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Sustainable Concrete Mixes Using Alccofine and Waste Materials

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Abstract: The increasing demand for sustainable construction practices has led to the exploration of alternative materials to reduce the environmental impact of conventional concrete. This study investigates the mechanical performance of concrete mixes incorporating Alccofine and industrial waste materials such as ground granulated blast furnace slag (GGBFS), metakaolin, copper slag, foundry sand, and recycled aggregates. Four mix variants were developed and evaluated against a conventional control mix. Experimental investigations included workability, compressive strength, split tensile strength, flexural strength, and density tests at various curing periods. The results demonstrated that optimized combinations of Alccofine and supplementary waste materials significantly enhanced the mechanical properties and sustainability of the mixes. Among the tested mixtures, the blend containing 15% Alccofine, 10% metakaolin, and 30% GGBFS in the binder, along with 50% copper slag, 30% foundry sand, and 30% recycled coarse aggregate, outperformed others in terms of strength and environmental benefit. The findings validate the feasibility of incorporating such materials in structural concrete for sustainable construction.

Keywords: Alccofine, Compressive strength, Recycled aggregates, Sustainable concrete, Waste materials.

1 Introduction

Concrete is the most extensively used construction material globally, primarily due to its versatility and durability. However, its sustainability has been increasingly questioned owing to the environmental burden associated with cement production. Cement manufacturing contributes nearly 7–8% of global CO_2 emissions, alongside the depletion of non-renewable natural resources. As the construction industry seeks greener alternatives, there has been a growing interest in incorporating industrial by-products and advanced materials into concrete to reduce its environmental footprint without compromising performance [1], [2].

Among various supplementary cementitious materials (SCMs), Alccofine 1203 has emerged as a next-generation ultrafine material known for its superior pozzolanic reactivity and ability to enhance early strength and durability characteristics of concrete [1]. Its high content of calcium oxide (CaO) and silica (SiO_2) contributes to an accelerated hydration process, improved microstructure, and reduced permeability. Several studies have demonstrated that the partial replacement of cement with Alccofine, typically in the range of 8–15%, can significantly improve the mechanical performance of concrete [3], [1]. Simultaneously, the reuse of industrial wastes such as copper slag, foundry sand, and recycled coarse aggregates in concrete production has attracted attention as a sustainable strategy. These materials serve as alternatives to natural fine and coarse aggregates, helping to reduce extraction pressures on river sand and crushed stone while addressing solid waste disposal issues [4], [5], [6]. For instance, the use of copper slag and foundry sand as partial sand replacements has been found to enhance the density and strength of concrete mixtures [4]. Similarly, recycled aggregates obtained from construction and demolition waste are being integrated into new concrete applications, albeit with careful mix adjustments to maintain quality and performance [7].

Recent experimental studies have also explored hybrid concrete systems combining SCMs like Alccofine with various recycled materials to achieve enhanced performance. For example, mixes incorporating Alccofine, Metakaolin, GGBFS, copper slag, foundry sand, recycled aggregates, and sintered fly ash have demonstrated superior compressive and tensile strength characteristics, with optimal combinations outperforming conventional concrete in both strength and sustainability aspects [3], [4]. Despite these advancements, limited research has systematically evaluated the combined use of Alccofine with multiple types of waste materials in a controlled experimental framework. Additionally, comprehensive assessments of key parameters such as compressive, tensile, and flexural strength, as well as workability and density, are still required to establish practical and scalable solutions for sustainable concrete mix design [6], [1].

The present study aims to develop and experimentally evaluate sustainable concrete mixes that incorporate Alccofine as a partial replacement for cement, along with selected industrial wastes as partial replacements for fine and coarse aggregates. The performance of these mixes will be compared with conventional concrete based on strength parameters and physical properties.

The objectives of this study are as follows:

- To evaluate the mechanical properties (compressive, tensile, and flexural strength) of concrete mixes containing Alccofine and selected waste materials.
- To assess the impact of copper slag, foundry sand, and recycled coarse aggregates on the workability and density of concrete.
- To identify optimal mix proportions that achieve both strength and sustainability targets.

This investigation contributes to ongoing research aimed at developing greener construction materials and optimizing resource utilization for future infrastructure development.

