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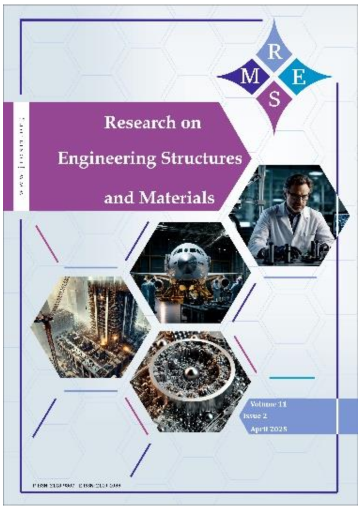

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Research Article

Recycled fine aggregate as a sustainable alternative to natural sand: Challenges, enhancement strategies, and performance evaluation

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Abstract

This study presents a systematic experimental investigation on the feasibility of using recycled fine aggregate (RFA) as a partial to full replacement of natural fine aggregate in structural concrete. Concrete mixtures were prepared with RFA replacement levels ranging from 0% to 100%, and their fresh, mechanical, and durability properties were evaluated. Compressive strength decreased by approximately 17.3% at 100% RFA replacement (from 38.19 MPa to 31.58 MPa), while split tensile strength showed a higher reduction of about 20.3% (from 3.16 MPa to 2.52 MPa). Compressive strength showed the least sensitivity to RFA incorporation, followed by flexural strength, while split tensile strength exhibited the highest sensitivity due to its dependence on interfacial transition zone quality. Statistical analysis confirmed strong linear correlations and significant relationships between RFA content and strength reduction. Durability performance assessed through water absorption increased by approximately 51% and sorptivity by about 38% at 40% RFA, while sharper increases were observed only at higher replacement levels (≥60%). Compressive, split tensile and flexural strength reduction below 7%, 12%, and 8% respectively, which remain within acceptable limits for structural-grade concrete. The combined results suggest that RFA can be effectively utilized as a sustainable alternative to natural sand at moderate replacement levels. The findings contribute to performance-based guidelines for RFA utilization and support its application in sustainable and circular concrete construction practices.

1. Introduction

During The rapid expansion of infrastructure and urban development has led to an unprecedented demand for natural fine aggregates, particularly river sand, which is a critical constituent of concrete. Excessive extraction of river sand has resulted in severe environmental consequences, including riverbed degradation, loss of aquatic ecosystems, lowering of groundwater tables, and increased erosion. In many regions, unregulated sand mining has also triggered legal restrictions and supply shortages, creating a growing material crisis for the construction industry. Consequently, identifying alternative fine aggregate sources has become an urgent necessity to ensure sustainable concrete production [1–3]. River sand is a widely used fine aggregate in concrete, but its excessive extraction has resulted in riverbed degradation, environmental imbalance, and supply shortages. At the same time, global construction and demolition waste (CDW) continues to grow, creating disposal challenges. Among the potential alternatives, RFA

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derived from CDW has emerged as a promising substitute for natural fine aggregate. The utilization of RFA not only reduces dependence on diminishing sand resources but also addresses the increasing challenge of CDW disposal by diverting waste from landfills [35-36]. Since fine aggregates constitute approximately 25–35% of the total concrete volume, even partial replacement of natural sand with recycled fines can lead to significant reductions in environmental impact, embodied energy, and raw material consumption [4,5]. Therefore, RFA represents a strategic material within the broader framework of sustainable and circular construction practices [6–9].

Despite these sustainability advantages, the widespread use of RFA in structural concrete remains limited due to several inherent technical challenges. Recycled fine aggregates typically contain adhered old mortar, microcracks, and a higher proportion of porous particles compared to natural sand [10–12]. These characteristics result in higher water absorption, lower density, increased porosity, and weaker particle–paste bonding, which adversely affect fresh, mechanical, and durability properties of concrete [13,14]. In particular, the quality of the interfacial transition zone (ITZ) between recycled fines and newly formed cement paste is often inferior, leading to reduced strength and increased permeability [15,16]. As a result, concrete incorporating high proportions of untreated RFA generally exhibits lower compressive strength, reduced tensile resistance, and inferior durability performance [17].

To mitigate these drawbacks, numerous studies have explored enhancement strategies for improving the performance of RFA concrete. Reported approaches include pre-soaking or moisture conditioning, mechanical beneficiation to remove loose adhered mortar, thermal and chemical treatments, carbonation curing, and the incorporation of supplementary cementitious materials such as silica fume, fly ash, and ground granulated blast-furnace slag. These techniques aim to reduce water absorption, densify the ITZ, refine pore structure, and improve aggregate–paste bonding [18,19]. Existing literature generally agrees that, with appropriate mix design and treatment methods, RFA can replace natural sand at moderate levels (typically 20–40%) without significant loss of mechanical performance, while higher replacement levels often result in pronounced deterioration unless advanced optimization measures are applied [20].

However, despite the growing body of research, several gaps remain. Many studies focus either on mechanical performance or durability characteristics in isolation, while comprehensive evaluations combining fresh properties, mechanical strength, durability indicators, and statistical analysis across a wide range of replacement levels are relatively limited [21-22]. In addition, the majority of published work emphasizes recycled coarse aggregates, whereas recycled fine aggregates—owing to their higher surface area and sensitivity to pore structure—require more focused investigation [23]. Clear performance-based justification for identifying an optimal RFA replacement level suitable for structural concrete is still lacking. Microstructural observations using SEM and X-ray techniques have also provided evidence of ITZ densification and reduced crack propagation in modified RFA-based concrete mixtures [24].

