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SUSTAINABLE DEVELOPMENT OF GREEN SELF-COMPACTING CONCRETE USING SLAG: ENHANCING MECHANICAL PROPERTIES AND REDUCING ENVIRONMENTAL IMPACT

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Abstract

The global construction industry is increasingly focused on sustainability, seeking materials that reduce environmental impact without compromising structural integrity. This study investigates the development of Green Self-Compacting Concrete (GSCC) by incorporating slag as a partial replacement for natural aggregates. The research examines the mechanical properties, workability, and durability of the GSCC, focusing on optimal slag replacement ratios. The findings demonstrate that partial slag replacement enhances compressive strength while significantly reducing the reliance on natural resources, thus providing a sustainable alternative to conventional concrete.

Keywords: Green Self-Compacting Concrete, Slag Aggregates, Sustainability, Compressive Strength, Workability, Durability

Introduction

The environmental impact of concrete production, especially due to its high consumption of natural resources and energy-intensive cement production, has become a pressing concern. Concrete is the most widely used construction material globally, accounting for a significant portion of the construction industry's carbon footprint. One of the promising developments in this area is Self-Compacting Concrete (SCC), which has revolutionized construction by offering superior workability and ease of placement, even in complex formworks, without the need for mechanical vibration.

This research explores the development of Green Self-Compacting Concrete (GSCC) with a focus on sustainability. The key innovation in GSCC is the partial replacement of natural aggregates with slag, a by-product of the iron and steel industries. This approach not only conserves natural resources but also reduces industrial waste, making it an environmentally friendly alternative to conventional concrete. The study examines the mechanical properties, workability, and durability of GSCC at various levels of slag replacement, providing insights into its potential for sustainable construction.

Objectives

The primary objectives of this research are:

1. To develop a self-compacting concrete mix using slag as a partial replacement for traditional aggregates.

2. To evaluate the compressive strength, workability, and durability of GSCC.
3. To determine the optimal percentage of slag replacement that offers the best performance while minimizing environmental impact.
4. To assess the environmental and economic benefits of using slag as a substitute for natural aggregates in concrete.

Literature Review

de Azevedo et al. (2020) studied the efficiency of mortars using pulp and paper industry waste, both wet and dry, and compared the outcomes. The longevity, environmental evaluation, and other criteria were investigated.

Ahmed et al., (2022) Talks about the current development and potential directions of SCC development. The most recent findings in the fields of specialized concrete construction (SCC) mix design, supplementary cementitious materials (SCM) usage, fiber-reinforced SCC, alkali-activated SCC, recycled aggregate use, and nanotechnology and artificial intelligence application are presented. Potential research needs to enhance the characteristics, uses, and sustainability credentials of SCC are also highlighted in this work.

Rabar et al., (2022) this study, An artificial neural network (ANN), a nonlinear model, a linear relationship model, and a multi-logistic model were all proposed as possible ways to forecast the compressive strength of SCC mixtures made from RP aggregates. The models were developed using information from a large dataset consisting of 400 mixes, with input variables including mixture proportions and curing durations. Several statistical assessments were used to determine the accuracy of the proposed models; these included the scatter index, coefficient of determination (R2), mean absolute error (MAE), root mean squared error (RMSE), and Objective (OBJ) value. Foretelling compressive strength of SCC mixes with RP aggregates, the ANN model outperformed other models. This model has an RMSE of 5.46 MPa, an MAE of 2.31 MPa, an OBJ of 4.26 MPa, and an R2 of 0.973.

Sahar et al., Self-compacting concrete (SCC) Is a modern concrete that doesn't need extra compaction and doesn't segregate or bleed, making it easier to work with. The research examined the effects of fly ash (FA), ground granulated blast-furnace slag (GGBS), and microsilica (MS) on the strength, workability, durability, carbon dioxide emissions, and prices of four distinct combinations. The mixes' workability, strength, and durability were evaluated using a battery of standard tests, such as those for resistance to chloride ion penetration, water penetration, water absorption, and initial surface absorption. At various intervals after setup, tests of compressive strength were also conducted. The mixes with FA, GGBS, and MS demonstrated greater durability in the tests compared to regular concrete. Incorporating 10% MS into a mixture significantly improved its early strength and durability. In addition, mixtures of FA, GGBS, and MS were shown to provide substantial cost savings with a marginal rise in carbon dioxide emissions.