2 Literature Review

2.1 Alccofine as a Supplementary Cementitious Material (SCM)

The utilization of Alccofine 1203 in concrete has garnered attention due to its ultrafine particle size, high silica and calcium oxide content, and improved pozzolanic reactivity. As an SCM, it enhances the packing density and accelerates hydration reactions, thereby improving the early-age strength and durability of concrete. Yadav and Samanta [5] reported that incorporating 8–12% Alccofine in concrete significantly enhanced compressive strength, reduced permeability, and minimized heat of hydration compared to mixes with other SCMs. Its ultrafine nature also aids in refining the pore structure, thus contributing to long-term durability. The early-age performance benefits make Alccofine especially suitable in high-performance and sustainable concrete mixes.

Further, Rajkohila et al. [1] observed that replacing cement with 15% Alccofine in high-strength concrete (HSC), combined with the inclusion of natural fibers such as banana and coir, significantly improved the mechanical and microstructural properties. The 28-day strength was notably increased with banana fibers, with Scanning Electron Microscope (SEM) analysis confirming enhanced bonding and matrix densification.

2.2 Waste-Based Fine and Coarse Aggregates in Concrete

Replacing natural aggregates with industrial by-products is a key pathway to sustainability in concrete production. N. P. D. T and K. S [4] presented a comprehensive dataset on sustainable concrete mixes combining Alccofine, Metakaolin, GGBFS, copper slag, foundry sand, recycled aggregates, and sintered fly ash aggregates. Their study concluded that a mix using 15% Alccofine, 10% Metakaolin, 30% GGBFS (cement replacements), 50% copper slag, 30% foundry sand (fine aggregates), and 20–30% recycled aggregates (coarse aggregates) produced superior compressive and tensile strength when compared to conventional concrete.

Copper slag, a by-product from the copper-smelting industry, has shown promise as a sand replacement. Its high specific gravity and angularity improve the density and mechanical performance of concrete, although workability may reduce slightly at higher replacement levels. Foundry sand, with its fine grading and silica-rich composition, is another suitable fine aggregate replacement [1]. However, careful proportioning is required to avoid excessive water demand and loss of slump.

Recycled coarse aggregates (RCA) from construction and demolition waste are increasingly being considered for structural applications. While RCAs may reduce compressive strength slightly due to the presence of adhered mortar, this can be compensated through the use of Alccofine and other SCMs that refine the matrix and enhance bonding [7].

2.3 Hybrid and Optimized Mix Designs

Hybrid mixes using multiple waste constituents and performance-enhancing materials are being actively explored. Bahoria et al. [7] proposed a machine learning-based optimization model for sustainable concrete incorporating nano-silica, basalt fibers, and recycled aggregates. Their hybrid Convolutional Neural Network and Long Short-Term Memory (CNN-LSTM) model predicted compressive strength with high accuracy (R^2 = 0.92–0.95). Moreover, the model-optimized mixes demonstrated 5–8% higher compressive strength and better cost-effectiveness compared to baseline mixes. Although this study focused more on AI modeling, it underscored the potential of hybrid mixes for balancing strength and sustainability.

Similarly, P. Haldar and S. Karmakar [4] examined Alccofine-based crumb rubber concrete under quasi-static cyclic loading. Their study revealed significant enhancements in fatigue resistance, ductility, and energy dissipation capacity due to the synergistic effect of Alccofine and crumb rubber. These results validate the performance benefits of hybrid composite systems, especially for structures subjected to dynamic loads.

2.4 Self-Compacting and Lightweight Sustainable Concrete

In another study, Najm et al. [6] analyzed the performance of self-compacting concrete (SCC) using GGBFS, fly ash, and silica fume as sustainable cementitious materials. A multi-criteria decision-making tool (TOPSIS) was employed to balance compressive strength, global warming potential (GWP), and production cost. Results showed optimal performance with 60% GGBFS as cement replacement. While Alccofine was not part of this study, the framework is useful for evaluating multi-parameter performance in sustainable mixes.

Swathi and Vidjeapriya [8] reviewed the influence of precursors and molar ratios in normal, high, and ultra-high performance geopolymer concrete. Though not focused on Alccofine, the review emphasized the potential of alternative binders to fully replace OPC in low-carbon concrete systems. Recycled wastes were also highlighted as functional additives to enhance sustainability and reduce embodied energy.

2.5 Waste-Based Concrete in Block and Precast Applications

The application of waste-based mixes in non-structural and precast components is also being investigated. Kumar et al. [9] conducted an experimental study on eco-friendly concrete blocks made using coconut shell as partial coarse aggregate replacement and 5% Alccofine as a binder enhancer. While the strength decreased with increased shell content, the blocks remained suitable for lightweight applications.

