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Enhancing the Performance and Sustainability of Cementitious Composites through the Optimized Use of Steel Slag: Particle Size and Activation Techniques

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Abstract. The utilization of industrial by-products such as steel slag in cementitious materials not only mitigates environmental impact but also enhances material properties. This study investigates the dual influence of steel slag particle size on the compressive strength and carbonation efficiency of cementitious composites. Through a systematic experimental approach, steel slag particles were incorporated into cement at varying sizes, and the resulting composites were subjected to mechanical and carbonation tests. Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX) are conducted in this paper. The findings reveal a positive correlation between increased particle size and compressive strength, attributed to the improved interfacial transition zone and packing density. Conversely, smaller particle sizes exhibited enhanced carbonation efficiency, likely due to the increased surface area facilitating the carbonation reaction. The presence of higher silica and calcium content in finer particles was confirmed by EDX, which contributed to the accelerated carbonation process. This study underscores the importance of particle size optimization in designing sustainable cementitious materials with balanced mechanical performance and carbon sequestration potential. The insights gained from the advanced analytical techniques offer a comprehensive understanding of the mechanisms at play, paving the way for the strategic use of steel slag in eco-friendly construction practices.

Keywords: Particle size, Compressive strength, Carbonation efficiency, Steel slag

1 Introduction

The construction industry is a major source of global carbon emissions, largely due to Portland cement production. As the demand for sustainable building materials increases, the integration of industrial by-products like steel slag into cementitious composites has become a promising alternative. Steel slag, a by-product from steel manufacturing, is known for its potential to enhance the mechanical properties of concrete while contributing to carbon sequestration. However, the effect of steel slag particle size on the performance of cementitious materials remains underexplored [1].

Although the benefits of using steel slag in cementitious materials are well-recognized, the specific relationship between particle size and the resulting composite properties has not been thoroughly defined. Larger particles are thought to improve compressive strength due to better packing and enhanced interfacial transition zones, while smaller particles may improve carbonation efficiency because of their increased surface area and reactivity. This trade-off creates a challenge in material optimization, as enhancing one property may compromise another. Therefore, a comprehensive investigation is necessary to fully understand the interactions between particle size, mechanical strength, and carbonation efficiency in steel slag cementitious composites [2].

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This study aims to fill this gap by providing empirical data and a mechanistic understanding of how steel slag particle size influences key properties of cementitious composites. The findings will help establish guidelines for the use of steel slag in concrete, addressing the dual needs for durable infrastructure and environmental sustainability. This paper addresses a critical gap in knowledge related to the optimization of steel slag usage in concrete. By focusing on the effects of particle size on both mechanical performance and carbonation, the research will provide practical insights for the construction industry, promoting eco-efficient and durable building practices [3].

2 Contribution of studies

This study makes significant contributions to the field of sustainable construction materials and material science. It offers a detailed evaluation of how different particle sizes of steel slag influence the compressive strength of cementitious composites, establishing a foundational understanding of how industrial by-products can be effectively integrated into construction materials. This finding opens the door for developing novel concrete formulations that leverage the strength-enhancing properties of larger steel slag particles, potentially leading to more durable and long-lasting infrastructure.

Additionally, the research provides valuable insights into carbonation dynamics by demonstrating that finer steel slag particles improve carbonation efficiency due to their larger surface area and reactivity. This knowledge is crucial for designing construction materials that not only serve structural purposes but also contribute to carbon capture, aiding efforts to mitigate the environmental impact of the construction industry.

Furthermore, the study advances analytical methodologies by employing techniques such as Energy Dispersive X-ray Spectroscopy (EDX) to identifies which elements are present and in what proportions such as calcium and silica. The multi-faceted approach enhances the reliability of the findings and sets a high standard for future research focused on the development of environmentally friendly building materials.

3 Literature Review

In recent decades, several scientific studies and research contributions which were inspired by the lessons learned from earlier research have led to the development of the application of slag waste streams as a carbon capture resource. Historical analyses by previous researchers indicate that these waste streams have latent potential as valuable tools in the carbon capture and storage (CCS) toolbox [4].

Metallurgical and geochemical studies served as the foundation for early research that revealed the compositional richness of slag waste streams. These studies showed that there are mineral phases in slag waste that have characteristics that naturally encourage the mineralization of carbon. Prior research, which included extensive mineralogical analyses and in-lab experiments, elucidated the complex geochemical relationships between carbon dioxide (CO_2) and the mineral constituents of slag waste streams. The fundamental processes by which CO_2 is changed into stable carbonate minerals and subsequently sequestered are these reactions, which are currently extensively documented in the scientific literature [4].

Along with technological considerations, past slag-assisted carbon sequestration has made a considerable impact upon environment related matters. Slag-based carbon capture has been assessed comprehensively through life cycle and environmental impact analyses relying on actual data from earlier research providing substantial insight into its environmental impacts and energy demand. Such an all-round knowledge encompasses economic evaluations of slag waste as a carbon capture technology in industrial projects as previous studies have showed the cost effectiveness of this idea [5].

