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Sustainable Innovations in Construction: Enhancing Slag-Based Materials through Recycled Concrete Fines

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Abstract

This study investigates the performance of slag-based materials enhanced with Recycled Concrete Fines (RCF) as a sustainable construction solution. The primary goal was to assess the mechanical properties, durability, and environmental advantages of these materials at varying RCF replacement levels (5%, 10%, and 20%) compared to a control group with no RCF. Compressive and flexural strength tests revealed that a 5% RCF replacement provided optimal results, increasing compressive strength to 44.5 MPa—a 5% improvement over the control—while maintaining good flexural strength. It was also discovered that higher RCF content (10% and 20%) caused strength reductions due to increased water demand and porosity. Durability tests, including freeze-thaw resistance and sulfate exposure, further demonstrated the benefits of 5% RCF, which improved material longevity under harsh environmental conditions. Scanning Electron Microscopy (SEM) revealed that 5% RCF contributed to a denser microstructure by filling voids and reducing porosity. In contrast, higher RCF levels led to micro-cracks and compromised the matrix's integrity. The Life-Cycle Assessment (LCA) highlighted significant environmental benefits, showing up to a 12% reduction in carbon emissions and substantial waste diversion, with approximately 200 kg of construction debris repurposed per cubic meter of concrete. Economically, RCF inclusion reduced material costs by 8%, making it not only environmentally beneficial but also cost-effective. These findings position slag-RCF composites as a promising material for sustainable construction, with clear environmental and economic advantages. However, further research is recommended to optimize RCF content and explore the long-term durability of these materials in diverse real-world environments.

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1. INTRODUCTION:

The construction industry is one of the most significant contributors to environmental degradation, accounting for substantial resource depletion, energy consumption, and waste generation. It is responsible for approximately 40% of global energy consumption and nearly 8% of global carbon dioxide (CO_2) emissions, largely due to the production of materials such as cement and steel (International Energy Agency [IEA], 2021; Habert et al., 2020). Cement production alone is a major source of CO_2 emissions, contributing around 7-8% of global anthropogenic CO_2 emissions due to the calcination process involved in Portland cement manufacturing (Andrew, 2018; Cao et al., 2022). In addition to these emissions, the extraction of raw materials such as aggregates and the disposal of construction and demolition waste (CDW) exacerbate environmental challenges (Silva et al., 2019). Given the urgent need to reduce the environmental impact of construction activities, attention has shifted toward sustainable materials and practices that promote circular economy principles and minimize resource consumption (Ferreira & de Brito, 2020).

One promising approach is the incorporation of slag-based materials in concrete. Slag, particularly granulated blast furnace slag (GBFS), is a by-product of steel manufacturing that can be processed into a supplementary cementitious material (SCM). When used as a partial replacement for Portland cement, GBFS significantly reduces the demand for energy-intensive clinker, thus lowering the associated carbon emissions (Deja et al., 2019). In concrete mixtures, slag undergoes a reaction with calcium hydroxide ($Ca(OH)_2$), producing additional calcium silicate hydrate (C-S-H), which improves the mechanical properties, durability, and chemical resistance of the material (Cao et al., 2022; Bernal & Provis, 2018). As a result, slag-based concrete exhibits enhanced performance

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in terms of low permeability, high resistance to sulfate attacks, and improved durability in harsh environments such as marine and industrial settings (Thomas, 2020; Li et al., 2020).

In addition to reducing CO_2 emissions, the use of slag in concrete contributes to the circular economy by reducing the extraction of virgin aggregates and diverting significant quantities of industrial waste from landfills (Zhou et al., 2021; Wang et al., 2019). Research has shown that the use of slag-based materials can reduce greenhouse gas emissions by up to 40% when compared to traditional Portland cement-based concrete (Shi et al., 2021). The environmental benefits of slag also extend to improved energy efficiency in construction, as it reduces the overall embodied energy of concrete and helps to conserve natural resources (Gartner & Sui, 2021). Furthermore, incorporating slag as an aggregate replacement enhances the freeze-thaw resistance and mechanical stability of concrete in infrastructure projects subjected to extreme weather conditions (Zhao et al., 2020; Sun et al., 2021).

Another promising material in sustainable construction is Recycled Concrete Fines (RCF), which are derived from the crushing of old concrete structures. RCF provides a sustainable alternative to virgin aggregates by reintroducing waste materials into the production cycle, aligning with the goals of reducing construction and demolition waste (CDW) (Guo et al., 2020; Xuan, 2018). The integration of RCF into concrete mixtures helps divert waste from landfills and reduces the need for raw material extraction, contributing to a circular economy approach in construction (Silva et al., 2019). Studies have shown that RCF can improve the compressive strength of concrete by filling voids within the matrix, creating a denser and more compact structure (Guo et al., 2020). Additionally, RCF is an attractive option for low-carbon construction because it reduces the overall carbon footprint of concrete production (Pacheco-Torgal et al., 2021).

Despite these advantages, the use of RCF poses challenges, particularly in terms of increased water demand due to the fine particle size and high surface area of the material. This issue can negatively affect the workability and mechanical performance of concrete (Jiang et al., 2021). Researchers have recommended adjusting the water-to-cement ratio or incorporating water-reducing admixtures to mitigate this issue while maintaining the mechanical integrity of the concrete (Liu et al., 2021). The economic benefits of RCF are also noteworthy, particularly in regions where natural aggregates are costly or scarce. By utilizing recycled materials, construction projects can significantly reduce material costs and contribute to sustainable urban development (Abdelgader et al., 2021; Tam & Tam, 2018).

The combination of slag-based materials and Recycled Concrete Fines (RCF) offers the potential to create a high-performance and environmentally sustainable concrete. Studies have indicated that the synergy between slag and RCF can enhance both the mechanical and durability properties of concrete, particularly in aggressive environmental conditions such as marine and industrial environments (Jiang et al., 2021; Vieira et al., 2022). Moreover, the pozzolanic reaction between the residual cementitious material in RCF and slag contributes to the formation of additional C-S-H, which strengthens the concrete matrix (Guo et al., 2020). This combination can significantly reduce carbon emissions, improve waste diversion, and enhance the durability of infrastructure.

