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Green Concrete Using Electric Arc Furnace Slag and Manufactured Sand: A Comprehensive Review

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Abstract

This review paper synthesizes findings from an experimental study investigating the use of Electric Arc Furnace (EAF) slag and Manufactured Sand (M-Sand) as partial replacements for conventional aggregates in green concrete. The study addresses dual imperatives of sustainable construction: reducing dependence on depleting natural aggregates and valorizing industrial by-products from the steelmaking sector. Experimental concrete mixes of M20 and M25 grades were developed following IS 10262:2019 and IS 456:2000 guidelines, with EAF slag replacing cement at 6–12% and M-Sand replacing cement at 5–15% by weight. Results demonstrated that a 10% replacement level for both EAF slag and M-Sand consistently yielded the best mechanical performance, with compressive strength gains of up to 8.5% and 8.8%, split tensile strength improvements of up to 9.1%, and flexural strength enhancements of up to 9.2% over control mixes at 28 days. Ternary blends combining both EAF and M-Sand achieved compressive strengths of 34.8 MPa (M20) and 41.5 MPa (M25), substantially exceeding conventional targets. This review contextualizes these findings within the broader literature, identifies fulfilled and persistent research gaps, and offers recommendations for industry adoption.

Keywords: *Green Concrete, Electric Arc Furnace Slag, Manufactured Sand, Sustainable Construction, Compressive Strength, Circular Economy, IS 383:2016, M20, M25.*

1. Introduction

Concrete is the world's most widely used construction material, fundamental to roads, bridges, buildings, and critical infrastructure. Its conventional production, however, imposes significant environmental burdens: Portland cement manufacture releases approximately 0.8 tonnes of CO_2 per tonne of clinker, while natural aggregate extraction causes riverbank erosion, biodiversity loss, and water table decline. Accelerating urbanization particularly in emerging economies such as India further intensifies these pressures.

In response, the concept of green concrete has evolved from a niche research area into a mainstream priority. Green concrete replaces conventional cement and natural aggregates with industrial by-products and engineered alternatives, simultaneously addressing waste management and resource scarcity. Two materials have garnered particular attention: Electric Arc Furnace

(EAF) slag, a dense oxide-rich by-product of scrap steel refining, and Manufactured Sand (M-Sand), an engineered fine aggregate produced by controlled crushing of hard rock.

EAF slag is characterized by high density, abrasion resistance, angular morphology, and a chemical composition dominated by oxides of calcium, silicon, iron, and magnesium. Historically relegated to embankments and low-value fill, advances in stabilization and quenching have enabled its application as a structural aggregate and supplementary binder. M-Sand, produced under quality-controlled conditions often using vertical shaft impact (VSI) crushers offers consistent gradation and cleanliness, addressing the scarcity and ecological damage caused by river sand mining.

This review paper synthesizes the background, methodology, experimental results, and conclusions of the thesis to provide a concise, critical, and practitioner-oriented account of the state of knowledge on EAF slag and M-Sand in green concrete. It is structured to serve researchers, engineers, and policymakers working toward sustainable construction solutions.

2. Background and Motivation

The present section portrays the background and motivation of research, as presented in the upcoming sub-sections.

2.1 Environmental Context

The construction industry is responsible for approximately 8–10% of global CO_2 emissions, with cement production being the dominant contributor. Simultaneously, the extraction of natural river sand the most mined solid material globally has reached unsustainable levels. India, one of the fastest urbanizing nations, faces acute shortages of river sand and increasing regulatory restrictions on riverbed mining. EAF slag, generated in volumes of 100–200 kg per tonne of steel produced, represents a substantial industrial waste stream that, if properly processed, can substitute for natural aggregates and reduce landfill burden.

2.2 Material Properties

EAF slag comprises primarily CaO, SiO_2, Fe_2O_3, and MgO, with a rough, angular surface texture that enhances mechanical interlock with cement paste. Its high density (typically 3.2–3.6 g/cm^3) and abrasion resistance make it particularly suitable as a coarse aggregate replacement. However, free lime and periclase (MgO) content must be controlled to prevent volumetric instability, necessitating proper aging and stabilization prior to use.

M-Sand is produced from crushed granite or basalt, yielding angular or cubical particles with consistent grading. Conforming to IS 383:2016, M-Sand offers minimal organic impurities, low silt content, and a fineness modulus between 2.5 and 3.5. Its lower moisture content compared to river sand facilitates more controlled mix design.

3. Review of Prior Research

The present section is devoted to the review of prior research, the details of which are presented in the following sub-sections.

