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Structural aspects of concrete incorporating recycled coarse aggregates from construction and demolished waste

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ABSTRACT: The study explores the potential of recycling construction and demolition waste into recycled coarse aggregates (RCA) to decrease waste generation and carbon footprint, using a standard compacting effort to calculate compressive strength and particle packing density in a specific cylindrical volume. This study investigates the impact of RCA on concrete's workability, compressive strength, flexural, split tensile, drying shrinkage, electrical resistivity, rapid chloride penetration, and microstructural characteristics using XRD, SEM, and EDAX. Test findings showed that increasing the replacement percentage beyond the optimum value (RCA 25) had detrimental effects on the strength and microstructure of the concrete. RCA 25 has a higher compressive, flexural, and split tensile strength in the order of 11.56%, 3.06%, and 5.17% respectively compared to reference concrete, as well as 5.23% increase in drying shrinkage, 8.79% higher electrical resistivity, and 4.68% higher resistance to chloride penetration than reference concrete.

KEY WORDS: Aggregate; Concrete; Hydration products; Ettringite formation; Portland cement.

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RESUMEN: *Aspectos estructurales del hormigón que incorpora áridos gruesos reciclados de residuos de construcción y demolición.* Este estudio explora el potencial del reciclaje de residuos de construcción y demolición en áridos gruesos reciclados (RCA) para reducir la generación de desechos y la huella de carbono, utilizando un esfuerzo de compactación estándar para calcular la resistencia a la compresión y la densidad de empaquetado de partículas en un volumen cilíndrico específico. La investigación evalúa el impacto del RCA en la trabajabilidad, resistencia a la compresión, resistencia a flexión, tensión por flexión, retracción por secado, resistividad eléctrica, penetración rápida de cloruro y características microestructurales utilizando XRD, SEM y EDAX. Los resultados muestran que aumentar el porcentaje de reemplazo más allá del valor óptimo (RCA 25) tiene efectos perjudiciales en la resistencia y microestructura del hormigón. El RCA 25 tiene una resistencia a la compresión, a flexión y tracción superior en un 11.56%, 3.06% y 5.17%, respectivamente, en comparación con el hormigón de referencia. Además, presenta un aumento del 5.23% en la retracción por secado, una resistividad eléctrica un 8.79% mayor y una resistencia a la penetración de cloruros un 4.68% superior al hormigón.

PALABRAS CLAVE: Árido; Hormigón; Productos de hidratación; Formación de etringita; Cemento portland.

1. INTRODUCTION

In the modern era, sustainable development has become a central concern, shaping discussions across various industries, especially in the construction sector (1). This field faces significant challenges related to resource depletion and environmental impact, making the integration of recycled materials a focal point (2). By 2030, construction and demolition (C&D) waste are projected to increase by 2.59 billion tonnes, reaching 3.40 billion tonnes by 2050 (3). Dumping this waste in landfills not only depletes disposal sites but also leads to adverse environmental effects. One viable solution to this problem is utilizing C&D waste as aggregates for producing new concrete, given that 70–80% of concrete volume comprises aggregates (4). With concrete production demands increasing at a rate of 7.7% annually, employing C&D waste as aggregates could be both economically and environmentally beneficial (5). However, to ensure the feasibility of C&D waste-produced concrete in various civil engineering projects, it must meet specific standards, necessitating thorough examination (6). Structural health monitoring (SHM) is crucial for maintaining the long-term performance of concrete made from C&D waste (7). Concrete structures often face stress due to drying-related shrinkage, leading to fractures. Analyzing shrinkage strain is essential for evaluating the long-term performance of fresh concrete (8). Moreover, surface electrical resistivity serves as a corrosion risk indicator for concrete structures, guiding structural health monitoring efforts (9). Assessing chloride ion penetration in concrete is vital for corrosion management, particularly when C&D waste is used as aggregates (10). The microstructural properties of concrete are significantly influenced by the interfacial transition zone (ITZ) between aggregates and cement paste (11). A dense and well-accounted ITZ fosters a strong bond, thereby enhancing concrete performance. Considering these factors, the integration of C&D waste into concrete production demands comprehensive analysis and monitoring to ensure both economic viability and environmental sustainability.

Concrete shrinkage poses a significant challenge in the construction industry, prompting extensive studies to understand its properties and effects. Well-designed laboratory experiments are essential for comprehending concrete shrinkage characteristics (12). In one investigation, the electrical resistivity of four different cement types was analyzed using alternating current (A.C.) and direct current (D.C.) electric fields, demonstrating that resistivity values moderately fluctuate based on the size distribution of coarse particles (13, 14). Recycled aggregates have a notable impact on the strength of hardened concrete. Studies indicate that recycled aggregates perform satisfactorily at replacement ratios of 50% and 100% (15). For instance, a study on M20 concrete mix made with crushed demolition and construction waste revealed that the compressive strength of recycled aggregate concrete is typically 87% of natural aggregate concrete on average. Although the slump of recycled aggregates is low, improvements are possible (16). When analyzing the drying shrinkage of recycled aggregate-based concrete with or without fly ash, it was found that drying shrinkage can be equivalent to conventional concrete. Without fly ash, there is a 25% increase in drying shrinkage, which reduces to 7% with fly ash (17). In terms of workability and compressive strength, substituting 30% of natural aggregates with recycled coarse aggregates yielded comparable results to conventional concrete (18). Concrete resistance to chloride ion permeability, assessed using RCPT (ASTM C1202), exhibited high reliability and accuracy, with a 10% lower performance cost compared to other equipment. However, this tested concrete proved less durable in marine environments (19). Moreover, experiments showed that the percentage of recycled aggregates impacts concrete permeability, emphasizing its potential in C&D waste-based concrete production (20). Concrete with recycled aggregates and cementing agents demonstrated lower permeability compared to conventional concrete, making it less sensitive to stress (21). Studies exploring the partial replacement of cement with demolished waste concrete powder over 10-20 years observed a 20% increase in compressive strength. Surprisingly, the age of the concrete powder from demolished waste had no discernible impact (22).

Electrical resistivity emerges as a valuable tool for investigating concrete strength and maturity in relation to curing time, binder type, and aggregates, without causing damage (23). Another study found that a mixture of 30% clay and 10% fly ash in ternary mixed concrete minimized drying shrinkage (24). Concrete made from demolished waste aggregates can be equivalent to conventional concrete with a 30% replacement for fine aggregates and 20% for coarse aggregates (25). Research revealed that replacing natural aggregates with demolition project waste and clay brick aggregates at a 25% ratio leads to superior concrete properties (26). Utilizing C&D waste for concrete production enhances compressive strength, especially when waste concrete materials (WCM) with admixtures (WCA) are used at a 90% aggregate replacement percentage compared to fresh concrete materials (FCM) (27). Furthermore, a study investigating the drying shrinkage properties of concrete from recycled heavy-weight glass and steel slag aggregates found that increasing the proportion of steel slag replacements reduces modulus and drying shrinkage, indicating enhanced durability (28). Lastly, the electrical resistance of concrete made from recycled brick aggregates decreases as the percentage of recycled brick aggregates (RBA%) rises (29). These findings collectively emphasize the potential and versatility of recycled materials in improving various aspects of concrete production.

Recycling construction and demolition (C&D) waste into recycled aggregates (RCA) has become increasingly popular for sustainable concrete production, contributing to reduced landfill waste, conservation of natural resources, and the promotion of the circular economy (30). However, ensuring the quality and performance of recycled aggregates meet industry standards is of paramount importance. Researchers have conducted various studies by replacing coarse aggregates in different proportions. Yet, no specific technique has been proposed to determine the optimal percentage of RCA replacement for achieving the highest strength in concrete. This study addresses this gap by focusing on these parameters, alongside an in-depth analysis of mechanical properties and other essential characteristics.

The notable aspects of this research are as follows:

1. This study delves into the efficient utilization of RCA for sustainable concrete production. While RCA is often incorporated into concrete at limited proportions, this research examines five different ratios (0%, 25%, 50%, 75%, and 100%) to comprehensively assess their impact.
2. The study bridges existing research gaps by employing standard compacting methods to establish the order of compressive strength. Additionally, it verifies the influence of RCA proportions on various aspects, including workability (fresh), and properties such as compressive strength, flexural strength, split tensile strength, drying shrinkage, electrical resistivity, and rapid chloride penetration (hardened). Microstructural characteristics are also examined through techniques like XRD, SEM, and EDAX. By comparing the results with the control mix, this study identifies the most significant differences.
3. The research investigates the effects of RCA on the morphology and composition, including chemical and mineralogical aspects, of RCA concrete. By analyzing the generation of microstructure, this study sheds light on the influence of RCA on the concrete's microstructure and emphasizes the importance of determining the optimum RCA content for sustainable concrete development.

