dunuweera & Rajapakse, 2018; John, 2020; Telschow et al., 2012; Worrell et al., 2001). Therefore, reducing carbon emissions in cement and concrete has become a major research and industry priority(Adesina, 2020; Miller et al., 2018). A recent trend in addressing this issue is the move towards environmentally friendly materials that can reduce the negative environmental impacts of manufacturing processes. The International Energy Agency (IEA) notes that the clinker-to-cement ratio is a key indicator of sustainability in the cement industry and observes that this ratio has recently increased in several regions, highlighting the urgent need to develop alternative binders and components that can be implemented on a large industrial scale (Busch et al., 2022;

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Junakova et al., 2025). In the same vein, the cement and concrete sector is increasingly moving towards the systematic evaluation of new sources of complementary cementitious materials, given the geographical constraints and variability of available traditional material supplies.

A wide range of sustainable materials are used as supplementary cementitious materials (SCMs), most notably fly ash, granulated blast furnace slag, calcined clay, and silica fume, in addition to emerging by-products like rice husk ash and slag from various metal smelting processes (Alsafasfeh et al., 2022; Aziz et al., 2024; Farahzadi et al., 2025; Ma et al., 2025; Singh et al., 2024; Snellings, 2016). The primary aim of employing these materials is to reduce the cement content in concrete, thereby minimizing the carbon emissions associated with energy-intensive manufacturing processes. In this context, copper slag stands out as a promising alternative material with dual potential, as it can be used not only as a partial replacement for binders but also as a substitute for fine aggregates in cement and concrete applications (Manjunatha et al., 2021; Pushpakumara & Bandara, 2025; Shi et al., 2008; Wu et al., 2010).

Reusing industrial waste is a cornerstone of the transition to more sustainable building materials, and numerous studies have demonstrated that copper slag—a byproduct of copper smelting—possesses physical and chemical properties that make it suitable for use in cement and concrete mixes. From an environmental perspective, incorporating copper slag helps reduce the amount of waste sent to landfills and limits the depletion of primary natural resources, particularly natural sand and clinker (Dassanayake et al., 2025; Pushpakumara & Bandara, 2025). Life cycle analysis studies have shown that partial replacement of conventional cement with copper slag can lead to a significant reduction in some environmental impact indicators, such as the consumption of non-renewable resources and greenhouse gas emissions (Nayak et al., 2025; Zhang et al., 2024; Zhou et al., 2024). However, the potential toxicity of some of its secondary components remains a subject of debate, necessitating a more comprehensive long-term environmental assessment. Accordingly, the present study focuses primarily on evaluating the chemical composition and mechanical performance of copper slag as a clinker replacement. Comprehensive environmental assessments, including heavy-metal leaching behaviour, are beyond the scope of this investigation and are recommended for future research.

From a mechanical perspective, the literature indicates that using low percentages of copper slag can maintain the compressive strength and basic mechanical properties of concrete in the short and long term and may even improve some properties related to density and durability in certain cases (Manjunatha et al., 2021; Nayak et al., 2025; Pushpakumara & Bandara, 2025; Shi et al., 2008; Wu et al., 2010). Conversely, studies show that large increases in replacement percentages can lead to a decline in mechanical performance and durability, especially in the absence of any effective pozzolanic treatment or activation of the copper slag (Mahajan & Muhammad, 2024; Wang et al., 2025; You et al., 2024).

Despite this growing interest, a review of the literature reveals that the vast majority of studies have focused on employing copper slag as an additive or partial replacement in concrete mixes, while research addressing its direct use within the cement industry itself—particularly in the formulation of composite cements as a clinker replacement—remains remarkably limited. This deficiency highlights a clear research gap that necessitates systematic studies to evaluate the chemical, mechanical, and environmental performance of cements containing copper slag, thereby supporting its potential as a practical solution for producing low-carbon cement.