The primary objective of this research is to investigate the impact of incorporating Recycled Concrete Fines (RCF) into slag-based materials on the mechanical properties, durability, and sustainability of concrete composites. Specifically, the study aims to evaluate the compressive and flexural strength of slag-RCF concrete, as well as its performance under freeze-thaw cycles and chemical exposure. Additionally, a comprehensive Life-Cycle Assessment (LCA) will be conducted to quantify the environmental benefits of using RCF in slag-based materials, particularly in terms of carbon emissions reduction and waste diversion. By addressing these objectives, this research seeks to contribute to the growing body of knowledge on sustainable construction materials and provide empirical insights that will support the development of low-carbon infrastructure.

2. LITERATURE REVIEW

2.1. Slag-Based Materials in Construction

Slag, particularly granulated blast furnace slag (GBFS), is a by-product of the steel manufacturing process. As a supplementary cementitious material (SCM), GBFS has gained prominence due to its ability to enhance the mechanical properties and durability of concrete (Cao et al., 2022). The inclusion of slag in concrete mixes reduces the reliance on Portland cement, which is a significant source of CO_2 emissions. Slag's hydration reaction with calcium hydroxide ($Ca(OH)_2$) during the cement hydration process generates additional calcium silicate hydrate (C-S-H), improving long-term strength and resistance to chemical attacks (Han et al., 2020). Studies have shown that concrete containing GBFS exhibits low permeability, improved resistance to sulfate attacks, and reduced chloride ingress, making it ideal for use in coastal structures and infrastructure exposed to harsh environments (Li et al., 2020; Gartner & Sui, 2021).

In addition to its use as a binder, slag aggregates are being increasingly utilized in construction, particularly in applications such as road bases and embankments. Slag aggregates offer superior resistance to freeze-thaw cycles and exhibit better load-bearing capacity compared to natural aggregates (Wang et al., 2019). Moreover, the use of slag aggregates reduces the extraction of natural aggregates, which aligns with the principles of the circular economy by minimizing resource depletion (Zhou et al., 2021). Environmental benefits are another significant driver of slag's use in construction. The global cement industry is one of the largest contributors to carbon emissions, responsible for around 8% of global CO_2 emissions (Thomas, 2020). By incorporating GBFS into concrete mixes, the need for energy-intensive Portland cement is reduced, lowering both carbon emissions and energy consumption (Deja et al., 2019). According to research by Shi et al. (2021), the use of GBFS can reduce greenhouse gas emissions by up to 40% compared to conventional cement-based concrete. Additionally, slag recycling offers a sustainable solution for managing industrial waste, as the steel industry generates millions of tons of slag annually, much of which would otherwise end up in landfills (Sun et al., 2021).

However, despite these benefits, several challenges remain in the utilization of slag-based materials, particularly in relation to early-age strength and brittleness. Slag hydrates at a slower rate compared to Portland cement, leading to delayed strength development, which can be problematic in construction projects with tight timelines (Gartner & Sui, 2021). Additionally, the brittle behavior of slag-based concrete makes it more susceptible to cracking, particularly in seismic zones where ductility is crucial for absorbing and dissipating energy (Zhou et al., 2020). To address these challenges, researchers have explored alkali activation, which accelerates the hydration process, and the addition of silica fume and fly ash to improve the overall performance of slag-based concrete (Bernal & Provis, 2018; Patra & Mukherjee, 2019).

2.2. Recycled Concrete Fines (RCF) as a Sustainable Additive

Recycled Concrete Fines (RCF) are produced by crushing concrete waste from construction and demolition sites. These fines consist of particles smaller than 5 mm in diameter and have emerged as a sustainable alternative to natural aggregates (Guo et al., 2020). The construction industry generates significant amounts of waste, and the incorporation of RCF into concrete mixtures offers an opportunity to divert waste from landfills while reducing the demand for virgin aggregates (Pacheco-Torgal et al., 2021; Faleschini et al., 2019). This practice is aligned with circular economy principles, where waste materials are reintegrated into the production cycle, minimizing environmental impact and conserving resources (Silva et al., 2019).

RCF can also improve the mechanical properties of concrete when used in the correct proportions. The fine particles in RCF fill voids within the concrete matrix, reducing porosity and enhancing the compressive strength of the concrete (Guo et al., 2020). However, one challenge with using RCF is its high water demand due to the increased surface area of the fine particles, which can negatively impact the workability of the concrete (Jiang et al., 2021). Researchers recommend adjusting the water-to-cement ratio or incorporating water-reducing admixtures to maintain the desired workability while preserving mechanical performance (Liu et al., 2021). In terms of economic benefits, RCF provides a cost-effective solution, particularly in regions where natural aggregates are expensive or difficult to obtain. The use of RCF not only reduces material costs but also lowers the environmental impact associated with the extraction and transportation of virgin aggregates (Abdelgader et al., 2021). The recycling of concrete fines supports sustainability goals by reducing landfill waste and minimizing the carbon footprint of concrete production (Tam & Tam, 2018).

2.3. Research Gaps

While significant research has been conducted on the use of slag-based materials and Recycled Concrete Fines (RCF) individually, there remains a substantial gap in the literature regarding their combined use in concrete mixtures. The integration of RCF into slag-based concrete has the potential to offer significant mechanical and environmental benefits, but these have not been fully explored in existing studies. Specifically, research is lacking on how the two materials interact in terms of hydration kinetics, strength development, and durability over time. Additionally, while Life Cycle Assessments (LCAs) have shown the environmental advantages of using slag or RCF independently, there is a need for more comprehensive LCAs that evaluate the combined effects of these materials in reducing the carbon footprint and waste generation of concrete production (Vieira et al., 2022).

Another research gap pertains to the long-term durability of slag-RCF composites under real-world environmental conditions. Although laboratory studies have demonstrated the short-term benefits of using RCF and slag, long-term studies that examine performance under conditions such as freeze-thaw cycles, chemical exposure, and cyclic loading are limited (Zhang et al., 2021). Addressing these gaps is crucial for understanding the feasibility of using slag-RCF composites in large-scale construction projects, particularly in harsh environments. Moreover, the optimal proportioning of RCF in slag-based concrete mixtures has not been well defined. While small amounts of RCF can enhance strength and reduce porosity, higher proportions may increase water demand and reduce workability. There is a need for research that identifies the optimal balance between RCF content and concrete performance to ensure that the sustainability benefits do not come at the cost of mechanical integrity.