In summary, this study not only explores the efficient use of RCA for concrete production but also addresses crucial research gaps by employing rigorous methodologies to assess a wide range of properties. Furthermore, it delves into the intricate details of microstructural changes, emphasizing the significance of finding the optimal RCA content to advance the development of sustainable concrete.

2. EXPERIMENTAL PROGRAMME

2.1. Materials

The study employs Ordinary Portland cement grade 43, compliant with IS 269-2015 (31). Table 1 presents the physical test results for the cement.

Table 1. Cement physical test results.

S.N.	Types	Value Measured	As per IS 269-2015 (31)
1	Consistency	31%	-
2	Initial Setting Time	58	> 30 Minutes
3	Final setting Time	435	< 10 Hours
4	Specific Gravity	3.11	3.0 to 3.15

For fine aggregate, natural sand with a particle size less than 4.75 mm, confirming to IS 383-2016 (Reaffirmed 2021) (32), is used. The coarse aggregates consist of crushed stone ranging from 4.75 mm to 20 mm, confirming to IS 383-2016 (Reaffirmed 2021) (32). This aggregate, passing through 40 mm sieves and retained on 4.75 mm sieves, has a passing percentage of 90.76% for 20 mm sieves and 4.52% for 10 mm sieves. Recycled coarse aggregates (RCA) from crushed concrete C&D waste are used after reducing them to the necessary size using an impact crusher. These RCA, also passing through 40 mm sieves and retained on 4.75 mm sieves, exhibit passing percentages of 92.10% for 20 mm sieves and 0.38% for 10 mm sieves. Table 2 provides a detailed overview of particle packing density within specific cylindrical volumes, achieved through standard compaction techniques.

Table 2. Weight within specific cylindrical volume achieved through standard compaction efforts.

S. No	Coarse Aggregates Mixtures	Weight
1	NCA	14.68
2	RCA 25 + NCA 75	15.25
3	RCA 50 + NCA 50	14.62
4	RCA 75 + NCA 25	13.73
5	RCA 100	13.15

This analysis involves various mixtures of coarse aggregates, revealing crucial insights into their compactness and structural viability. Firstly, the table outlines the results for NCA (Natural Coarse Aggregates), where the weight attained within the specific cylindrical volume stands at 14.68 units. Subsequently, the combination of RCA 25 + NCA 75 showcases a notably higher packing density, registering a weight of 15.25 units. Another blend, RCA 50 + NCA 50, which comprises equal parts of Recycled Coarse Aggregates (RCA) and Natural Coarse Aggregates (NCA), exhibits a weight of 14.62 units within the specified volume. A mixture with RCA 75 + NCA 25 composition, consisting of 75% RCA and 25% NCA, yields a slightly lower weight of 13.73 units. Lastly, using RCA 100, indicating the complete substitution of Natural Coarse Aggregates with 100% Recycled Coarse Aggregates, results in a weight of 13.15 units within the specific cylindrical volume. Significantly, the data highlights that the blend of RCA 25 + NCA 75boasts the densest packing density among these combinations. This finding is essential, indicating superior structural integrity. This critical insight, complemented by Figure 1 showcasing particle size distribution, informs the selection of optimal concrete compositions for construction applications, ensuring the durability and stability of structures.

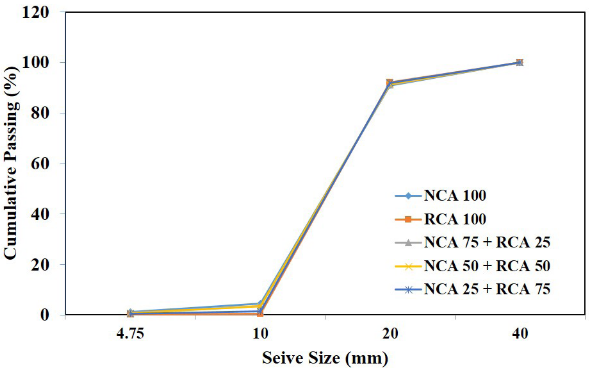

Figure 1. Gradation curves illustrating coarse aggregates in various mixtures.

Table 3 presents the physical and mechanical properties of both natural and recycled coarse aggregates, alongside natural fine aggregates (NFA), natural coarse aggregates (NCA), and recycled coarse aggregates (RCA).

Table 3. Physical and mechanical properties of aggregates.

Property	NFA	NCA	RCA	Standard Limits
Bulk Density (kg/m^3)	1625	1740	1660	1200-1750 (33)
Specific gravity	2.675	2.754	2.681	2.30-2.90 (33)
Water Absorption (%)	0.51	1.12	2.35	≤ 2.0 (IS 2386 Part 3) (33)
Abrasion Loss (%)	15.52	25.43	28.76	< 30 (IS 2386 Part 4) (34)
Crushing Value (%)	16.21	26.24	27.71	< 30 (IS 2386 Part 4) (34)
Impact Value (%)	15.31	17.31	20.68	< 30 (IS 2386 Part 4) (34)

Furthermore, a chemical admixture in the form of super-plasticizers (C-MAX), conforming to IS 9103-1999 (35), is used at 1% by weight of cement. Potable water from the laboratory is employed for mixing and curing purposes, ensuring consistent and reliable experimental conditions.

2.2. Mix proportions

To investigate the viability and impact of recycled coarse aggregates on the mechanical properties of concrete, five distinct concrete mixtures were formulated to achieve target strength of 27MPa. The compositions of these mixtures are detailed in Table 4. The reference mixture (RC) was crafted using natural aggregates. Additionally, four other mixtures, namely RCA-25, RCA-50, RCA-75, and RCA-100, were created by substituting natural coarse aggregates with recycled coarse aggregates at replacement percentages of 25%, 50%, 75%, and 100%, respectively. All these concrete blends were meticulously prepared through the weight batching method, maintaining a consistent water-cement ratio of 0.50. This methodical approach allowed for a systematic exploration of the mechanical behavior of concrete when integrating various proportions of recycled coarse aggregates, offering valuable insights into their feasibility and effectiveness in enhancing the concrete's overall performance.

2.3. Testing programs

Various tests were conducted to assess different aspects of structural concrete. Workability, following the IS 1199-1959 standard (36), was measured to gauge the freshness of the concrete. Additionally, mechanical characteristics were evaluated through tests for compressive strength, flexural strength, and split tensile strength. To analyze the long-term performance of concrete, tests were performed for drying shrinkage (in accordance with IS 516 Part 6, 2020 (37)), electrical resistivity (following RILEM TC 154-EMC standards (38)), and rapid chloride penetration (as per ASTM C1202 guidelines (39)). Moreover, the microstructural features of concrete samples from different mixtures were examined using scanning electron microscopy (SEM), energy-dispersive X-ray spectros-

Table 4. Concrete mix compositions (kg/m^3).

S. No.	Mixture ID	NFA	NCA	RCA	Cement	W/C Ratio	Admixture
1	RC	444.48	1511	0	400	0.5	4
2	RCA 25	444.48	1133.25	377.75	400	0.5	4
3	RCA 50	444.48	755.5	755.5	400	0.5	4
4	RCA 75	444.48	377.75	1133.25	400	0.5	4
5	RCA 100	444.48	0	1511	400	0.5	4

copy (EDAX), and X-ray diffraction (XRD) analyses. These comprehensive assessments provided valuable insights into the various properties and performance aspects of the concrete structures under study.

3. RESULTS AND DISCUSSION

3.1. Workability

A slump test, in accordance with IS 1199-1959 (36), was conducted to assess the workability of concrete mixes containing varying proportions of Construction and Demolition (C&D) waste in the form of recycled coarse aggregates. The results of these tests are summarized in Table 5.

Table 5. Slump measurements for various mixtures.