This study investigates the effect of replacing clinker with varying proportions of copper slag on performance characteristics, while maintaining a constant gypsum content. The methodology includes chemical analysis using X-ray fluorescence spectroscopy (XRF), along with a range of mechanical tests, including compressive strength at different curing ages, flexural strength, tensile strength, and modulus of elasticity. Through a systematic comparison of different replacement levels, the study aims to determine the optimal proportion of copper slag that can maintain acceptable mechanical performance while minimizing clinker dependence. The results contribute to the development of low-carbon cement and promote the recycling of industrial waste, particularly copper slag, in the building materials industry.

2. Materials and Methodology

2.1 Materials and Preparation Process

The primary components of cement production, clinker and gypsum, were obtained from the LafargeHolcim-Rashadiyah plant with an average particle size of ~2 cm (**Figure 1**). Copper slag, a by-product of ancient copper smelting processes, was collected from an old copper mine in southern Jordan, with particle sizes of ~10 cm. As illustrated in **Figure 2**, Clinker and copper slag were initially crushed using a laboratory jaw crusher and subsequently ground in a laboratory disk mill under dry conditions. The ground materials were sieved through a 75 μm (No. 200) sieve using a mechanical sieve shaker, and only the passing fraction was used for preparing the cement mixtures. Therefore, the reported value of 75 μm refers to the nominal sieve opening rather than the mean particle size or particle-size distribution. The fineness of the ground clinker and copper slag was determined using the Blaine air-permeability method in accordance with ASTM C204. All materials were stored in sealed containers at laboratory temperature (23 ± 2°C) before mixing. The chemical composition of clinker and copper slag was determined using X-ray fluorescence (XRF) analysis following the manufacturer's standard operating procedure. The analysis was conducted using a calibrated laboratory XRF instrument, and the oxide compositions were reported as weight percentages.

Fig. 1. Samples of Gypsum and Clinker Used in This Study.

Fig. 2. Preparation of the Comminution Process Used in This Study.

2.2 Mixture Design

Six mixtures of samples were prepared in proportions of each ground material, with a total weight of 500 g per sample. As shown in **Table 1**, the first sample was prepared as a baseline mixture containing no copper slag, with 96% clinker and 4% gypsum. This baseline mixture is represented as the standard composition in the LafargeHolcim- Rashadiyah plant in Portland cement manufacturing. The other five mixtures were prepared by adding portions of copper slag to the clinker at 5%, 10%, 15%, and 20%, with no change in the gypsum content. Mortar specimens were prepared with a water-to-cement ratio of 0.485 and a cement-to-standard-sand ratio of 1:2.75 by mass (Radwan et al., 2025). Mixing was performed using a laboratory mortar mixer according to ASTM C305, then the mixture was poured into 100 mm side-length cubes.

Table 1. Mixture Design for Cement Samples.

Experiment (Exp)	Clinker		Gypsum		Copper Slag		Total Weight
	(%)	(g)	(%)	(g)	(%)	(g)	(g)
1 (Baseline)	96	480	4	20	0	0	500
2	91	455	4	20	5	25	500
3	86	430	4	20	10	50	500
4	81	405	4	20	15	75	500
5	76	380	4	20	20	100	500
6	71	355	4	20	25	125	500

The fineness of the ground cement mixtures was determined using the Blaine air-permeability method in accordance with ASTM C204. The measured Blaine fineness values ranged from 3850 to 3965 cm²/g, as presented in **Figure 3**. These values confirm that all cement blends had comparable fineness, allowing evaluation of the influence of copper slag replacement on mechanical properties.

