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Sustainable Concrete: Exploring Fresh, Mechanical, Durability, and Microstructural Properties with Recycled Fine Aggregates

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Abstract

The growing construction industry and global population have led to increased demand for concrete, resulting in increased waste production. Recycling construction and demolition (C&D) waste as recycled fine aggregates (RFA) in concrete could help reduce waste and conserve natural resources. This research delves into the meticulous examination of particle packing density within specific cylindrical volumes under standard compacting efforts, elucidating an order of compressive strength. The study comprehensively explores various concrete properties, including workability, compressive strength, flexural strength, split tensile strength, drying shrinkage, electrical resistivity, rapid chloride penetration, and microstructural characteristics (analyzed through XRD, SEM, and EDAX). RFA particles, ranging from 0.15 to 4.75 mm, were employed as partial replacements for fine aggregates, with replacement percentages varying from 0% to 100% in increments of 25%. The empirical findings underscore that the incorporation of RFA significantly enhances concrete properties. However, it was observed that surpassing the optimum replacement percentage of 25% (RFA 25) adversely impacts the concrete's strength and microstructure. Specifically, RFA 25 exhibited remarkable improvements, with a 14.75% increase in compressive strength, a 6.61% boost in flexural strength, and a 13.14% enhancement in split tensile strength compared to conventional concrete (RC). Furthermore, RFA 25 demonstrated a 4.16% increment in drying shrinkage, 17.65% higher electrical resistivity, and an 18.83% superior resistance to chloride penetration compared to RC. The analysis of XRD, SEM, and EDAX results elucidated that at lower replacement percentages, the pozzolanic reaction enhances strength by forming additional hydration products. Conversely, at higher replacement levels, strength diminishes.

Keywords

construction and demolished waste, durability properties, recycled fine aggregates, mechanical properties, microstructural properties

1 Introduction

In the 21st century, rapid advancements in construction have led to the creation and demolition of structures, resulting in a significant upswing in construction and demolition (C&D) waste, projected to reach 2.59 billion tonnes by 2030 and 3.40 billion tonnes by 2050 [1]. The disposal of this waste in landfills not only depletes landfill sites but also adversely affects the land. A potential solution lies in repurposing C&D waste as aggregates in fresh concrete production, a sector where aggregates constitute 70-80% of the volume [2]. The demand for concrete is soaring, increasing annually at a rate of 7.7% [3]. To mitigate environmental impact, the global construction industry is increasingly embracing sustainable practices, requiring innovative approaches to reduce concrete's ecological footprint [4]. Recycling fine aggregates from C&D waste presents a promising solution. However, it necessitates rigorous evaluation to ensure the resulting concrete meets industry standards [5]. This study addresses this imperative need by systematically exploring various proportions of recycled fine aggregates (RFA) ranging from 0% to 100%.

Structural concrete made from C&D waste requires continuous structural health monitoring (SHM) to guarantee its long-term performance [6]. Concrete structures undergo stress due to drying-induced shrinkage, which leads to the formation of cracks. Drying shrinkage occurs as free water escapes through pores and passages near the surface of the element into the surrounding air. Consequently, analyzing shrinkage strain is essential for conducting a comprehensive study of the long-term performance of fresh concrete [7]. Surface electrical resistivity

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of concrete is increasingly utilized as a corrosion risk indicator in the monitoring of concrete structures. Evaluating the concrete's surface electrical resistivity serves as a vital parameter for corrosion risk assessment and is essential for performance evaluation [8]. To control corrosion, concrete must be thoroughly inspected for chloride ion penetration. The impact of weathering on concrete, especially when C&D waste is used as aggregates, must be meticulously examined for chloride ion penetration [9]. The interfacial transition zone (ITZ) between aggregates and cement paste significantly influences the microstructural characteristics of concrete. Optimal performance is achieved when the ITZ is dense and responsible for a strong bond between the two components [10]. Additionally, recycled aggregate can substantially impact the strength of hardened concrete. Research on the effects of fine recycled concrete aggregates (FRCA) revealed that FRCA can be utilized in proportions of up to ten percent for C30 concrete and between twenty to fifty percent for C25 concrete [11]. According to a study, recycled aggregate concrete may experience higher drying shrinkage compared to conventional concrete [12]. Recycled fine aggregates can be effectively used in concrete, offering comparable strength to natural sand aggregates [13]. The permeability of concrete, when using recycled concrete aggregates and pozzolanic materials, is significantly lower than that of concrete produced with natural aggregates [14]. Concrete incorporating 30% demolished replaced fine aggregates and 20% demolished coarse aggregates can replace conventional concrete [15]. Research involving fly ash and recycled concrete aggregates showed that water absorption increases, and electrical resistivity decreases with higher levels of recycled concrete aggregate incorporation. However, the opposite occurs when fly ash is added for both tests [16]. A study on the high slump attributes of standard and high-strength concrete created from recycled fine aggregates (RFA) demonstrated that the compressive strength and elastic modulus of RFA concrete were approximately 70–90% of those of natural aggregates [17]. In their examination of RFA performance using a unique mix proportioning technique, recycled fine aggregates (RFA) concrete exhibited superiority in terms of CO_2-e and cost compared to conventional concrete [18]. The mechanical performance of recycled fine aggregates, supplemented with waste carbon fibers, indicated that adding waste fibers and recycled fine aggregates to concrete improves the material's characteristics [19]. Utilizing adhered cement paste elimination and fly ash treatment significantly enhanced the compressive strength and elastic modulus of recycled fine aggregates (RFA) concrete during the multi-technique approach in optimizing the properties of RFA concrete [20].

The use of recycled aggregates from C&D waste in concrete production is a growing trend, aligning with economic and environmental goals [21]. This practice reduces landfill waste and conserves natural resources [22], adhering to the principles of the circular economy [23]. However, ensuring concrete quality and performance according to industry standards is crucial [24]. Despite various studies on fine aggregate replacements, there's a lack of a definitive method to determine the ideal percentage of RFA replacement for maximum strength. This research addresses this gap by meticulously analyzing particle packing density in specific cylindrical volumes using standardized compacting methods. By exploring these parameters, the study aims to establish a systematic relationship between particle arrangement and compressive strength in concrete specimens. This endeavor is essential in meeting the urgent need for sustainable alternatives in concrete production, emphasizing the importance of balancing environmental concerns with structural integrity in construction practices.

This research presents new and innovative methods:

1. **Efficient utilization of RFA:** Unlike conventional practices where RFA is incorporated in concrete at lower proportions, this study explores a wide range of percentages (0%, 25%, 50%, 75%, and 100%) to identify the most effective utilization of RFA in sustainable concrete production.
2. **Comprehensive assessment:** The study bridges existing research gaps by subjecting concrete mixes to standard compacting efforts. It meticulously analyzes the impact of RFA proportions on fresh properties (workability), hardened properties (compressive strength, flexural strength, split tensile strength, drying shrinkage, electrical resistivity, and rapid chloride penetration of structural concrete), and microstructural features (XRD, SEM, and EDAX). The results are then meticulously compared with a control mix to unveil the most significant differences.
3. **Microstructural investigation:** The research delves into the effects of RFA on the morphology and composition (both chemical and mineralogical) of RFA concrete, crucial for understanding the generation of microstructure. This exploration sheds light on the influence of RFA on microstructure and identifies the optimum content required for sustainable concrete development.