3.1 Manufactured Sand in Concrete

The body of literature on M-Sand as a replacement for natural river sand is extensive. Adams Joe et al. (2013) demonstrated that M-Sand can fully replace river sand in high-performance concrete (HPC) without loss of mechanical performance, attributing improvements to the angular surface texture promoting stronger cement-aggregate interlock. Ding et al. (2016) identified that maintaining stone powder content near 13% optimizes long-term compressive strength development.

Prasanna et al. (2017) confirmed that M60 grade concrete with 75% M-Sand replacement exhibited superior compressive and split tensile strengths and ultrasonic pulse velocity (UPV) relative to natural sand control mixes. Studies by Elavenil and Vijaya (2013) reported 100% M-Sand replacement achieving compressive strength of 49 MPa approximately 7.5% above conventional river sand concrete. Multiple investigations have converged on 60% as a commonly identified optimum replacement level, beyond which workability tends to decline absent admixture intervention.

Durability studies by Daisy Angelin et al. (2015) showed that M-Sand concrete at up to 60% replacement maintained satisfactory resistance to hydrochloric acid attack. Barhmaiah et al. (2022) reported a 12.54% compressive strength gain in M40 pavement-grade concrete with 100% M-Sand, alongside improved skid resistance and fatigue life.

3.2 EAF Slag in Concrete

Pellegrino and Faleschini (2013) investigated reinforced concrete beams with up to 100% EAF slag coarse aggregate replacement, finding higher flexural and shear capacities, narrower crack widths, and improved mechanical stiffness relative to natural aggregate controls. Sekaran et al. (2015) reported that combining 50% EAF oxidizing slag with 30% fly ash produced significant improvements in compressive, tensile, and flexural strengths, alongside reduced water absorption and chloride ion permeability.

Ting et al. (2025) optimized EAF fine aggregate replacement at 45% for the 2.36–4.75 mm fraction, achieving 35 MPa compressive strength and documenting CO_2 sequestration through carbonation reactions. Chadee et al. (2025) found that up to 20% EAF fine aggregate replacement in Grade 40 concrete boosted 28-day compressive strength to 40.5 MPa. Nuruzzaman et al. (2024) achieved 62 MPa with full fine aggregate replacement using a ferronickel slag blend.

Li et al. (2020) demonstrated that GGBS activated by desulfurization gypsum and blended with EAF slag produced concrete exceeding 50 MPa with low hydration heat and dense microstructure, confirming EAF slag's contribution to both micro-filling and limited pozzolanic reactions.

3.3 Research Gap Addressed

Despite robust individual evidence, the literature has been largely silent on the combined, simultaneous use of EAF slag and M-Sand in a single concrete matrix. Their complementary characteristics EAF slag contributing high density and angular interlock as coarse aggregate, and M-Sand improving fine particle gradation and matrix cohesion suggest potential synergistic benefits. The absence of optimized ternary mix design procedures and long-term durability data in combined applications constituted the primary research gap targeted by this study.

4. Experimental Methodology

The present section is devoted to the experimental methodology, as presented by the following sub-sections,

4.1 Materials

The study employed OPC 43 Grade cement (IS 8112:1989), conforming to a 28-day compressive strength guarantee of 43 MPa. Natural Zone II sand and 20 mm coarse aggregate served as the baseline fine and coarse aggregates, respectively. EAF slag was sourced from a local steel plant, air-cooled, crushed, and sieved to the required gradation. M-Sand was produced from crushed granite under VSI processing and graded to Zone II specifications per IS 383:2016. Material characterization included sieve analysis, specific gravity, water absorption, bulk density, and chemical composition testing.

4.2 Mix Design

Mix designs for M20 and M25 grade concrete were developed per IS 10262:2019. Target mean strengths were set at 26.6 MPa and 31.6 MPa respectively, incorporating a statistical margin of 1.65 standard deviations. Key design parameters are summarized in Table 4.1.

Table 4.1: Conventional Mix Design Parameters (Common to M20 and M25)

Parameter	M20	M25
Target Mean Strength	26.6 MPa	31.6 MPa
Max w/c Ratio	0.50	0.45
Cement (kg/m³)	372	414
Sand Zone II (kg/m³)	681	633
Coarse Aggregate 20 mm (kg/m³)	1133	1185

Water (kg/m³)	186	186
Density (kg/m³)	~2372	~2418

EAF slag was incorporated as a partial cement replacement at 6%, 8%, 10%, and 12% by weight. M-Sand was introduced as a partial cement replacement at 5%, 10%, and 15% by weight, while maintaining total binder content constant. Ternary mixes combined both EAF slag and M-Sand at their respective optimum levels (10% each). A water-binder ratio of 0.50 (M20) and 0.45 (M25) was maintained throughout.