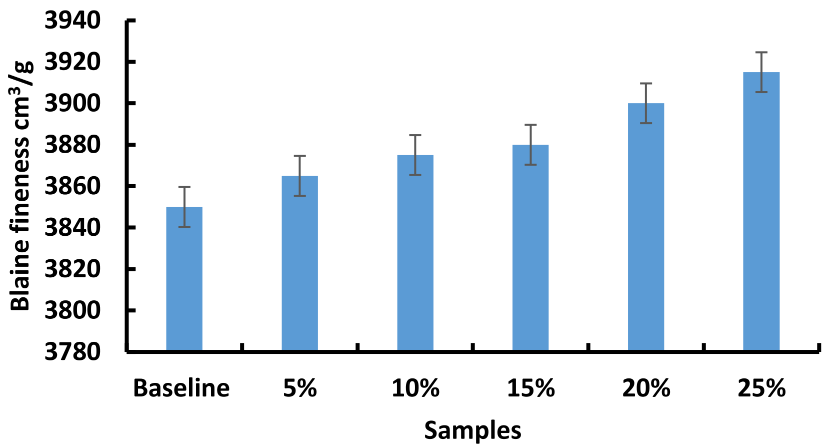

Fig. 3. Blaine Fineness of Cement Mixtures.

2.3 Compressive Strength Testing

Compressive strength tests were conducted for each mixture at each curing age (2, 7, and 28 days), and the reported values represent the average compressive strength. The compressive strength was measured using a Hydraulic Universal Test Machine HUD-B616, where a gradual load was applied to the samples until failure and cracks. The maximum load was recorded to calculate the compressive strength.

2.4 Flexural and Tensile Strength

Flexural and tensile strength tests were conducted to evaluate the behavior of the concrete under bending and tension, as these conditions are representative of real construction conditions. Flexural strength was tested using standard mortar prisms according to ASTM C348, while the tensile strength test follows C496. Flexural strength was tested at 7 and 28 days using a three-point bending setup. Both tests were conducted using a Hydraulic Universal Test Machine HUD-B616.

2.5 Elastic Modulus

The stiffness of the samples was studied by measuring the elastic modulus of concrete from a stress–strain curve in the linear range, where the slope indicates the sample's resistance to deformation. The elastic modulus was evaluated following the procedure described in ASTM C469.

2.6 Setting Time Tests

Both initial and final setting times were recorded for all samples to calculate the setting time using a Vicat apparatus according to ASTM C191. These times represent the total hardening time and help assess workability and construction scheduling. The samples were mixed with water in accordance with ASTM C187 for 5 minutes, then gradually poured into Vicat cubes. The initial setting time was recorded when needle penetration stopped at a distance of 25 ± 2 mm from the bottom of the sample. For the final setting time, the needle was lowered to touch the sample surface and allowed to move freely, leaving no visible mark. Each mechanical test experiment was conducted on three replicate specimens. Results are presented as the mean ± standard deviation. Error bars in the figures represent one standard deviation.

3. Results and Discussion

3.1 XRF Analysis of Materials

All raw materials and mixtures were analyzed by XRF to determine the chemical composition of each sample. As presented in **Table 2**, the clinker contains 67.5% of calcium oxide (CaO), 21.6% silicon dioxide (SiO_2), 4.9% aluminium oxide (Al_2O_3), and 2.9% iron (III) oxide (Fe_2O_3). All these chemical compositions are considered primary components of cement production. On the other hand, copper slag contains high components of SiO_2, Fe_2O_3, and Al_2O_3 with 35%, 28%, and 8%, respectively, which are commonly reported in the literature as constituents that may contribute to the reactivity of supplementary cementitious materials.

As shown in **Table 3**, incorporating copper slag into the cement mixture can increase Fe_2O_3 and SiO_2 levels, thereby enhancing strength properties. But increasing the copper slag content reduced CaO as well, making cement production inefficient, since CaO is the primary component that serves as the main source for the formation of calcium silicate hydrates (C-S-H).

As presented, the four main components in mixture #2 and mixture #3 (where copper slag content was 5% and 10 %, respectively) are within the range of cement production, which was reported to be CaO between 60-69%, SiO_2 between 18-26%, Al_2O_3 between 4-6%, and Fe_2O_3 between 2-4.6%. While other mixtures are out of range.

