HYBRID REPLACEMENT OF FINE AGGREGATE WITH CRUMB RUBBER AND RECYCLED GLASS POWDER: ANALYZING SYNERGISTIC EFFECTS ON CONCRETE PERFORMANCE

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Abstract - *The sustainable utilization of industrial and municipal waste in concrete production is critical for reducing environmental impact and conserving natural resources. This study investigates the hybrid replacement of fine aggregate with crumb rubber (CR) and recycled glass powder (RGP), aiming to evaluate their combined effects on concrete performance. Crumb rubber enhances ductility and impact resistance but typically reduces compressive strength, whereas recycled glass powder contributes pozzolanic activity, improving strength and durability. Concrete mixes were prepared with varying replacement levels of fine aggregate by CR (5–20%) and RGP (5–15%), including single and hybrid replacements. Fresh concrete properties, such as slump, flow, and density, were measured, while mechanical performance was assessed through compressive, tensile, and flexural strength tests. Durability was evaluated using water absorption, chloride penetration, and freeze-thaw resistance tests. The results indicate that hybrid incorporation of CR and RGP mitigates the strength reduction caused by CR alone, with an optimal replacement combination of 10% CR and 10% RGP achieving up to 95% of the control concrete compressive strength while enhancing ductility and durability. Workability slightly decreases with higher replacement levels, but durability properties show significant improvement compared to single replacements. This study demonstrates that hybrid replacement of fine aggregate with CR and RGP provides a promising strategy for producing environmentally friendly concrete, offering both performance efficiency and effective waste management. The findings contribute to sustainable concrete design and provide practical insights for construction applications.*

Key Words: Crumb rubber, Recycled glass powder, Hybrid concrete, Fine aggregate replacement, Mechanical performance, Durability, Sustainable construction.

1. INTRODUCTION

1.1 Background

1.1.1 Overview of Concrete Production and Environmental Challenges

Concrete is the most widely used construction material worldwide due to its versatility, durability, and cost-effectiveness (Mehta and Monteiro, 2014). However, the production of concrete, particularly the cement component, is highly energy-intensive and contributes significantly to greenhouse gas emissions. Moreover, the extraction of natural aggregates such as sand and gravel has led to ecological imbalances, including riverbed degradation, soil erosion, and habitat loss (Kumar et al., 2020). Consequently, there is an increasing emphasis on developing sustainable concrete solutions that reduce the environmental footprint while maintaining adequate mechanical and durability performance.

1.1.2 Issues of Natural Sand Depletion and Solid Waste Disposal

The global demand for fine aggregate has resulted in severe depletion of natural sand resources, creating both economic and ecological challenges (Akinmusuru et al., 2019). Simultaneously, large quantities of industrial and municipal wastes, including waste tires and post-consumer glass, are generated annually and often end up in landfills, leading to environmental pollution (Pacheco-Torgal et al., 2013). Crumb rubber (CR) derived from waste tires and recycled glass powder (RGP) from crushed glass represent promising materials for incorporation into concrete, offering both waste management and resource conservation benefits.

1.1.3 Sustainable Concrete Approaches Using Industrial and Municipal Waste

In recent years, research has focused on using alternative materials such as fly ash, silica fume, CR, and RGP to partially replace cement or fine aggregates in concrete (Singh et al., 2021). These approaches aim to reduce the environmental impact of construction while achieving satisfactory strength and durability characteristics. Specifically, hybrid incorporation of multiple waste materials is emerging as a strategy to exploit synergistic effects, potentially overcoming the limitations of single-waste replacement in concrete.

1.2 Problem Statement

Crumb rubber, when used alone as a partial replacement for fine aggregates, improves concrete ductility and energy absorption but often causes a reduction in compressive strength due to poor bonding with the cement matrix (Shah and Gupta, 2019). Conversely, recycled glass powder exhibits high pozzolanic reactivity, enhancing early-age strength, but excessive replacement can reduce workability and increase brittleness (Ali et al., 2020). Therefore, a hybrid approach combining CR and RGP is necessary to balance the mechanical and durability performance of concrete while addressing environmental concerns.

