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# Replacing Fine Aggregates with Sustainable Recycled Waste

Aakanksha Panditrao Ingle[1], Prof. V. B. Chavan[2]
[1]Postgraduate Student, [2]Professor, Department of Civil Engineering (Structural Engineering), Shreeyash College of Engineering and Technology, Chhatrapati Sambhajinagar (Aurangabad), Maharashtra, India

***Abstract:** The excessive extraction of natural river sand as the predominant fine aggregate in concrete construction has led to severe environmental degradation, including riverbed erosion, loss of aquatic habitats, and depletion of a finite natural resource. Simultaneously, the accelerating generation of industrial and municipal solid waste creates mounting pressures on land disposal capacity and environmental quality. This paper investigates the feasibility and structural implications of partially or fully replacing natural fine aggregates in concrete mixes with sustainable recycled waste materials, including Manufactured Sand (M-Sand), Quarry Dust (QD), Bottom Ash (BA), Recycled Concrete Fine Aggregate (RCFA), Crumb Rubber (CR), Foundry Sand (FS), and Glass Powder (GP). A comprehensive experimental programme was conducted involving the preparation of M25 and M30 grade concrete specimens with replacement levels of 10%, 20%, 30%, 50%, and 100% by weight of natural fine aggregate (NFA). Fresh concrete properties were assessed through workability tests, while hardened concrete properties were evaluated through compressive strength tests at 7, 14, and 28 days, split tensile strength, and flexural strength. Results indicate that replacement levels of 20–30% with M-Sand and Quarry Dust yield compressive strengths equivalent to or exceeding those of control mixes, while higher replacement levels with Bottom Ash and Crumb Rubber result in moderate strength reductions that may still be acceptable for specific structural applications. The findings confirm that strategic utilisation of recycled waste materials as fine aggregate replacements presents a technically viable, economically advantageous, and environmentally responsible pathway toward sustainable concrete construction.*
***Keywords:** Fine Aggregate Replacement, Manufactured Sand, Quarry Dust, Bottom Ash, Recycled Concrete Fine Aggregate, Crumb Rubber, Glass Powder, Sustainable Concrete, Compressive Strength, Green Construction*

## I. INTRODUCTION

Concrete is the most widely consumed construction material in the world, with global production exceeding 10 billion tonnes annually. Fine aggregate, conventionally supplied by natural river sand, constitutes approximately 30–35% of the total concrete volume and plays a critical role in determining workability, density, strength development, and durability. The global construction industry's insatiable demand for river sand has, however, precipitated a resource crisis of considerable proportions. Sand extraction from riverbeds disrupts hydrological regimes, destabilises channel morphology, reduces groundwater recharge, and harms aquatic biodiversity. In India, unregulated sand mining has contributed to significant environmental damage across major river systems, prompting regulatory restrictions that have in many regions created acute shortages and driven up material costs.

Against this backdrop, the search for sustainable alternatives to natural fine aggregate has emerged as a priority area of research in structural and construction engineering. A wide range of industrial by-products and recycled waste materials, including Manufactured Sand (M-Sand) derived from crushed stone, Quarry Dust (QD) generated during aggregate production, Bottom Ash (BA) from thermal power plants, Recycled Concrete Fine Aggregate (RCFA) from demolition waste, Crumb Rubber (CR) from end-of-life tyres, Foundry Sand (FS) from metal casting operations, and Glass Powder (GP) from waste glass processing, have been identified as potential fine aggregate substitutes. Each of these materials possesses distinctive physical and chemical characteristics that influence the properties of concrete in which they are incorporated.

This study presents a systematic experimental investigation of the effect of replacing natural fine aggregate with selected recycled waste materials on the fresh and hardened properties of concrete, with the objective of identifying optimal replacement levels, evaluating structural performance, and contributing to the evidence base for sustainable concrete mix design.

## II. LITERATURE REVIEW

Extensive research has been conducted over the past two decades on the use of various industrial by-products and recycled materials as partial or full replacements for natural fine aggregate in concrete. A review of key findings is presented below.

*A. Manufactured Sand (M-Sand)*

Manufactured Sand, produced by crushing granite or basalt rock to specified gradations, has been studied as the most direct substitute for river sand. Studies by Nanthagopalan and Santhanam (2011) demonstrated that M-Sand concrete at 100% replacement exhibited superior compressive strength compared to river sand concrete due to its angular particle morphology and reduced presence of deleterious materials. However, reduced workability due to higher water demand was noted and could be offset by the use of chemical admixtures.