Table 2. Chemical Composition of Clinker and Copper Slag.

Component	Clinker (%)	Copper Slag (%)
Fe_2O_3	2.9	35.0
TiO_2	0.17	0.5
CaO	67.5	3.0
K_2O	0.17	0.1
SiO_2	21.6	28.0
Al_2O_3	4.9	8.0
MgO	2.09	2.5
SO_3	0.67	0.2

Table 3. Chemical Composition of the Six Mixtures with Varying Copper Slag Content.

Exp No.	Fe_2O_3 (%)	TiO_2 (%)	CaO (%)	K_2O (%)	SiO_2 (%)	Al_2O_3 (%)	MgO (%)	SO_3 (%)
1(baseline)	2.7	0.21	69.9	0.12	19.6	4.7	2.09	0.68
2	3.72	0.20	64.0	0.16	23.8	5.3	2.15	0.67
3	4.54	0.23	60.5	0.15	26.0	5.7	2.21	0.67
4	4.64	0.26	57.0	0.14	28.2	6.1	2.27	0.67
5	6.18	0.29	53.5	0.13	30.4	6.5	2.33	0.67
6	7.01	0.31	50.0	0.12	32.6	6.9	2.39	0.67

3.2 Compressive Strength Results

The results of compressive strength in 2 days, 7 days, and 28 days for the six mixtures are presented in **Figure 4**. As indicated in **Table 1**, the baseline mixture, the reference standard sample for comparison, exhibited the highest compressive strength at the 2-day test with a value of 32.5 MPa, which provided rapid early hydration compared to other mixtures. When the copper slag takes a portion of the mixtures, the results decrease slightly, reflecting the slower pozzolanic reaction compared to the baseline mixture (Feng et al., 2019; Song et al., 2020a).

At the 7-day test, mixtures #2 and #3 showed compressive strengths comparable to the baseline mixture. The tests show 46.8 MPa and 47.1 MPa, respectively, compared to 45 MPa in the baseline mixture. The increase in compressive strength observed at 5% and 10% copper slag replacement may be associated with the chemical composition of the slag and improved particle packing, which is consistent with mechanisms reported in previous studies (Mahajan & Muhammad, 2024; Wang et al., 2025). When the copper content exceeded 10%, it exhibited slightly lower strength due to clinker dilution.

The same behavior was shown in the 28-day test. Mixtures containing 5% and 10% copper slag had higher strength than the baseline mixture. The improved long-term compressive strength observed for the mixtures containing 5% and 10% copper slag is consistent with findings reported in previous studies on copper slag-containing cementitious materials (Al-Jabri et al., 2009). Although enhanced hydration products such as calcium silicate hydrate (C-S-H) have been reported in previous studies, their formation was not directly verified in this study because no mineralogical characterization was performed (Tixier et al., 1997). Mixtures with higher copper slag contents showed reduced strength due to decreased CaO availability for complete hydration and bonding.