By focusing on fresh properties, mechanical strength, durability, and microstructure, this research strives to provide profound insights that could revolutionize the methods by which concrete is produced and utilized in construction projects globally.

2 Experimental programme

2.1 Material

The study employs Ordinary Portland cement of grade 43, adhering to IS 269 (2015) [25] standard. Table 1 shows physical test results carried out on the cement.

Natural sand, compliant with IS 383 (1970, Reaffirmed 2002) [26], serves as the fine aggregate with a size range of 4.75 mm and below. Crushed stone aggregates, ranging from 4.75 mm to 20 mm, meet the criteria of IS 383 (1970, Reaffirmed 2002) [26] and constitute coarse aggregates. These aggregates pass through 40 mm sieves and retain 100% on 4.75 sieves. Passing percentages on 20 mm and 10 mm sieves are 90.76% and 4.52% respectively. Recycled fine aggregates (RFA) are obtained by crushing concrete from C&D waste to the required size using an impact crusher.

The research explores the particle packing density in specific cylindrical volumes through standard compaction efforts, leading to various mixtures (as shown in Table 2). Table 2 outlines the weights of different fine aggregate mixtures in specific cylindrical volumes, offering valuable insights into their densities. Among these, RFA 25 + NFA 75 offers the densest mixture. The other mixtures, namely RFA 50 + NFA 50, NFA 100, RFA 75 + NFA 25, and RFA 100, exhibit decreasing density in the specified order. Firstly, the Natural Fine Aggregate (NFA) alone, listed as the initial entry, weighs 14.52 kg in the specified volume, serving as a baseline measurement. Secondly, the mix denoted as RFA 25 + NFA 75, consisting of 25% Recycled Fine Aggregate (RFA) and 75% Natural Fine Aggregate, demonstrates a higher weight at 15.27 kg. This mixture reveals that incorporating a quarter of recycled fine aggregate with three-quarters of natural fine aggregate results in increased density, making it the heaviest among the options. Moving on, the composition RFA 50 + NFA 50, with an equal balance of RFA and NFA, weighs 14.74 kg. Despite a higher percentage of recycled material compared to the previous mix, the overall density is slightly lower due to the equal distribution of the aggregates. The mixture labeled RFA 75 + NFA 25 contains 75% RFA and weighs 13.84 kg, showcasing a significant reduction in weight and density due to the higher proportion of recycled material. Lastly, the blend known as RFA 100 comprises entirely of Recycled Fine Aggregate (RFA), weighing 13.27 kg, representing the lightest option among all. The exclusive use of recycled material significantly reduces the mixture's weight. These variations highlight the impact of different ratios of recycled and natural fine aggregates on the density of concrete mixes, providing crucial data for optimizing sustainable concrete compositions while maintaining structural integrity. Table 3 [27, 28] illustrates the physical and mechanical properties of both natural and recycled fine aggregates, alongside natural coarse aggregates.

Table 1 Physical test results on cement

S. No.	Types	Value measured	As per IS 269 (2015) [25]
1	Consistency (%)	31%	–
2	Initial setting time (minutes)	58 minutes	>30 minutes
3	Final setting time (minutes)	435 minutes	<10 hours
4	Specific gravity (–)	3.11 (–)	3.0 to 3.15

Table 2 Weight in specific cylindrical volume

S. No.	Fine aggregates mixtures	Weight (kg)
1	NFA	14.52
2	RFA 25 + NFA 75	15.27
3	RFA 50 + NFA 50	14.74
4	RFA 75 + NFA 25	13.84
5	RFA 100	13.27

Super-plasticizers in the form of chemical admixtures (C-MAX), complying with both IS 9103 (1999) [29] and IS 2645 (2003) [30] standards, are incorporated at a ratio of 1% by weight of cement. Mixing and curing are performed using potable water sourced from the laboratory. Fig. 1 provides a visual representation of the particle size distribution of the fine aggregates.

2.2 Mix proportions

To investigate the viability and impact of recycled fine aggregates on the mechanical properties of concrete, five distinct concrete mixtures were formulated aiming for a target strength of 27 MPa. The compositions of these mixtures are outlined in Table 4. The reference mixture (RC) was prepared using natural aggregates. Additionally, mixtures denoted as RFA-25, RFA-50, RFA-75, and RFA-100 were created by replacing natural fine aggregates with recycled fine aggregates at varying percentages: 25%, 50%, 75%, and 100%, respectively. All these mixes were

Table 3 Physical and mechanical characteristics of aggregates

Property	NFA	RFA	NCA	Standard limits
Bulk density (kg/m^3)	1625	1580	1740	1200–1750 [27]
Specific gravity (–)	2.675	2.654	2.754	2.30–2.90 [27]
Water absorption (%)	0.51	1.12	0.62	≤2.0 (IS 2386 Part 3) [27]
Abrasion loss (%)	15.52	18.44	25.43	<30 (IS 2386 Part 4) [28]
Crushing value (%)	16.21	17.34	26.24	<30 (IS 2386 Part 4) [28]
Impact value (%)	15.31	18.74	17.31	<30 (IS 2386 Part 4) [28]

NFA – Natural Fine Aggregates, NCA – Natural Coarse Aggregates, RFA – Recycled Fine Aggregates

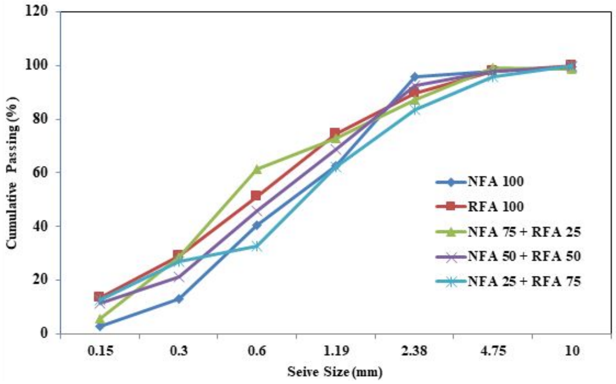


Fig. 1 Gradation curve for fine aggregates

carefully prepared using the weight batching method while maintaining a consistent water-cement ratio of 0.50. This systematic approach allowed for a thorough exploration of the influence of recycled fine aggregates on the concrete's mechanical behavior, providing valuable insights for sustainable construction practices.

2.3 Testing programs

Several tests have been conducted to assess various aspects of structural concrete. The workability of fresh concrete was gauged, and mechanical characteristics such as compressive strength, flexural strength, and split tensile strength were measured. To evaluate the long-term performance of the concrete, tests for drying shrinkage (Fig. 2), electrical resistivity (Fig. 3), and rapid chloride penetration (Fig. 4) were carried out. Additionally, scanning electron microscopy (SEM) was employed, along with energy-dispersive X-ray spectroscopy (EDAX) and X-ray diffraction (XRD) analyses, to examine the microstructural features of powdered concrete samples from different mixtures. These comprehensive assessments provided detailed insights into the structural and long-term properties of the concrete, contributing valuable data for further analysis and applications in construction.