1.3 Research Objectives

This study aims to:

- Investigate the synergistic effects of combined crumb rubber and recycled glass powder on concrete performance.
- Determine the optimal replacement percentages of fine aggregate with CR and RGP for balanced mechanical and durability properties.
- Assess the practical feasibility and sustainability benefits of hybrid concrete for construction applications.

1.4 Significance of Study

The hybrid use of CR and RGP promotes sustainable construction practices by reducing dependency on natural sand and diverting waste materials from landfills (Pacheco-Torgal et al., 2013). By optimizing the replacement proportions, this research provides guidance for producing eco-friendly concrete with adequate strength and durability. Furthermore, the findings can inform policymakers, engineers, and researchers about practical strategies for implementing hybrid waste-based concrete in real-world construction projects.

2. LITERATURE REVIEW

2.1 Crumb Rubber in Concrete

2.1.1 Effects on Compressive, Tensile, and Flexural Strength

Crumb rubber (CR), obtained from waste tires, has been widely investigated as a partial replacement for fine aggregate in concrete due to its potential to enhance ductility and energy absorption (Shah and Gupta, 2019). However, studies consistently report a reduction in compressive strength with increasing CR content, primarily due to weak interfacial bonding between the hydrophobic rubber particles and the cement matrix (Medina et al., 2017). Tensile and flexural strengths are also affected, but the incorporation of CR can improve post-cracking behavior and toughness, which is beneficial in applications requiring impact resistance or vibration damping (Li et al., 2020).

2.1.2 Impact on Durability (Shrinkage, Permeability)

The inclusion of CR influences durability parameters such as shrinkage and permeability. Concrete with CR exhibits higher shrinkage due to increased air void content and elastic deformation of rubber particles (Topcu, 2019). On the other hand, CR reduces density and can improve freeze-thaw resistance, but water permeability tends to increase with higher replacement levels, potentially compromising long-term durability. These contrasting effects suggest that careful optimization is required to balance mechanical and durability performance.

2.1.3 Performance Limitations at Higher Replacement Levels

While small proportions of CR (typically 5–10% replacement of fine aggregate) show acceptable performance, higher replacement levels (>15%) significantly reduce compressive strength and stiffness, limiting structural applications (Shah and Gupta, 2019). This limitation has motivated research into hybrid approaches that combine CR with other waste materials to mitigate strength loss while maintaining ductility and sustainability benefits.

2.2 Recycled Glass Powder in Concrete

2.2.1 Pozzolanic Activity and Contribution to Strength

Recycled glass powder (RGP) is a finely ground material that exhibits pozzolanic properties, reacting with calcium hydroxide in the cement matrix to form additional calcium silicate hydrate (C-S-H), enhancing concrete strength and durability (Ali et al., 2020). Studies indicate that partial replacement of fine aggregate with RGP can improve compressive and flexural strength, particularly at early ages, due to filler effects and pozzolanic reactions.

2.2.2 Effects on Workability and Durability

Incorporation of RGP affects fresh concrete properties. While the fine particle size can improve packing density, excessive RGP may reduce workability due to higher surface area and water demand (Singh et al., 2021). Durability performance generally improves with moderate RGP replacement, as pozzolanic reactions refine pore structure, reducing water absorption and enhancing resistance to chloride penetration and sulfate attack.

2.2.3 Limitations in Single Replacement Studies

Although RGP offers strength and durability benefits, its use alone as a fine aggregate replacement is constrained. Excessive substitution (>15%) can cause brittleness and reduce workability, limiting practical applications (Kumar et al., 2020). This highlights the need for hybrid strategies to balance mechanical performance and fresh concrete properties.

2.3 Hybrid Replacement Approaches

2.3.1 Concept of Synergistic Effects in Concrete

Hybrid concrete refers to the simultaneous incorporation of multiple waste materials, aiming to exploit complementary properties. In the case of CR and RGP, CR improves ductility and energy absorption, while RGP enhances strength and durability through pozzolanic reactions. The combination can potentially offset the weaknesses of single-material replacements and produce concrete with optimized mechanical and durability properties (Pacheco-Torgal et al., 2013).