Concrete Mix	Slump (mm)
RC	111
RCA 25	101
RCA 50	95
RCA 75	83
RCA 100	70

The variations in slump for the different concrete mixtures are graphically represented in Figure 2. The figure illustrates a consistent decrease in concrete slump with the increase in recycled coarse aggregates. The workability of concrete incorporating Recycled Coarse Aggregates (RCA) falls within the medium range of 50 to 100 mm, as indicated by the slump values across all mixtures. This reduction in slump is attributed to RCA absorbing more water than natural aggregates, primarily due to the presence of old adhered mortar on the RCA surface, which absorbs additional water. The trend clearly demonstrates that an escalation in RCA content leads to a decrease in the concrete slump. This pattern aligns with findings from a previous study (40), confirming the consistent impact of increasing RCA content on reducing concrete workability.

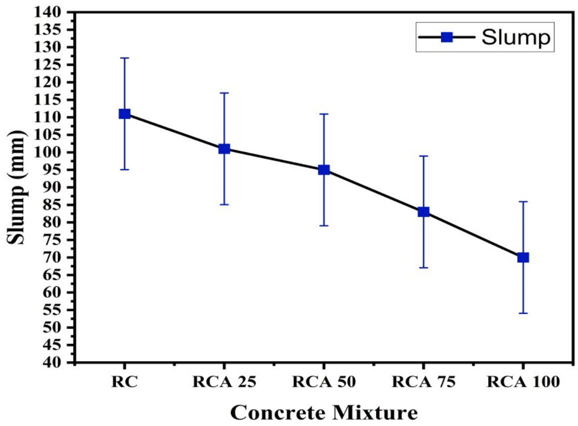

Figure 2. Slump values across various concrete mixtures.

3.2. Compressive strength

A total of 30 specimens, moulded in steel cubes with dimensions 15×15×15 cm, were cast, cured, and subjected to compressive strength testing across various concrete mixtures. Using a compression testing machine with a capacity of 2000 KN, the samples were analyzed at 7 and 28 days, and the results are detailed in Table 6. Figure 3 visually represents the variations in compressive strength at 7 and 28 days for different replacement percentages of Recycled Coarse Aggregates (RCA) concerning the reference mixture. The results clearly indicate that concrete mixtures with higher RCA replacements exhibit lower compressive strength compared to the reference mixture. Notably, the optimum replacement percentage of recycled coarse aggregates is 25%.

This observed trend can be explained by examining the voids and particle packing within the mixtures. At higher percentage of RCA, especially at 25% replacement, results in fewer voids and optimal particle packing, leading to higher strength. The study further emphasizes the importance of fine aggregates' particle size, specifically particles smaller than 600 microns, in forming a sufficient paste to fill voids in larger particles. A considerable gap between these particle sizes results in enhanced strength within specified limits. Conversely, smaller gaps lead to reduced strength. At

Table 6. Percentage variations in compressive strength among different mixtures.

Concrete Mix	Compressive Strength (MPa)			
	7 Days	% Variation With Respect to RC	28 Days	% Variation With Respect to RC
RC	22.71	-	31.99	-
RCA 25	25.44	+12.02	35.69	+11.56
RCA 50	22.12	-02.59	31.45	-01.68
RCA 75	19.02	-16.24	27.74	-13.28
RCA 100	16.31	-28.18	22.99	-28.13

+ sign represents increase in strength and – sign represents decrease in strength.

higher replacement percentages, increased void content and the presence of old adhered mortar weaken the bonding with aggregates, causing a decline in strength. Among the mixtures, RCA 25 exhibits the highest compressive strength (35.69 MPa), while RCA 100 displays the lowest (22.92 MPa). These findings align with previous studies, such as those by Kessal et al. (41), and support the results of Ankesh et al. (42), study, indicating that a 30% replacement of recycled coarse aggregates achieves strength exceeding the target levels.

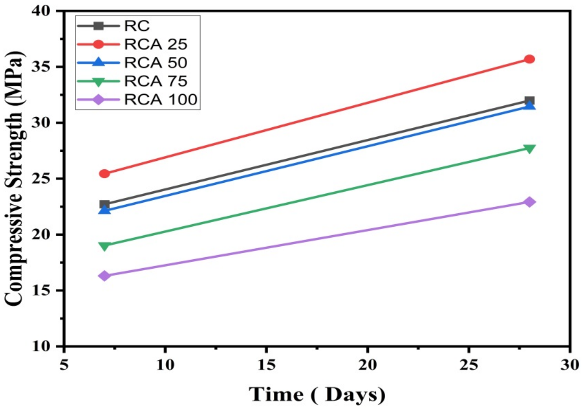

Figure 3. Compressive strength variations among various concrete mixtures.

The strategic incorporation of Recycled Concrete Aggregate (RCA) at a 25% replacement rate has showcased its significant potential, prompting a detailed exploration of its multifaceted applications (43). This optimized mixture has proven highly advantageous across diverse construction sectors. Non-structural elements like decorative facades and interior designs can now benefit from an eco-friendly and cost-effective solution. In the domain of pavements, where durability and load-bearing capacity are critical, this blend aligns seamlessly with sustainable infrastructure goals. Furthermore, its adaptability extends to specialized projects, particularly in eco-friendly constructions and landscaping efforts, where minimizing the carbon footprint is imperative. In these contexts, RCA-integrated concrete emerges as a sustainable choice, combining aesthetic appeal with environmental consciousness. While higher RCA percentages do impact concrete properties, the construction industry's commitment to sustainability leads to exploration beyond traditional structural applications. In scenarios where sheer structural strength isn't the sole focus, such as in landscaping or road base layers prioritizing stability, RCA-integrated concrete proves invaluable. In environmentally conscious construction projects emphasizing innovation and eco-friendliness, this approach gains significant traction. The versatility of RCA-integrated concrete expands beyond conventional boundaries, finding utility in diverse construction contexts. By exploring these alternative paths and carefully evaluating different construction scenarios, the industry can harness the adaptability and effectiveness of this optimized blend. This method not only tackles challenges associated with higher RCA percentages but also pioneers a future where sustainability and ecological responsibility drive construction practices. Through these strategic integrations, the industry edges closer to its sustainability objectives while enriching the landscape of eco-conscious construction methodologies.

3.3. Flexural strength

Thirty specimens, cast in steel rectangular moulds measuring 50×10×10 cm, underwent curing and flexural strength testing across various concrete formulations. These samples were meticulously evaluated using a flexural testing machine with a capacity of 2000 KN. The average flexural strength values were derived from three specimens for each mix, and the tests were conducted at both 7 and 28 days, with the results documented in Table 7.

Figure 4 graphically illustrates the variations in flexural strength at 7 and 28 days for different replacement percentages of Recycled Coarse Aggregates (RCA) concerning the reference mixture. Notably, the results mirrored a pattern similar to compressive strength, demonstrating that concrete mixtures with higher RCA replacement percentages exhibit lower flexural strength than the reference mixture. Among the mixtures, RCA 25 showcased the highest flexural strength (4.04 MPa), while RCA 100 displayed the

Table 7. Percentage variations in flexural strength among different mixtures.

Concrete Mix	Flexural Strength (MPa)			
	7 Days	% Variation With Respect to RC	28 Days	% Variation With Respect to RC
RC	3.18	-	3.92	-
RCA 25	3.28	+03.14	4.04	+03.06
RCA 50	3.09	-02.83	3.87	-01.27
RCA 75	2.90	-08.80	3.62	-07.65
RCA 100	2.68	-15.72	3.34	-14.79

+ sign represents increase in strength and – sign represents decrease in strength.

lowest flexural strength (3.34 MPa). These findings are consistent with the observations made by other researchers (40, 44), indicating a parallel trend between compressive and flexural strength concerning varying RCA replacement percentages.

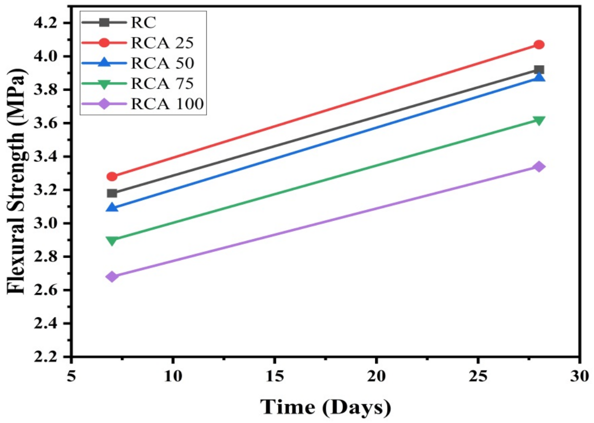

Figure 4. Variability in flexural strength across different concrete mixtures.