2.3.1 Workability

A slump test, in accordance with IS 1199 (1959) [31] standards, has been conducted to evaluate the workability of concrete mixes containing varying replacement percentages of C&D waste in the form of recycled fine aggregates. The outcomes of these tests are presented in Fig. 5.

2.3.2 Compressive strength

A total of 30 specimens, cast in steel cube molds measuring 15 × 15 × 15 cm, were meticulously prepared, cured, and subjected to compressive strength testing for different concrete compositions. The tests were conducted using a compression testing machine with a capacity of 2000 KN. The average compressive strength value for each mix was derived from three specimens. These evaluations were performed at both 7 and 28 days, and the detailed results are depicted in Fig. 6.

2.3.3 Flexural strength

Similarly, 30 specimens, cast in steel rectangular molds sized 50 × 10 × 510 cm, were created, cured, and tested to

Table 4 Concrete mixtures proportions (in kilograms per cubic meter)

S. No.	Mixture ID	NFA	RFA	NCA	Cement	*W*/*C* ratio	Admixture
1	RC	444.48	0	1511	400	0.5	4
2	RFA 25	333.36	111.12	1511	400	0.5	4
3	RFA 50	222.24	222.24	1511	400	0.5	4
4	RFA 75	111.12	333.36	1511	400	0.5	4
5	RFA 100	0	444.48	1511	400	0.5	4

RC – Reference Concrete, NFA – Natural Fine Aggregates, NCA – Natural Coarse Aggregates, RFA – Recycled Fine Aggregates

Fig. 2 Drying shrinkage apparatus and sample testing

Fig. 3 Resistivity meter and sample testing

Fig. 4 Typical layout of RCPT unit (ASTM C1202-12 [34])

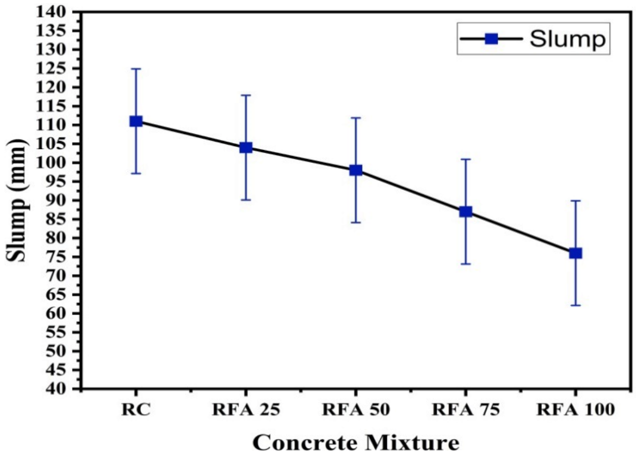


Fig. 5 Slump value for different concrete mixtures

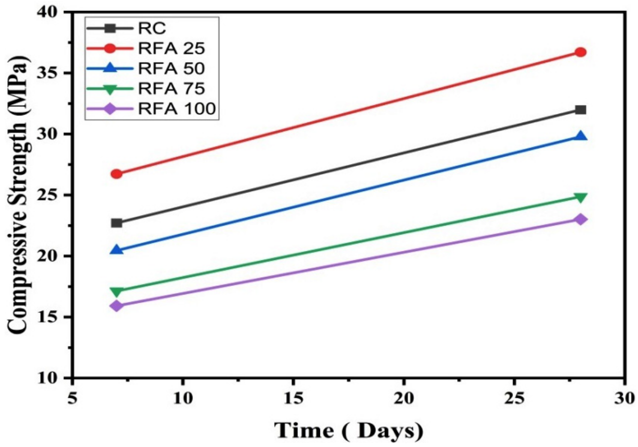


Fig. 6 Variations of compressive strength for different concrete mixtures

determine the flexural strength of various concrete mixes. Utilizing a flexural testing machine with a 2000 KN capacity, the average flexural strength value was calculated from three specimens per mix. Tests were carried out at 7 and 28 days, with the results illustrated in Fig. 7.

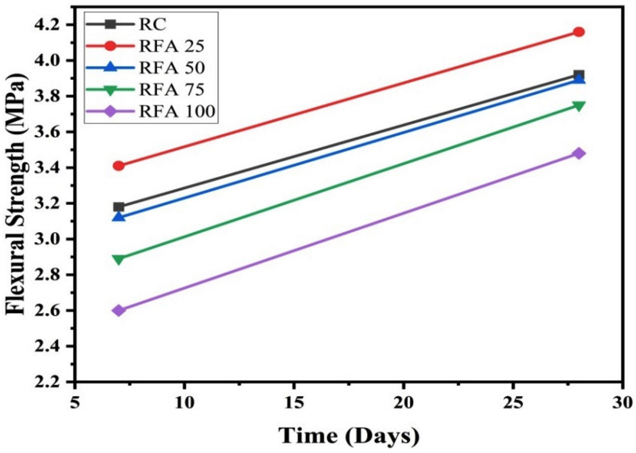


Fig. 7 Variations of flexural strength for different concrete mixtures

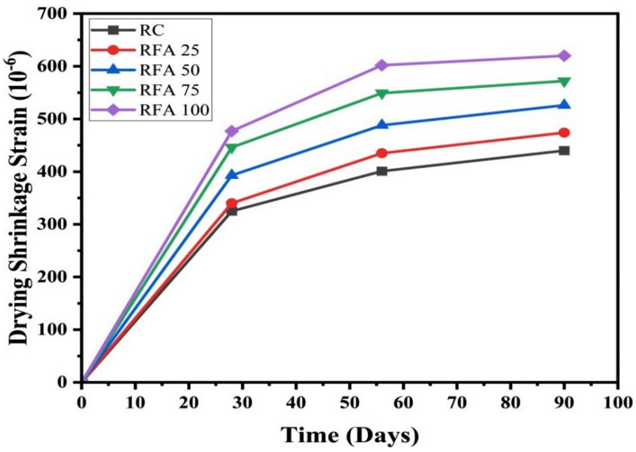


Fig. 9 Shrinkage strain for different concrete mixtures

2.3.4 Split tensile strength

For split tensile strength analysis, 30 specimens were cast in steel cylindrical molds with a diameter (ϕ) of 15 cm and a height (H) of 30 cm. These specimens were tested in a lateral position on a compression testing machine with a capacity of 2000 KN. The average split tensile strength values, derived from three specimens for each mix, were assessed at 7 and 28 days. The detailed outcomes are presented in Fig. 8.

2.3.5 Drying shrinkage

To assess drying shrinkage, 45 specimens measuring 75 × 75 × 285 mm were cast for the five different mixtures. These specimens were stored for 28 days and evaluated according to IS 516 (Part 6) (2020) [32] standards. Length variation over time was recorded using length comparator tools, and the results, displayed in Fig. 9, provided insights into the concrete mixes' drying shrinkage properties.