Materials and Methods

Materials Used:

- **Cement:** Ordinary Portland Cement (OPC) was used as the primary binder.

- **Coarse and Fine Aggregates:** Natural aggregates (crushed stone and sand) were partially replaced by slag at varying percentages.
- **Slag:** Slag, a by-product of the steel industry, was used as a replacement for both coarse and fine aggregates.
- **Superplasticizers:** To enhance the flowability and workability of the concrete, superplasticizers were added to the mix.
- **Water:** Potable water was used for mixing and curing the concrete samples.

Mix Design: Several mix designs were developed with different percentages of slag replacing the natural aggregates. The replacement levels ranged from 0% (control) to 50% by volume. The water-to-cement ratio was kept constant across all mixes to maintain consistency in the results.

Experimental Procedure:

1. **Slump Flow Test:** The workability of the GSCC was evaluated using the slump flow test, which measures the flowability and filling ability of the concrete mix.
2. **Compressive Strength Test:** Concrete cubes (100 mm x 100 mm) were cast and cured for 7, 14, and 28 days, after which compressive strength tests were performed.
3. **Durability Test:** Sorptivity tests were conducted to assess the water absorption capacity of the GSCC, which is an indicator of its durability.
4. **Environmental Impact Assessment:** The embodied energy and carbon emissions associated with the production of GSCC were calculated and compared to those of conventional SCC.

Results and Discussion

The experimental results revealed that partial replacement of aggregates by slag significantly improved the compressive strength of the GSCC. The optimal replacement level was found to be 30%, where the compressive strength showed a marked improvement compared to the control mix (0% slag). Beyond 30%, the compressive strength began to decrease, suggesting that excessive slag content may reduce the bonding between the paste and aggregates.

Workability: The slump flow test showed that GSCC exhibited excellent workability, with all mixes meeting the criteria for self-compacting concrete. The inclusion of slag improved the flowability of the mix, making it easier to place in densely reinforced structures. The use of superplasticizers further enhanced the workability, allowing the concrete to flow under its own weight without segregation.

Compressive Strength: The compressive strength of the GSCC increased with the percentage of slag replacement up to 30%. At 28 days of curing, the mix with 30% slag replacement exhibited a 15% higher compressive strength than the control mix. This improvement can be attributed to the pozzolanic properties of slag, which contribute to the formation of additional calcium silicate hydrate (C-S-H) during hydration, enhancing the concrete's strength.

Durability: The sorptivity test results indicated that GSCC with slag had lower water absorption compared to conventional SCC. This suggests that GSCC is more durable and resistant to water ingress, which is a critical factor in the longevity of concrete structures.

Environmental Impact: The use of slag as a partial replacement for natural aggregates reduced the overall carbon footprint of the concrete. The embodied energy of GSCC was lower than that of conventional SCC, primarily due to the reduced consumption of virgin materials and the recycling of industrial by-products. The carbon emissions associated with GSCC were also significantly lower, making it a more sustainable option for construction.

Table 1: Mix Design Proportions for GSCC with Slag Replacement

Mix ID	Cement (kg/m³)	Water (kg/m³)	Coarse Aggregate (kg/m³)	Fine Aggregate (kg/m³)	Slag Replacement (%)	Superplasticizer (%)
M1 (Control)	400	180	850	700	0%	1.2%
M2	400	180	765	630	10%	1.1%
M3	400	180	680	560	20%	1.0%
M4	400	180	595	490	30%	0.9%
M5	400	180	510	420	40%	0.8%
M6	400	180	425	350	50%	0.7%

The mix design proportions for GSCC with varying slag replacement percentages highlights a progressive decrease in coarse and fine aggregates as the slag replacement percentage increases. Mix M1, the control mix, contains 0% slag and uses the highest quantities of both coarse (850 kg/m³) and fine aggregates (700 kg/m³), requiring a 1.2% superplasticizer to maintain flowability. As slag replaces the aggregates, from 10% in M2 to 50% in M6, the aggregate content steadily decreases, reflecting the substitution with slag. Notably, M4, with 30% slag replacement, shows a significant reduction in aggregates, reaching 595 kg/m³ of coarse and 490 kg/m³ of fine aggregates, with only 0.9% superplasticizer required, which is optimal for maintaining workability. The gradual reduction in superplasticizer from 1.2% to 0.7% as slag content increases suggests that the introduction of slag enhances the concrete's flowability, reducing the need for chemical admixtures. This balance of materials illustrates that GSCC can maintain structural integrity and workability while minimizing the use of natural aggregates, making it a sustainable option.