It is important to emphasize that RFA differs substantially from recycled coarse aggregate (RCA) in terms of mineral phases, particle morphology, and surface characteristics. While RCA typically contains large, adhered mortar patches that can be physically removed by abrasion or thermal treatment, RFA has a much higher specific surface area and finer, adhered micro-mortar layers that are difficult to detach solely through mechanical techniques [25,26]. Consequently, RFA is more sensitive to surface-chemistry modification, moisture conditioning, and the addition of supplementary cementitious materials than RCA. Therefore, direct extrapolation of RCA treatment findings to RFA may be inappropriate without comprehensive investigation of RFA-specific behavior. The literature also indicates that fines content smaller than 150 μm plays a decisive role in determining packing density, micro-pore structure, and long-term shrinkage properties, requiring precise control of particle gradation and mixture proportioning [27,28].

Another significant challenge associated with RFA utilization is the high heterogeneity across recycling sources, parent concrete grades, and crushing processes. This inconsistency often leads to conflicting conclusions in reported results and hinders standardization efforts. For example, recycled sand obtained from high-strength concrete demolitions may demonstrate comparatively superior performance than RFA derived from low-grade demolished concrete [29].

RFA can substitute a significant percentage of natural sand in mortar and concrete, but its higher porosity, water absorption, and variability still limit full-scale structural use without proper quality control and enhancement treatments. The purpose of the present study, emphasizing the experimental evaluation of mechanically processed RFA (obtained through crushing and screening) and its effects on fresh, mechanical, and durability properties of concrete. [30].

Similarly, industrial secondary crushing and controlled screening processes generally produce higher-quality recycled fines than rudimentary field-based crushing. Therefore, standardized characterization protocols and classification systems are essential to ensure reliable quality assessment and consistent use of RFA in concrete. Recent studies have begun proposing performance-based acceptance criteria focused on water absorption, particle density, fines content, and mortar content, but comprehensive, universal guidance remains insufficient.

Considering these research gaps, the primary objective of the study is to investigate the physical, mechanical, and durability performance of concrete incorporating RFA under controlled replacement ratios. Therefore, the present study focuses on evaluating the effects of RFA incorporation on fresh properties, mechanical characteristics, and durability behavior of concrete mixtures [31]. The outcomes are expected to contribute to establishing performance-based utilization strategies and to providing a scientific basis for recommending optimal replacement levels of RFA in sustainable concrete applications [32-34].

2. Objective of The Study Using RFA

In this context, the present study aims to systematically evaluate the feasibility of using RFA as a partial to full replacement of natural fine aggregate in concrete. The study investigates the effects of RFA incorporation on workability, compressive strength, split tensile strength, flexural strength, water absorption, and sorptivity, supported by regression and statistical analyses to establish quantitative relationships between RFA content and performance degradation. By integrating mechanical and durability perspectives, this research seeks to identify a performance-based optimal replacement level for RFA and to provide practical guidance for its application in sustainable concrete construction.

3. Materials and Methods

3.1 Cement

Portland Pozzolana Cement (PPC) conforming to the relevant Indian Standards was used as the binding material in this study. The cement was tested in the laboratory prior to use, and its specific gravity was determined to be 3.12. All concrete mixtures were prepared using the same batch of cement to eliminate variability arising from material differences.

3.2 Natural Fine Aggregate

Natural fine aggregate consisted of river sand conforming to Zone II grading as per IS 383. The sand was clean, free from organic impurities, and oven-dried prior to testing. Physical properties such as specific gravity, water absorption, bulk density, and fineness modulus were determined in accordance with standard test procedures and are reported in Table 1.

3.3 Recycled Fine Aggregate

3.3.1 Source of Construction and Demolition Waste

The recycled fine aggregate was produced exclusively from demolished concrete waste, obtained from reinforced concrete structural elements of residential/commercial buildings. No brick masonry, mortar debris, tiles, or mixed construction waste was included. The parent concrete was estimated to be of M25 grade, based on available construction records and field assessment, with an approximate service age of 20–25 years.

3.3.2 Crushing Procedure

The demolished concrete was initially broken into manageable sizes and subjected to mechanical crushing using a laboratory-scale jaw crusher for primary size reduction. Crushing was conducted in a controlled manner to limit excessive generation of ultra-fine particles and to preserve aggregate morphology as much as possible. No secondary chemical, thermal, or carbonation-based treatment was applied at any stage.

3.3.3 Screening and Processing

The crushed material was subsequently screened using standard sieves, and particles passing the 4.75 mm sieve were collected as recycled fine aggregate. Oversized particles were discarded or re-crushed. The screened RFA was air-dried and stored in sealed containers to prevent moisture variation prior to testing and concrete production.

The RFA was used in its untreated, mechanically processed state, representing realistic field conditions commonly encountered in practical recycling operations.

3.3.4 Physical Properties of RFA

The recycled fine aggregate exhibited lower density and higher water absorption compared to natural sand due to the presence of adhered old mortar and micro-porosity introduced during crushing. The physical properties of NFA and RFA, including specific gravity, water absorption, bulk density, and fineness modulus, were determined in accordance with IS 2386 (Part I): Methods of Test for Aggregates for Concrete – Particle Size and Shape and IS 2386 (Part III): Methods of Test for Aggregates for Concrete – Specific Gravity, Density, Voids, Absorption, and Bulking. The measured properties of RFA, including specific gravity, water absorption, bulk density, and fineness modulus, are presented alongside those of NFA in Table 1. These properties directly reflect the parent concrete quality and the adopted crushing and screening process.