3.4. Split tensile strength

A comprehensive evaluation was conducted on 30 specimens cast in steel cylindrical moulds with a diameter (ϕ) of 15 cm and height (H) of 30 cm. These specimens were meticulously cured and subjected to split tensile strength testing using a compression testing machine with a capacity of 2000 KN. The average split tensile strength values were derived from three specimens for each mix, and the tests were conducted at both 7 and 28 days, with the results detailed in Table 8.

The variation in split tensile strength for different replacement percentages of Recycled Concrete Aggregate (RCA) concerning the reference mixture is depicted in Figure 5. The trend observed in the results parallels that of compressive strength. It was discerned that the split tensile strength of concrete mixtures decreased concerning the reference mixture with higher proportions of RCA replacement. Among the mixtures, RCA 25 exhibited the highest split tensile strength (2.64 MPa), while RCA 100 displayed the lowest (2.11 MPa) in the group. These findings align with the work reported by Kessal et al. (41).

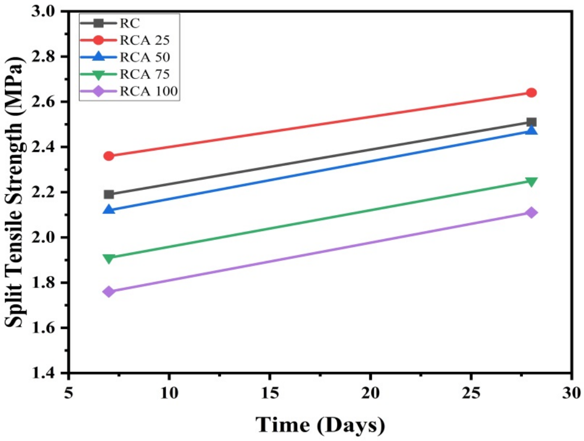

Figure 5. Variability in split tensile strength across various concrete mixtures.

3.5. Drying shrinkage

The assessment of concrete mixes' drying shrinkage involved measuring their length variations over time, adhering to IS 516 (Part 6) 2020 (37) standards, as depicted in Figure 6. Each of the 5 different mixtures was represented by three specimens of size 75×75×285 mm, which were stored for 28 days. Initial readings were recorded using length comparator tools with a precision count of 0.005 mm. Subsequent readings were taken at 28, 56, and 90 days using dial gauges, with each specimen's length change calculated based on the difference between the final and initial values. The outcomes of the drying shrinkage tests are summarized in Table 9.

Figure 7 illustrates the variations in shrinkage strain concerning different concrete mixtures at different drying ages. The graph demonstrates how concrete contracts more as it dries, indicated by the relationship between the two factors. Notably, the slope of the drying shrinkage curve changes from steep to flat as drying time increases, indicating a decreasing rate of change in drying shrinkage over time.

Table 8. Percentage variability in split tensile strength across different mixtures.

Concrete Mix	Split Tensile Strength (MPa)			
	7 Days	% Variation With Respect to RC	28 Days	% Variation With Respect to RC
RC	2.19	-	2.51	-
RCA 25	2.36	+07.76	2.64	+05.17
RCA 50	2.12	-03.19	2.47	-01.59
RCA 75	1.91	-12.78	2.25	-10.35
RCA 100	1.76	-19.63	2.11	-15.93

+ sign represents increase in strength and – sign represents decrease in strength.

Figure 6. Drying shrinkage apparatus and sample testing process.

Table 9. Percentage variations in drying shrinkage among different mixtures.

Concrete Mix	Drying Shrinkage (10^{-6}) 28 Days	% Variation With Respect to RC	56 Days	% Variation With Respect to RC	90 Days	% Variation With Respect to RC
RC	344	-	422	-	461	-
RCA 25	362	+05.23	457	+08.29	496	+07.59
RCA 50	415	+20.63	501	+18.72	549	+19.08
RCA 75	464	+34.88	562	+33.17	595	+29.06
RCA 100	499	+45.05	624	+47.86	641	+39.04

+ sign represents increase in drying shrinkage and – sign represents decrease in drying shrinkage.

Additionally, it was observed that the drying shrinkage of concrete steadily increases with the rise in the percentage of coarse aggregate replacement at all drying ages. This increase can be attributed to the presence of additional cement around the surface of Recycled Concrete Aggregate (RCA), absorbing more water and shrinking significantly during the drying process. While the addition of RCA led to increased drying shrinkage due to its higher water absorption, all mixtures remained within the typical range specified by Indian Standards, indicating that RCA can be used within specific limits without adversely affecting its shrinkage properties. These findings align with previous studies, such as Kioumarsi et al. (45), and support the systematic increase in concrete's drying shrinkage with higher proportions of recycled coarse aggregates, as observed by Yu et al. (8).

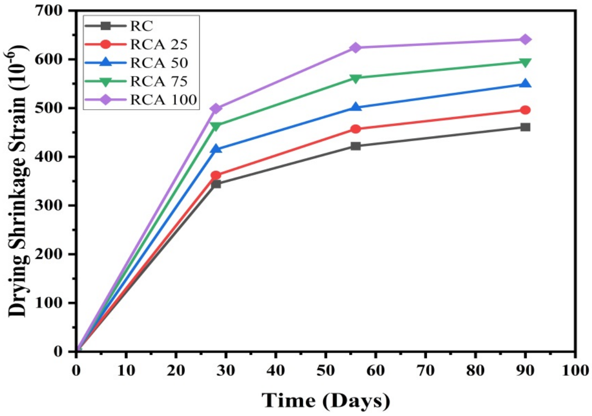

Figure 7. Shrinkage strain in various concrete mixtures.

3.6. Electrical resistivity

The electrical resistivity of concrete is a critical factor in assessing the risk of corrosion for the steel reinforcement bars within the concrete structure. The method employed measures the surface electrical resistivity of fresh concrete using a four-electrode setup. Utilizing the Resipod Resistivity Meter, illustrated in Figure 8, which features a 4-point Wenner Probe following the RILEM TC 154-EMC (38) standard, concrete samples are prepared in cylindrical molds with a diameter of 100 mm and a height of 200 mm.

Tests are conducted at 28 and 56 days, and the results are presented in Table 10.

The variation for the 28 and 56 days old electrical resistivity for different replacement percentages of C&D waste aggregates concerning the reference mixture is shown in Figure 9.

The results reveal that concrete mixtures with higher percentages of RCA replacement exhibit lower electrical resistivity compared to the reference mixture, indicating reduced corrosion risks. The high porosity of RCA traps water with dissolved ions, creating a low-resistance route for electric current, thereby lowering electrical resistivity. Specifically, RCA 25 demonstrates the highest electrical resistivity, while RC and RCA 50 are comparable. In descending order, RCA 75 and RCA 100 exhibit the least electrical resistivity. These findings suggest that concrete produced with up to 75% RCA replacement poses a low risk of corrosion, whereas concrete with 100% RCA replacement presents a moderate risk. This aligns with prior studies (45). and resonates with Arredondo-Rea et al.'s research (46), which concluded that electrical resistivity in concrete is minimally impacted when replacing up to 30% of coarse aggregates and 20% of fine aggregates with recycled counterparts. Consequently, concrete derived from C&D waste indicates a moderate risk of corrosion for the embedded steel bars.

3.7. Rapid chloride penetration

The RCPT unit, depicted in Figure 10, follows the ASTM C1202 (39) standard, featuring a mold measuring 100 mm in diameter and 50 mm in height. Thirty specimens were prepared for the study. The unit comprises two chambers filled with sodium chloride (NaCl) at a concentration of 0.24M and sodium hydroxide (NaOH) at 0.3M. Specimens and test cells are meticulously sealed. A 60V current source connects the negative end to the NaCl cell and the positive end to the NaOH cell. Readings are taken at 30-minute intervals for up to 6 hours. Tests at 28 and 56 days gauge the charge passed, indicating resistance to chloride ion penetration. Results are presented in Table 11.

The variation in chloride permeability for different replacement percentages of C&D waste aggregates concerning the reference mixture is demonstrated in Figure 11.