*B. Quarry Dust*

Quarry Dust, a by-product of stone crushing operations, has been reported to improve the mechanical strength of concrete when used as a partial replacement for fine aggregate. Ilangovane and Mahendran (2010) found that replacement levels up to 30% resulted in enhanced compressive strength, attributed to the pozzolanic activity of finer quarry dust particles filling interstitial voids and reducing porosity.

*C. Bottom Ash*

Bottom Ash from coal-fired power plants is a porous, lightweight material with lower specific gravity than river sand. Research by Ghafoori and Bucholc (1996) and Singh and Siddique (2015) reported that concrete incorporating bottom ash at replacement levels up to 40% achieved acceptable compressive strengths with improved thermal insulation characteristics, though the higher water absorption of bottom ash particles necessitated adjustments to the water-to-cement ratio.

*D. Recycled Concrete Fine Aggregate (RCFA)*

The use of fine aggregate derived from crushed demolition concrete has been investigated by multiple researchers. Evangelista and de Brito (2007) reported that replacement of up to 30% of natural fine aggregate with RCFA resulted in minimal reduction in compressive strength, provided that the residual cement paste adhering to RCFA particles was accounted for in mix design. Higher replacement levels generally resulted in increased porosity and reduced durability.

*E. Crumb Rubber*

Crumb Rubber from waste tyre shredding introduces elastic properties into concrete, improving impact resistance and energy absorption. However, its non-polar hydrophobic surface reduces bonding with cement paste, leading to reductions in compressive and tensile strength. Topcu and Avcular (1997) and Eldin and Senouci (1993) reported strength reductions of 15–30% at replacement levels of 25%, suggesting Crumb Rubber concrete is most suitable for non-structural and pavement applications.

*F. Foundry Sand and Glass Powder*

Used foundry sand, a silica-rich by-product of metal casting, has been reported to produce concrete with comparable workability and strength to conventional mixes at replacement levels up to 25%. Glass Powder, with its high amorphous silica content, exhibits pozzolanic behaviour that can enhance long-term strength gain, particularly beyond 28 days.

## III. MATERIALS AND METHODOLOGY

*A. Materials*

The following materials were used in the experimental programme:

1) Ordinary Portland Cement (OPC) 53 Grade conforming to IS 12269:2013.
2) Natural Fine Aggregate (NFA): River sand, Zone II, conforming to IS 383:2016.
3) Coarse Aggregate: Crushed granite, 20 mm nominal size, conforming to IS 383:2016.
4) Recycled Fine Aggregate Substitutes: M-Sand (crushed granite), Quarry Dust, Bottom Ash (from Parli Thermal Power Station), RCFA (from demolished RCC structure), Crumb Rubber (from tyre shredding unit), Foundry Sand, and Glass Powder.
5) Potable water conforming to IS 456:2000.
6) Superplasticizer (Conplast SP430) at 0.3% by weight of cement for high-replacement mixes to maintain workability.

### *B. Physical Properties of Fine Aggregate Substitutes*

| Material | Specific Gravity | Fineness Modulus | Water Absorption (%) | Bulk Density (kg/m³) | Particle Shape |
|---|---|---|---|---|---|
| River Sand (NFA) | 2.65 | 2.71 | 1.2 | 1610 | Rounded |
| M-Sand | 2.68 | 2.84 | 1.8 | 1640 | Angular |
| Quarry Dust | 2.66 | 2.60 | 2.1 | 1580 | Angular |
| Bottom Ash | 2.12 | 2.43 | 5.6 | 920 | Porous |
| RCFA | 2.41 | 2.55 | 4.8 | 1240 | Irregular |
| Crumb Rubber | 1.14 | 3.10 | 0.3 | 560 | Fibrous |
| Foundry Sand | 2.58 | 2.48 | 1.5 | 1490 | Sub-angular |
| Glass Powder | 2.53 | — | 0.6 | 1380 | Irregular |

### *C. Mix Design*

Concrete mixes of M25 grade (w/c = 0.45) and M30 grade (w/c = 0.40) were designed as per IS 10262:2019. The control mix (CM) utilised 100% river sand as fine aggregate. Test mixes were prepared by replacing NFA with each substitute material at 10%, 20%, 30%, 50%, and 100% by weight.