Table 1. Physical properties of fine aggregates

Property	NFA	RFA
Specific gravity	2.65	2.45
Water absorption (%)	1.3	8.12
Bulk density (kg/m^3)	1645	1540
Fineness modulus	2.76	3.05

It is noted that the RFA exhibited a significantly higher water absorption (8.12%) compared to NFA (1.3%), primarily due to the presence of adhered old mortar and increased porosity. To mitigate the influence of this high absorption on the effective water–cement ratio and workability, both NFA and RFAs were brought to a Saturated Surface Dry (SSD) condition prior to concrete mixing.

No additional mixing water was added to compensate for aggregate absorption, and the designed water–cement ratio was maintained constant for all mixtures. This procedure ensured uniform moisture conditions and reliable comparison of concrete performance across different RFA replacement levels.

3.4 Coarse Aggregate

Crushed granite coarse aggregate of 20 mm and 10 mm nominal sizes was used. The aggregates were angular, clean, and free from deleterious materials. All coarse aggregates conformed to IS 383 requirements. Physical properties such as specific gravity and water absorption IS 2386 (Part I) were determined prior to mix design.

3.5 Water and Chemical Admixture

Potable water suitable for drinking was used for both mixing and curing of concrete. A polycarboxylate ether (PCE)–based superplasticizer was employed to achieve the desired workability while maintaining a constant water–cement ratio across all mixtures. The following properties of the PCE–based superplasticizer are:

- Physical form: Liquid
- Density: ~1.08–1.10 g/cm^3
- Solid content: ~30% (±2%)
- Recommended dosage range: 0.6–1.2% by weight of cement

These values are typical of commercially available PCE-based high-range water reducers and are sufficient for reproducibility without disclosing proprietary product names. A baseline superplasticizer dosage of 0.8% (by weight of cement) was adopted for the control mix and the dosage was not adjusted to achieve constant slump as the RFA content increased. This approach was intentionally selected to evaluate the inherent effect of RFA incorporation on fresh concrete behavior under a constant water–cement ratio. No additional mixing water was added.

3.6 Concrete Mix Proportions

Concrete was designed for M30 grade using standard mix design procedures. Natural fine aggregate was partially or fully replaced with recycled fine aggregate at 0%, 20%, 40%, 60%, and 100% by weight. The same cement content, water–cement ratio, and coarse aggregate content were maintained for all mixes to isolate the effect of RFA replacement. Minor dosage adjustments of superplasticizer were made to maintain workable consistency.

3.7 Specimen Preparation and Curing

Concrete was mixed in a laboratory pan mixer. Dry materials were first blended to ensure uniformity, followed by the addition of water and superplasticizer. Fresh concrete was cast into moulds in layers and compacted using a table vibrator. Specimens were demoulded after 24 hours and cured in water at room temperature until the age of testing.

3.8 Test Methods

- Workability was assessed using the slump test in accordance with relevant standards.
- Compressive strength was determined on 150 mm cube specimens at 28 days using a 2000 kN compression testing machine.
- Split tensile strength was measured on cylindrical specimens.
- Flexural strength was evaluated using prism specimens under third-point loading.
- Water absorption and sorptivity tests were conducted to assess durability-related performance.

Each reported value represents the average of at least three specimens to ensure reliability of results.

3.9 Statistical Analysis

To improve result reliability and quantify the influence of RFA content, statistical analyses including correlation analysis, linear regression, and one-way ANOVA were performed. These analyses were used to evaluate the significance of strength reduction trends and to establish statistically supported relationships between RFA replacement level and concrete performance.

4. Concrete Mix Proportions

Concrete was designed for M30 grade in accordance with standard mix design procedures. The water–cement ratio was maintained constant at 0.45 for all mixtures to isolate the effect of RFA replacement. NFA was replaced by recycled fine aggregate at 0%, 20%, 40%, 60%, and 100% by weight. Cement content, water content, and coarse aggregate content were kept constant for all mixes. A polycarboxylate ether–based superplasticizer was used to maintain workable consistency. The detailed mix proportions per cubic meter of concrete are presented in Table 2.

Table 2. Mix proportions per cubic meter of concrete

Mix ID	RFA Replacement (%)	Cement (kg/m^3)	Water (kg/m^3)	w/c Ratio	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	Superplasticizer (% of cement)
M0	0	400	180	0.45	650 (NFA)	1180	0.8
M20	20	400	180	0.45	520 NFA + 130 RFA	1180	0.8
M40	40	400	180	0.45	390 NFA + 260 RFA	1180	0.9
M60	60	400	180	0.45	260 NFA + 390 RFA	1180	1.0
M100	100	400	180	0.45	650 (RFA)	1180	1.1

5. Concrete Properties

5.1 Fresh Concrete Properties

The slump value decreased progressively from 110 mm for the control mix to 97 mm, 84 mm, 72 mm, and 57 mm for concrete containing 20%, 40%, 60%, and 100% RFA, respectively, as illustrated in Figure 1. The progressive reduction in slump from 110 mm for the control mix to 57 mm at 100% RFA replacement can be directly attributed to the intrinsic physical characteristics of RFA. RFA exhibits a significantly higher water absorption capacity (8.12%) compared to natural sand (1.3%). Despite using aggregates in SSD condition, the porous adhered old mortar associated with RFA increases internal water demand and reduces the availability of free water for lubrication of the cementitious matrix, leading to lower consistency.

In addition, RFA particles possess rougher surfaces, angular shapes, and micro-cracks generated during the crushing process. These characteristics increase internal friction and inter-particle interlocking within the fresh concrete, further restricting flowability. The combined effect of high-water absorption and unfavorable particle morphology explains the pronounced loss of workability with increasing RFA content, even under constant water–cement ratio and controlled admixture dosage.