Table 2: Workability and Flowability Test Results

Mix ID	Slump Flow (mm)	T50 Time (seconds)	V-Funnel (seconds)	L-Box (H2/H1 ratio)
M1 (Control)	680	2.5	10.5	0.90
M2	700	2.3	9.8	0.92
M3	720	2.1	8.9	0.95
M4	740	2.0	8.5	0.98
M5	710	2.4	9.0	0.91

Mix ID	Slump Flow (mm)	T50 Time (seconds)	V-Funnel (seconds)	L-Box (H2/H1 ratio)
M6	690	2.6	9.4	0.89

The workability and flowability tests for the GSCC mix designs shows a clear improvement in workability with increased slag replacement. The slump flow values increase from 680 mm in the control mix (M1) to a maximum of 740 mm at 30% slag replacement (M4), indicating improved flowability. Correspondingly, the T50 time, which measures the time taken for the mix to spread 500 mm, decreases from 2.5 seconds (M1) to 2.0 seconds (M4), further emphasizing enhanced flow. The V-Funnel time, reflecting the mix's ability to pass through narrow openings, improves from 10.5 seconds in the control mix to 8.5 seconds in M4, showing reduced viscosity and better filling ability. The L-Box test, which evaluates the mix's ability to pass through reinforcements, also improves with slag content, with the H2/H1 ratio increasing from 0.90 (M1) to 0.98 (M4). However, beyond 30% slag replacement (M5 and M6), there is a slight decline in workability, as evidenced by the reduction in slump flow and a rise in V-Funnel times. This suggests that 30% slag replacement offers the optimal balance for workability and flowability in GSCC.

Mix ID	Compressive Strength (7 Days, MPa)	Compressive Strength (28 Days, MPa)	Sorptivity (mm)	Water Absorption (%)
M1 (Control)	22.5	31.8	5.8	2.1%
M2	24.1	33.5	5.4	1.9%
M3	25.8	36.2	4.9	1.7%
M4	26.4	37.1	4.5	1.6%
M5	25.0	35.0	5.1	1.8%
M6	23.7	33.0	5.3	2.0%

Table 3: Compressive Strength and Durability Results

The compressive strength and durability metrics for the various GSCC mixes indicate that the inclusion of slag as a partial replacement for natural aggregates enhances performance, particularly in compressive strength and resistance to water ingress. At 7 days, all slag-replaced mixes (M2 to M6) show higher compressive strengths compared to the control (M1), with M4 (30% slag) achieving the highest early strength of 26.4 MPa. This trend continues at 28 days, with M4 reaching 37.1 MPa, a significant improvement over the control's 31.8 MPa, confirming that 30% slag replacement optimizes the compressive strength.

In terms of durability, lower sorptivity values are observed as slag content increases, with M4 again performing best at 4.5 mm, indicating reduced water absorption. Similarly, water absorption percentage decreases with slag content, with M4 recording the lowest value at 1.6%. However, mixes M5 and M6, with 40% and 50% slag replacement, show a slight decline in both compressive strength and durability, with sorptivity and water absorption increasing. This suggests that while slag significantly enhances concrete properties up to 30% replacement, exceeding this threshold may reduce its effectiveness, likely due to a reduction in aggregate-cement bonding efficiency at higher slag levels.

Conclusion

This research demonstrates that Green Self-Compacting Concrete (GSCC) with partial replacement of natural aggregates by slag is a viable and sustainable alternative to conventional concrete. The optimal slag replacement level of 30% resulted in improved compressive strength, enhanced durability, and excellent workability. Furthermore, the use of slag significantly reduced the environmental impact of concrete production by conserving natural resources and repurposing industrial waste.

Future research should explore the long-term performance of GSCC in different environmental conditions and investigate the potential for incorporating other industrial by-products to further enhance sustainability. Additionally, cost-benefit analyses should be conducted to evaluate the economic feasibility of large-scale GSCC production for commercial applications.

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