2.3.6 Electrical resistivity

Electrical resistivity, a key indicator of steel reinforcement bar corrosion risk in concrete, was determined for 30 specimens cast in cylindrical molds with 100 mm diameter and 200 mm height. Tests, conducted at 28 and 56 days using the Resipod Resistivity Meter following RILEM TC 154-EMC standards [33], are depicted in Fig. 10.

2.3.7 Rapid Chloride Penetration Test (RCPT)

Fig. 4 illustrates the standard configuration of the Rapid Chloride Penetration Test (RCPT) unit. Compliant with ASTM C1202-12 [34] guidelines, the mold has dimensions of 100 mm in diameter and 50 mm in height. Thirty specimens were meticulously prepared for this investigation. The RCPT setup consists of two separate chambers, one filled with sodium chloride (NaCl) at a concentration of 0.3 M, and the other with sodium hydroxide (NaOH) at a similar concentration. To ensure precision, the boundaries of the specimens and test cells were securely sealed. A constant current source of 60 V was connected, with the negative end linked to the NaCl solutions cell and the positive end to the NaOH solutions cell. Readings were recorded every 30 minutes for a duration of 6 hours until the current ceased. The tests were repeated at the ages of

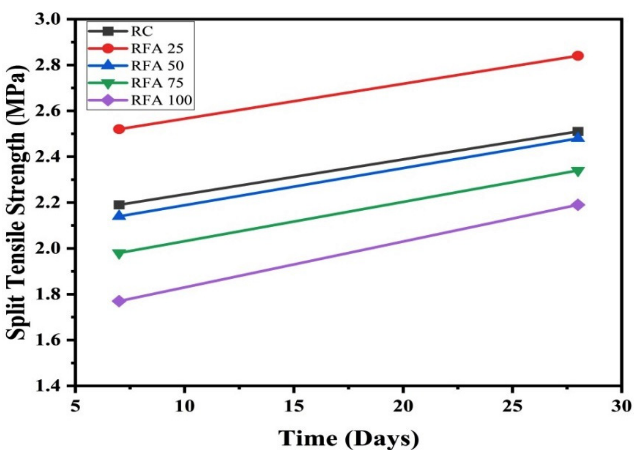


Fig. 8 Variations of split tensile strength for different concrete mixtures

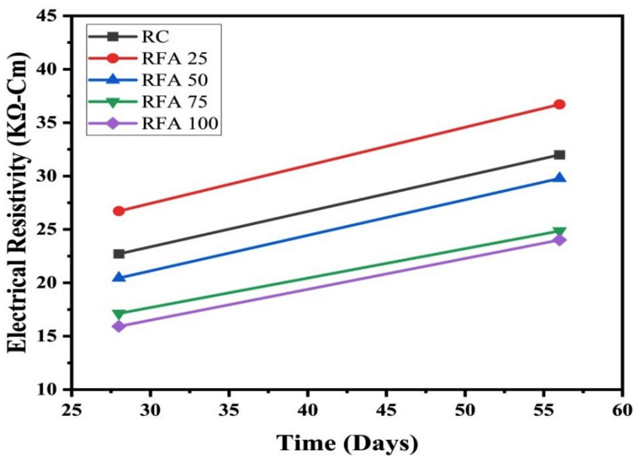


Fig. 10 Variation of electrical resistivity with RFA

28 and 56 days, where the total charge passed indicated the resistance to chloride ion penetration. Detailed results from these tests are presented in Fig. 11.

2.3.8 X-Ray Diffraction (XRD)

X-ray diffraction is employed to discern the phase characteristics and conduct mineralogical analysis of crystalline minerals within a concrete powder sample, particularly in various mixtures incorporating recycled fine aggregates. The Bruker D-8 advanced diffractometer system is utilized for scanning the samples within an angular range of 3–70 degrees, with a scanning speed of 2 degrees per minute and a sampling interval of 0.005 degrees at an angle of 2 degrees. The acquired scans are then analyzed using the Jade 7 X-ray diffraction software. The resulting peak intensities are graphically represented against 2 theta degrees on the *x*-axis, ranging from 0 to 70 degrees, while the intensity is plotted on the *y*-axis. The detailed test results are presented in Fig. 12.

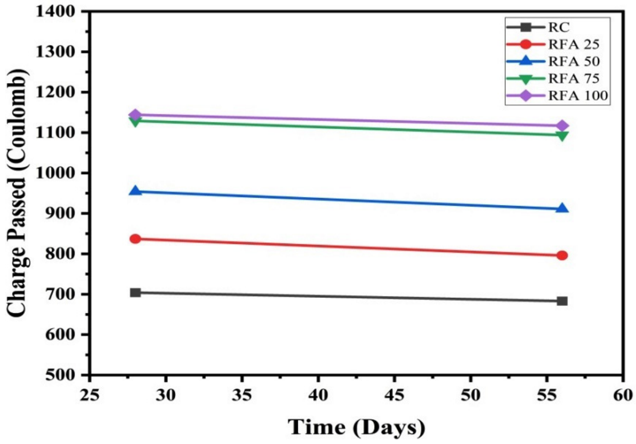


Fig. 11 Variation of chloride permeability with RFA

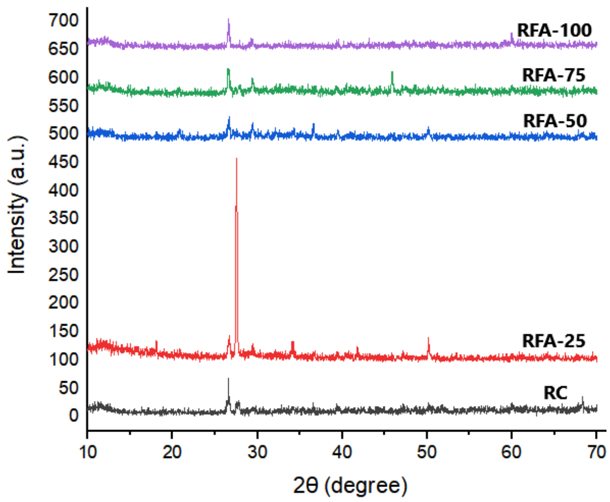


Fig. 12 XRD pattern for different concrete mixtures

2.3.9 Scanning Electron Microscopy (SEM)

SEM analysis was conducted to characterize Recycled Fine Aggregate (RFA) materials, involving a detailed examination of the microstructure and surface morphology of concrete samples from various concrete mixtures. The analysis was carried out using the JSM 6610V scanning electron microscope at the University Science Instrumentation Center (USIC) in Delhi, operating at 30 KV. The outcomes of the test are presented in Fig. 13.

2.3.10 Energy-Dispersive X-Ray Spectroscopy (EDAX)

Energy-dispersive X-ray spectroscopy (EDAX) is employed to conduct a detailed statistical analysis of the chemical composition of concrete samples. This study utilizes EDAX to qualitatively and quantitatively analyze the presence of different elements in various concrete mixtures. The outcomes of the tests are illustrated in Fig. 14.

