Journal of Science Engineering Technology and Management Science
Volume 02, Issue 08, August 2025 *ISSN: 3049-0952*
www.jsetms.com *DOI:10.63590/jsetms.2025.v02.i08.360-370*

REPLACEMENT OF FINE AGGREGATE WITH INDUSTRIAL WASTE

[1] A UDAY , [2] U.NAGARANI, [3] V.GEETHA, [4] D.AKHILA,[5] P.SWAPNA, [6] S.SREEJA

[1] Assistant Professor, Department Of Civil Engineering, Princeton Institute of Engineering & Technology for Women, Hyderabad, India

[2,3,4,5,6] B.Tech Students , Department of Civil Engineering , Princeton Institute of Engineering & Technology for Women, Hyderabad, India

To Cite this Article
A Uday, U.Nagarani, V.Geetha, D.Akhila, P.Swapna, S.Sreeja, "Replacement Of Fine Aggregate With Industrial Waste", Journal of Science Engineering Technology and Management Science, Vol. 02, Issue 08, August 2025,pp: 360-370, DOI: http://doi.org/10.63590/jsetms.2025.v02.i08.pp360-370
Submitted: 10-07-2025 *Accepted: 16-08-2025* *Published: 23-08-2025*

Abstract:

The construction industry is one of the largest consumers of natural resources worldwide, with fine aggregates (sand) being a critical component in concrete production. The excessive demand for natural sand, driven by rapid urbanization, infrastructure expansion, and population growth, has resulted in environmental degradation, scarcity of resources, and escalating costs. This has prompted researchers to explore sustainable alternatives for fine aggregates in concrete production. Industrial waste materials, generated in massive quantities across the globe, offer a promising and eco-friendly solution for replacing fine aggregates. Common industrial wastes such as fly ash, blast furnace slag, quarry dust, foundry sand, copper slag, marble dust, silica fume, ceramic waste, and stone dust not only reduce reliance on natural sand but also contribute to solving the problem of waste disposal. The reuse of industrial by-products in concrete offers multiple benefits: conservation of natural resources, cost reduction, environmental protection, and improved mechanical and durability properties of concrete. Several studies have demonstrated that partial or complete replacement of fine aggregates with industrial waste enhances compressive strength, tensile strength, flexural behavior, density, and resistance to chemical attacks. However, the performance of concrete depends significantly on the type, fineness, and chemical composition of the waste material. Furthermore, integrating such wastes in construction practices supports sustainable development goals (SDGs), particularly those related to responsible consumption, waste management, and climate change mitigation. This study aims to comprehensively review the potential of industrial wastes as replacements for fine aggregates in concrete. It examines the physical and chemical properties of various industrial wastes, their effects on fresh and hardened concrete, the environmental advantages of waste utilization, and the challenges associated with large-scale adoption. The findings underscore that industrial waste can serve as a viable substitute for sand, provided appropriate mix design, proportioning, and quality control are ensured.

I.INTRODUCTION

Concrete is the most widely used construction material on Earth, second only to water in terms of human consumption. It is a composite material consisting of cement, coarse aggregates, fine aggregates, and water. Among these constituents, fine aggregates (sand) play a vital role by filling voids between coarse aggregates and contributing to the strength, durability, and workability of concrete. Fine aggregates typically make up 30–40% of the volume of concrete. Traditionally, natural river sand has been the primary source of fine aggregates due to its availability and compatibility with cement paste. However, the extraction of natural sand at an unsustainable rate has created serious environmental issues, such as riverbank erosion, reduced groundwater levels, loss of biodiversity, and ecological imbalances.

With the construction sector projected to expand at unprecedented rates, particularly in developing countries such as India, China, and Brazil, the demand for sand continues to rise sharply. Reports indicate that sand mining has exceeded natural replenishment rates in many parts of the world, leading to scarcity and skyrocketing prices. This unsustainable practice necessitates the urgent

search for alternative fine aggregate materials that are locally available, cost-effective, and environmentally friendly. Simultaneously, industries generate enormous amounts of solid wastes, often creating disposal challenges and environmental hazards. For instance, fly ash from thermal power plants, copper slag from the metallurgical industry, quarry dust from stone crushers, marble powder from the marble industry, and foundry sand from metal casting units are produced in millions of tons every year. Most of these wastes are dumped in landfills or left untreated, causing land pollution, air contamination, and groundwater toxicity. Reusing such industrial by-products in concrete production can help close the loop in resource utilization while also addressing the sand shortage problem.