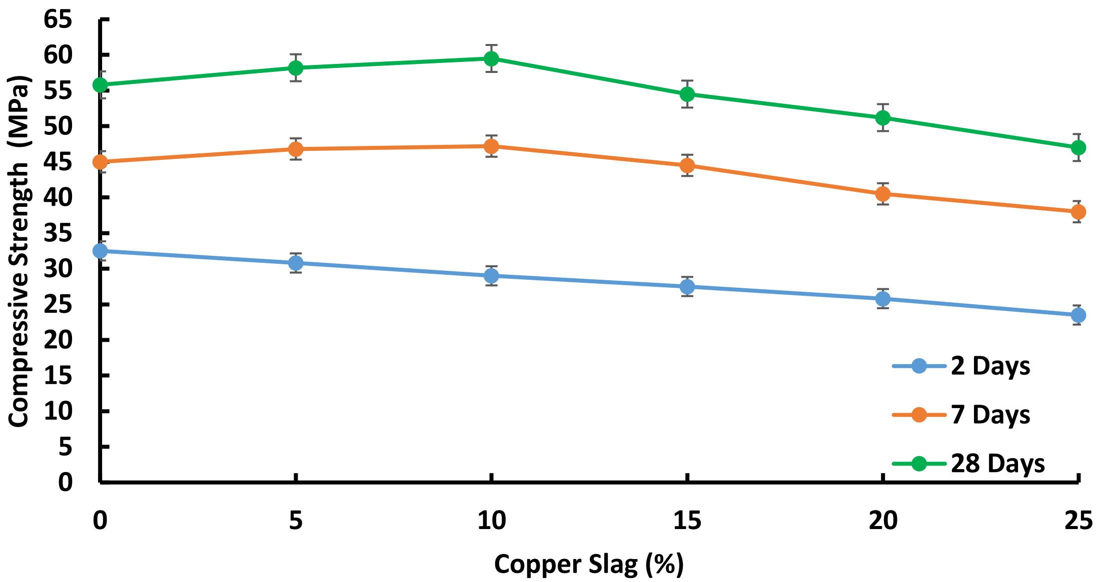

Fig. 4. Compressive Strength of Mortar Mixtures Containing Different Copper Slag Replacement Levels After 2, 7, and 28 Days of Curing.

3.3 Flexural and Tensile Strength

The results of the flexural and tensile strength tests at 28 days are shown in **Figure 5**. As mentioned earlier, this test was performed to check the ability of mixtures to resist bending and pulling forces. As shown, the baseline mixture has a flexural strength of 6.2 MPa and a tensile strength of 4.1 MPa. Previous studies show that, with a typical 28-day compressive strength of 55 MPa, using the Eurocode 2 formula, the typical range of tensile strength is 2.9-5.3 MPa. While ACI 318 (empirical expression for flexural strength) is between 5.0 – 6.0 MPa (Kępniak & Woyciechowski, 2016; Luongo et al., 2023; Salama et al., 2024)

Higher cracking resistance and better durability were observed with 5% and 10% copper slag. Tensile strength values were increased to 4.3 MPa and 4.4 MPa, respectively. Higher flexural strength values than the baseline mixture increase allowable bending stresses and confirm that it can withstand higher load repetitions.

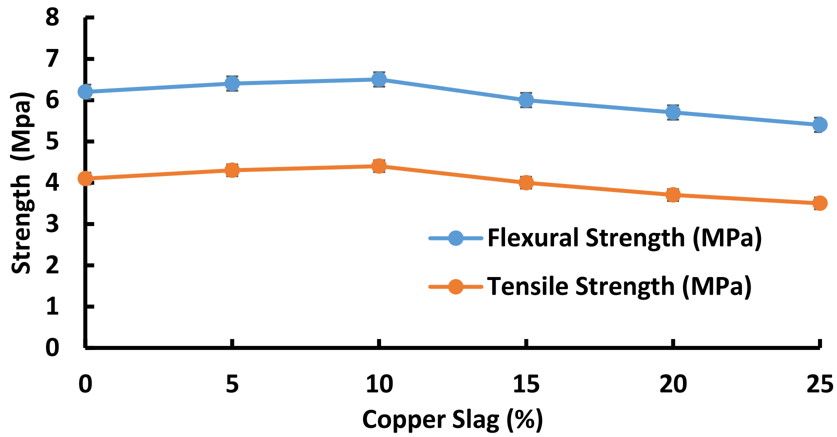

Fig. 5. Flexural And Splitting Tensile Strengths of Mortar Mixtures Containing Different Copper Slag Contents at 28 Days.