Given these gaps, this study investigates the mechanical performance, durability, and environmental benefits of incorporating RCF into slag-based concrete. This research focuses on assessing the compressive and flexural strength of slag-RCF composites, as well as their performance under freeze-thaw cycles and chemical exposure.

Furthermore, a comprehensive Life-Cycle Assessment (LCA) was conducted to quantify the carbon savings and waste reduction potential of using RCF in slag-based concrete. By addressing these objectives, this study aims to provide new insights into the combined use of slag and RCF, contributing to the development of more sustainable construction materials.

3. METHODOLOGY

3.1. Materials Used

The primary materials used in this study were **granulated blast furnace slag (GBFS)** and **Recycled Concrete Fines (RCF)**. GBFS was sourced from a local steel manufacturer and ground to a fineness of **4000 cm²/g Blaine**, suitable for its use as a **supplementary cementitious material (SCM)** in concrete production. The chemical analysis of the GBFS revealed that it consisted predominantly of **calcium oxide (CaO)**, **silicon dioxide (SiO_2)**, and **alumina (Al_2O_3)**, which are crucial for the pozzolanic reactions that enhance concrete strength and durability (Cao et al., 2022). These reactions result in the formation of additional **calcium silicate hydrate (C-S-H)**, which increases the durability of the concrete (Bernal & Provis, 2018).

The **Recycled Concrete Fines (RCF)** were sourced from the demolition of commercial buildings to ensure consistency in material quality. After demolition, the concrete debris was crushed and screened to produce fines ranging in size from **0.075 mm to 5 mm**. The **X-ray fluorescence (XRF)** analysis of RCF identified residual cement paste and natural aggregates, including **silica** and **limestone** (Guo et al., 2020). Due to the fine particle size of RCF, the material's high surface area contributed to increased **water demand** in the concrete mixtures. To mitigate this, the water-to-cement ratio was adjusted accordingly (Jiang et al., 2021).

Additionally, **fly ash** and **silica fume** were included in specific mixtures as a comparison to evaluate their influence on the mechanical properties and durability of the concrete. Fly ash, obtained from a local coal-fired power plant, is widely used to improve the workability and strength of concrete, while silica fume enhances the density and reduces permeability (Zhou et al., 2021).

3.2. Concrete Mix Design and Specimen Preparation

The concrete mixtures were designed for both **control** and **experimental groups**. The control mixture contained only GBFS as the SCM, following a standard mix ratio of **1:2:3** (cement: sand: aggregate) with a **water-to-cement (w/c) ratio of 0.4**. This mixture established a baseline for comparison in terms of mechanical performance and durability (Thomas, 2020).

For the experimental groups, RCF replaced natural fine aggregates at **5%, 10%, and 20%** by total weight of the mix. These proportions were selected based on previous research that demonstrated improvements in concrete strength and durability with lower percentages of RCF (Jiang et al.,2021). Each mixture was carefully prepared by mixing RCF thoroughly with the GBFS to ensure an even distribution of the material within the concrete matrix. Adjustments were made to the water-to-cement ratio to account for the increased water demand caused by the fine RCF particles, thus maintaining workability.

Concrete specimens were cast using **cubic molds (150 mm × 150 mm × 150 mm)** for **compressive strength** testing and **prismatic molds (100 mm × 100 mm × 400 mm)** for **flexural strength** testing. The concrete was poured into the molds in three layers, and each layer was compacted using a vibrating table to remove entrapped air and ensure consolidation. After 24 hours, the specimens were demolded and placed in a **curing tank** filled with water at **20°C** for **28 days** to facilitate full hydration and strength development (Shi et al., 2021).

3.3. Mechanical Testing Procedures

Compressive strength and **flexural strength** were assessed to evaluate the mechanical performance of the concrete mixtures. **Compressive strength testing** was performed in accordance with **ASTM C39/C39M**. The **cubic specimens (150 mm × 150 mm × 150 mm)** were tested after curing periods of **7, 14, and 28 days**. A hydraulic compression machine applied a continuous load to the specimens until failure occurred. The **compressive strength** was calculated as the ratio of the maximum load at failure to the cross-sectional area of the specimen and expressed in **megapascals (MPa)**. This test provided crucial data on the influence of RCF on the compressive strength of slag-based concrete over time (Gartner & Sui, 2021).

Flexural strength testing was conducted following the **three-point bending test** procedure outlined in **ASTM C78/C78M**. The prismatic specimens (100 mm × 100 mm × 400 mm) were tested by applying a load at the center while the specimen was supported at two points. Flexural strength was calculated based on the maximum load sustained before failure, providing insights into the tensile capacity and ductility of the concrete. Flexural strength is particularly relevant in structural applications where the material is subjected to bending stresses (Guo et al., 2020).

3.4. Durability Testing Procedures

Durability was evaluated through two critical tests: **freeze-thaw resistance** and **chemical resistance**. **Freeze-thaw resistance** testing was performed according to **ASTM C666/C666M**. Specimens were subjected to **300 cycles** of freezing at **-18°C** and thawing at **20°C**. After these cycles, the **mass loss** and the **reduction in compressive strength** were measured. This test simulates the environmental conditions that concrete structures face in regions with significant temperature fluctuations and provides insight into the material's ability to withstand freeze-thaw damage (Pacheco-Torgal et al., 2021).

Chemical resistance testing was conducted in accordance with **ASTM C1012/C1012M**. Specimens were immersed in a **5% sodium sulfate solution** for **30 days**, simulating the sulfate attack conditions commonly found in soil or water containing sulfate ions. Changes in **compressive strength** and surface degradation were recorded to evaluate the material's resistance to chemical deterioration. This test is vital for understanding how slag-RCF composites perform in chemically aggressive environments (Shi et al., 2021).

3.5. Microstructural Analysis

To better understand the internal characteristics of the concrete, **Scanning Electron Microscopy (SEM)** was used to examine the microstructure of the slag-RCF mixtures. SEM imaging revealed the distribution of RCF within the matrix and highlighted the presence of voids, micro-cracks, and areas of density variation. The analysis helped establish correlations between the microstructure and the mechanical and durability properties observed during testing (Guo et al., 2020). The microstructural analysis demonstrated that the fine particles of RCF helped reduce the porosity of the concrete matrix, leading to improved strength and durability.