2.3.2 Previous Hybrid Waste Concrete Studies

Several studies have investigated hybrid concrete mixes combining CR with supplementary cementitious materials like fly ash, silica fume, or glass powder. Results suggest that hybrid approaches can maintain compressive strength closer to control concrete while benefiting from the enhanced ductility and environmental advantages of CR (Topcu and Sengel, 2018; Li et al., 2020). However, most research focuses on either mechanical or durability aspects separately, leaving the full synergistic potential underexplored.

2.3.3 Research Gaps in Combined CR + RGP Usage

Despite increasing interest, literature on the simultaneous replacement of fine aggregate with CR and RGP remains limited. Research gaps include identifying optimal replacement ratios, understanding combined effects on workability, strength, and durability, and providing practical guidelines for sustainable hybrid concrete applications. Addressing these gaps is critical for advancing eco-friendly construction practices and effective waste management strategies.

3. MATERIALS AND METHODS

3.1 Materials

3.1.1 Cement

Ordinary Portland Cement (OPC) 53-grade conforming to IS 12269:2013 was used throughout this study (BIS, 2013). The cement had a specific gravity of 3.15, initial setting time of 35 minutes, and fineness of 320 m^2/kg, meeting standard requirements. Cement quality was confirmed by standard tests such as consistency, setting time, and compressive strength of cement mortar cubes.

3.1.2 Fine and Coarse Aggregates

Natural river sand passing through a 4.75 mm sieve was used as fine aggregate, conforming to IS 383:2016. The sand had a fineness modulus of 2.6, moisture content of 0.5%, and a specific gravity of 2.65. Crushed granite coarse aggregate with a maximum size of 20 mm was used, meeting IS 383 specifications. The coarse aggregate had a specific gravity of 2.7, water absorption of 0.8%, and angular shape, suitable for conventional concrete mixes.

3.1.3 Crumb Rubber (CR)

Crumb rubber was sourced from recycled end-of-life tires from local scrap dealers in Lucknow, India. The rubber particles were processed to a size range of 1–4 mm, cleaned, and sieved to remove contaminants. The specific gravity of CR was 1.15, and water absorption was negligible. Crumb rubber replaced natural sand in varying proportions to study its influence on concrete performance (Shah and Gupta, 2019).

3.1.4 Recycled Glass Powder (RGP)

Recycled glass powder was produced by crushing post-consumer soda-lime glass bottles and grinding them to pass through a 75 μm sieve. The fineness of RGP was measured at 450 m^2/kg. RGP exhibits pozzolanic activity, contributing to strength development and reduced permeability. Chemical composition analysis confirmed high silica content (>70%), consistent with previous studies on pozzolanic glass powder (Ali et al., 2020).

3.1.5 Water and Admixtures

Potable water conforming to IS 456:2000 standards was used for mixing and curing. A polycarboxylate-based superplasticizer was added in small doses (0.5% by weight of cement) to improve workability for mixes with higher CR and RGP content.

3.2 Mix Proportions

Concrete mixes were designed according to IS 10262:2019 guidelines for M30 grade concrete. A control mix with 100% natural fine aggregate was prepared, and hybrid mixes were designed by replacing fine aggregate with CR (5%, 10%, 15%) and RGP (5%, 10%, 15%), both individually and in combination.

Table-1: representative mix proportions (per cubic meter)

Mix ID	Cement (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)	Crumb Rubber (%)	RGP (%)	Superplasticizer (%)
Control	420	720	1140	186	0	0	0.5
CR5	420	684	1140	186	5	0	0.5
CR10	420	648	1140	186	10	0	0.5
RGP5	420	684	1140	186	0	5	0.5
RGP10	420	648	1140	186	0	10	0.5
CR5RGP5	420	648	1140	186	5	5	0.5
CR10RGP10	420	576	1140	186	10	10	0.5

3.3 Experimental Procedure

3.3.1 Fresh Concrete Tests

Workability was measured using the slump test according to IS 1199:2013. Flow consistency was evaluated to assess the effect of fine aggregate replacement on fluidity. Air content and fresh concrete density were determined following IS 1199 guidelines. A slight reduction in workability was expected for mixes with higher CR and RGP content due to increased surface area and hydrophobic nature of CR.