For example, slag crushing is carried out with sieving through 4 grades of particle sizes including 3.5 to 7mm. Surprisingly, < 3.5mm grade can be used as raw material for subsequent iron making in the basic oxygen furnace. Specific gravity, pH, moisture content, and free CaO were measured, in the immediate analysis of the same slag particles of a particular size. The dried slags were then heated in an oven at 105°C until they became homogeneous. The chemical composition of the BOF slags was determined through "alkali digestion" using a mixture of lithium tetraborate (Li_2BO4). Subsequently, the molten sample was dissolved in HCl solution before being analyzed using an inductively coupled plasma-atomic emission spectrometer [6].

A stainless-steel rotary kiln is being used as the carbonation reactor. It can function in the range of room temperature to roughly 450°C. Instead of using static reactors, the rotary kiln was selected to enhance the interaction between the gaseous and solid phases. An integrated gas mixing chamber upstream of the rotary kiln allowed exact control over the gas's composition. Three distinct gases were mixed and precisely measured in this chamber: water vapour ($H_2O(g)$), gaseous CO_2, and air. This blended gas was then poured into the rotary kiln. To avoid water vapour condensing into droplets, the gas mixing chamber was heated to a temperature equivalent to that of the rotary kiln [7].

During the carbonation process, measurable quantities of the BOF slag samples were added to the rotary kiln. The 24-hour retention period was chosen to allow sufficient time for comprehensive answers. This study specifically looked at three important carbonation parameters: the relative humidity (RH), which covered values from 0% to 80%, the CO_2 concentration, which ranged from 0% to 40%, and the kiln temperature, which covered 25°C to 250°C [7].

Nugmanova (2023) modified these parameters one by one to determine the individual and combined influence of such changes on the characteristics of the BOF slags with different grain sizes. Using a slag sample to determine the pH of the BOF slags at a ratio of 1.0 L of water per kilogram of slag. Using a specialized pH electrode, the pH of the mixture after 20 minutes of vigorous stirring was determined. In compliance with the methodology of ASTM C 114, chemical extraction was applied to determine the level of free CaO in the BOF slag. This approach allows for accurate determination of the amount of free CaO and contributes to holistic characterization of slag's chemical compositions [8].

Furthermore, a slag sample was soaked in a boiled glycerin-ethanol solution prior to the start of the extraction procedure. Lastly, the final extract was diluted and titrated with a standardized standard ammonium acetate solution prepared in 0.005 g/ml of CaO. This process was executed in order to precisely measure the amount of CaO present in the sample. The mineralogical composition of the original and carbonated BOF slag were assessed using X-ray diffraction (XRD). The employed methodological model used an X-ray diffractometer with a Cu ka radiation commonly denoted as Rigaku D-MAX 2000. The systematic use of x-ray diffraction provided important insights into the crystalline structures of the investigated materials [9].

In summary, earlier research has been crucial in helping to recognize slag waste streams as a valuable and long-term source for carbon capture. Their combined efforts which include assessments of sustainability, industrial applications, and mineralogical insights have not only confirmed the feasibility of slag-mediated carbon capture but also highlighted the revolutionary potential of repurposing industrial byproducts to address the urgent problems associated with CO_2 emissions reduction.

4 Methodology

The methodology for this research begins with the collection of steel slag from a steel manufacturing facility. The slag is then subjected to sieve analysis to isolate particles within the 3.5mm to 7mm size range. Following the sieving process, the selected steel slag samples are oven-dried at a temperature of approximately 105°C to ensure the removal of all moisture, which could otherwise affect the consistency of subsequent analyses. Using this different size of steel slag, several samples are made and shown with details in table 1.

Once dried, the steel slag particles undergo a series of characterization techniques. The elemental composition is determined through Energy-Dispersive X-ray Spectroscopy (EDX) conducted in tandem with SEM. For the concrete mix design, a control mix is prepared using Ordinary Portland Cement (OPC) without any steel slag to serve as a benchmark. Additional concrete mixes are created by replacing OPC with the prepared steel slag at various ratios to investigate the effect of slag content on the composite properties. The fresh concrete is then poured into standardized molds, such as 150mm cubes, and vibrated to ensure proper compaction and to eliminate air voids. The samples are cured under controlled conditions, typically at 23°C and 95% relative humidity, for a standard period of 28 days to allow for proper hydration and strength development.

Subsequently, the concrete mix design is expanded to include not only a control mix with no steel slag but also several experimental mixes where the steel slag replaces the fine aggregate at different percentages. Specifically, mixes are prepared with steel slag replacing 15%, 30%, and 45% of the fine aggregate by weight. These proportions are chosen to investigate the effects of incremental increases in steel slag content on the concrete's performance.