Chloride permeability tests reveal that concrete with higher percentages of C&D waste aggregate replacement has increased chloride permeability compared to the reference mixture, indicating reduced durability. This rise is attributed to the high porosity of C&D waste aggregates, trapping water with ions, creating a low-resistance path for electric current. The highest chloride permeability occurs at 100% RCA replacement. Concrete with up to 50% RCA replacement exhibits high durability, whereas concrete with over 75% RCA replacement shows moderate durability. Increasing RCA replacement decreases concrete durability and increases chloride permeability. The study aligns with Yang and Lee's findings (47), indicating decreased chloride ion penetration with concrete age regardless of RCA content. This research aligns with Arredondo-Rea et al.'s study (46), underscoring that C&D waste concrete exhibits moderate chloride permeability.

Figure 8. Resistivity meter setup and sample testing process.

Table 10. Percentage variations in electrical resistivity among different mixtures.

Concrete Mix	Electrical Resistivity (KΩ)			
	28 Days	**% Variation With Respect to RC**	**56 Days**	**% Variation With Respect to RC**
RC	48.54	-	59.19	-
RCA 25	52.81	+08.79	63.45	+07.19
RCA 50	46.69	-03.81	57.28	-03.22
RCA 75	37.33	-23.09	47.76	-19.31
RCA 100	16.01	-67.01	26.29	-55.58

+ sign represents increase in electrical resistivity and – sign represents decrease in electrical resistivity.

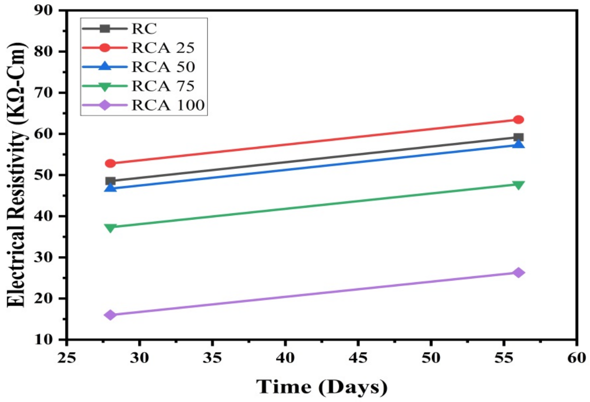

Figure 9. Electrical resistivity variations with recycled concrete aggregates (RCA).

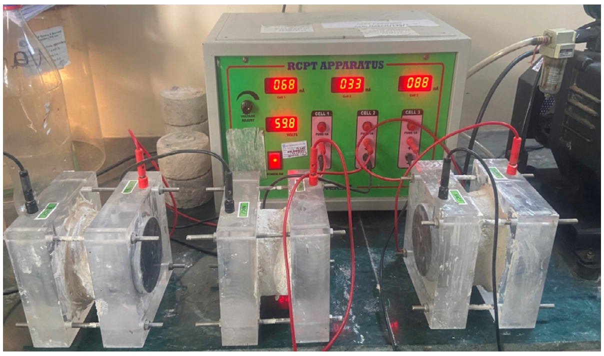

Figure 10. Standard configuration of RCPT unit (ASTM C1202).

Table 11. Percentage variations in passed charge among different mixtures.

Concrete Mix	Charge Passed (Coulomb)			
	28 Days	% Variation With Respect to RC	56 Days	% Variation With Respect to RC
RC	704	-	683	-
RCA 25	671	-04.68	636	-06.88
RCA 50	824	+17.04	782	+14.49
RCA 75	953	+35.36	950	+39.09
RCA 100	1053	+49.57	1050	+53.73

+ sign represents increase in charge passed and – sign represents decrease in charge passed.

3.8. X-Ray Diffraction (XRD)

X-ray Diffraction (XRD) is a powerful analytical technique employed to explore the crystalline characteristics and mineralogical composition of concrete samples, especially when incorporating recycled coarse aggregates. In this study, the Bruker D-8 advanced diffractometer system was utilized, scanning samples at an angle of 2 degrees within the range of 3-70 degrees. The scanning speed was set at 2 degrees per minute with a sampling interval of 0.005 degrees. The obtained data were analyzed using Jade 7 X-ray diffraction software. The XRD analysis revealed intriguing insights. As the replacement percentage of Recycled Coarse Aggregates (RCA) increased, the net intensity of minerals such as Calcium Silicate Hydrate (CSH), Calcium Hydroxide (CH), and Ettringite decreased. This decrease indicated a reduction in the density of total CSH in the concrete mixtures. Figure 12 vividly displays the XRD patterns for different concrete mixtures, including RC, RCA 25, RCA 50, RCA 75, and RCA 100. To provide a comprehensive understanding, the diffraction peak angles of various compounds are presented in Table 12.

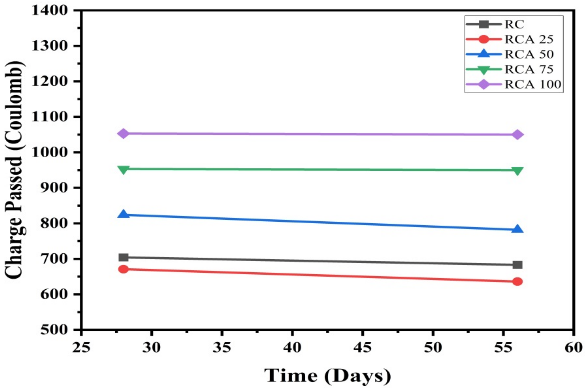

Figure 11. Chloride permeability variations with recycled concrete aggregates (RCA).

The XRD analysis clearly illustrates that the incorporation of recycled coarse aggregates significantly influences the phase composition of minerals in concrete. The table presents detailed information regarding the diffraction peak angles of three essential compounds - Calcium Silicate Hydrate (CSH), ettringite, and Calcium Hydroxide (CH) - in various concrete mixtures. These mixtures are denoted as RC, RCA 25, RCA 50, RCA 75, and RCA 100. CSH, a vital mineral

Table 12. Diffraction peak angles of different compounds in various concrete mixtures.

Concrete Mix	CSH (2Θ)	ETTRINGITE (2Θ)	CH (2Θ)
RC	26.65	37.84	50.00
RCA 25	26.66	40.48	50.22
RCA 50	27.86	39.24	48.32
RCA 75	21.24	29.50	48.48
RCA 100	27.58	39.40	50.12

CSH- Calcium Silicate Hydrate, CH- Calcium Hydroxide, Ettringite- Hydrated Calcium Aluminum Sulfate.

phase in concrete responsible for its strength and durability, is represented by a diffraction peak angle of 26.65° in regular concrete (RC). Ettringite, a hydrated calcium aluminum sulfate compound, exhibits a peak at 37.84°, while CH, also known as hydrated lime, shows a peak at 50.00° in this standard mixture. It is important to note that the intensity of these peaks indicates the quantity of these compounds; however, the non-homogeneity of the concrete samples at the microscopic level was considered during the analysis. The analysis extends to concrete mixtures incorporating recycled concrete aggregate (RCA) at different percentages. Specifically, RCA 25, RCA 50, RCA 75, and RCA 100 represent concrete mixes with 25%, 50%, 75%, and 100% recycled aggregate content, respectively. As the proportion of recycled aggregate increases, the diffraction peak angles for CSH, ettringite, and CH vary. For instance, in the RCA 75 mixture, the diffraction peak angles for CSH, Ettringite, and CH shift to 21.24°, 29.50°, and 48.48°, respectively. This alteration in peak angles suggests potential changes in the crystal structure of CSH and ettringite due to the introduction of 75% recycled concrete aggregate. This study aligns with previous research conducted by Joseph et al. (48), highlighting the consistency of these findings in the scientific community. In summary, the table's data offers insights into the composition of concrete mixtures, focusing on changes in key compounds (CSH, ettringite and CH) as recycled concrete aggregate percentages vary. These changes significantly impact concrete properties and performance in construction, emphasizing the need for effective material engineering and construction practices.

3.9. Scanning electron microscopy (SEM)

The analysis of Scanning Electron Microscopy (SEM) plays a pivotal role in understanding the intricate microstructure and surface morphology of concrete samples, especially when incorporating Recycled Coarse Aggregates (RCA). In this study, the JSM 6610V scanning electron microscope, operating at 30KV, was utilized at the University Science Instrumentation Center (USIC) in Delhi. Figure 13 showcases detailed micrographs obtained at 28 days for different concrete mixtures, shedding light on the formation of crucial hydration products at the microstructural level, which significantly influence concrete strength. In these micrographs, distinct features reveal the presence of key compounds formed during the hydration process. Hexagonal crystal formations signify the presence of calcium hydroxide (CH), while flower-shaped structures indicate calcium silicate hydrate (CSH) gel, and needle-like structures are evidence of ettringite. These compounds are essential contributors to concrete strength and durability.