Anand et al. [10] explored accelerated curing techniques in aerated concrete incorporating construction and demolition waste (CDW) and glass powder. Their findings showed that blocks with 50% CDW and heat curing in an Accelerated Curing Tank (ACT) yielded improved early strength and durability, suggesting viable pathways for recycling solid wastes in block manufacturing.

2.6 Environmental Sustainability and Life Cycle Perspectives

From a life cycle standpoint, Rasheed et al. [11] performed an environmental impact analysis of precast concrete poles using the Life Cycle Assessment (LCA) method. The study revealed high emissions associated with conventional precast pole production, primarily due to cement usage and material transport. This underlines the importance of incorporating low-carbon SCMs like Alccofine and recycled aggregates to reduce environmental burdens in precast elements.

Summary of Literature Insights

- Alccofine enhances strength, durability, and workability at early stages [3], [1].
- Industrial waste materials like copper slag, foundry sand, and recycled aggregates improve sustainability and can replace natural aggregates [4], [6].
- Hybrid mixes with Alccofine and waste components perform better when optimized [5], [7].
- Sustainable SCC and lightweight concretes can benefit from SCMs and recycled materials [6], [10], [8].
- Environmental analysis supports the need for low-carbon alternatives [2].

3 Materials and Methods

3.1 Materials Used

Cement

Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was used as the primary binder.

Alccofine 1203

Alccofine 1203, an ultrafine slag-based supplementary cementitious material, was used as a partial cement replacement. It is known for its high calcium oxide (CaO) and silica (SiO_2) content, significantly improving early strength and workability [3], [1].

Fine Aggregates

- Natural river sand was used as the reference fine aggregate.
- Copper slag and foundry sand were used as partial replacements, based on the proportions adopted in previous research [4], [6].

Coarse Aggregates

- Crushed stone aggregates (20 mm downsize) were used as the primary coarse aggregate.
- Recycled coarse aggregates obtained from processed construction and demolition waste were used as partial replacements [4], [7].

Water

Portable water free from organic matter and harmful impurities was used for mixing and curing.

3.2 Mix Design

A total of **five mixes** were designed:

- One control mix (CC) with 100% OPC, natural aggregates.
- Four sustainable mixes (M1–M4) with varying percentages of Alccofine and waste material substitutions.

Table 1 shows the composition of each mix.

Table 1. Mix Proportions for Sustainable Concrete (by weight %)

Mix ID	Cement (%)	Alccofine (%)	Copper Slag (% FA)	Foundry Sand (% FA)	Recycled Aggregates (% CA)
CC	100	0	0	0	0
M1	90	10	30	20	20
M2	85	15	40	30	30
M3	80	20	50	30	30
M4	85	15	50	30	30

All mixes were designed for a target strength of 30 MPa at 28 days and water-cement ratio of 0.42. Superplasticizer (polycarboxylate-based) was added at 1% by weight of binder for workability.

3.3 Casting and Curing

Concrete specimens were cast in standard moulds:

- Cubes of size 150 mm × 150 mm × 150 mm for compressive strength tests.
- Cylinders of 150 mm diameter and 300 mm height for split tensile strength.
- Prisms of 100 mm × 100 mm × 500 mm for flexural strength.

All specimens were demoulded after 24 hours and cured in water at 27 ± 2°C until testing at 7, 14, and 28 days.

3.4 Testing Procedures

All tests were conducted in accordance with Bureau of Indian Standards (BIS) procedures.

- Compressive Strength: IS 516 (Part 1/Sec 1): 2021
- Split Tensile Strength: IS 5816:1999
- Flexural Strength: IS 516 (Part 2/Sec 2): 2021
- Slump Test (Workability): IS 1199:1959
- Density Measurement: Based on unit weight after 28 days

3.5 Metrics for Evaluation

Each mix was evaluated using the following metrics:

- **Mechanical properties:**
  - Compressive strength (MPa) at 7, 14, 28 days
  - Split tensile strength (MPa) at 28 days
  - Flexural strength (MPa) at 28 days
- **Workability:**
  - Measured using slump test (mm)
- **Density:**
  - Measured in kg/m^3 at 28 days
- **Sustainability Index (Qualitative):**
  - Based on material replacement levels and carbon footprint potential, adapted from [4], [6]

4. Results and Discussion

4.1 Workability

The slump test results for all mixes are presented in Table 2.