4.3 Specimen Preparation and Testing

Concrete specimens were prepared using standard dimensions: 150 mm cubes for compressive strength, 150 mm × 300 mm cylinders for split tensile strength, and 150 mm × 150 mm × 700 mm beams for flexural strength. Each mix was tested with three specimens per age. After casting and 24 hours of initial curing at 27 ± 2°C and >90% RH, specimens were demoulded and submerged in clean water until the test age (7, 14, or 28 days). Tests were conducted according to IS 516-1959 and IS 509-1959.

5. Sustainability and Environmental Implications

The present section is devoted to sustainability and environmental implications, the details of which are presented in upcoming sub-sections.

5.1 Circular Economy Contribution

The valorization of EAF slag an industrial by-product historically consigned to landfills or low-value embankment fill as a structural concrete material directly advances circular economy principles. For every tonne of EAF slag utilized as aggregate, an equivalent volume of natural stone quarrying is avoided, and landfill burden from steelmaking is reduced. At typical Indian EAF production rates, the potential slag available for concrete applications represents a substantial resource stream that, if redirected, could meaningfully reduce the embodied environmental impact of construction.

5.2 River Sand Conservation

The substitution of M-Sand for natural river sand addresses one of the most pressing ecological challenges facing Indian infrastructure development. Unregulated riverbed mining has caused significant riverbank erosion, disruption of aquatic habitats, and depletion of groundwater recharge zones. M-Sand, produced under controlled quality conditions from abundant hard rock sources, provides a scalable and environmentally responsible alternative that aligns with IS 383:2016 and supports regulatory compliance.

5.3 Carbon Footprint Reduction

Beyond direct material substitution, EAF slag-bearing concretes offer additional CO_2 uptake potential through mineral carbonation, whereby free CaO and other reactive oxides absorb atmospheric CO_2 to form stable carbonates. Ting et al. (2025) quantified this CO_2 sequestration benefit in optimized EAF fine aggregate mixes. The enhanced durability of green concrete mixes evidenced by reduced permeability and resistance to chemical attack further extends service life, reducing life-cycle maintenance emissions and embodied carbon relative to conventional concrete requiring more frequent repair or replacement.

6. Research Gaps and Future Directions

The present section is devoted to research gaps and future directions of the research, the details of which arepresented in upcoming sub-sections.

6.1 Gaps Addressed

The experimental study directly addressed the most significant gap identified in the literature: the lack of systematic data on the combined, simultaneous application of EAF slag and M-Sand in concrete. By studying both individual and ternary blends across two concrete grades and multiple curing ages, the research established quantitative evidence for synergistic strength gains and confirmed the practical feasibility of combined substitution.

6.2 Persistent Gaps

Notwithstanding the contributions of this work, several important research gaps remain:

- Long-term durability data (>28 days, including 90-day and 365-day performance) under aggressive exposure conditions including chloride-laden coastal environments, acidic industrial atmospheres, and freeze-thaw cycles are not yet available for combined EAF + M-Sand mixes.
- Microstructural characterization using scanning electron microscopy (SEM), X-ray diffraction (XRD), and mercury intrusion porosimetry (MIP) would elucidate the ITZ densification and hydration product evolution responsible for the observed strength gains.
- The study examined EAF slag as a cement replacement; exploration of higher replacement levels (30–50%) as a coarse aggregate substitute, which is the more common application mode reported in the literature, remains an avenue for further work.
- Quantitative life-cycle assessment (LCA) incorporating regional material availability, transportation distances, and end-of-life recyclability is needed to build the full sustainability case for industry and policy audiences.
- Investigation of self-compacting concrete (SCC) formulations and fiber-reinforced variants incorporating these materials would expand the applicability envelope.
- Economic analyses benchmarking the cost-effectiveness of green concrete formulations against conventional mixes especially under Indian market conditions are essential for motivating industry uptake.

6.3 Recommendations for Practice

Based on the experimental findings, the following recommendations are proposed for practitioners and policymakers:

- EAF slag should undergo rigorous pre-treatment including weathering, quenching, crushing, and testing for free lime and magnesia before use in structural concrete. Documentation of source and volumetric stability testing is mandatory.
- A 10% cement replacement level (by weight) with EAF slag is recommended for M20 and M25 grade structural concrete, offering significant strength gains without workability compromise.
- M-Sand conforming to IS 383:2016 Zone II grading with microfines ≤10% is advocated as a complete or partial replacement for river sand across most concrete grades. A 10% cement replacement (as studied) or use as full fine aggregate replacement (per broader literature) are both viable depending on application.
- Ternary blends of EAF slag + M-Sand at 10% each offer compressive performance in the M40+ range from M25 base mixes and are particularly suitable for high-performance structural applications.
- Supplementary cementitious materials (fly ash, GGBS) and high-range water-reducing admixtures should be incorporated in mix designs using both EAF slag and M-Sand to optimize workability, compensate for elevated water absorption of EAF slag, and further enhance durability.
- Standards bodies (BIS, ASTM, and EN) are encouraged to develop explicit guidelines for combined EAF slag – M-Sand green concrete, including blending ratios, acceptance testing, and accelerated approval pathways for projects demonstrating verifiable sustainability metrics.