By replacing fine aggregates with industrial waste, the construction industry can simultaneously achieve sustainability, cost savings, and technical improvements. Such replacements not only conserve natural sand but also improve concrete properties in many cases. For example, quarry dust and copper slag increase compressive strength, marble dust improves resistance to sulphate attack, and silica fume enhances density and microstructure. Therefore, the replacement of fine aggregates with industrial wastes is not just an environmental necessity but also a pathway toward green concrete technology and circular economy models in the construction sector.

II.RELATED WORKS

Several researchers and industry experts have extensively studied the potential of industrial waste as an alternative to fine aggregates.

- Fly Ash: Studies have shown that fly ash, due to its fine particle size and pozzolanic reactivity, improves the workability and long-term strength of concrete. Kumar and Sharma (2016) reported that replacing 20–30% of sand with fly ash significantly improved durability and reduced permeability. Similarly, fly ash enhances resistance to sulphate and chloride attacks, making it suitable for marine and aggressive environments.
- Quarry Dust: Ilangovan et al. (2008) demonstrated that partial replacement of sand with quarry dust increased compressive and tensile strength due to its angular particle shape, which improved bonding between particles. Replacements up to 40% were found optimal in balancing strength and workability. Quarry dust also reduces shrinkage and enhances concrete's resistance to wear and tear.
- Copper Slag: As a by-product of copper smelting, copper slag has a high specific gravity and glassy texture. Al-Jabri et al. (2011) found that copper slag replacement up to 50% increased the density and strength of concrete, while also enhancing its abrasion resistance. However, higher percentages reduced workability, requiring the use of admixtures.
- Foundry Sand: Naik et al. (2003) investigated the use of foundry sand and observed that up to 30% replacement improved workability and minimized shrinkage cracks. The silica-rich composition of foundry sand contributes positively to the pozzolanic reaction, enhancing long-term strength.
- Marble Dust: Singh and Choudhary (2018) reported that marble powder, when used as a

sand substitute, refined the pore structure of concrete and improved compressive strength up to 20% replacement. Beyond this limit, workability and strength decreased due to excessive fineness. Marble dust also improves the aesthetic appeal of white concrete.

- Ceramic Waste Powder: Studies by Medina et al. (2012) indicated that ceramic waste powder improved the durability and density of concrete due to its micro-filler effect. Replacements up to 25% improved compressive and flexural strength, though excessive use caused brittleness.
- Silica Fume: Known for its ultra-fine particle size, silica fume enhances the microstructure of concrete by reducing voids and permeability. Siddique (2011) concluded that silica fume, combined with other waste materials, significantly improves durability against chemical attack and increases compressive strength.

In addition to individual materials, recent studies have explored the combined use of industrial wastes to maximize performance. For example, combining fly ash and quarry dust balances workability and strength, while using copper slag with silica fume enhances density and durability. These synergies open new avenues for designing high-performance green concrete.

Overall, related works consistently emphasize that industrial wastes can replace fine aggregates effectively when used in controlled proportions. The results highlight not only improvements in strength and durability but also significant environmental benefits through reduced carbon footprint, minimized waste disposal, and conservation of natural sand.

III. MATERIAL USED

In this study, the primary materials required for the production of concrete include cement, coarse aggregates, fine aggregates (partially replaced with industrial wastes), water, and admixtures. Additionally, various types of industrial waste materials are incorporated to replace fine aggregates either partially or fully, depending on mix design requirements.

Cement: Ordinary Portland Cement (OPC) of grade 43 or 53 is commonly used as the main binding material. Its role is to hydrate and bind aggregates into a cohesive matrix. In some cases, blended cements such as Portland Pozzolana Cement (PPC), which already contain fly ash, can also be employed for additional pozzolanic activity.

Coarse Aggregates: Crushed granite or basalt with a nominal size of 20 mm and 10 mm are typically used. They provide bulk, stability, and strength to the concrete mixture. Proper grading and angularity ensure better interlocking and reduced void content.

Fine Aggregates: Natural river sand is traditionally used, but in this study, it is partially or completely replaced by industrial waste materials. The natural sand serves as the control benchmark for comparison with mixes containing industrial by-products.