Following the curing period, the compressive strength of both the control and steel slag-amended concrete samples is tested using a calibrated compression testing machine. The peak load at failure is recorded for each sample to calculate the compressive strength. The results from the SEM and EDX analyses are then analyzed in conjunction with the compressive strength data to assess the impact of steel slag content and particle size on the mechanical properties of the concrete.

The final stage of the methodology involves a comprehensive data analysis and comparison. The compressive strength of the concrete samples containing steel slag is compared to that of the control mix to determine the influence of the slag's particle size and replacement ratio on the concrete's performance. The findings are documented in a detailed report that discusses the potential of steel slag as a concrete additive, considering both the enhancement of mechanical properties and the environmental benefits. The report concludes with recommendations for the incorporation of steel slag in concrete production, balancing structural integrity with sustainability.

Table 1. Description of sample type (R1, R2, R3)

Sample Name	Description
R1	Samples consists of 0.8-2.36mm size of steel slag
R2	Samples consists of 2.36-4.75mm size of steel slag
R3	Samples consists of 4.75-7mm size of steel slag

5 Results and Discussion

The study on the use of steel slag as a replacement for fine aggregate in concrete demonstrates a positive correlation between the incorporation of steel slag and increased compressive strength. Table 1 shows the results of the control sample, without steel slag, showed a compressive strength of 24.79 MPa which shown in table 2. In contrast, steel slag samples exhibited varying strengths depending on the replacement level. The R1 samples, with the lowest replacement level, had a lower strength of 19.81 MPa compared to the control. However, as the replacement level increased to R2 and R3, the compressive strengths improved to 25.33 MPa and 30.42 MPa, respectively, suggesting that higher replacement levels and larger particle sizes enhance the concrete's strength.

The improved performance is attributed to better particle packing, an enhanced interfacial transition zone, and the pozzolanic activity of the steel slag. The angularity and rough texture of the slag particles likely contribute to mechanical interlocking within the concrete matrix. Despite these promising results, the variability in steel slag composition and the long-term durability of slag-containing concrete requires further investigation.

Furthermore, table 3 revealed the control samples had a calcium content of 56.21% and a silica content of 17.5%. With the introduction of steel slag, the calcium content increased, and the silica content decreased across the replacement levels. The R1 samples had 65.13% calcium and 14.92% silica, R2 had 63.42% calcium and 12.77% silica, and R3 had 62.04% calcium and 7.84% silica. The higher calcium content in the slag samples is believed to contribute to the formation of additional C-S-H gel, enhancing compressive strength, especially at higher replacement levels.

The study concludes that steel slag can be a sustainable and performance-enhancing alternative to natural fine aggregates, with the potential to produce stronger concrete. The increased calcium content in steel slag correlates with increased strength, and the reduced silica content does not seem to negatively impact performance. Standardizing steel slag quality and further research on durability and environmental resistance are recommended to establish steel slag as a reliable material in sustainable construction.

Table 2. Compressive Strength Test Results

Samples	Compressive Strength, MPa			Average value, MPa
	Cube 1	Cube 2	Cube 3	
Control sample	23.91	27.18	23.29	24.79
R1	19.52	19.60	20.32	19.81
R2	26.04	24.79	25.15	25.33
R3	30.76	29.83	30.68	30.42

Table 3. Percentage results of element contained

Samples	Element percentage, %					
	Ca	Mg	O	Al	Si	C
Control sample	56.21	1.41	19.19	4.21	17.5	1.48
R1	65.13	2.75	12.14	4.12	14.92	0.94
R2	63.42	3.16	16.91	2.2	12.77	1.54
R3	62.04	7.84	17.29	1.13	7.84	0.65

6 Conclusion

In conclusion, the research indicates that steel slag, when used as a replacement for fine aggregate in concrete, can lead to an increase in compressive strength, particularly at higher replacement levels and with larger particle sizes. The study demonstrates that the control sample, without steel slag, had a compressive strength of 24.79 MPa, while the steel slag samples showed varying strengths, with the highest replacement level (R3) reaching 30.42 MPa. The enhanced performance is likely due to improved particle packing, a better interfacial transition zone, and the pozzolanic reactions of the steel slag, which contribute to a denser and stronger concrete matrix.

Energy-dispersive X-ray spectroscopy (EDX) further supports these findings, revealing that steel slag samples have higher calcium content and lower silica content compared to the control. This altered chemical profile, particularly the increased calcium content, is associated with the formation of more C-S-H gel, a key contributor to concrete strength.

The study suggests that steel slag can be a valuable resource for the construction industry, offering a sustainable alternative to natural fine aggregates and enhancing the mechanical properties of concrete. However, the variability in steel slag composition and the need for further research on long-term durability and environmental resistance highlight the importance of standardizing steel slag quality for its reliable use in construction.

Overall, the positive implications of incorporating steel slag in concrete production are clear, with the potential for both environmental benefits, by diverting waste from landfills, and performance improvements in concrete structures. Future research should aim to address the remaining questions regarding the consistency and long-term performance of steel slag concrete to fully realize its potential in sustainable construction practices.

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