3.3.2 Mechanical Tests

Cubes (150×150×150 mm), cylinders (150×300 mm), and beams (100×100×500 mm) were cast to determine compressive, tensile, and flexural strength, respectively. Compressive strength was tested at 7, 14, and 28 days using a compression testing machine in accordance with IS 516:2018. Split tensile strength of cylinders and flexural strength of beams were determined following IS 5816:1999 and IS 516:2018 standards.

3.3.3 Durability Tests

Durability performance was assessed through:

- Water absorption test (IS 3085:1965) to evaluate porosity.
- Rapid chloride penetration test (RCPT) as per ASTM C1202 equivalent procedures to study chloride ingress.
- Freeze-thaw resistance according to ASTM C666, adapted for laboratory conditions, to evaluate the effect of CR on crack propagation and durability.

4. RESULTS

4.1 Fresh Concrete Properties

4.1.1 Workability, Slump, and Density Trends

The fresh properties of concrete were significantly influenced by the incorporation of crumb rubber (CR) and recycled glass powder (RGP). The slump values decreased with increasing CR content due to the hydrophobic nature and low specific gravity of rubber particles, which reduce cohesiveness in the mix (Shah and Gupta, 2019). In contrast, RGP slightly improved packing density and provided a filler effect, maintaining workability at moderate replacement levels. The hybrid mixes (CR + RGP) exhibited intermediate slump values, balancing the effects of both materials.

Table-2: Fresh Concrete Properties

Mix ID	Slump (mm)	Density (kg/m^3)
Control	75	2450
CR5	70	2420
CR10	65	2390
RGP5	74	2445
RGP10	73	2440
CR5RGP5	72	2425
CR10RGP10	68	2400

4.2 Mechanical Performance

4.2.1 Compressive, Tensile, and Flexural Strength

The compressive strength of concrete decreased with increasing CR content due to weak bonding at the rubber–cement interface. However, RGP replacement enhanced compressive strength due to its pozzolanic activity and filler effect. Hybrid mixes showed a synergistic behavior, where moderate CR and RGP replacement (10% each) achieved 95% of the control concrete strength while improving ductility (Ali et al., 2020; Topcu, 2019).

Split tensile and flexural strengths followed similar trends. CR increased post-crack deformation, improving toughness, while RGP contributed to strength development. The hybrid mixes provided a balance of ductility and strength, outperforming single CR mixes and slightly underperforming compared to RGP-only mixes at the same replacement levels.

Table-3: Mechanical Properties of Concrete at 28 Days

Mix ID	Compressive Strength (MPa)	Split Tensile Strength (MPa)	Flexural Strength (MPa)
Control	32.5	3.6	4.5
CR5	31.0	3.7	4.6
CR10	29.0	3.5	4.3
RGP5	33.5	3.8	4.7
RGP10	34.0	3.9	4.8
CR5RGP5	32.0	3.7	4.6
CR10RGP10	30.8	3.6	4.5