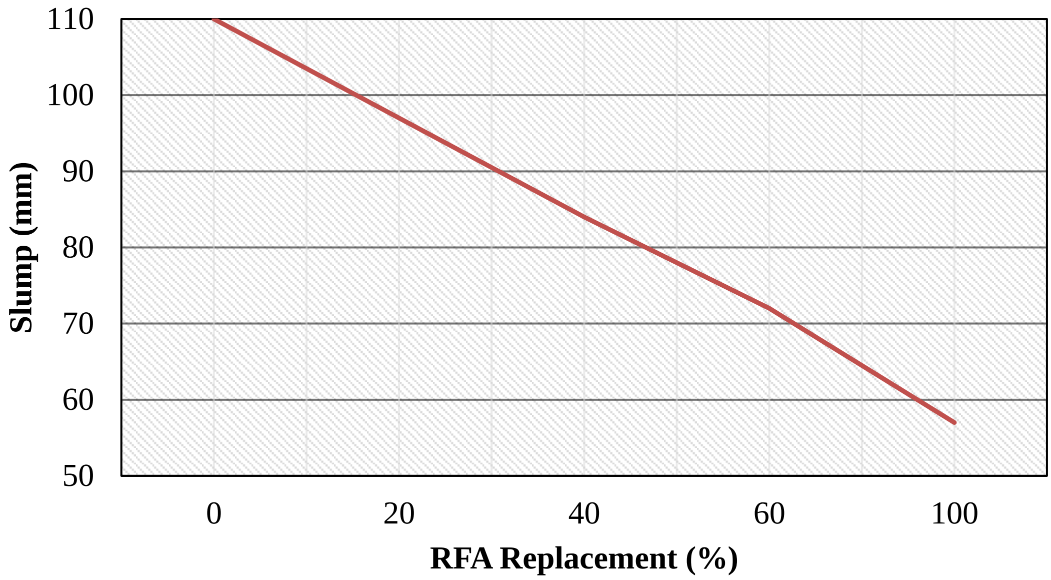

Fig. 1. Slump vs RFA Content

5.2. Hardened Concrete Properties

5.2.1 Compressive Strength

The 28-day compressive strength decreased progressively from 38.19 MPa (0% RFA) to 36.94 MPa, 35.61 MPa, 33.82 MPa, and 31.58 MPa for concrete containing 20%, 40%, 60%, and 100% RFA, respectively, as illustrated in Figure 2. For each RFA replacement level, compressive strength was determined as the average of three cube specimens tested at 28 days. The standard deviation and coefficient of variation (COV) were calculated separately for each mixture, rather than combining data across different replacement levels. This approach ensures statistically meaningful interpretation and allows assessment of variability associated with increasing RFA content. The reduction in compressive strength increases progressively with RFA replacement is presented in Table 3 and Figure 2.

Table 3: Compressive strength at 28 days

RFA (%)	Mean Strength (MPa)	Standard Deviation (MPa)	Standard Reduction (%)	COV (%)
0	38.19	1.12	-	2.93
20	36.94	1.35	3.27	3.65
40	35.61	1.58	6.75	4.44
60	33.82	1.92	11.44	5.68
100	31.58	2.21	17.31	7.00

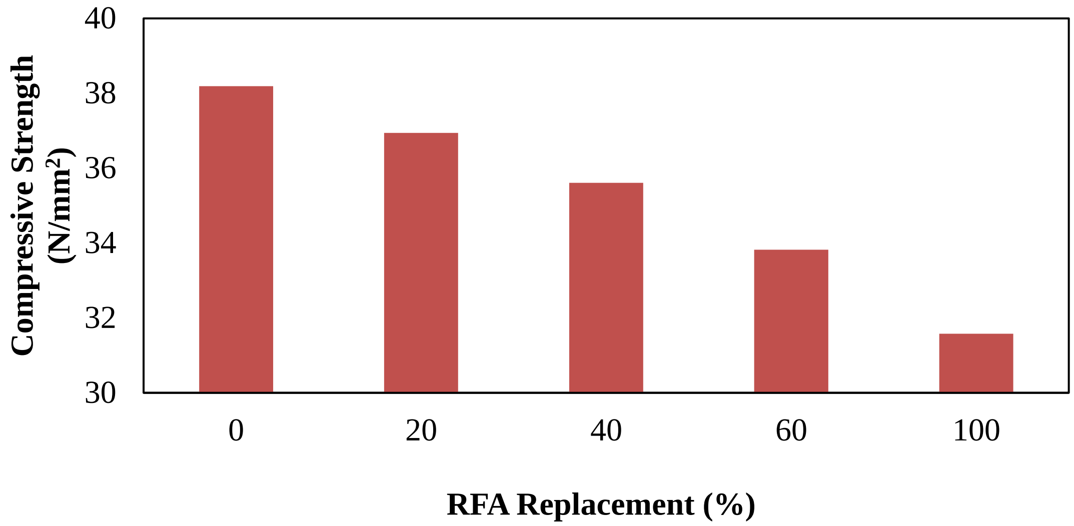

Fig. 2. Compressive Strength vs RFA Content

The correlation analysis performed and the Pearson correlation coefficient (r) = −0.99. This indicates a very strong negative correlation, confirming that compressive strength decreases almost linearly with increasing RFA content. A linear regression model describing the relationship between compressive strength and RFA content is;

$$f_c=38.46-0.067(RFA\%) \tag{1}$$

The coefficient of determination (R^2) = 0.98. Approximately 98% of the variation in compressive strength is described by RFA replacement percentage, indicating excellent predictive reliability. Regression analysis confirms that the influence of RFA content on compressive strength is statistically significant ($p < 0.05$).