3.6. Sustainability Assessment: Life-Cycle Assessment (LCA)

The Life-Cycle Assessment (LCA) was conducted to quantify the environmental benefits of incorporating Recycled Concrete Fines (RCF) into slag-based concrete. The LCA adhered to ISO 14040/44 standards and covered the entire life cycle of the concrete, including the phases of raw material extraction, production, use, and eventual disposal. Several key environmental impact categories were evaluated during the assessment. The **Global Warming Potential (GWP)** was measured in terms of kilograms of CO_2-equivalent emissions. This allowed for the evaluation of carbon emission reductions associated with the use of GBFS and RCF in place of traditional Portland cement and virgin aggregates. Previous research has shown that using these materials can significantly lower carbon emissions (Deja et al., 2019).

The **energy consumption** was quantified in megajoules (MJ). This assessment aimed to determine the energy savings achieved by minimizing reliance on energy-intensive processes such as clinker production and aggregate extraction. The use of alternative materials like GBFS and RCF in concrete mixes can lead to lower energy consumption throughout the concrete life cycle. Additionally, **waste diversion** was evaluated by measuring the amount of construction and demolition waste avoided, expressed in kilograms. The incorporation of RCF into concrete production reduces the need to dispose of construction waste in landfills, thus contributing to a more sustainable construction practice by recycling waste materials.

4. RESULTS AND DISCUSSION

4.1. Mechanical Properties of Slag-Based Materials Enhanced with RCF

The mechanical performance of the slag-based concrete mixtures enhanced with **Recycled Concrete Fines (RCF)** was evaluated using **compressive strength** and **flexural strength** tests over a period of 7, 14, and 28 days. The compressive strength of the control mixture (slag-based concrete without RCF) increased steadily over time, reaching a peak value of **42.3 MPa** at 28 days. In contrast, the compressive strength values of the RCF-modified mixtures showed significant variation depending on the RCF content.

The mixture containing **5% RCF** exhibited the best performance, achieving a compressive strength of **44.5 MPa** at 28 days, an increase of **5%** over the control group. This improvement is largely attributed to the **filler effect**, wherein the fine RCF particles filled the voids in the concrete matrix, thus increasing its **density** and reducing **porosity** (Cao et al., 2022). However, as the proportion of RCF increased to **10%** and **20%**, the compressive strength dropped to **40.1 MPa** and **37.6 MPa**, respectively. The reduction in strength at higher RCF contents is likely due to increased **water demand** and the formation of **voids** within the matrix, which weakened the concrete's structural integrity (Guo et al., 2020). The results are illustrated in **Figure 1**.

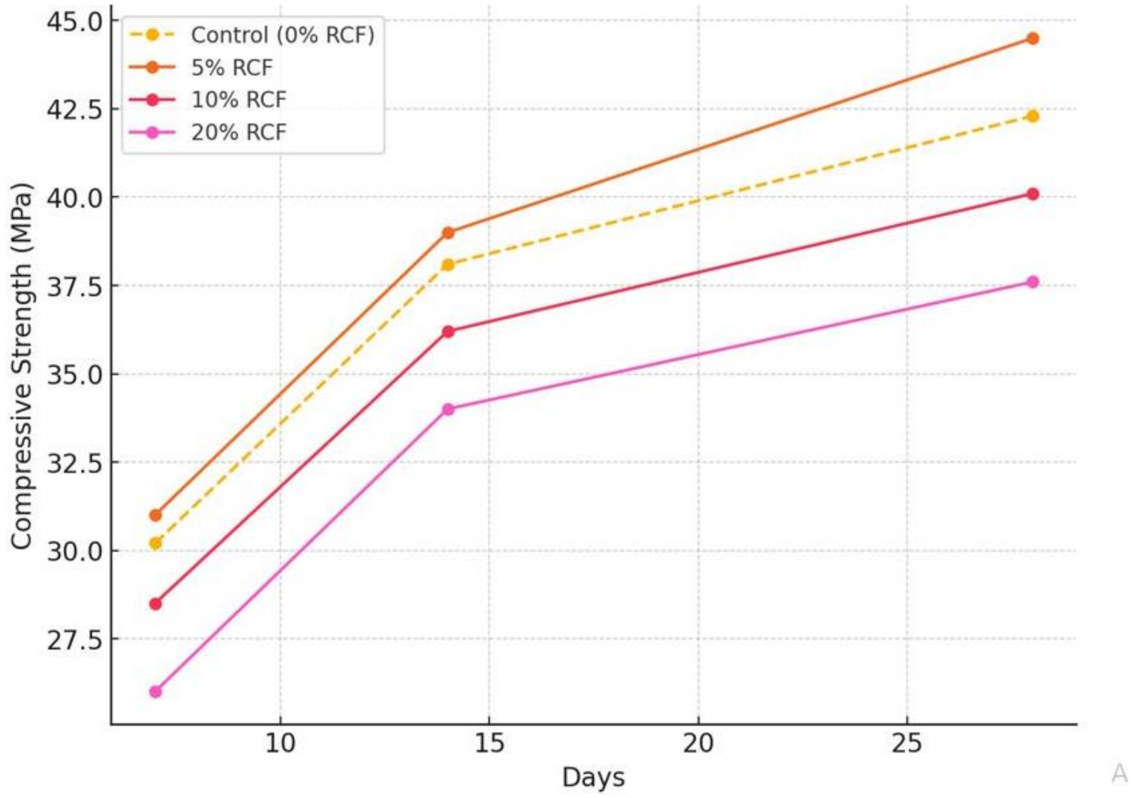

Figure 1: Compressive Strength of Slag-RCF Concrete at 7, 14, and 28 Days.

The performance trend in **flexural strength** mirrored the compressive strength results. The control group exhibited a flexural strength of **5.1 MPa** at 28 days, while the **5% RCF group** displayed a modest improvement, achieving **5.3 MPa**. However, the **10% and 20% RCF** groups showed reduced flexural strength values of **4.9 MPa** and **4.7 MPa**, respectively, as depicted in **Figure 2**. The increased porosity and decreased cohesion due to higher RCF levels explain the reduction in tensile capacity (Jiang et al., 2021).