7. Conclusions

This review paper has synthesized the findings of an experimental investigation into green concrete formulated with EAF slag and Manufactured Sand. The study established the following key conclusions:

- Both EAF slag and M-Sand, when used individually at 10% cement replacement, consistently improved 28-day compressive, split tensile, and flexural strengths by 8.4–9.5% in M20 and M25 grade concrete relative to conventional control mixes.
- The ternary combination of EAF slag (10%) and M-Sand (10%) produced synergistic strength gains far exceeding individual replacement effects, achieving 34.8 MPa compressive strength for M20 (target 26.6 MPa) and 41.5 MPa for M25 (target 31.6 MPa) effectively performing in the M40+ range.
- Workability of all mixes remained within IS specification limits with appropriate admixture adjustment, confirming practical implementability.

- The adoption of EAF slag diverts a major industrial waste stream from landfills, while M-Sand eliminates ecologically harmful river sand extraction, collectively advancing circular economy goals and reducing the construction sector's carbon footprint.
- The study conforms fully to IS 10262:2019, IS 456:2000, and IS 383:2016 requirements, reinforcing its applicability within the prevailing Indian regulatory framework.

These results affirm that EAF slag and M-Sand represent viable, scalable, and performance-enhancing alternatives for sustainable concrete production, particularly relevant for India and similar regions confronting acute resource scarcity and environmental regulatory pressures. Continued research especially on long-term durability, microstructural mechanisms, and life-cycle economics will be instrumental in transitioning the concrete sector toward truly circular and resilient practices.

References

- Adams Joe, J., et al. (2013). Experimental investigation on the performance of M-Sand as complete and partial replacement for river sand in high-performance concrete. International Journal of Civil Engineering, 10(2), 45–52.
- Barhmaiah, B., et al. (2022). Evaluation of 100% M-Sand in M40 grade concrete for rigid pavement applications. Construction and Building Materials, 315, 125702.
- Chadee, A., et al. (2025). Influence of EAF slag as fine aggregate in Grade 40 concrete under wetting and drying cycles. Construction and Building Materials, 402, 132150.
- Daisy Angelin, A., et al. (2015). Durability performance of M-Sand concrete in acidic environments. Journal of Civil Engineering and Construction Technology, 6(3), 21–29.
- Ding, X., et al. (2016). Long-term compressive strength development of concrete incorporating manufactured sand with varying stone powder content. Construction and Building Materials, 125, 450–458.
- Elavenil, S., & Vijaya, B. (2013). Manufactured sand: A solution and an alternative to river sand in concrete manufacturing. Journal of Engineering, Science and Management Education, 6(1), 20–24.
- Faleschini, F., et al. (2016). Compressive and flexural behavior of concrete with EAF slag aggregate after stabilization treatment. Construction and Building Materials, 111, 266–275.
- Lee, N. K., et al. (2019). Feasibility of EAF slag as partial cement replacement in concrete: Comparison with GGBS. Cement and Concrete Composites, 99, 247–256.
- Li, Z., et al. (2020). Green concrete incorporating GGBS activated by desulfurization gypsum and EAF slag: Mechanical performance and microstructure. Cement and Concrete Composites, 112, 103668.
- Nuruzzaman, M., et al. (2024). Mechanical behavior of concrete with full fine aggregate replacement using quarry dust and ferronickel slag blend. Construction and Building Materials, 390, 131782.

- Pellegrino, C., &Faleschini, F. (2013). Experimental behavior of reinforced concrete beams with electric arc furnace slag as recycled aggregate. ACI Materials Journal, 110(2), 197–206.
- Prasanna, P. K., et al. (2017). Evaluation of M60 grade high-strength concrete with 75% M-Sand replacement. Materials Today: Proceedings, 4(2), 2581–2589.
- Sekaran, A., et al. (2015). Strength and durability properties of EAF oxidizing slag and fly ash concrete. International Journal of ChemTech Research, 8(2), 817–825.
- Ting, T., et al. (2025). Optimization of EAF fine aggregate replacement for improved compressive strength and CO_2 sequestration. Journal of Cleaner Production, 438, 140765.
- Yajurved Reddy, K. S., et al. (2015). Performance evaluation of M-Sand in M20 and M30 grade concrete at 60% replacement. International Journal of Emerging Technology and Advanced Engineering, 5(4), 112–117.