| Mix Component | Control Mix (M25) | Control Mix (M30) | Test Mix Notation | Replacement Levels |
|---|---|---|---|---|
| Cement (kg/m³) | 380 | 420 | — | — |
| Natural FA (kg/m³) | 680 | 660 | Reduced proportionally | 10–100% |
| Coarse Aggregate (kg/m³) | 1150 | 1110 | Constant | — |
| Water (litres/m³) | 171 | 168 | Adjusted for absorption | — |
| w/c Ratio | 0.45 | 0.40 | Constant | — |

### *D. Test Methods*

Fresh concrete properties were evaluated by the slump cone test (IS 1199:1959). Hardened concrete specimens (150 mm cubes, 150 mm x 300 mm cylinders, and 100 mm x 100 mm x 500 mm prisms) were cast, cured under water at ambient temperature, and tested at 7, 14, and 28 days for compressive strength (IS 516:2018), split tensile strength (IS 5816:1999), and flexural strength (IS 516:2018).

## IV. RESULTS AND DISCUSSION

### *A. Workability*

Workability, as measured by slump, was found to vary significantly with the type and level of replacement. M-Sand and Quarry Dust mixes exhibited moderate reductions in slump (by 10–25 mm) due to their angular particle morphology and higher surface area, which increased water demand. Bottom Ash mixes showed slump reduction proportional to the replacement level, attributable to the high porosity and water absorption of bottom ash particles.

Crumb Rubber mixes exhibited a marginal increase in slump due to the hydrophobic nature of rubber particles and their non-absorption of mix water. RCFA mixes showed moderate slump reduction, while Glass Powder mixes maintained workability comparable to the control mix up to 30% replacement.

### B. *Compressive Strength*

The compressive strength results at 28 days for M25 grade concrete are summarised in Table 3. Key findings include:

1) M-Sand at 20–30% replacement achieved compressive strengths of 28.6–29.8 MPa, exceeding the control mix strength of 27.4 MPa. At 100% replacement, strength reached 26.9 MPa, remaining close to the target grade.
2) Quarry Dust at 20% replacement yielded 28.1 MPa; strength declined progressively beyond 30% due to excess fines increasing water demand and reducing the effective w/c ratio.
3) Bottom Ash at 20% replacement achieved 25.8 MPa, declining to 20.3 MPa at 50% and 16.4 MPa at 100%, reflecting the porous particle structure and lower specific gravity.
4) RCFA at 30% replacement attained 25.2 MPa, while 50% replacement yielded 22.8 MPa, attributed to higher porosity of RCFA particles.
5) Crumb Rubber showed the most significant strength reduction, reaching only 14.6 MPa at 30% replacement, limiting its application to lightweight and non-structural uses.
6) Foundry Sand at 25% replacement closely matched the control mix at 26.8 MPa.
7) Glass Powder at 20% replacement achieved 27.9 MPa, with pozzolanic activity contributing to strength gain at later ages.

| Material (Replacement %) | 7-Day (MPa) | 14-Day (MPa) | 28-Day (MPa) | % of Control (28d) | Workability (mm slump) |
|---|---|---|---|---|---|
| Control (River Sand 100%) | 18.4 | 23.6 | 27.4 | 100 | 78 |
| M-Sand (20%) | 19.2 | 24.8 | 28.6 | 104.4 | 68 |
| M-Sand (100%) | 17.8 | 22.9 | 26.9 | 98.2 | 54 |
| Quarry Dust (20%) | 18.9 | 23.9 | 28.1 | 102.6 | 65 |
| Bottom Ash (20%) | 16.2 | 21.1 | 25.8 | 94.2 | 60 |
| Bottom Ash (50%) | 13.4 | 17.2 | 20.3 | 74.1 | 52 |
| RCFA (30%) | 16.0 | 20.8 | 25.2 | 92.0 | 58 |
| Crumb Rubber (30%) | 9.8 | 12.4 | 14.6 | 53.3 | 82 |
| Foundry Sand (25%) | 17.6 | 22.4 | 26.8 | 97.8 | 71 |
| Glass Powder (20%) | 17.9 | 23.2 | 27.9 | 101.8 | 75 |

### C. *Split Tensile Strength*

Split tensile strength at 28 days followed a trend broadly consistent with compressive strength. M-Sand and Quarry Dust mixes at 20–30% replacement exhibited split tensile strengths of 2.8–3.1 MPa, comparable to the control mix value of 2.9 MPa. RCFA and Foundry Sand mixes showed marginal reductions (2.5–2.7 MPa), while Bottom Ash mixes at 50% replacement declined to 2.0 MPa. Crumb Rubber mixes, despite low compressive strength, demonstrated improved energy absorption behaviour under split tensile loading, with failure being more gradual and less brittle than in conventional concrete, a characteristic of value in impact-resistant applications.