3 Results and discussion

3.1 Workability

In Fig. 5, the graph illustrates the variations in slump values across different concrete mixtures. It is evident from Fig. 5 that as the proportion of recycled fine aggregates (RFA) increases, the slump of concrete decreases. The workability of concrete containing RFA falls within the medium range, ranging from 50 to 100 mm, as indicated by the slump values observed in all the mixtures. This decrease in slump is attributed to the higher water absorption capacity of RFA compared to natural aggregates. RFA contains old, adhered mortar on its surface, which absorbs more water. Consequently, at higher replacement percentages, more water is required to facilitate the hydration process. This increased water requirement leads to a reduction in slump, resulting in less workable concrete. The observed trend indicates that an escalation in the proportion of RFA correlates with a decrease in the slump of concrete. This pattern aligns with findings from previous studies conducted by Zhao et al. [35] and Kirthika and Singh [36], where a similar decrease in slump was observed with increasing RFA content in concrete.

3.2 Compressive strength

Fig. 6 presents the variations in compressive strength at 7 and 28 days for different replacement percentages of Recycled Fine Aggregates (RFA) concerning the reference mixture. When the C&D waste fine aggregates were replaced by 25%, the compressive strength of RFA 25 increased to 17.65% and 14.75% in comparison to the

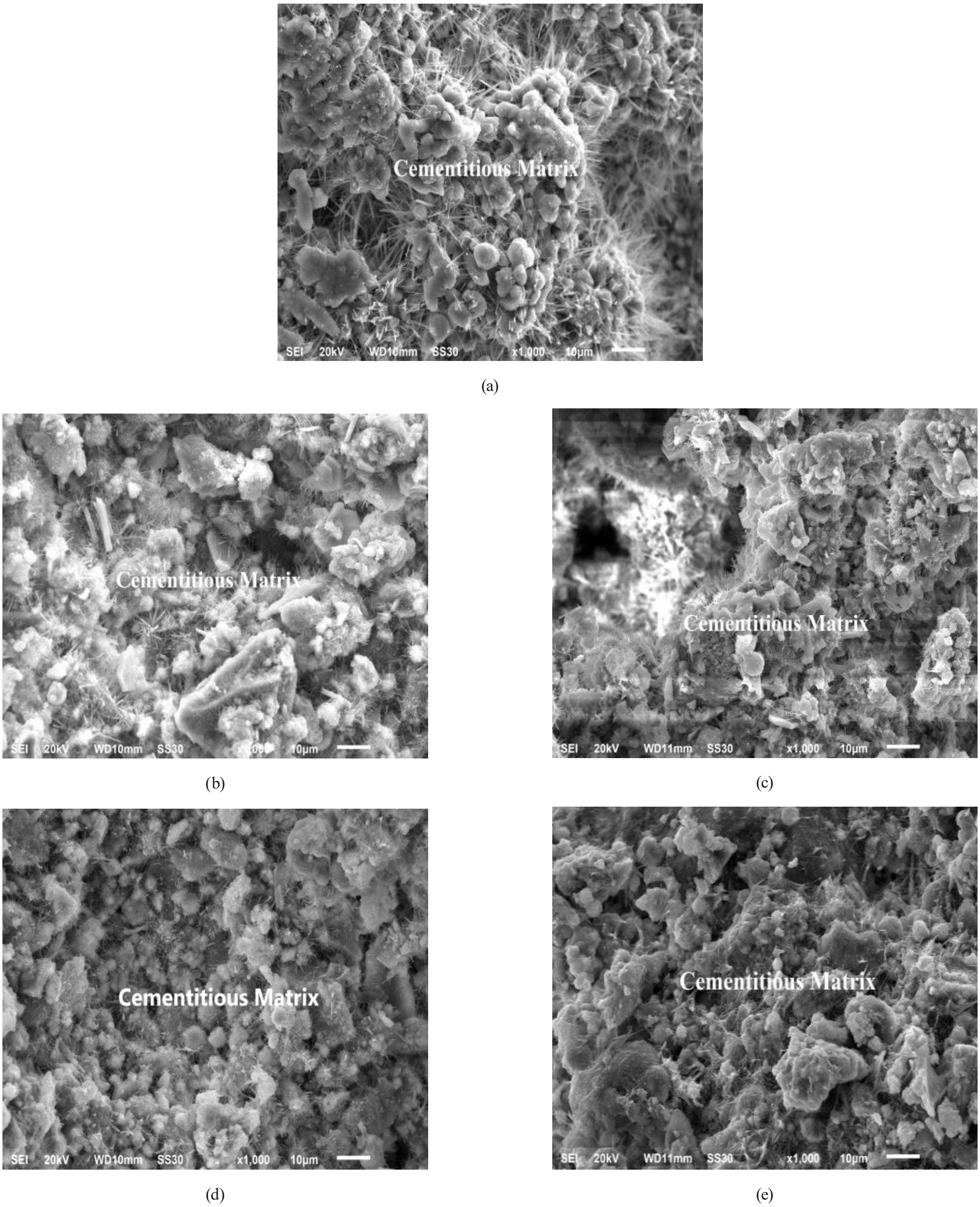
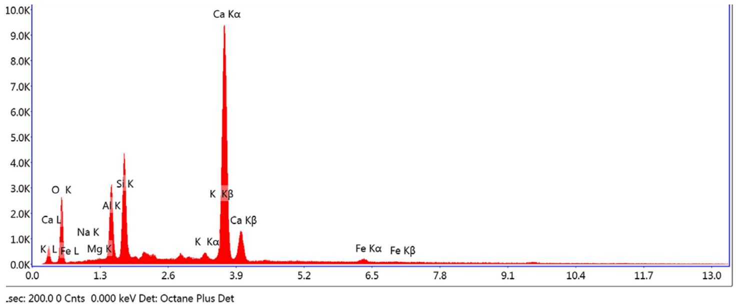
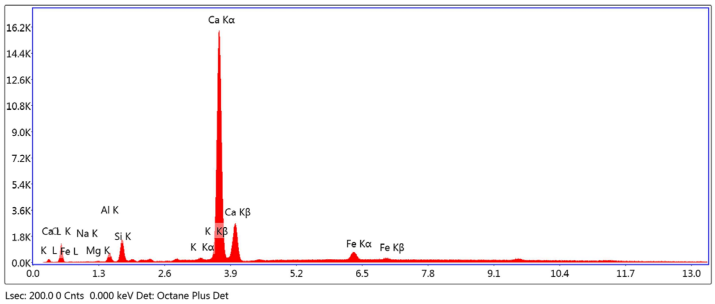


Fig. 13 SEM micrographs for different concrete mixtures (a) for RC, (b) for RFA 25, (c) for RFA 50, (d) for RFA 75, and (e) for RFA 100

reference mixture at 7 and 28 days, respectively. However, increasing the RFA replacement to 50% resulted in a significant reduction in compressive strength, with RFA 50 showing a decrease to 9.95% and 6.90% at 7 and 28 days, respectively. Further escalating the RFA replacement to 75% led to a faster decline, with RFA 75 exhibiting reductions to 24.57% and 22.28% at 7 and 28 days, respectively. In the case of 100% RFA replacement, the compressive strength of RFA 100 plummeted to 29.89% and 24.94% concerning the reference mixture at 7 and 28 days, respectively.