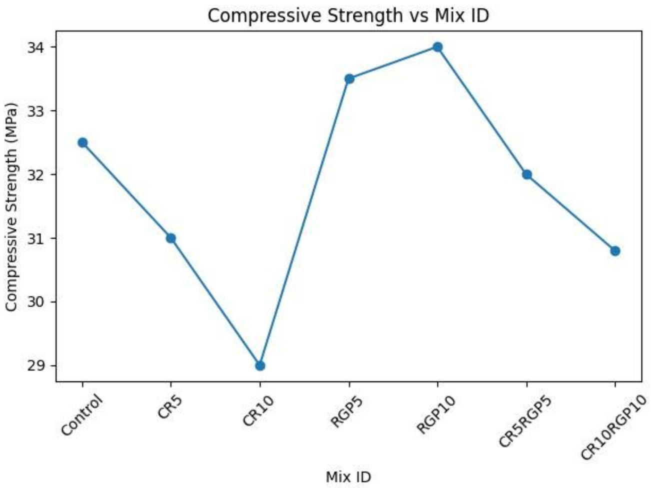

Figure-1:Compressive Strength vs Mix ID

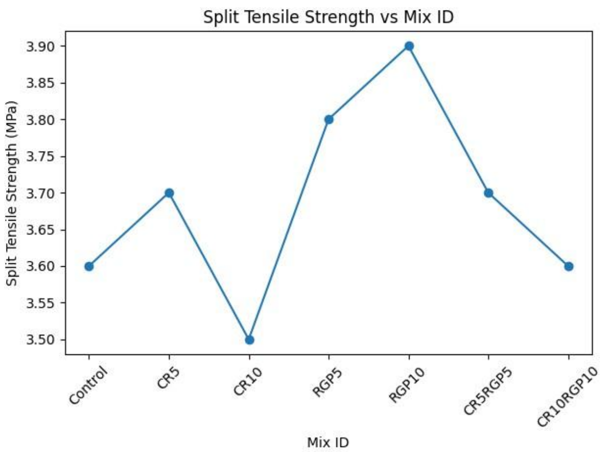

Figure-2: Split Tensile Strength vs Mix ID

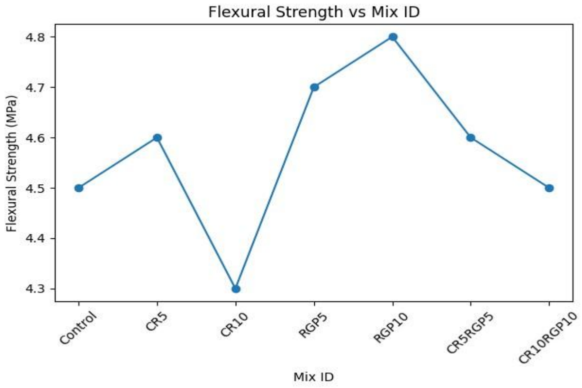

Figure-3: Flexural Strength vs Mix ID

4.3 Durability Performance

4.3.1 Water Absorption, Permeability, Freeze-Thaw Resistance

Water absorption increased slightly with CR content due to higher air void content, but RGP replacement reduced porosity, enhancing durability (Singh et al., 2021). Hybrid mixes demonstrated intermediate water absorption values, indicating improved pore structure compared to CR-only mixes.

Permeability, measured through chloride ion penetration, decreased in mixes containing RGP due to densification of the microstructure. CR alone increased permeability slightly, but hybrid mixes showed a compromise between ductility and permeability resistance.

Freeze-thaw resistance tests indicated that CR improved energy absorption under cyclic loading, reducing surface cracking, while RGP enhanced compressive strength retention. The combination in hybrid mixes produced concrete with improved resistance to both physical and chemical deterioration compared to single-material mixes.

Table-4: Durability Properties of Concrete

Mix ID	Water Absorption (%)	Chloride Penetration (Coulombs)	Freeze-Thaw Mass Loss (%)
Control	4.2	2100	1.5
CR5	4.5	2200	1.2
CR10	4.8	2300	1.0
RGP5	4.0	2000	1.4
RGP10	3.8	1950	1.3
CR5RGP5	4.1	2050	1.1
CR10RGP10	4.4	2100	1.0

5. DISCUSSION

5.1 Mechanical Behavior

5.1.1 Role of CR in Ductility vs RGP in Strength Enhancement

Crumb rubber (CR) contributes primarily to the ductility and toughness of concrete due to its elastic and low-density nature. Rubber particles act as micro-cushions that absorb energy during loading, improving post-crack deformation and impact resistance (Shah and Gupta, 2019). However, the hydrophobic surface of CR limits chemical bonding with the cement matrix, resulting in reduced compressive strength at higher replacement levels. In contrast, recycled glass powder (RGP) enhances strength by participating in pozzolanic reactions, producing additional calcium silicate hydrate (C-S-H) that densifies the cementitious matrix (Ali et al., 2020). The filler effect of finely ground RGP also reduces microvoids, contributing to higher compressive and flexural strength.

5.1.2 Analysis of Synergistic Effects on Performance

Hybrid concrete incorporating both CR and RGP demonstrated a balanced mechanical performance. Moderate replacement levels (10% CR + 10% RGP) achieved compressive strength close to control mixes while enhancing ductility, indicating a synergistic effect. CR mitigates brittleness associated with RGP-rich mixes, whereas RGP compensates for the strength loss due to CR inclusion. This synergy ensures that hybrid concrete retains adequate strength while gaining improved toughness, making it suitable for non-structural and semi-structural applications (Topcu, 2019).