The ANOVA results confirm that RFA replacement has a significant influence on the compressive strength of concrete. The regression sum of squares accounts for most total variation, while the residual error remains very small, indicating a strong and reliable relationship between RFA percentage and strength reduction. By using the ANOVA the effect of RFA content on compressive strength is presented in Table 4.

Table 4. Effects of RFA content on Compressive Strength using ANOVA

Source of Variation	Degrees of Freedom (df)	Sum of Squares (SS)	Mean Square (MS)	F-value	p-value
Regression (RFA %)	1	28.96	28.96	147.9	< 0.001
Residual (Error)	3	0.59	0.20	—	—
Total	4	29.55	—	—	—

The statistical interpretation for the F-value (147.9) is much higher than the critical F-value at 95% confidence. The p-value < 0.001 indicates that the effect of RFA replacement on compressive strength is highly statistically significant. More than 98% of the total variation in compressive strength is explained by RFA content.

The statistically significant F-value demonstrates that changes in compressive strength are not due to random variation but are directly associated with RFA replacement level. The small residual error indicates consistent experimental results and validates the linear regression model. These findings confirm that RFA content is a dominant parameter controlling compressive strength. From an engineering perspective, the results support the use of RFA up to moderate replacement levels, where strength loss remains controlled and predictable. Higher replacement levels, while statistically valid, result in notable strength reduction and limited to non-structural concrete applications.

The compressive strength of concrete decreases steadily with increasing RFA replacement. The control mix achieved the highest strength of 38.19 MPa, while concrete with 100% RFA recorded 31.58 MPa. Strength reduction remained below 7% up to 40% RFA replacement, demonstrating acceptable performance within this range. Statistical indicators, including low coefficient of variation, strong negative correlation, and high coefficient of determination, confirm consistent and predictable strength behavior.

The decrease in compressive strength with increasing RFA. This occurs due to the higher porosity, lower particle strength, and presence of adhered old mortar in RFA, which weaken the interfacial transition zone. At lower replacement levels (≤40%), these adverse effects are limited, allowing the concrete to maintain strength comparable to conventional mixes. At higher replacement levels (≥60%), increased void content and microcracking result in more pronounced strength loss. The strong linear relationship observed suggests that compressive strength reduction due to RFA incorporation is predictable and can be effectively managed through optimized mix design. Overall, the results support the sustainable use of RFA up to moderate replacement levels in structural concrete, while higher replacement ratios may be more suitable for non-structural applications.

The gradual increase in COV with increasing RFA content indicates higher heterogeneity and variability at higher replacement levels, which is attributable to the porous and heterogeneous nature of recycled fine aggregates.

5.2.2 Split Tensile Strength

The split tensile strength of concrete decreased progressively with increasing recycled fine aggregate content. The control mix achieved a tensile strength of 3.16 MPa, while concrete incorporating 100% RFA recorded a value of 2.52 MPa, corresponding to an overall reduction of approximately 20.25%. Up to 40% RFA replacement, the reduction remained below 12%, indicating acceptable tensile performance for structural applications. The results are presented in Table 5 and Fig. 3.

The reduction in split tensile strength with increasing RFA content is primarily governed by crack initiation and propagation mechanisms. Cracks tend to initiate at the aggregate–paste interface, where recycled fine aggregates exhibit weaker bonding due to adhered old mortar and higher porosity. At lower replacement levels, the presence of natural sand helps maintain effective stress transfer across the matrix, limiting crack growth. As the RFA content increases, the cumulative effect of porous particles facilitates easier crack propagation, resulting in reduced tensile resistance. This behavior explains the gradual decline in split tensile strength observed with increasing RFA replacement.

Table 5: Split tensile strength (MPa)

RFA	0%	20%	40%	60%	100%
Strength (N/mm^2)	3.16	2.97	2.81	2.68	2.52
Strength Reduction (%)	-	6.01	11.08	15.19	20.25