3.4 Elastic Modulus

The stiffness of the samples was measured in accordance with ASTM C469. The results of the elastic modulus are shown in **Figure 6**. The mixtures #2 and #3, which used 5% and 10% copper slag, have 29.2 GPa and 29.5 GPa, respectively. These results show that a small amount of copper slag makes the cement more rigid and better resists deformation under load. The increase in elastic modulus observed for mixtures containing 5% and 10% copper slag indicates improved stiffness compared with the reference mixture. Similar trends have been reported in previous studies and have been attributed to mechanisms such as improved particle packing, reduced porosity, or limited microstructural densification (Gopalakrishnan & Nithiyanantham, 2020; Song et al., 2020b; Tixier et al., 1997).

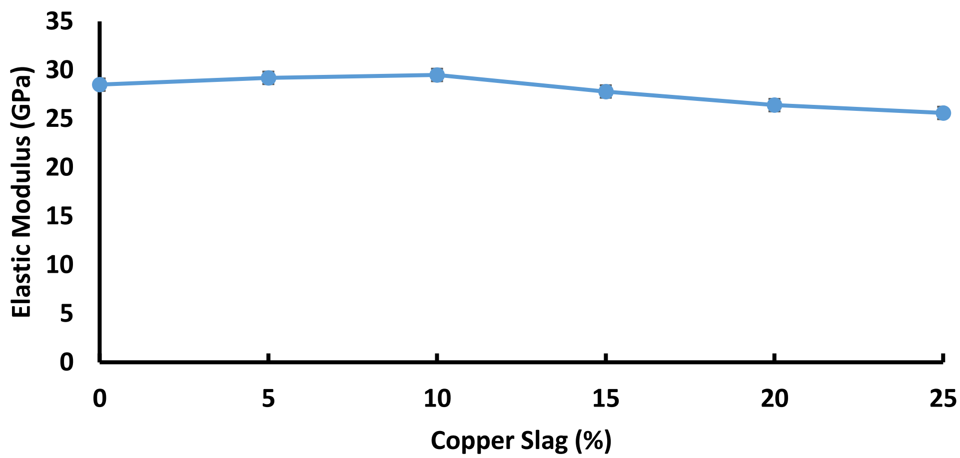

Fig. 6. Elastic Modulus of Mortar Mixtures Containing Different Copper Slag Contents.

3.5 Setting Time

Sample workability and strength development have been investigated by studying the setting time tests. As presented in **Figure 7**, the baseline mixture had an initial setting time of 115 min and a final setting time of 195 min, which is within the average range of concrete setting time. Mixtures #2 and #3 had slightly longer setting times compared to the baseline mixture, with differences of about 5-10 min in both initial and final setting time, which is still acceptable and it's among the range of standard concrete.

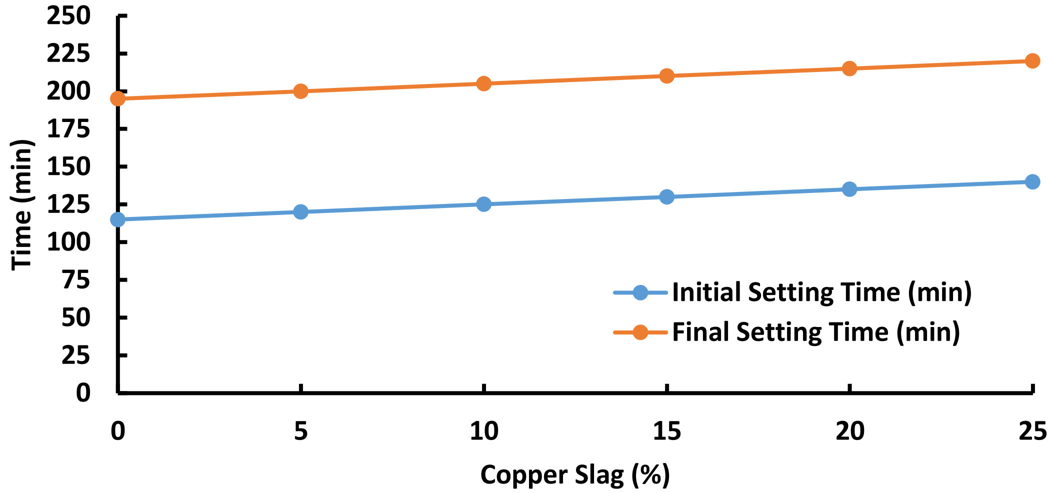

Fig. 7. Initial and Final Setting Times of Mortar Mixtures Containing Different Copper Slag Contents.