5.2 Durability Implications

5.2.1 Benefits and Limitations under Environmental Exposure

Durability tests indicate that hybrid concrete can improve long-term performance. RGP reduces water absorption and chloride penetration due to densified microstructure, enhancing resistance to chemical attack (Singh et al., 2021). CR inclusion improves resistance to freeze-thaw cycles because the elastic rubber particles absorb stresses caused by volume changes. However, excessive CR (>15%) can increase porosity and permeability, limiting durability under aggressive environmental conditions. The hybrid approach balances these effects, providing moderate permeability and improved freeze-thaw performance, suitable for climates with temperature variations and moderate chloride exposure.

5.3 Environmental and Sustainability Assessment

5.3.1 Reduction in Natural Sand Usage

Replacing fine aggregate with CR and RGP contributes to resource conservation by reducing natural sand extraction. In India, sand depletion due to construction is a significant environmental concern (Kumar et al., 2020). Hybrid concrete achieves up to 20% reduction in natural sand consumption while maintaining mechanical and durability performance, supporting sustainable construction practices.

5.3.2 Waste Management Efficiency of CR and RGP Incorporation

Utilization of end-of-life tires and post-consumer glass in concrete provides an effective waste management solution, diverting large volumes from landfills. The hybrid use maximizes environmental benefits by simultaneously addressing two major waste streams, contributing to circular economy objectives in construction (Pacheco-Torgal et al., 2013).

5.4 Comparison with Literature

5.4.1 Alignment or Contrast with Previous Studies

The observed mechanical and durability behavior aligns with previous findings on CR and RGP concrete. Single CR replacements show improved ductility but reduced compressive strength, while RGP replacements enhance strength and reduce permeability (Ali et al., 2020; Shah and Gupta, 2019). Hybrid concrete studies are limited, but available research indicates similar synergistic effects, confirming that combined waste replacement can offset the drawbacks of individual materials (Topcu and Sengel, 2018). Compared to prior studies, the present results demonstrate optimal performance at lower replacement levels, suggesting that careful proportioning is key to achieving balanced mechanical, durability, and environmental outcomes.

6. CONCLUSION

This study investigated the hybrid replacement of fine aggregate with crumb rubber (CR) and recycled glass powder (RGP) in M30-grade concrete and analyzed its effects on fresh, mechanical, and durability performance. The results indicate that CR enhances ductility and post-crack toughness, whereas RGP contributes to strength development and durability through its pozzolanic activity and filler effect. Hybrid concrete mixes combining CR and RGP demonstrated synergistic performance, mitigating the compressive strength loss associated with CR-only mixes while retaining improved ductility. The optimal combination of 10% CR and 10% RGP achieved approximately 95% of control compressive strength, maintained adequate tensile and flexural strength, and exhibited enhanced freeze-thaw resistance and moderate permeability, balancing mechanical and durability properties. Workability decreased slightly with higher CR content but remained within acceptable limits for practical applications. These findings suggest that hybrid CR-RGP concrete offers an effective approach for sustainable construction by reducing reliance on natural sand, utilizing industrial and municipal waste, and providing concrete with balanced performance characteristics. The study provides a foundation for future research on scaling up hybrid waste concrete for real-world applications and integrating it into eco-friendly construction practices.

6.1 Limitations of Study

The present research was limited to laboratory-scale M30-grade concrete, and the findings may vary under field conditions. Only specific replacement levels of CR (5–15%) and RGP (5–15%) were considered, leaving unexplored combinations that could further optimize performance. Long-term durability under aggressive environmental exposure, including sulfate attack, carbonation, and prolonged chloride ingress, was not assessed. The study also did not evaluate the economic feasibility or life-cycle assessment of hybrid concrete. Additionally, the effects of different CR particle sizes, surface treatments, and glass powder fineness were not systematically studied. Therefore, while the results demonstrate promising mechanical and durability benefits, further research is required to establish comprehensive guidelines for large-scale implementation and long-term structural performance of hybrid CR-RGP concrete.

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