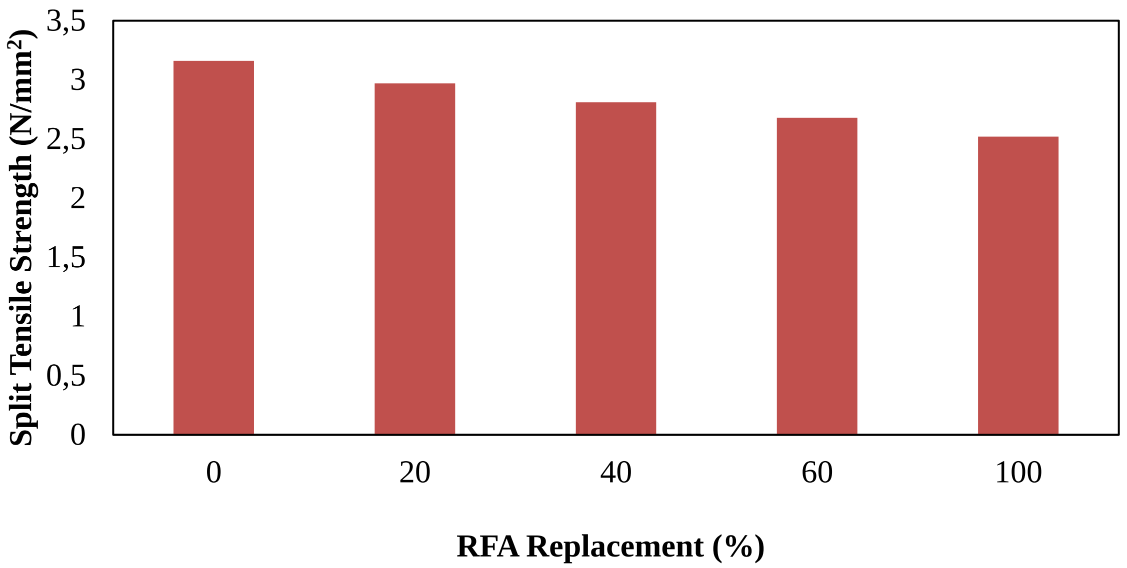

Fig 3. Split tensile strength vs RFA content

5.2.3 Flexural Strength

The flexural strength of concrete decreased gradually with increasing RFA. The control mix exhibited a flexural strength of 4.63 MPa, while concrete containing 100% RFA recorded a value of 3.82 MPa, corresponding to an overall reduction of approximately 8.0%. Up to 40% RFA replacement, the reduction remained below 5%, indicating relatively good flexural performance. The results are presented in Table 6 and Fig.4.

Table 6. Flexural strength (MPa)

RFA	0%	20%	40%	60%	100%
Modulus of Rupture (N/mm^2)	4.63	4.41	4.28	4.01	3.82
Reduction in MOR (%)	-	4.75	7.56	13.39	17.49

The gradual reduction in flexural strength can be attributed to the lower density and higher porosity of RFAs, as evidenced by their reduced specific gravity and higher water absorption compared to natural sand. These characteristics weaken the aggregate–paste bond and reduce resistance to tensile stresses developed under bending. Nevertheless, the absence of abrupt strength loss indicates that flexural performance deteriorates progressively with increasing RFA content rather than exhibiting sudden degradation.

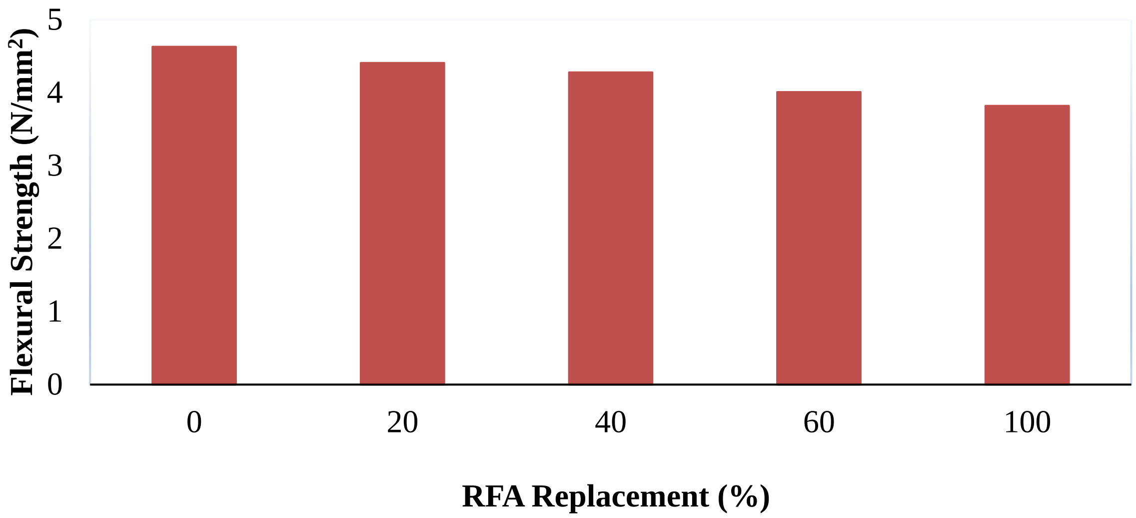

Fig. 4. Flexural strength vs RFA sontent

The gradual reduction in modulus of rupture with increasing RFA content is linked to the weaker ITZ and higher porosity associated with RFA. Flexural strength is governed by the tensile behavior of concrete under bending, making it particularly sensitive to microcracks, voids, and aggregate–paste bonding quality.

At lower RFA replacement levels (≤40%), the presence of natural fine aggregates dominates the matrix, ensuring effective stress transfer and crack-bridging capability. Consequently, the reduction in flexural strength is moderate and does not significantly compromise structural performance. This behavior suggests that partial replacement of natural sand with RFA can be adopted without severe loss of bending resistance.

At higher replacement levels (≥60%), the increased proportion of recycled fines introduces more adhered old mortar and micro-defects, which accelerate crack initiation and propagation under flexural loading. This leads to a more pronounced reduction in modulus of rupture. However, the strength reduction remains gradual rather than abrupt, indicating a progressive reduction trend rather than an abrupt loss of strength.

Overall, the results demonstrate that RFA can be safely incorporated up to 40% replacement in concrete where flexural performance is a design consideration. Higher replacement levels viable for non-structural elements.

Regression analysis reveals a strong linear relationship between water absorption and sorptivity, with a coefficient of determination of $R^2 = 0.95$. The corresponding Pearson correlation coefficient ($r = 0.97$) indicates a very strong positive correlation, confirming that increased pore connectivity associated with recycled fine aggregate content governs both capillary suction and bulk water absorption behavior.

5.3 Mechanism on Mechanical Strength

Although microstructural investigations such as SEM analysis were not conducted in the present study, the observed reduction in mechanical strength can be consistently explained using the experimentally measured physical properties of recycled fine aggregate. As shown in Table 1, RFA exhibits lower specific gravity and significantly higher water absorption compared to natural fine aggregate, indicating a more porous internal structure associated with adhered old mortar.