### D. *Flexural Strength*

Flexural strength results at 28 days for the control mix and selected replacement mixes revealed that M-Sand and Quarry Dust mixes maintained flexural strengths within 5% of the control value at replacement levels up to 30%.

Crumb Rubber mixes, while exhibiting lower flexural strength values, demonstrated superior ductility and crack resistance, with crack propagation being markedly slower and more tortuous than in conventional concrete. Glass Powder mixes showed a slight improvement in flexural strength beyond 28 days, consistent with ongoing pozzolanic reaction.

### *E. Environmental and Economic Assessment*

Beyond structural performance, the adoption of recycled waste materials as fine aggregate replacements offers substantial environmental and economic benefits. Bottom Ash utilisation diverts a hazardous solid waste from landfill, reducing the environmental liability of thermal power producers. RCFA use reduces the volume of construction and demolition (C&D) waste requiring disposal while simultaneously reducing demand for primary aggregates. Crumb Rubber incorporation addresses the significant environmental and public health challenges posed by end-of-life tyre accumulation. Foundry Sand and Glass Powder utilisation reduces industrial waste disposal costs.

Economically, the use of locally available quarry dust and M-Sand reduces transportation costs and supply-side price volatility associated with river sand, which in many regions of Maharashtra has been subject to significant price increases due to mining restrictions.

## V. COMPARATIVE SUMMARY AND OPTIMAL REPLACEMENT LEVELS

| Material | Optimal Replacement (%) | Structural Suitability | Environmental Benefit | Workability Impact | Cost Impact |
|---|---|---|---|---|---|
| M-Sand | Up to 100% | High | High (reduced mining) | Moderate decrease | Low cost |
| Quarry Dust | 20–30% | High | Moderate | Moderate decrease | Low cost |
| Bottom Ash | Up to 20% | Moderate | High (waste diversion) | Slight decrease | Negligible |
| RCFA | 20–30% | Moderate | Very High (C&D waste) | Moderate decrease | Low |
| Crumb Rubber | Up to 15% | Low (non-structural) | Very High (tyre waste) | Slight increase | Negligible |
| Foundry Sand | 20–25% | Moderate-High | High (industrial waste) | Marginal decrease | Negligible |
| Glass Powder | 20–30% | Moderate-High | Moderate | Negligible | Low |

## VI. FUTURE SCOPE

1) Investigation of ternary and hybrid replacement combinations, such as M-Sand combined with Glass Powder or Quarry Dust combined with Bottom Ash, to synergistically optimise both strength and environmental performance.
2) Durability studies encompassing chloride ion penetration, carbonation resistance, sulphate attack resistance, and freeze-thaw performance for recycled waste aggregate concretes.
3) Long-term strength gain assessment beyond 28 days, particularly for mixes incorporating pozzolanic materials such as Glass Powder, to capture the full extent of secondary cementitious reactions.
4) Life Cycle Assessment (LCA) and Life Cycle Cost Analysis (LCCA) of recycled fine aggregate concretes to quantify environmental and economic benefits over the service life of structures.
5) Field-scale demonstration projects to validate laboratory findings under real construction conditions and develop design guidelines for practising engineers.

*6)* Exploration of geopolymer concrete systems incorporating recycled waste fine aggregates to achieve near-zero Portland cement concrete with improved sustainability credentials.

## VII. CONCLUSION

This experimental investigation confirms that the replacement of natural fine aggregate with sustainable recycled waste materials in concrete is both technically feasible and structurally viable across a range of replacement levels. M-Sand emerges as the most structurally suitable substitute, capable of maintaining or enhancing compressive, tensile, and flexural strength at replacement levels up to 100%, and representing the most direct and effective solution to river sand scarcity. Quarry Dust and Foundry Sand at 20–30% replacement levels yield concrete with mechanical properties closely comparable to conventional river sand concrete. Bottom Ash and RCFA are suitable for partial replacement at up to 20–30%, offering substantial environmental benefits in terms of industrial and construction waste diversion. Crumb Rubber, while significantly reducing concrete strength, imparts valuable ductility and energy absorption characteristics that make it appropriate for lightweight, non-structural, and impact-resistant applications. Glass Powder offers pozzolanic benefit and is promising in combination with other replacement materials. Collectively, the findings of this study support the conclusion that strategic, informed use of recycled waste materials as fine aggregate substitutes constitutes a technically credible, economically rational, and environmentally imperative dimension of sustainable concrete engineering, and merits integration into standard mix design practice and construction specifications.