Industrial Wastes Used as Fine Aggregate Replacements:

- Fly Ash: Collected from thermal power plants, it is fine, spherical, and pozzolanic, improving workability and long-term strength.
- Quarry Dust / Stone Dust: Generated from quarrying operations, it is angular, coarse-fine material that enhances particle packing.
- Copper Slag: A by-product of copper smelting with high specific gravity, increasing density and abrasion resistance.
- Foundry Sand: Waste from metal casting industries, rich in silica, with properties similar to natural sand.
- Marble Powder: Waste obtained from cutting and polishing marble stones; fine and white in color, improves strength and aesthetics.
- Granite Powder: Waste from granite cutting industries, often used as filler to improve density.
- Ceramic Waste Powder: Finely ground ceramic industry waste, used to refine pore structure.
- Silica Fume: Extremely fine waste from silicon and ferro-silicon industries, improving microstructure and strength.
- Water: Potable, clean water free from oils, acids, and salts is used for mixing and curing. Water-cement ratio is maintained according to IS:10262 or ACI guidelines.
- Admixtures: Superplasticizers (high-range water reducers) are used to improve workability, particularly when very fine waste materials (such as marble powder or silica fume) reduce slump. Sometimes, air-entraining admixtures are added to improve freeze-thaw durability.

IV. REPLACEMENT OF FINE AGGREGATE

Fig 4.1 Replacement Of Fine Aggregate

The given image provides a comprehensive overview of the sustainable utilization of solid waste using advanced technological and economic assessment frameworks. The process begins with solid waste sorting, where wastes from three major streams—municipal waste, agricultural residues, and industrial by-products—are collected and classified. Municipal waste typically contains plastics, papers, and organic matter; agricultural waste consists of crop residues, husks, and lignocellulosic materials; while industrial waste may include fly ash, slag, and construction debris. Once segregated, these wastes are mapped using Geographical Information System (GIS) technology, which helps identify waste generation hotspots, optimize transportation routes, and locate suitable treatment plants, thereby reducing operational costs and environmental impact.

After sorting, the waste undergoes pre-treatment processes to enhance its suitability for recycling or reuse. One such process is waste drying, where renewable energy sources like solar panels are employed to reduce the moisture content, thus lowering energy requirements for subsequent valorization. Agricultural wastes rich in lignocellulosic compounds (cellulose, hemicellulose, lignin) often require mechanical, chemical, or biological pretreatments to break down complex structures for further conversion into biofuels or bio-based products. In some cases, bacterial cultivation techniques are integrated, where specific microbial strains are used to decompose organic matter, produce bio-enzymes, or generate biogas through anaerobic digestion. Industrial wastes, such as fly ash and slag, can be processed into construction materials, while organic municipal wastes can be composted or anaerobically digested to produce renewable energy.

The next stage focuses on solid waste valorization, which emphasizes converting waste into value-added products instead of mere disposal. This may include generating bioenergy, compost, fertilizers, recyclable materials, or even advanced construction composites. Valorization reduces the dependency on natural resources, minimizes landfill use, and supports the concept of a circular economy. However, the success of these processes is closely linked to their economic feasibility assessment, which evaluates crucial parameters like technology readiness levels, capital investment requirements, operational and pre-treatment expenses, return on investment, and market acceptance. A holistic economic analysis ensures that solid waste management projects are not only environmentally sustainable but also financially viable in the long term, making them attractive for governments, investors, and industries.

Overall, the diagram emphasizes a shift from traditional waste disposal methods toward a sustainable, technology-driven, and economically feasible waste management system. By integrating GIS-based planning, renewable energy sources, advanced microbial technologies, and economic assessment tools, the model ensures that municipal, agricultural, and industrial wastes can be transformed into resources. This approach directly contributes to reducing environmental pollution, conserving natural resources, mitigating greenhouse gas emissions, and promoting green growth, thereby addressing both ecological and socio-economic challenges.

V. METHODOLOGY

The methodology adopted for replacing fine aggregate with industrial waste in concrete involves a structured sequence of steps that ensure accuracy, consistency, and reliability of results. It is broadly divided into **material characterization, mix design, casting, curing, and testing**.