The progressive reduction in compressive, split tensile, and flexural strengths with increasing RFA content therefore aligns with these material characteristics, confirming that the higher porosity and reduced particle integrity of RFA weaken the load-transfer mechanism within the concrete matrix. This indirect evidence, combined with consistent trends reported in the literature, supports the interpretation that strength loss is governed by the inherent physical nature of recycled fine aggregates rather than experimental variability.

IS 383:2016 currently permits the use of recycled concrete aggregate in reinforced concrete construction with a maximum replacement level of 20%, and restricts its application to concrete grades up to M25. These provisions are intentionally conservative and are based on ensuring reliability across a wide range of material sources, construction practices, and exposure conditions.

In contrast, the present study experimentally observed that concrete incorporating up to 40% untreated RFA achieved acceptable fresh, mechanical, and short-term durability performance for M30-grade concrete under controlled laboratory conditions. It is important to emphasize that this finding represents a performance-based observation, not a recommendation to override existing code limits.

The discrepancy between the experimental results and the prescriptive limits of IS 383:2016 highlights the fundamental difference between code-based conservative provisions and controlled experimental evaluations. Indian Standards are formulated to ensure safety and durability under diverse field conditions, including variability in recycled aggregate quality, limited quality control, and long-term exposure effects such as shrinkage, carbonation, and chloride ingress, which were not fully addressed in the present study.

6. Durability Properties

6.1 Water Absorption

Water absorption increases steadily with increasing RFA content. The control concrete exhibited the lowest absorption of 2.15%, while concrete with 100% RFA showed a maximum absorption of 4.67%, representing an overall increase of roughly 117% compared to the control concrete. The results are presented in Fig.5.

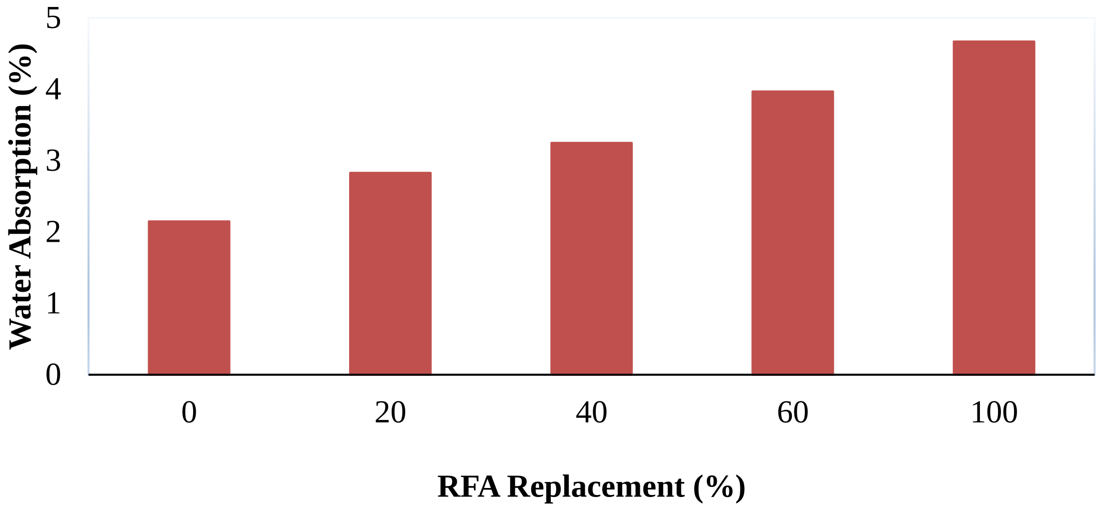

Fig. 5. Water absorption vs RFA content

The progressive increase in water absorption with increasing RFA content is primarily attributed to the inherent porous nature of recycled fines and the occurrence of adhered old mortar on their surfaces. These characteristics introduce additional capillary pores into the concrete matrix, leading to higher water uptake compared to conventional concrete made with natural sand.

Although the water absorption increased by approximately 51% at 40% RFA replacement, the absolute absorption value (3.25%) remained within acceptable limits for structural concrete. The relatively controlled increase suggests that partial substitution of natural sand with RFA does not significantly compromise durability-related properties at these levels. However, at higher replacement levels (≥60%), a substantial rise in water absorption is observed. This behavior indicates the formation of a more interconnected pore network due to increased recycled fine content, which can facilitate moisture ingress and potentially accelerate durability-related deterioration mechanisms such as carbonation and chloride penetration.

The strong correlation between increasing water absorption and decreasing mechanical strengths observed in RFA concrete highlights the critical role of pore structure and interfacial transition zone quality. Although full replacement leads to a noticeable increase in absorption, the values remain within acceptable limits for non-structural applications. These findings suggest that RFA replacement up to 40% offers a practical balance between sustainability and durability, while higher replacement levels require mix optimization strategies such as the use of supplementary cementitious materials or pore-refining admixtures to mitigate permeability concerns. The measured water absorption values remained below 5%, which is generally considered acceptable for structural concrete based on durability performance criteria adopted in standard practice (IS-based evaluation).

6.2 Sorptivity

Sorptivity values increase consistently with increasing RFA content. The control concrete exhibited the lowest sorptivity of 0.094, whereas concrete with 100% RFA showed the highest value of 0.169, corresponding to an overall increase of approximately 80%. The experimental results are presented in Fig.6. Up to 40% RFA replacement, sorptivity remains below 0.13, indicating relatively controlled capillary water ingress.