(a)



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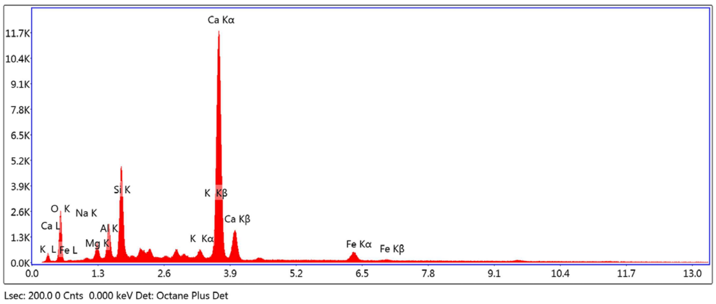

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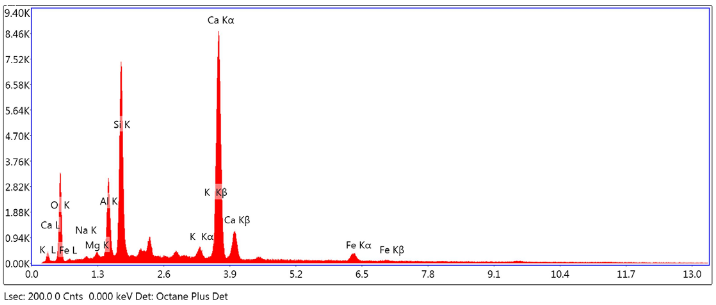

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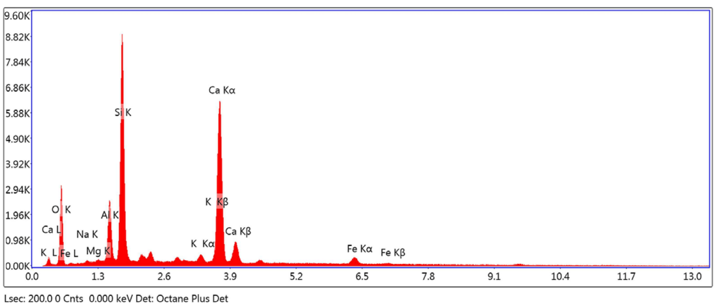

(e)

Fig. 14 EDAX analysis for different concrete mixtures (a) for RC, (b) for RFA 25, (c) for RFA 50, (d) for RFA 75, and (e) for RFA 100

The analysis of compressive strength test results reveals that concrete mixtures with higher percentages of replaced Recycled Fine Aggregates (RFA) exhibit lower compressive strength compared to the reference mixture. The ideal replacement percentage for recycled fine aggregates stands at 25%. However, the increase in compressive strength observed at the 25% replacement level of RFA can be attributed to the dense microstructure of RFA 25 concrete. It was observed that introducing RFA into concrete mixtures at a 25% replacement level results in minimal voids and optimal particle packing, which accounts for the higher strength observed in RFA 25. Particles of fine aggregates smaller than 600 microns play a significant role in forming the paste, and this paste must be present in sufficient quantity to fill the voids of larger particles. The strength order is closely linked to the percentage of fine aggregates passing between 600 and 150 microns. A wider gap between these sizes leads to higher strength within specified limits, whereas a smaller gap results in lower strength. At higher replacement percentages, there is an increase in void content and the presence of old adhered mortar, which weakens the bond with aggregates, ultimately leading to reduced strength. Among the mixtures, RFA 25 exhibited the highest compressive strength at 36.71 MPa, while RFA 100 displayed the lowest compressive strength at 24.01 MPa. Similar conclusions were drawn in studies conducted by Kirthika and Singh [36]. Furthermore, the results align with the findings of Srivastava et al. [37], where a 20% replacement of fine aggregates with demolished waste in a concrete grade of M25 showed improved workability and strength. Similarly, Ankesh et al.'s [38] research demonstrated that replacing 15% of recycled fine aggregates led to concrete with greater strength than the target strength. These findings substantiate the significance of replacement percentages in determining concrete strength and quality.

3.3 Flexural strength

Fig. 7 illustrates the variations in flexural strength at 7 and 28 days for different percentages of RFA replacement in comparison to the reference mixture. The results exhibit a consistent pattern similar to compressive strength. Notably, concrete mixes with higher RFA replacement percentages demonstrate decreased flexural strength compared to the reference mix. For a 25% RFA replacement, the flexural strength of the RFA 25 mix increased by 7.23% and 4.59% at 7 and 28 days, respectively, compared to the reference mix. Increasing the RFA replacement to 50% resulted in a marginal reduction of 1.88% and 0.76% in flexural strength at 7 and 28 days, respectively, for the RFA 50 mix in comparison to the reference mix. Further raising the RFA replacement to 75% led to a faster reduction in flexural strength, decreasing by 9.11% and 4.33% at 7 and 28 days, respectively, for the RFA 75 mix in comparison to the reference mix. In the case of 100% RFA replacement, the flexural strength of the RFA 100 mix was significantly reduced by 18.23% and 11.22% at 7 and 28 days, respectively, in comparison to the reference mix. Among the mixtures, RFA 25 exhibited the highest flexural strength at 4.16 MPa, whereas RFA 100 displayed the lowest flexural strength at 3.48 MPa. Similar observations have been made by other researchers [35, 38].

3.4 Split tensile strength

Fig. 8 displays the variation in split tensile strength at 7 and 28 days for different percentages of RFA replacement in comparison to the reference mixture. The results show a trend similar to compressive strength. It was observed that the split tensile strength of concrete mixtures is lower than that of the reference mix when RFA replacement is at a higher proportion. For a 25% RFA replacement, the split tensile strength of the RFA 25 mix increased by 15.0% and 13.14% at 7 and 28 days, respectively, compared to the reference mix. Increasing the RFA replacement to 50% resulted in a marginal reduction of 2.28% and 1.19% in split tensile strength at 7 and 28 days, respectively, for the RFA 50 mix in comparison to the reference mix. Further increasing the RFA replacement to 75% led to a faster reduction in split tensile strength, decreasing by 9.58% and 6.77% at 7 and 28 days, respectively, for the RFA 75 mix in comparison to the reference mix. In the case of 100% RFA replacement, the split tensile strength of the RFA 100 mix was significantly reduced by 19.17% and 12.74% at 7 and 28 days, respectively, in comparison to the reference mix. Specifically, the strength of RFA 25 increased by 13.14%, whereas the strength of RFA 100 decreased by 12.74% compared to the reference mix, which aligns with the findings reported by Kirthika and Singh [36].