4. Conclusion

This study evaluated the potential of using copper slag as a substitute for clinker in cement production. The experimental results demonstrate that replacing clinker with 5–10 wt.% copper slag improved the measured mechanical properties while maintaining acceptable setting times. These improvements are consistent with findings reported in previous studies on copper slag as a supplementary cementitious material. However, the present study did not directly investigate hydration products or reaction mechanisms; therefore, the observed performance should be interpreted based on the measured mechanical behavior rather than confirmed mineralogical changes.

Mechanical properties include compressive strength, flexural strength, tensile strength, elastic modulus, and setting time demonstrate that the mixtures that have 5% and 10% copper slag achieved high strength compered to baseline mixture at 28 days, which highlights the potential of utilization copper slag as alternative in cement production and it contribute to reduce the CO_2 emissions due the clinker processing which required heating the limestone and clay to extreme temperatures which consuming massive energy, and fuel combustion. Based on the measured clinker CaO content of 67.5 wt.%, the theoretical reduction in calcination-related CO_2 emissions resulting from replacing 10 percentage points of clinker was estimated using a stoichiometric mass balance. For one tonne of cement, 10 wt.% clinker replacement corresponds to 0.10 tonne of avoided clinker. Using the molar mass ratio of CO_2 to CaO in the calcination reaction, the theoretical avoided emission is equivalent to approximately 53 kg CO_2 per tonne of cement. This value represents only the theoretical reduction in process emissions associated with limestone decarbonation. Emissions associated with kiln fuel, electricity, transportation, slag processing, and other life-cycle stages were not evaluated.

4.1 Limitations of the Study and Future Work

The present investigation focused on evaluating the influence of copper slag as a partial clinker replacement through chemical composition analysis (XRF), mechanical testing, and setting time measurements. Although the results demonstrate promising mechanical performance at replacement levels of 5–10%, the study did not include detailed characterization of hydration kinetics or phase evolution. Consequently, the mechanisms responsible for strength development were inferred from the published literature rather than direct experimental evidence.

Furthermore, environmental aspects such as heavy-metal leaching, long-term durability under aggressive exposure conditions, and life-cycle assessment were beyond the scope of this work. Future studies incorporating techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM), thermogravimetric analysis (TGA), and standardized leaching tests are recommended to provide a more comprehensive assessment of the reaction mechanisms and environmental sustainability of copper slag-containing cement.

CRediT Author Contribution Statement

M. Al-E'bayat: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Writing – Review & Editing
D. A. Alfuqara: Methodology, Investigation, Data Curation, Formal Analysis, Writing – Original Draft
H. Abu Hamam: Investigation, Experimental Work, Data Curation
S. Amra: Investigation, Experimental Work, Data Curation
D. Abuhamad: Investigation, Experimental Work, Data Curation
R. Hamdan: Investigation, Experimental Work, Data Curation
A. Alsafasfeh: Supervision, Project Administration, Funding Acquisition, Writing – Review & Editing

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Conflicts of Interest
The authors declare no conflict of interest.

Use of AI Tools

During the preparation of this work, the author(s) used ChatGPT to proofread and improve the English language. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

Nomenclature

Symbol / Abbreviation	Description
ASTM	American Society for Testing and Materials
C-S-H	Calcium silicate hydrate
IEA	International Energy Agency
SCMs	Supplementary cementitious materials
SEM	Scanning electron microscopy
TGA	Thermogravimetric analysis
XRD	X-ray diffraction
XRF	X-ray fluorescence

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