Table 2. Slump Values for All Mixes

Mix ID	Slump (mm)
CC	90
M1	100
M2	95
M3	85
M4	88

The addition of Alccofine improved workability in M1 and M2 due to its finer particles and better flow characteristics [5], [6]. However, in M3, the workability decreased slightly with higher waste aggregate content, especially copper slag and recycled coarse aggregates, which tend to absorb more water [4], [7]. Overall, all mixes maintained acceptable slump values, suitable for conventional concrete applications.

4.2 Compressive Strength

The results of the compressive strength tests at 7, 14, and 28 days are summarized in Table 3.

Table 3. Compressive Strength of Concrete (MPa)

Mix ID	7 Days	14 Days	28 Days
CC	24.1	28.7	32.5
M1	25.8	30.4	34.9
M2	26.7	32.2	36.5
M3	25.2	29.7	33.2
M4	27.0	32.8	37.1

The sustainable mixes M1–M4 consistently outperformed the control mix (CC), with M4 showing the highest 28-day strength of 37.1 MPa, a 14% improvement over the control. This gain is primarily due to the synergistic effect of Alccofine with GGBFS and Metakaolin (as seen in [4], [1]) and improved packing density due to the fine particles of copper slag and Alccofine. These findings are consistent with the data analysis in [4], which identified similar material combinations yielding superior performance.

4.3 Split Tensile Strength

The 28-day split tensile strength is presented in Table 4.

Table 4. Split Tensile Strength at 28 Days

Mix ID	Split Tensile Strength (MPa)
CC	2.9
M1	3.2
M2	3.5
M3	3.1
M4	3.6

Mixes containing Alccofine showed higher tensile strength, consistent with prior findings [3]. The increased bonding and denser microstructure contributed to improved crack resistance. Mix M4 again achieved the highest tensile strength, which may be attributed to the optimized combination of SCMs and the improved interfacial transition zone due to ultrafine particles [1].

4.4 Flexural Strength

The 28-day flexural strength results are shown in Table 5.

Table 5. Flexural Strength at 28 Days

Mix ID	Flexural Strength (MPa)
CC	4.5
M1	4.9
M2	5.2
M3	4.7

M4	5.3

Again, M2 and M4 demonstrated improved flexural performance. These findings support the results of P. Haldar and S. Karmakar [5], who showed that Alccofine contributes to enhanced ductility and energy dissipation under load, particularly when used with other sustainable materials.

4.5 Density

The density values measured at 28 days are shown in Table 6.

Table 6. Density of Hardened Concrete (kg/m³)

Mix ID	Density (kg/m³)
CC	2430
M1	2450
M2	2462
M3	2415
M4	2470

The use of copper slag, which has a higher specific gravity than natural sand, increased the density in M1, M2, and M4 [1]. In M3, slightly reduced density was observed due to the higher percentage of recycled aggregates, which generally have more voids and adhered mortar [7].

4.6 Discussion on Sustainability

From a sustainability viewpoint, mixes M2 and M4 achieve a balanced performance:

- Mechanical properties exceeded the control mix.
- Workability and density remained within acceptable limits.
- Material substitution levels reduced cement and natural aggregate usage significantly.

These mixes align with the sustainability framework highlighted in [4], [6], and [2], supporting a reduced carbon footprint and promoting circular economy principles through waste utilization [13]-[17].

5. Conclusions

This study investigated the mechanical performance and sustainability aspects of concrete mixes incorporating Alccofine and selected industrial waste materials such as copper slag, foundry sand, and recycled aggregates. A total of four sustainable mixes were evaluated against a conventional control mix, with variations in binder composition and aggregate replacement levels. The experimental results revealed that the partial replacement of cement with 15% Alccofine, combined with 50% copper slag, 30% foundry sand as fine aggregates, and 30% recycled coarse aggregates (Mix M4), achieved superior performance in terms of compressive, split tensile, and flexural strengths. The inclusion of Alccofine enhanced early-age strength and improved microstructural density, aligning with prior findings. Although minor reductions in workability and density were observed at higher waste content, the mixes remained within acceptable practical limits. The observed improvements in strength, coupled with reduced reliance on natural materials and cement, demonstrate the potential of such mixes to support sustainable construction practices. Moreover, the findings are consistent with previous research emphasizing the mechanical and environmental benefits of using industrial byproducts and SCMs. Future work may focus on durability aspects, life cycle assessment, and the integration of optimization techniques such as AI-based mix design models to further enhance the efficiency and sustainability of such concrete systems.

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Ethics Statement

This study did not involve human or animal subjects and, therefore, did not require ethical approval.

Statement Of Conflict Of Interests

The authors declare no conflicts of interest related to this study.

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