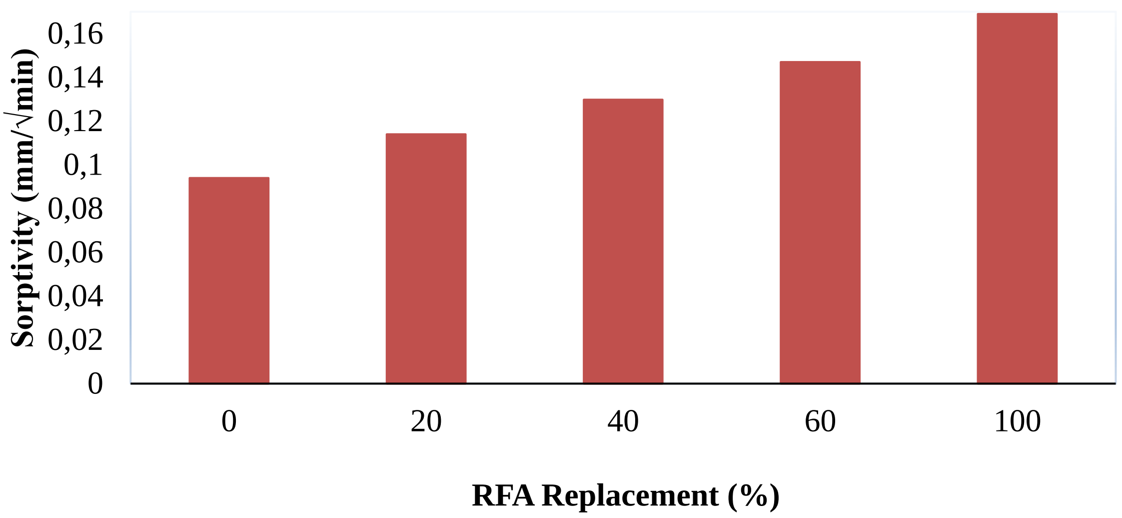

Fig. 6. Sorptivity vs RFA content

The observed increase in sorptivity with increasing recycled fine aggregate content is primarily attributed to the higher porosity and water absorption capacity of recycled fines, resulting from adhered old mortar and microcracks on their surfaces. Sorptivity reflects the rate of capillary suction, which is highly sensitive to pore connectivity and surface roughness of aggregates.

Although sorptivity increased by approximately 38% at 40% RFA replacement, the absolute sorptivity value (0.1298 mm/min^{0.5}) remained relatively low and within commonly accepted durability limits for structural concrete. The capillary network remains relatively discontinuous, limiting rapid water ingress. This behavior suggests that partial replacement of natural sand with RFA does not significantly compromise early-age moisture transport properties. However, at higher replacement levels (≥60%), the increase in sorptivity becomes more pronounced due to the formation of a more continuous and interconnected pore network. This enhanced capillary action facilitates faster water movement into the concrete matrix, which may adversely affect long-term durability.

The strong correlation between sorptivity and water absorption observed in RFA concrete confirms that permeability-related properties are governed by similar microstructural mechanisms. Although higher RFA contents increase sorptivity, the gradual nature of the increase indicates predictable durability behavior. Overall, the results suggest that RFA replacement up to 40% provides an acceptable balance between sustainability and durability, while higher replacement levels require additional mix optimization measures such as supplementary cementitious materials or pore-refining admixtures to control capillary water transport.

8. Conclusion

This study investigated the feasibility of incorporating recycled fine aggregate (RFA) as a partial or full replacement of natural fine aggregate in concrete, with emphasis on fresh properties, mechanical performance, durability characteristics, and statistical reliability of the observed trends. Based on the experimental results and subsequent analysis, the following conclusions are drawn:

- The incorporation of RFA resulted in a progressive reduction in workability, primarily due to the higher water absorption, angularity, and rough surface texture of recycled fine aggregates. The observed slump reduction followed a consistent and predictable trend under a constant water–cement ratio and fixed superplasticizer dosage.
- Mechanical properties, including compressive, split tensile, and flexural strengths, decreased gradually with increasing RFA content. Up to 40% RFA replacement, the reduction in strength remained within acceptable limits for structural concrete, whereas higher replacement levels led to more pronounced deterioration due to the porous nature and lower particle integrity of RFA.
- Statistical analysis confirmed that the reduction in mechanical strength parameters exhibited a strong linear relationship with RFA replacement level. Regression and ANOVA results demonstrated that the observed trends were statistically significant, ensuring reliability and consistency of the experimental findings.
- Durability-related properties, namely water absorption and sorptivity, increased with increasing RFA content. Although relative increases were substantial, the absolute values remained within commonly accepted durability limits for structural concrete at replacement levels up to 40%, based on standard performance criteria.
- A strong correlation was established between water absorption and sorptivity, supported by Pearson correlation and regression analysis. This relationship confirms that both parameters are governed by the same pore-structure characteristics introduced by recycled fine aggregates.
- The combined interpretation of mechanical and durability results indicates that strength and durability degradation occur progressively rather than abruptly with increasing RFA content. This predictable behavior supports the controlled use of RFA in concrete without sudden performance loss.
- Overall, the study demonstrates that mechanically processed, untreated RFA can be safely incorporated into concrete at replacement levels up to 40%, offering a sustainable alternative to natural sand while maintaining acceptable mechanical and durability performance under practical conditions.

Future studies incorporating **microstructural characterization** and long-term durability evaluation are recommended to further substantiate the mechanisms governing RFA concrete behavior and to refine performance-based usage limits.

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