3.5 Drying shrinkage

Fig. 9 illustrates the variations in shrinkage strain for different concrete mixtures at various drying ages. The graph demonstrates that as concrete dries, it experiences increased shrinkage, a relationship evident in the data. Notably, the slope of the drying shrinkage curve transitions from steep to flat over time, indicating a decrease in the rate of change of drying shrinkage. Additionally, it was observed that as the percentage of fine aggregate replacement rises, the drying shrinkage of concrete consistently increases across all drying ages.

At the 28-day drying age, the shrinkage strain in RFA 25, RFA 50, RFA 75, and RFA 100 is respectively 4.61%, 20.92%, 37.23%, and 46.76% higher than that in the reference mixture. This discrepancy continues to grow, with RFA 100 exhibiting a 50.1% increase in shrinkage strain at 90 days compared to the reference mix. Remarkably, all mixtures' shrinkage strain values remained within the standard range outlined by Indian Standards, indicating their acceptability. Notably, RFA addition amplifies drying shrinkage due to the higher water absorption of RFA. This increase is attributed to the additional cement present around the surface of RFA, absorbing more water and subsequently shrinking significantly during the drying process. Despite this, all mixtures maintained their shrinkage within acceptable limits according to Indian Standards. Hence, RFA can be utilized within specific boundaries without adversely affecting shrinkage properties. This pattern aligns with the findings of Kirthika and Singh [36] indicating a systematic rise in drying shrinkage with increased proportions of recycled fine aggregates in concrete. These results corroborate the research by Mushtaq et al. [39] supporting the notion of a systematic increase in concrete drying shrinkage with higher proportions of waste foundry sand at various drying ages.

3.6 Electrical resistivity

Fig. 10 illustrates the variations in electrical resistivity for concrete mixtures with different percentages of C&D waste aggregates in comparison to the reference mixture at 28 and 56 days. In the case of a 25% replacement of C&D waste aggregates, the electrical resistivity of the RFA 25 mix decreased by 14.94% and 14.85% at 28 and 56 days, respectively, compared to the reference mixture. Increasing the C&D waste aggregates replacement to 50% resulted in a substantial reduction in electrical resistivity, with the RFA 50 mix showing decreases of 17.06% and 16.80% at 28 and 56 days, respectively, in comparison to the reference mix. Further increasing the replacement percentage to 75% led to a faster reduction in electrical resistivity, with the RFA 75 mix showing decreases of 34.28% and 34.25% at 28 and 56 days, respectively. In the case of 100% replacement of C&D waste aggregates, the electrical resistivity of the RFA 100 mix decreased by 44.70% and 44.68% at 28 and 56 days, respectively, compared to the reference mixture.

The results indicate that concrete mixtures with higher percentages of C&D waste aggregates exhibit lower electrical resistivity compared to the reference mixture. This decrease in electrical resistivity can be attributed to the high porosity of the C&D waste aggregates, which trap water with dissolved ions, creating a low-resistance path for electric current. Among the mixtures, RC and RFA 50 have comparable resistivity, followed by RFA 75 and RFA 100, which have the lowest electrical resistivity. Based on these findings, it can be concluded that concrete produced with up to 75% replacement of C&D waste aggregates has a low risk of corrosion; whereas concrete produced with 100% replacement poses a moderate risk of corrosion. Similar results regarding the electrical resistivity of concrete after increasing C&D waste aggregate replacement have been reported in previous studies [36]. This study aligns with the research conducted by Arredondo-Rea et al. [40] who found that replacing no more than 30% of coarse aggregates and 20% of fine aggregates with recycled aggregates does not significantly influence concrete's electrical resistivity. When comparing these findings, it suggests that concrete made with C&D waste aggregates poses a moderate risk of corrosion to the steel bars used within the concrete.

3.7 Rapid chloride penetration

Fig. 11 displays the variations in chloride permeability for concrete mixtures with different percentages of C&D waste aggregates in comparison to the reference mixture at 28 and 56 days. When the RFA replacement percentage was 25%, the chloride permeability of the RFA 25 mix decreased by 18.89% and 16.54% at 28 and 56 days, respectively, compared to the reference mixture. Increasing the replacement percentage to 50% resulted in a substantial reduction in chloride permeability, with the RFA 50 mix showing decreases of 35.51% and 33.38% at 28 and 56 days, respectively, compared to the reference mix. Further increasing the RFA replacement to 75% led to a faster reduction in chloride permeability, with the RFA 75 mix showing decreases of 60.36% and 60.17% at 28 and 56 days, respectively. At 100% replacement of RFA, the chloride permeability of the RFA 100 mix reduced by 62.50% and 63.54% at 28 and 56 days, respectively, compared to the reference mix.

The results indicate that concrete mixtures with higher percentages of C&D waste aggregates exhibit higher chloride permeability compared to the reference mixture, implying a decrease in concrete durability. This decline in chloride permeability is attributed to the high porosity of the C&D waste aggregates, which trap water containing dissolved ions, creating a path of low resistance to electrical current. Notably, the highest chloride permeability is observed at 100% replacement of RFA. Based on these findings, it can be concluded that concrete produced with up to 50% replacement of C&D waste aggregates possesses high durability, while concrete produced with more than 75% replacement of RFA exhibits moderate durability. The increase in RFA replacement percentage in concrete leads to elevated chloride permeability and reduced durability. Specifically, concrete made with RFA demonstrates high durability at up to 50% replacement and moderate durability at 75% and 100% replacement percentages. Similar patterns were noted by Kirthika and Singh [36], indicating reduced penetration of chloride ions as concrete ages, regardless of RFA content. These findings align with the research conducted by Arredondo-Rea et al. [40], examining the impact of recycled aggregates on concrete's chloride permeability. A comparative analysis reveals that concrete made with C&D waste aggregates exhibits moderate chloride permeability.

3.8 X-Ray Diffraction (XRD)

The XRD results reveal a decrease in the net intensity of minerals like CSH, CH, and Ettringite in response to the increasing replacement percentage of RFA. This decrease signifies a reduction in the overall density of CSH in the concrete. Fig. 12 displays the XRD patterns for various concrete mixtures, including RC, RFA 25, RFA 50, RFA 75, and RFA 100. The diffraction peak angles for different compounds are detailed in Table 5.

The XRD analysis demonstrates that the incorporation of recycled fine aggregates impacts the phase composition of concrete minerals, such as C-S-H, CH, and Ettringite, indicating the formation of a dense microstructure. Peaks with higher net intensity are associated with lower RFA replacement percentages. As the percentage of RFA replacement increases, the net intensity of different minerals at various peaks decreases. Consequently, the study reveals a decline in concrete strength with higher RFA replacement percentages. This research aligns remarkably with a study by Silva et al., who investigated cement paste incorporating 12% concrete floor polishing waste (CPFW) [41].