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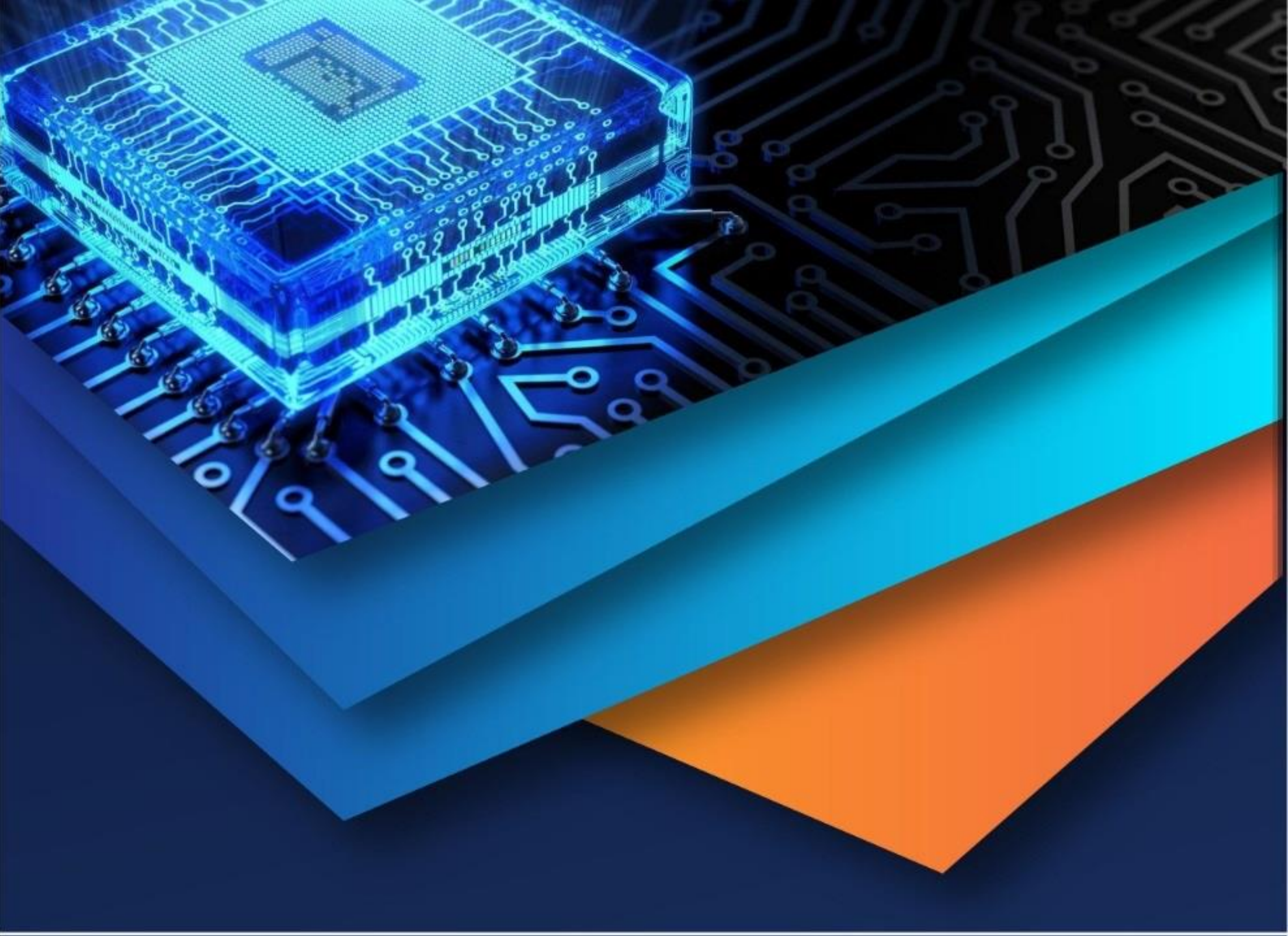

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