The SEM analysis yielded crucial insights. Incorporating 25% RCA led to a significant enhancement of the concrete microstructure, producing a dense cement paste. This dense paste fostered a robust bond with aggregates, ultimately enhancing the compressive strength of the concrete. However, when the RCA replacement percentage was increased to 50%, the resulting concrete exhibited lower density, leading to a reduction in compressive strength. A further increase to 75% RCA content resulted in the formation of voids and loose structures, leading to decreased compressive strength. Remarkably, an RCA replacement of 100% yielded a porous microstructure, where incomplete hydration reactions occurred around the recycled coarse aggregates, resulting in fewer hydration products and, consequently, reduced strength. The SEM findings highlighted a crucial pattern: lower proportions of RCA in the mixtures promoted the formation of more calcium silicate hydrate (CSH) gel, which densified the cement paste matrix and consequently increased the concrete's strength. However, excessive RCA incorporation led to fragile mixtures with inadequate CSH production, resulting in insufficient strength. These observations align with similar interpretations made in previous studies (48), reinforcing the consistency and reliability of these findings in the scientific community.

3.10. Energy dispersive X-ray spectroscopy (EDAX)

Energy-Dispersive X-ray Spectroscopy (EDAX) serves as a powerful tool in dissecting the intricate

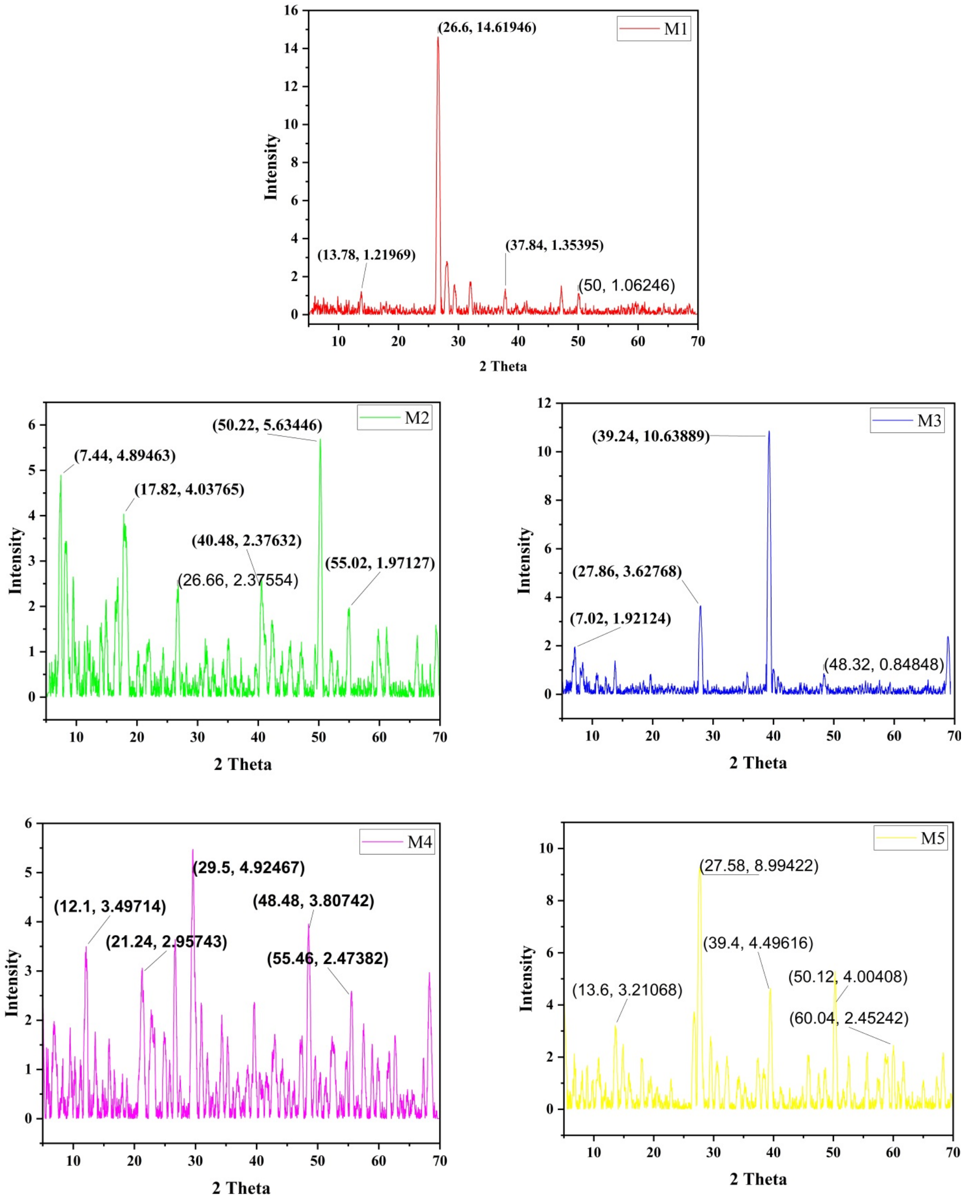

Figure 12. XRD Analysis of concrete mixtures (M1) for RC, (M2) for RCA 25, (M3) for RCA 50, (M4) for RCA 75, and (M5) for RCA 100.

chemical composition of concrete. This study delves into qualitative and quantitative analyses of diverse elements within different concrete mixtures. Figures 14 meticulously delineate these analyses, offering a comprehensive view of the elemental content.

The EDAX analysis reveals the presence of pivotal elements: Calcium (Ca), Oxygen (O), Silicon (Si), Aluminum (Al), Iron (Fe), Potassium (K), Sodium (Na), and Magnesium (Mg). In-depth scrutiny illustrates intriguing patterns. In mixture RCA 25, calcium content surges, fostering the creation of hydration products like Calcium Hydroxide (CH), Calcium Silicate Hydrate (CSH), and Calcium Aluminosilicate Hydrate (CASH). Contrastingly, higher RCA replacement percentages witness a decline in calcium content, leading to diminished hydration products. Simultaneously, silica content diminishes at lower RCA replacement percentages but exhibits a gradual increase with higher RCA replacements. The lower alumina content in these mixtures curtails ettringite formation. SEM results corroborate these findings, evidencing robust CSH formation up to a 25% RCA replacement. The chemical compositions highlighted by EDAX validate this observation. Notably, higher RCA replacements inhibit calcium compound formation, directly correlating with decreased concrete strength. Table 13 encapsulates the quantitative chemical composition, providing a succinct overview. It is essential to note