Table 5 Diffraction peaks angles of various compounds for different concrete mixtures

Concrete mix	CSH (degree)	Ettringite (degree)	CH (degree)
RC	26.450	36.780	47.299
RFA 25	26.337	34.146	50.175
RFA 50	26.596	36.606	50.110
RFA 75	26.575	39.385	60.001
RFA 100	26.571	39.523	59.930

CSH – Calcium Silicate Hydroxide, CH – Calcium Hydroxide,
Ettringite – Hydrated Calcium Aluminum Sulfate Hydroxide

3.9 Scanning Electron Microscopy (SEM)

Fig. 13 presents SEM micrographs obtained at 28 days for various concrete mixtures subjected to SEM analysis. These micrographs reveal the formation of crucial hydration products responsible for concrete strength, including calcium hydroxide (CH), calcium silicate hydroxide (CSH), and ettringite. These compounds manifest as distinct crystal structures: hexagonal shapes indicate CH gel, flower-shaped structures signify CSH gel and needle-like formations represent ettringite.

The SEM micrographs demonstrate that in the concrete mixture RFA 25, there is heightened growth of CH, CSH, and ettringite compared to RC, leading to increased strength. The additional cement surrounding the recycled fine aggregates fosters the production of more hydration products, thereby enhancing concrete strength. Conversely, in RFA 50, CH, CSH, and ettringite development is less than in RC, resulting in a decrease in strength due to inadequate hydration of cement particles. The presence of non-reacted particles in the hardened cement paste further weakens the concrete. In RFA 75, minimal calcium crystal presence was found on the cement paste particles, indicating voids and loose structures, leading to decreased compressive strength. RFA 100 results in a porous microstructure as the cement around recycled fine aggregates does not undergo complete hydration, yielding fewer hydration products. SEM analysis indicates that lower proportions of RFA generate denser CSH gel, strengthening the cement paste matrix. However, excessive RFA leads to fragile mixtures and insufficient CSH production, resulting in reduced strength. In summary, the findings show that adding 25% RFA improves concrete microstructure, enhancing compressive strength. A 50% replacement results in less dense concrete and reduced strength. At 75% replacement, voids and loose structures weaken the concrete, while a 100% replacement yields a porous microstructure and insufficient strength. These results emphasize the delicate balance needed when incorporating RFA, ensuring optimal strength and durability in concrete mixtures.

3.10 Energy Dispersive X-Ray Spectroscopy (EDAX)

Fig. 14 shows quantitate and qualitative analyses of various elements present in different mixtures by EDAX analysis.

The EDAX analysis reveals the presence of elements such as Calcium (Ca), Oxygen (O), Silicon (Si), Aluminum (Al), Iron (Fe), Potassium (K), Sodium (Na), and Magnesium (Mg) in the concrete mixtures. Specifically, in the RFA 25 mix, there is an increase in the percentage of calcium compared to RC, fostering the formation of crucial hydration products like CH, CSH, and CASH. However, at higher RFA replacement percentages, the calcium content decreases, leading to a reduction in hydration products. Conversely, silica content decreases at lower RFA replacement percentages but gradually increases at higher replacements. The lower alumina content results in diminished ettringite formation. SEM results offer compelling evidence that additional CSH is formed up to a 25% replacement level for RFA. The chemical composition obtained via EDAX confirms that higher RFA replacement percentages diminish the formation of calcium compounds by decreasing calcium content in the mixture. This reduction weakens the concrete mixture's strength. A quantitative summary of the chemical composition of different elements, as determined by EDAX analysis, is outlined in Table 6.

4 Conclusions

This research paper advocates for the development of sustainable concrete by utilizing Construction and Demolition (C&D) waste as Recycled Fine Aggregates (RFA), thereby endorsing eco-friendly practices, waste reduction, and the promotion of circular economy principles. The study underscores that replacing natural fine aggregates with recycled counterparts significantly influences the properties of hardened concrete.

Key conclusions drawn from the study are as follows:

- The mechanical properties of concrete show an increase up to a specific limit and then decline beyond the optimum point. The ideal replacement percentage for RFA in concrete is 25%. Concrete exhibits superior strength characteristics at this replacement level and diminishes in quality at 100% replacement.
- Concrete with 25% recycled fine aggregates outperforms that with natural fine aggregates. RFA 25 exhibits a 14.75% increase in compressive strength, 6.61% in flexural strength, and 13.14% in split tensile strength compared to traditional concrete. Concrete with 50% RFA yields strength equivalent to that with 100% natural fine aggregates.
- The addition of RFA increases drying shrinkage due to higher water absorption. Proper curing of RFA-incorporated concrete is crucial to maintaining its shrinkage properties.
- Higher RFA replacement reduces electrical resistivity, potentially increasing the corrosion rate of steel reinforcements. RFA 25 demonstrates 17.65% higher electrical resistivity than traditional concrete, indicating superior corrosion resistance.
- Higher RFA replacement leads to increased chloride permeability and reduced durability. RFA 25 exhibits an 18.83% higher resistance to chloride penetration compared to traditional concrete. RFA 25 and RFA 50 display high durability, whereas RFA 75 and RFA 100 show moderate durability.
- XRD, SEM, and EDAX analyses reveal that at lower replacement percentages, the pozzolanic reaction enhances strength by forming additional hydration products. Conversely, at higher levels, strength diminishes as the hydration process has not reached the desired level.

Table 6 Percentage weight of various elements for different mixtures

Mixture ID	(%)	Ca-K	O-K	Si-K	Al-K	Fe-K	K-K	Na-K	Mg-K
RC	Weight	42.76	38.06	8.89	6.62	2.51	1.15	0.01	0
	Atomic	26.14	58.27	7.75	6.01	1.1	0.72	0.01	0
RFA-25	Weight	64.84	21.29	3.01	1.28	9.15	0.32	0.09	0.02
	Atomic	49.33	40.57	3.27	1.45	5.0	0.25	0.12	0.02
RFA-50	Weight	45.84	33.15	8.68	3.44	5.44	1.46	0.12	1.88
	Atomic	29.56	53.55	7.99	3.29	2.52	0.96	0.14	2.0
RFA-75	Weight	35.4	36.93	14.33	5.92	5.07	1.72	0.26	0.36
	Atomic	21.64	56.55	12.5	5.37	2.22	1.08	0.28	0.36
RFA-100	Weight	30.92	36.84	19.62	5.61	5.11	1.44	0.33	0.13
	Atomic	18.69	55.78	16.92	5.03	2.22	0.89	0.34	0.13

Ca – Calcium, O – Oxygen, Si – Silicon, Al – Aluminum, Fe – Iron, K – Potassium, Na – Sodium, and Mg – Magnesium

This approach not only mitigates construction industry waste but also conserves natural resources. Sustainable concrete, with comparable mechanical properties to traditional concrete, emerges as a viable alternative for construction projects. Future research endeavors can focus on optimizing this process for wider adoption within the industry.

Statements and declarations

Author's credit statement

Harish Panghal: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing, Original Draft Preparation, Writing Review and Editing, and Visualization.

Awadhesh Kumar: Conceptualization, Methodology, Validation, Resources, Review and Editing, Supervision, Project Administration, and Funding Acquisition.

Data availability

All the data, materials, and methodology adopted during the research have been mentioned in this article in the form of figures and tables.

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Each of the authors confirms that this manuscript has not been previously published and is not currently under consideration by any other journal.

Consent to participate

The authors declare consent to participate in the research work.

Consent to publication

The authors of the research paper agree with the publication.

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