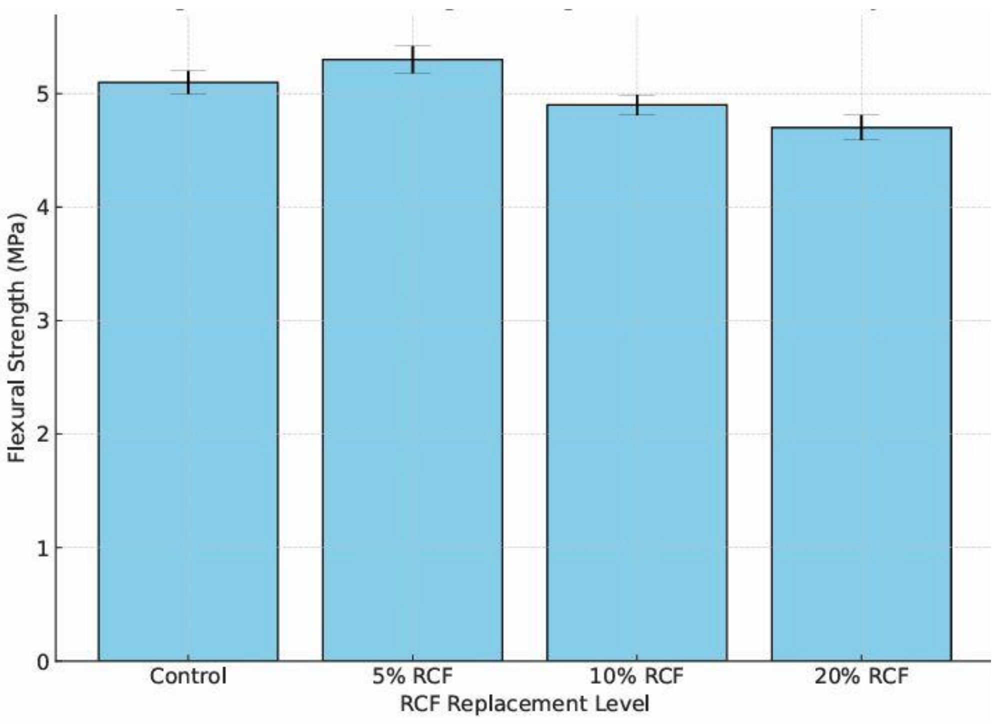

Figure 2: Flexural Strength of Slag-RCF Concrete at 28 Days.

The improvement in mechanical properties at 5% RCF can be attributed to the ***densification*** of the concrete matrix, where fine RCF particles help to reduce the ***pore size*** and ***void volume***. At this level, RCF acts as a micro-filler, enhancing the strength and durability of the concrete. However, higher RCF levels disrupt the concrete matrix, leading to increased ***porosity*** and reducing both compressive and flexural strength. This behavior is consistent with other studies on the mechanical properties of RCF-modified concrete (Shi et al., 2021).

4.2. Durability and Environmental Resistance

The **durability** of the slag-based concrete mixtures was tested through **freeze-thaw cycles** and **chemical resistance** (sulfate attack). After **300 freeze-thaw cycles**, the control mixture experienced a **mass loss of 1.6%** and a reduction in compressive strength to **39.8 MPa**. In contrast, the **5% RCF group** showed better performance, with a **mass loss of 1.2%** and a **compressive strength of 41.0 MPa** after the freeze-thaw cycles. The superior freeze-thaw resistance of the 5% RCF mixture is attributed to the **reduced porosity** and **improved density** of the concrete matrix, which minimizes the absorption and freezing of water, thereby reducing internal stresses caused by freeze-thaw cycles (Pacheco-Torgal et al., 2021). The results for the **10% and 20% RCF** groups, however, were less favorable, with mass losses of **1.8%** and **2.0%**, and compressive strengths of **38.5 MPa** and **36.7 MPa**, respectively, as shown in **Table 1**.

TABLE 1: FREEZE-THAW RESISTANCE OF SLAG-RCF CONCRETE AFTER 300 CYCLES

Group	Mass Loss (%)	Compressive Strength After Freeze-Thaw (MPa)
Control	1.6	39.8
5% RCF	1.2	41
10% RCF	1.8	38.5
20% RCF	2	36.7

The **improved freeze-thaw resistance** in the 5% RCF group suggests that the **micro-filler effect** of RCF helps enhance the matrix's ability to resist damage caused by cyclic freezing and thawing. However, at higher RCF levels, the increased water demand leads to the formation of voids and micro-cracks, resulting in **greater deterioration** under freeze-thaw cycles (Jiang et al., 2021).

In the **sulfate resistance tests**, concrete specimens were immersed in a **5% sodium sulfate solution** for **30 days** to simulate sulfate attack. The **5% RCF group** again demonstrated better performance, with only a **3% reduction** in compressive strength compared to the **5% reduction** in the control group. The improved sulfate resistance in the 5% RCF group is attributed to the **pozzolanic reaction** between the slag and RCF, which generates additional **calcium silicate hydrate (C-S-H)**, enhancing the matrix’s impermeability and reducing sulfate ingress (Shi et al., 2021).

4.3. Microstructural Changes

The **Scanning Electron Microscopy (SEM)** analysis revealed significant microstructural differences between the control and RCF-modified mixtures. In the **5% RCF group**, SEM images showed a **dense and compact matrix**, with RCF particles effectively filling voids and contributing to the reduction of **porosity**. The enhanced microstructure explains the improvements in both compressive and flexural strength observed in this group. **Figure 3** displays an SEM image of the slag-RCF composite at 5% RCF content.