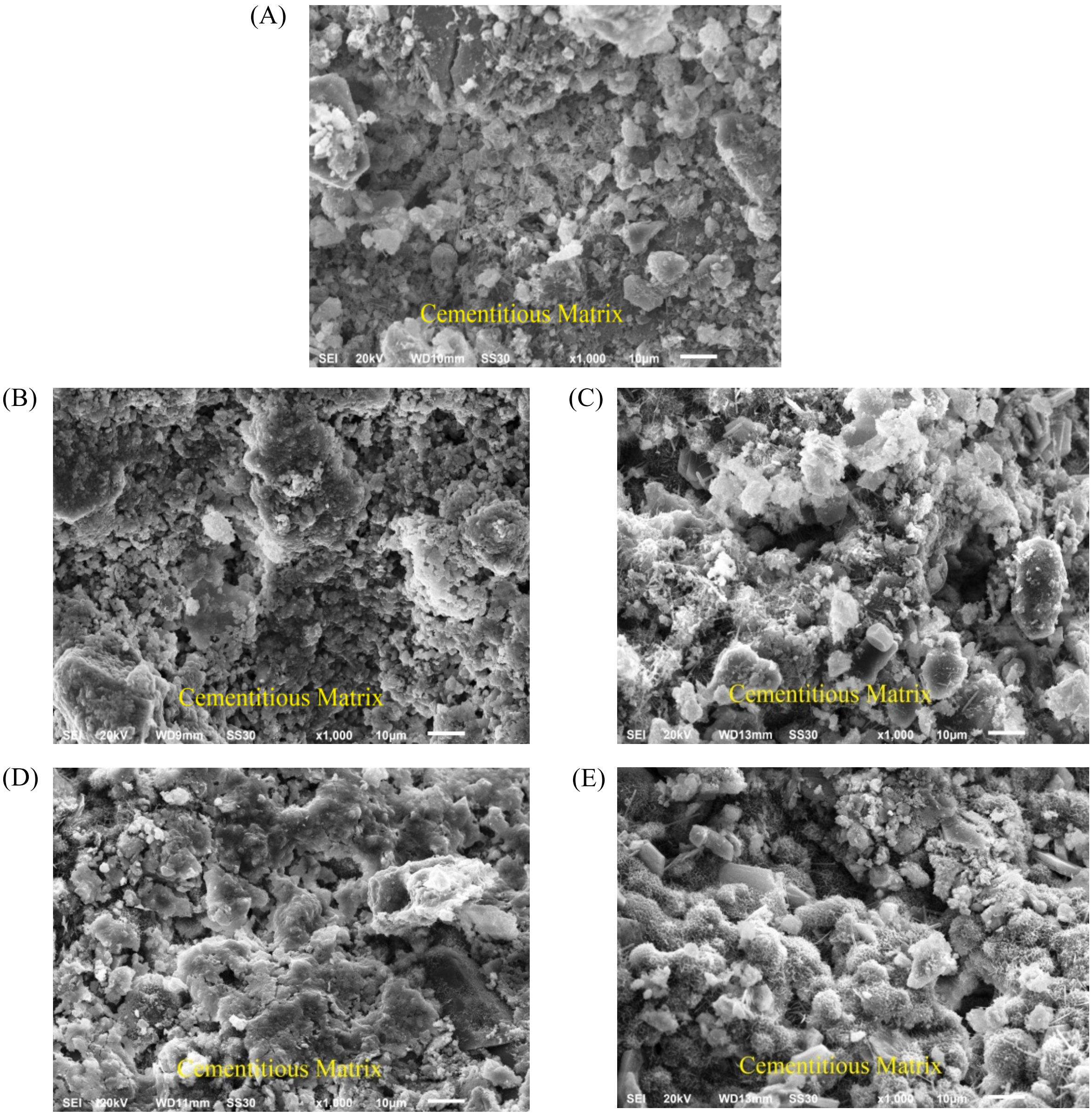

Figure 13. SEM images for different concrete mixtures (A) for RC, (B) for RCA 25, (C) for RCA 50, (D) for RCA 75, and (E) for RCA 100.

that all EDAX graphs affirm the presence of varied elements like calcium, aluminum, iron, etc. However, due to microscopic heterogeneity, specific peaks lack visual representation. This comprehensive EDAX analysis not only dissects the elemental intricacies but also substantiates the influence of RCA replacement percentages on concrete composition and, consequently, its mechanical properties.

4. ANALYTICAL INVESTIGATION

In the realm of concrete technology, understanding the interplay between different properties is paramount. Employing the sophisticated technique of linear regression analysis, this study meticulously delves into the properties of concrete infused with varying proportions of recycled coarse aggregates (RCA). Through empirical analysis, a linear relationship was established between key properties of fresh concrete, correlating them linearly with the RCA replacement ratio. This correlation, based on extensive experimental data collected from various properties of recycled coarse aggregate concrete after 28 days of water curing, was graphically represented using Origin Software, resulting in well-fitted curves reflecting the intricate dynamics at play.

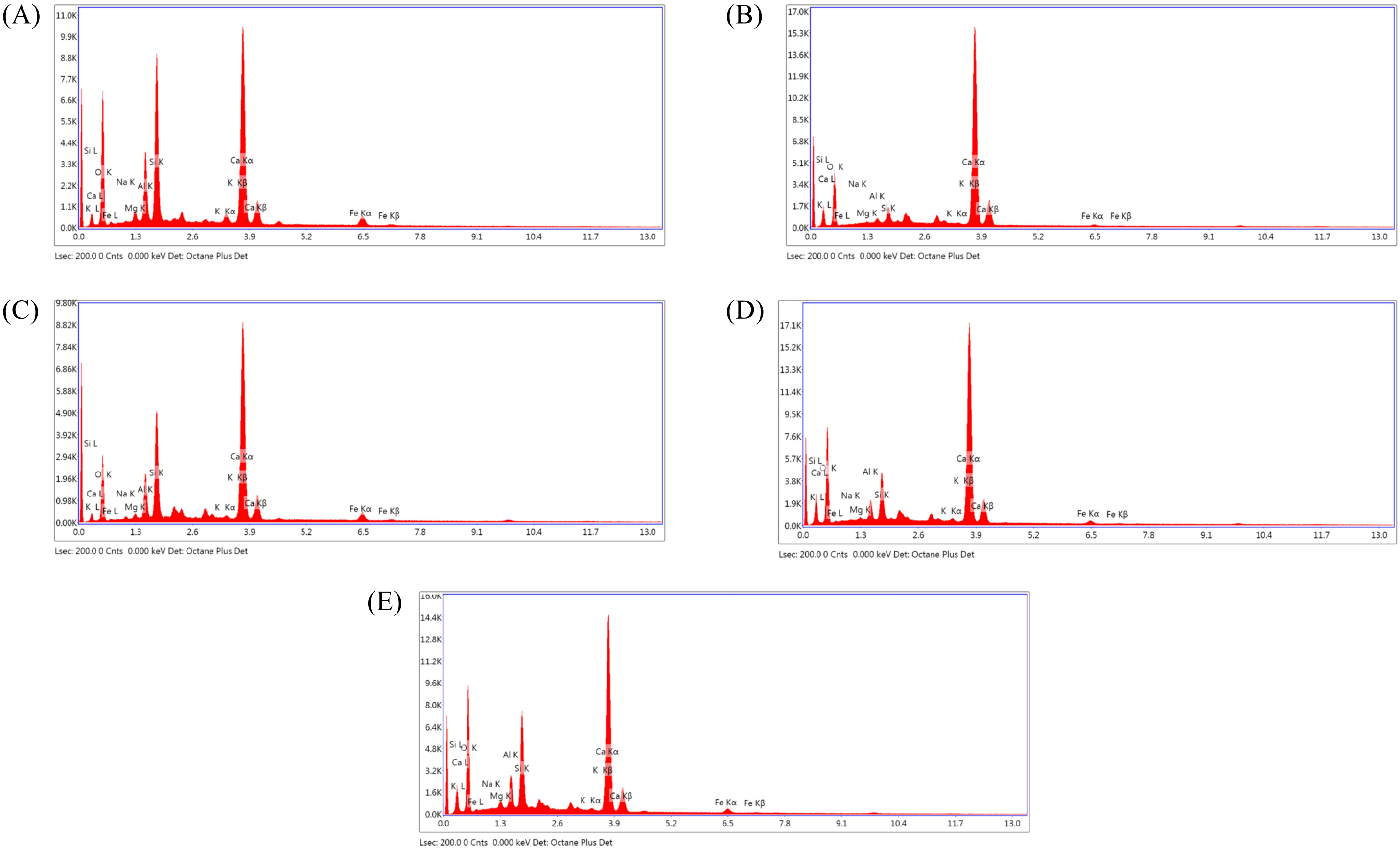

FIGURE 14. EDAX analyses for different concrete mixtures (A) for RC, (B) for RCA 25, (C) for RCA 50, (D) for RCA 75, and (E) for RCA 100.

TABLE 13. Percentage composition of different elements in various mixtures.