1. **Collection and Preparation of Materials**
   Industrial waste materials such as fly ash, quarry dust, copper slag, and foundry sand are sourced from respective industries. The materials are dried, sieved through a 4.75 mm IS sieve to remove oversized particles, and stored in airtight containers to prevent contamination and moisture absorption. Cement and aggregates are procured from local suppliers, ensuring conformity to IS/ASTM standards.
2. **Characterization of Materials**
   All raw materials are tested for their physical and chemical properties. Key tests include:
   - **For Cement**: Specific gravity, standard consistency, setting time, fineness, and compressive strength.

- **For Fine Aggregates & Wastes**: Specific gravity, bulk density, sieve analysis (grading), moisture content, water absorption, and chemical composition (e.g., SiO_2, Al_2O_3 content).
- **For Coarse Aggregates**: Crushing value, impact value, abrasion value, and flakiness index.
- **For Water**: pH, chloride, and sulphate content.

3. **Mix Design**
Concrete mix proportions are designed as per IS 10262 (2019), ACI 211.1, or other standard codes. A control mix (without industrial waste) is prepared first. Then fine aggregates are replaced with industrial waste in varying proportions (e.g., 10%, 20%, 30%, 40%, and 50%). In some trials, combined use of different wastes is also explored. The water-cement ratio is optimized for each mix to achieve desired workability.
4. **Mixing of Concrete**
The concrete is mixed using a laboratory drum mixer to ensure uniform distribution of materials. First, dry materials (cement, aggregates, and waste materials) are mixed, followed by the gradual addition of water and admixtures. Homogeneity is carefully checked to avoid segregation.
5. **Casting of Specimens**
Fresh concrete is tested for **slump** (workability) and **compaction factor**. Standard specimens are then cast:
    - **Cubes (150 mm × 150 mm × 150 mm)** for compressive strength.
    - **Cylinders (150 mm × 300 mm)** for split tensile strength.
    - **Prisms (100 mm × 100 mm × 500 mm)** for flexural strength. Moulds are filled in three layers, compacted properly, and covered with plastic sheets to prevent evaporation.
6. **Curing**
After 24 hours, specimens are demoulded and placed in a curing tank filled with clean water at 27 ± 2 °C. Specimens are cured for 7, 14, and 28 days. For long-term durability studies, curing may extend up to 90 or 120 days.
7. **Testing of Hardened Concrete**

- **Compressive Strength**: Using a compression testing machine (CTM) at 7, 14, and 28 days.
- **Split Tensile Strength**: To assess concrete's resistance to cracking under tension.
- **Flexural Strength**: Measured using a two-point loading setup.
- **Durability Tests**: Acid resistance, sulphate attack, chloride penetration, water absorption, sorptivity, and permeability tests.
- **Microstructural Analysis**: SEM (Scanning Electron Microscope) and XRD (X-ray Diffraction) are used to study the interfacial transition zone (ITZ) and hydration products.

8. **Data Analysis and Interpretation**
   Results are compared with control mixes to determine the effect of industrial waste on strength, workability, density, and durability. Optimum replacement levels are identified where concrete achieves the best balance of performance and economy.
9. **Sustainability Assessment**
   A Life Cycle Assessment (LCA) or carbon footprint analysis is performed to quantify environmental benefits such as reduction in CO_2 emissions, energy savings, and landfill reduction.

VI.CONCLUSION

The replacement of fine aggregate with industrial waste represents a sustainable and economically viable approach in modern construction practices. By utilizing industrial by-products such as fly ash, quarry dust, copper slag, foundry sand, and other solid waste materials, the dependency on natural river sand can be significantly reduced, thereby conserving natural resources and minimizing environmental degradation. The use of such waste materials not only helps in reducing landfill accumulation but also provides a cost-effective alternative for construction industries. Incorporating these industrial wastes in concrete improves certain mechanical and durability properties while aligning with the principles of circular economy and sustainable development. Furthermore, the integration of advanced methods like waste pre-treatment, microbial valorization, and GIS-based planning enhances feasibility and large-scale implementation. However, careful evaluation of strength parameters, workability, durability, and environmental impact is essential before large-scale adoption. In conclusion, replacing fine aggregates with industrial waste not only addresses the challenges of resource depletion and waste management but also paves the way for green construction practices that are both environmentally responsible and economically beneficial for future infrastructure development.

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