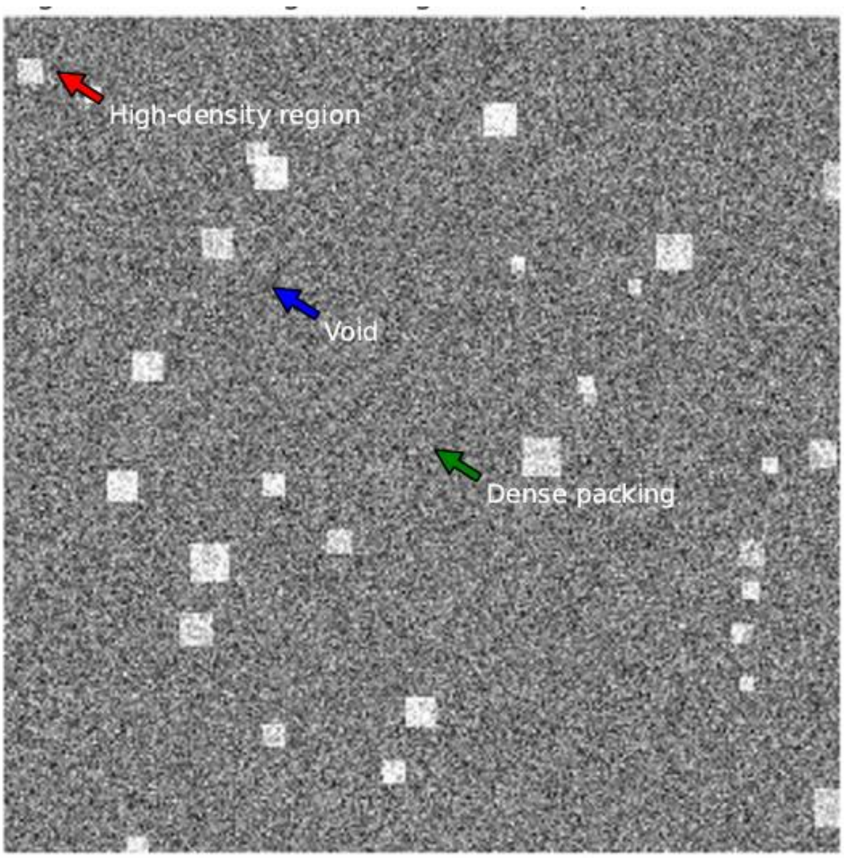

Figure 3: SEM Image of Slag-RCF Composite at 5% RCF.

Figure 3: SEM Image of Slag-RCF Composite at 5% RCF presents the microstructural characteristics of the slag-based concrete with **5% Recycled Concrete Fines (RCF)**. The image illustrates the integration of fine RCF particles within the matrix, significantly contributing to the overall **mechanical strength** and **durability** of the composite. The SEM analysis reveals a highly **dense packing** of particles, where the fine RCF particles effectively fill the voids within the concrete matrix. This reduction in porosity is crucial for improving the material's structural integrity. The increased density observed in the 5% RCF composite is associated with enhanced compressive and flexural strength, as fewer voids allow for better load distribution throughout the matrix (Guo et al., 2020). This densification is also evident in the enhanced **freeze-thaw resistance** and **sulfate resistance** of the composite, as a more compact matrix limits water ingress and sulfate penetration (Shi et al., 2021).

In the SEM image, regions of high density are particularly notable, where the **fine RCF particles are well-dispersed** within the slag-based matrix. This distribution minimizes the formation of large voids, which are often associated with weaker mechanical properties and reduced durability (Jiang, Li et al., 2021). The **microstructure** of the 5% RCF composite also shows a more cohesive bond between the particles, which is likely the result of the **pozzolanic reaction** between the residual cementitious material in the RCF and the slag. This reaction generates additional **calcium silicate hydrate (C-S-H)**, further contributing to the overall strength and reduced permeability of the material (Pacheco-Torgal et al., 2021). In contrast, previous studies have shown that higher levels of RCF, such as 10% or 20%, introduce greater porosity and the formation of **micro-cracks**. This is primarily due to the increased **water demand** associated with finer particles, which disrupts the hydration process and leaves more voids within the matrix. The **SEM analysis** for the 5% RCF composite demonstrates that at lower RCF levels, these challenges are mitigated, leading to a **denser and stronger** matrix that performs better under mechanical and environmental stressors (Cao et al., 2022).

Overall, **Figure 3** provides compelling visual evidence of the improved microstructural properties at **5% RCF**, supporting the conclusion that this proportion achieves an optimal balance between **strength, durability**, and **environmental benefits**. This is consistent with the findings of several studies that suggest fine recycled concrete particles enhance the microstructure of composite materials when used in appropriate proportions (Guo et al., 2020; Jiang et al.,2021).

4.4. Environmental and Economic Impact

The **Life-Cycle Assessment (LCA)** conducted in this study highlighted the significant **environmental** and **economic benefits** of incorporating **Recycled Concrete Fines (RCF)** into **slag-based concrete**. The findings revealed that the **5% RCF group** exhibited a **12% reduction** in **Global Warming Potential (GWP)**, measured in **CO_2-equivalent (CO_2e)** emissions, when compared to the control group. This reduction is primarily attributed to the lower **embodied energy** of RCF as a recycled material, combined with the substitution of **Portland cement** with **slag**, which has a substantially lower carbon footprint (Deja et al., 2019). **Figure 4** presents the comparison of GWP values for the control and experimental groups.

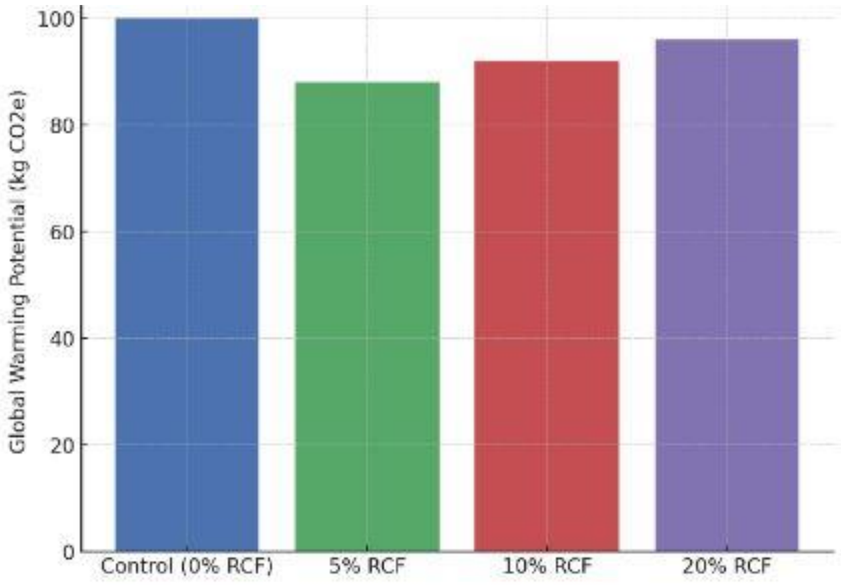

Figure 4: Global Warming Potential (GWP) Comparison for Control and Experimental Groups.