Mixture ID	(%)	Ca-K	O-K	Si-K	Al-K	Fe-K	K-K	Na-K	Mg-K
RC	Weight	28	48.21	10.49	5.27	4.12	1.43	1.04	1.46
	Atomic	15.54	67.03	8.3	4.34	1.64	0.81	1	1.33
RCA-25	Weight	46.76	48.8	1.6	0.58	0.64	0.42	0.92	0.29
	Atomic	26.71	69.81	1.31	0.49	0.26	0.24	0.91	0.27
RCA-50	Weight	38.7	41.3	9.22	4.26	4.59	0.87	0..64	0.43
	Atomic	23.08	61.71	7.84	3.77	1.97	0.53	0.67	0.42
RCA-75	Weight	36.12	52.23	4.08	2.25	1.57	0.92	1.88	0.94
	Atomic	19.74	71.48	3.18	1.82	0.62	0.52	1.79	0.85
RCA-100	Weight	30.81	52.78	6.99	3.25	1.97	0.75	1.82	1.64
	Atomic	16.57	71.13	5.36	2.6	0.76	0.41	1.71	1.45

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

The linear correlations between the RCA replacement level and different mechanical properties were expressed mathematically. The equations derived for compressive strength (Fc), flexural strength (Ff), split tensile strength (Fs), drying shrinkage (Fd), electrical resistivity (FE), and rapid chloride permeability (FR) are represented respectively as Equations [1], [2], [3], [4], [5] and [6]:

$$F_c = 35.162 - 0.1038R_r \qquad [1]$$

$$F_f = 4.086 - 0.00644R_r \qquad [2]$$

$$F_s = 2.634 - 0.00476R_r \qquad [3]$$

$$F_d = 334.4 + 1.648R_r \qquad [4]$$

$$F_E = 63.584 - 0.41816R_r \qquad [5]$$

$$F_R = 685 + 3.52R_r \qquad [6]$$

Here, Fc represents compressive strength, Ff denotes flexural strength, Fs signifies split tensile

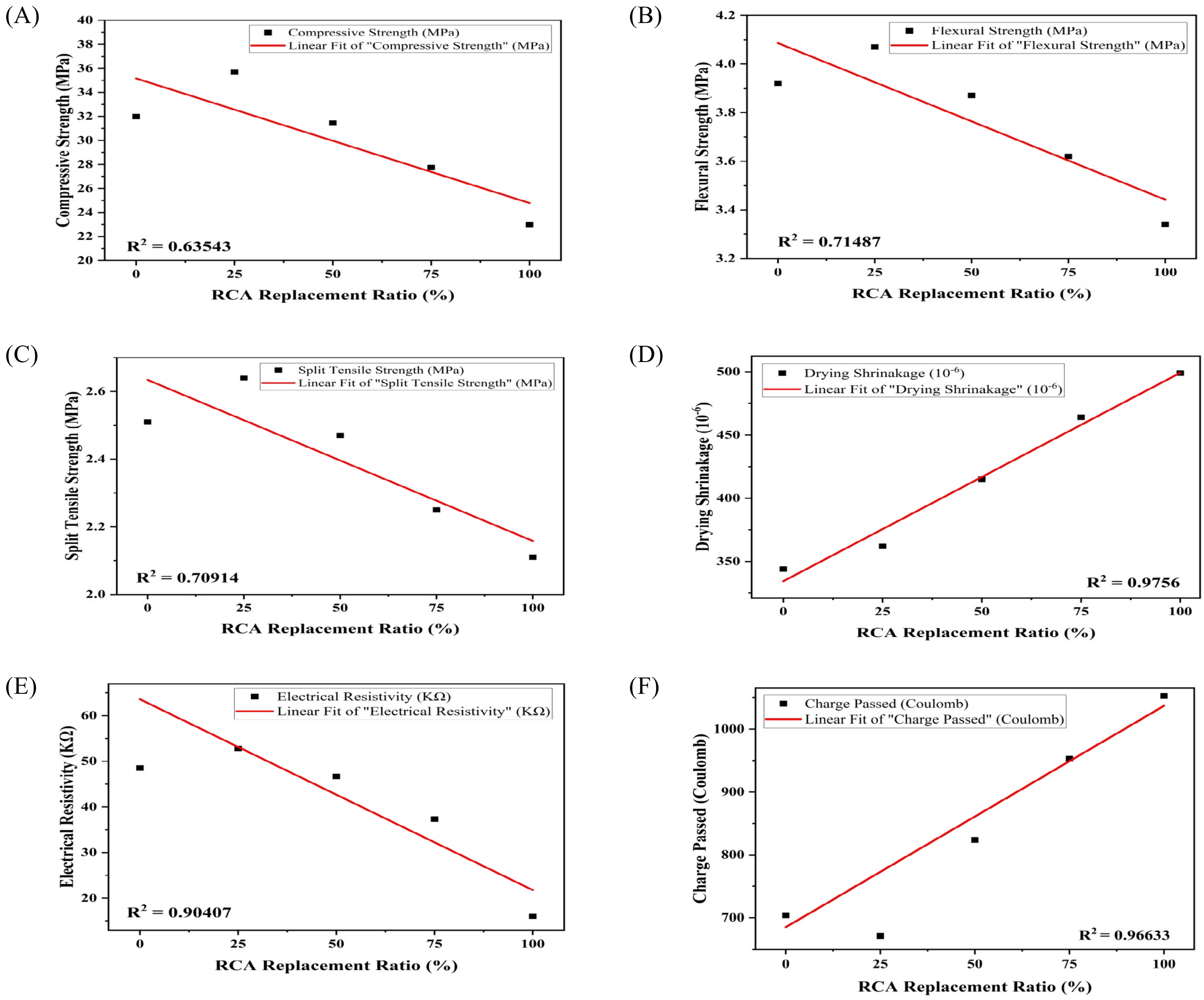

Figure 15. Relationships between RCA replacement ratio and (A) compressive strength, (B) flexural strength, (C) split tensile strength, (D) drying shrinkage, (E) electrical resistivity, and (F) passed charge.

strength, Fd illustrates drying shrinkage, FE quantifies electrical resistivity, and FR characterizes rapid chloride permeability. The parameter Rr corresponds to the percentage of the RCA replacement level, encapsulating the essence of the study. This comprehensive analysis, yielding coefficients of determination (R^2) such as 0.64073, 0.56775, 0.40756, 0.96623, 0.6101 and 0.94818 for compressive, flexural, and split tensile strength, drying shrinkage, electrical resistivity, and rapid chloride permeability respectively, signifies the robustness of the correlation. These values affirm the efficacy of the linear regression model in predicting concrete properties accurately, ensuring a reliable bridge between theoretical predictions and experimental results.

5. CONCLUSIONS

This study marks a significant stride in promoting sustainable construction practices by harnessing Construction and Demolition (C&D) waste as Recycled Coarse Aggregates (RCA), thereby championing circular economy principles and waste reduction. The exploration into the influence of RCA on hardened concrete unveils pivotal insights crucial for eco-conscious construction practices.

Key Findings and Recommendations:

- The study reveals a nuanced relationship between RCA content and concrete properties. Concrete exhibits enhanced mechanical properties up to an optimum replacement threshold

of 25% RCA. Beyond this point, there's a decline in performance. The findings underline the significance of adhering to this 25% replacement ratio for optimal concrete strength.
- Considering the notable 11.56% increase in compressive strength, 3.06% improvement in flexural strength, and 5.17% enhancement in split tensile strength compared to natural coarse aggregates, it's recommended that a mandatory 25% inclusion of RCA be established. This ratio ensures concrete strength surpasses that of traditional mixes.
- RCA-optimized concrete at 25% replacement demonstrates exceptional strength, making it ideal for non-structural elements, pavements, and specific projects. However, higher RCA percentages compromise structural integrity, making them suitable for landscaping and road base layers, avoiding critical applications.
- RCA inclusion increases drying shrinkage due to higher water absorption. RCA 25 exhibited a 5.23% higher shrinkage than conventional concrete, emphasizing the need for meticulous curing practices. Additionally, higher RCA percentages lower electrical resistivity, increasing corrosion risk, and reduce chloride permeability, impacting durability. RCA 25 and 50 exhibit high durability, whereas RCA 75 and 100 demonstrate moderate durability.
- Robust linear correlations were established, offering predictions for concrete properties based on RCA content. These models can serve as valuable tools in sustainable construction projects, ensuring informed decision-making regarding material selection.

This research not only mitigates construction industry waste but also conserves natural resources. Sustainable concrete, exhibiting comparable mechanical properties to conventional counterparts, emerges as a viable construction alternative. Future studies can delve deeper, optimizing this process for wider industry adoption, and exploring innovative avenues to further enhance the sustainability quotient of concrete structures. As construction endeavors move forward, the integration of RCA promises a greener, more responsible future for the industry.

Data availability

All data, materials, and methodologies employed in this research are detailed in the form of Figures and Tables within this article.

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Authorship contribution statement

Harish Panghal: Conceptualization, Methodology, Formal Analysis, Investigation, Resources, Data Curation, Writing – original draft, Writing – review & editing, Visualization.

Awadhesh Kumar: Conceptualization, Methodology, Validation, Resources, Writing – review & editing, Supervision, Project Administration, Funding Acquisition.

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