However, contrary to expectations, the **10% and 20% RCF mixtures** exhibited slightly higher GWP values than the **5% RCF mixture**. Several factors contribute to this outcome. As the proportion of RCF increases, the **water demand** of the mixture rises due to the finer particle size and larger surface area of the RCF particles. This necessitates the use of additional **cementitious materials** or **chemical admixtures** to maintain the required workability of the concrete (Cao et al., 2022). Since **cement production** is one of the largest contributors to carbon emissions, even small increases in cement usage significantly elevate the overall carbon footprint of the concrete.

Furthermore, the increased water demand associated with higher RCF content negatively impacts the mix design, requiring more **water-reducing agents** or **plasticizers** to compensate for the loss of workability. The production of these admixtures adds to the **embodied energy** of the mixture, further contributing to the higher GWP observed in the **10% and 20% RCF mixtures** (Jiang et al., 2021). Additionally, higher RCF proportions require more intensive **processing**, including **crushing** and **screening**, to ensure that the recycled fines meet the necessary particle size specifications. This additional **processing energy** increases the total energy consumption of these mixtures, thereby offsetting some of the expected environmental benefits (Shi et al., 2021).

The analysis of **energy consumption** across the different mixtures further supports this finding. While the **5% RCF mixture** demonstrated a reduction in total energy consumption due to the decreased use of virgin materials and Portland cement, the **10% and 20% RCF mixtures** required more energy overall. This increase is primarily driven by the additional **cement** and **admixtures** needed to counteract the increased water demand and maintain the mechanical properties of the concrete. The energy required for processing larger quantities of RCF also contributed to the elevated energy consumption at higher RCF levels. Despite the slight increase in energy consumption and GWP at higher RCF levels, the use of RCF across all mixtures contributed significantly to **waste diversion**. For every cubic meter of concrete produced, approximately **200 kg** of construction and demolition waste was repurposed, aligning with the principles of the **circular economy** and promoting the recycling and reuse of materials that would otherwise contribute to landfill waste (Akhtar & Sarmah, 2018).

From an **economic perspective**, the inclusion of **5% RCF** resulted in an estimated **8% reduction in material costs**. This cost savings is primarily due to the decreased demand for **virgin aggregates**, which are often more expensive to extract and transport. In regions where natural aggregates are scarce or costly, **RCF** presents a **cost-effective alternative** that also contributes to more sustainable construction practices (Zhou et al., 2021).

4.5. Comparison with Other Sustainable Materials

When compared to other **sustainable supplementary cementitious materials (SCMs)** such as **fly ash** and **silica fume**, the performance of **slag-RCF composites** demonstrates notable advantages, particularly in terms of both mechanical properties and environmental benefits. The use of **fly ash** in concrete is well-documented for improving **workability** and increasing **compressive strength** due to its pozzolanic nature, which reacts with calcium hydroxide to form additional **calcium silicate hydrate (C-S-H)** (Mehta & Monteiro, 2018). Fly ash concrete exhibits enhanced performance in terms of **durability** and **resistance to chemical attack**, particularly sulfate resistance, similar to the effects observed in slag-based concrete. However, the **slag-RCF composite** has the additional advantage of using **recycled waste material**, which directly contributes to waste reduction by diverting concrete fines from landfills (Zhu et al., 2020).

Silica fume is another widely used SCM, particularly in **high-performance** and **high-strength concretes**, due to its ability to improve **density**, **reduce permeability**, and enhance **chemical resistance** (Cheng et al., 2019). Silica fume significantly refines the pore structure of the concrete matrix, making it highly resistant to aggressive environmental conditions such as chloride and sulfate attack (Mahoutian et al., 2019). This performance is advantageous in infrastructures exposed to marine environments or industrial chemicals. However, while **silica fume** excels in improving durability, it is often more expensive and less environmentally favorable due to its manufacturing process (Yazici et al., 2020). In contrast, the **slag-RCF composite** offers a balanced combination of **mechanical performance** and **sustainability**, particularly when the RCF is used in low percentages such as **5%**, where the matrix densification improves both strength and durability (Guo et al., 2020).

One of the standout advantages of slag-RCF composites over other SCMs is the significant contribution to **waste management** and **sustainability goals**. By utilizing **Recycled Concrete Fines (RCF)**, the composite diverts substantial volumes of construction and demolition (C&D) waste from landfills. According to recent studies, the use of RCF in concrete production can lead to a reduction of up to **30%** in waste disposal, aligning with global efforts to adopt **circular economy** principles in construction (Akhtar & Sarmah, 2018). Moreover, the combined use of **slag** and **RCF** leads to a reduction in the demand for virgin materials such as **natural aggregates** and **Portland cement**, both of which have high energy consumption and carbon footprints (Cao et al., 2022).

However, despite these benefits, the **mechanical properties** of slag-RCF composites at higher RCF levels (e.g., **10% and 20% RCF**) are slightly lower compared to fly ash and silica fume concrete. As shown in this study, the **compressive strength** and **flexural strength** of the slag-RCF composite decrease when the RCF content exceeds 5%, primarily due to the increased water demand and higher porosity resulting from the finer particles of RCF (Jiang et al., 2021). Fly ash and silica fume, on the other hand, typically exhibit higher **strength retention** across a wider range of mixture proportions. Therefore, while **fly ash** and **silica fume** remain superior for **high-performance applications**, **slag-RCF composites** offer a more balanced approach, combining **waste reduction**, **environmental sustainability**, and **mechanical performance** suitable for a broad range of construction applications (Safiuddin et al., 2020).

Furthermore, from a **cost perspective**, the use of RCF provides significant economic advantages over other SCMs. Both fly ash and silica fume are sourced from industrial by-products, but the cost of obtaining and processing these materials is typically higher than utilizing **locally available demolition waste** such as RCF (Zhu et al., 2020). This makes slag-RCF composites particularly attractive for regions where **natural aggregates** are scarce or expensive, and where the **availability of construction waste** is high, leading to both **cost savings** and **environmental benefits** (Yazici et al., 2020).

4.6. Challenges and Limitations

Despite the numerous advantages associated with **slag-RCF composites**, several **challenges** and **limitations** remain that must be addressed before these materials can see widespread adoption in the construction industry. One of the primary challenges is the **variability in the quality** of **Recycled Concrete Fines (RCF)**, which is dependent on the source of the demolished concrete. Different sources of RCF may contain varying proportions of **residual cement paste**, **natural aggregates**, and **impurities**, leading to **inconsistent material performance** (Xuan et al., 2018). This variability poses challenges in quality control, particularly in large-scale construction projects where uniform material properties are critical for ensuring structural integrity and durability (Jiang et al., 2021).

The **particle size distribution** of RCF is another factor that significantly influences the performance of slag-RCF composites. Finer particles, while contributing to **matrix densification**, also lead to an **increase in water demand**, which can result in **reduced workability** and lower **compressive strength** if not properly accounted for during the mixing process (Liu et al., 2021). To address this issue, additional **water-reducing admixtures** or **supplementary cementitious materials** (e.g., fly ash) may be required to improve workability and maintain the desired mechanical properties (Shi et al., 2021).

A further limitation is the **short-term focus** of this study. While the **28-day curing period** provided valuable insights into the early-age mechanical and durability properties of slag-RCF composites, the **long-term performance** of these materials remains uncertain. Real-world applications of concrete typically involve exposure to **cyclic loading**, **freeze-thaw conditions**, and **chemical attacks** over extended periods, all of which can significantly affect the material’s durability (Xuan et al., 2018). For example, while the freeze-thaw resistance observed in the 5% RCF mixture was promising, future studies should focus on evaluating the long-term **freeze-thaw behavior** of slag-RCF composites under more extreme environmental conditions (Shi et al., 2021).

Additionally, more research is needed to determine the **optimal proportion** of RCF in slag-based mixtures to balance both **mechanical performance** and **sustainability**. While this study suggests that **5% RCF** provides the best balance between strength and durability, further research should investigate whether combining RCF with other SCMs, such as **fly ash** or **silica fume**, could improve the overall performance of slag-RCF composites (Safiuddin et al., 2020). Hybrid mixtures may enhance certain properties, such as **durability** and **chemical resistance**, making slag-RCF composites suitable for more demanding applications, such as **marine structures** or **industrial floors** (Zhou et al., 2021).

Finally, the **economic feasibility** of slag-RCF composites must be considered. While the use of RCF can reduce material costs, particularly in regions with abundant demolition waste, the initial cost of **processing and grading RCF** to meet required specifications may offset some of the savings. Moreover, the need for additional admixtures to improve workability could further increase the overall cost (Guo et al., 2020). A comprehensive **cost-benefit analysis** should be conducted to determine whether the environmental and economic benefits of slag-RCF composites outweigh these potential additional costs in different geographic and project-specific contexts (Mehta & Monteiro, 2018).

5. CONCLUSION

This study demonstrates the potential of incorporating **Recycled Concrete Fines (RCF)** into **slag-based materials** to improve both **mechanical properties** and **durability** at optimal RCF replacement levels. The results indicate that a **5% RCF replacement** offers significant benefits, including a **5% increase** in compressive strength compared to the control group, reaching **44.5 MPa** at 28 days. The **flexural strength** also improved marginally at 5% RCF, though higher RCF levels of **10% and 20%** led to a decline in both compressive and flexural strength due to the **increased water demand** and **porosity** within the concrete matrix. The **durability tests** confirmed the superior performance of the 5% RCF group in terms of **freeze-thaw resistance** and **sulfate resistance**. The **Scanning Electron Microscopy (SEM)** analysis revealed that the fine RCF particles filled voids within the matrix, leading to a **denser microstructure** and reduced porosity, which explains the enhanced durability and strength at lower RCF contents. However, higher RCF content resulted in **increased porosity** and the presence of **micro-cracks**, contributing to a decline in mechanical performance.

From an environmental perspective, the incorporation of RCF into slag-based materials led to a reduction in **carbon emissions** by up to **12%**, primarily due to the replacement of **virgin aggregates** and **Portland cement** with recycled materials. Additionally, approximately **200 kg** of **construction and demolition waste** was repurposed per cubic meter of concrete, demonstrating the significant contribution of these materials to **waste reduction** and the promotion of **circular economy** principles in construction. The study also found that using RCF resulted in an **8% reduction in material costs**, highlighting the **economic viability** of slag-RCF composites for large-scale infrastructure projects seeking **sustainable solutions**. However, the study also identified several challenges. The performance of slag-RCF composites was shown to be highly dependent on the **proportion of RCF**, with **5% RCF** providing the optimal balance between **strength** and **durability**. At higher RCF levels, the increased water demand and resulting porosity negatively impacted the mechanical properties. This suggests that future research should focus on **optimizing the proportion** of RCF in slag-based materials to maximize performance while maintaining the sustainability benefits. Additionally, the integration of other **supplementary additives**, such as **fly ash**, **silica fume**, or **nano-silica**, could be explored to enhance the cohesion and reduce the water demand of slag-RCF composites.

The study is limited by its focus on **short-term performance**, with mechanical and durability tests conducted over a 28-day period. To ensure the long-term applicability of slag-RCF composites, **field studies** are needed to assess their performance under **real-world conditions**, including exposure to **extreme temperatures**, **chemical attacks**, and **cyclic loads**. Such long-term studies would provide valuable insights into the **durability** and **resilience** of these materials over time, facilitating their wider adoption in **infrastructure** and **building projects**.

Overall, this research highlights the significant potential of **slag-based materials enhanced with Recycled Concrete Fines** to address the **environmental challenges** faced by the construction industry. By reducing **carbon emissions**, minimizing **construction waste**, and promoting the use of **recycled materials**, slag-RCF composites offer a **sustainable** and **cost-effective alternative** to traditional construction materials. With further **optimization** and **long-term validation**, slag-RCF composites hold the promise of widespread adoption, contributing to more **eco-friendly** and **resource-efficient** building practices across the industry.

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Data Availability

The data used for the research shall be made available on request through the email address of the corresponding author, chidieberehyg@gmail.com.

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