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Research Article

Impact of ultrafine fly ash on mechanical properties of recycled concrete aggregate: A factorial design study

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Abstract

The increasing generation of construction and demolition waste has led to resource depletion and waste accumulation. This research evaluates the mechanical properties of concrete formulated with recycled concrete aggregates (RCA) and ultrafine fly ash (UFFA) as partial substitutes for natural aggregates and Portland cement. Replacement levels ranged from 0% to 100% for RCA and 0% to 15% for UFFA. A 4^2 factorial design and statistical tools including ANOVA and regression were employed to analyze compressive, flexural, and tensile strengths alongside workability. While RCA incorporation generally reduced strength due to its higher porosity, the inclusion of UFFA improved all measured properties. The mix with 15% UFFA and 66% RCA showed optimal split tensile strength (4.75 MPa), while maximum compressive strength (49 MPa) occurred with 15% UFFA and 0% RCA. The blending of 7.5% UFFA and 50% RCA achieved a balance of sustainability and strength. The statistical results identified UFFA as the dominant factor influencing mechanical performance and workability, underscoring its efficacy in developing environmentally responsible structural concrete.

1. Introduction

The construction industry significantly contributes to greenhouse gas emissions and resource depletion. Akthar and Samrah's [1] review highlighted the global generation of over 3 billion tonnes of construction and demolition waste annually, mainly from China, India, and the USA. It addressed recycled aggregates' inferior quality and proposed supplementary materials to enhance recycled concrete properties. The study recommended 30-50% recycled aggregates with supplementary materials to match the concrete strength made up of natural aggregates, emphasizing research on unconventional materials, structural analysis of RAC, and standardized guidelines for low-risk applications. It advocated improved waste management, especially in developing countries. A sustainable approach involves recycled concrete aggregates from demolished structures and ultra-fine fly ash as a supplementary cementitious material. RCAs can reduce natural coarse aggregate demand, while ultra-fine fly ash can enhance concrete's mechanical properties, durability and environmental footprint. Despite benefits, RCA adoption remains limited globally due to insufficient understanding of recycling methods and material characteristics. Challenges include adhered mortar on RCAs, which can compromise concrete quality. Implementing these materials helps in conserving resources, minimizing waste disposal, and supporting eco-friendly construction practices [2]. Many works have been done on the utilization of RCA and other supplementary materials in concrete. The study by Faiz Shaikh [3] explored the effectiveness of using ultra-fine fly ash (UFFA) as a partial cement replacement in concrete containing recycled coarse aggregates (RCA) sourced from construction and demolition waste. The inclusion of 10% UFFA improved the compressive strength of RCA concrete by up to

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5%, allowing a 25% RCA mix to achieve 94% of the control concrete's strength at 56 days. Although tensile strength slightly decreased, reaching approximately 88% of the control, Sorptivity reduced by 38–54% and chloride ion permeability dropped by up to 40%, significantly enhancing durability. These findings suggested that UFFA can effectively mitigate the shortcomings of RCA and produce sustainable, high-performance concrete suitable for structural use. Padmini et al. [4, 5] conducted an investigation into the influence of aggregate size on the properties of recycled aggregate concrete (RAC), revealing that an increase in maximum aggregate size results in reduced porosity, water absorption, and fluid transmission in RAC. These effects were more pronounced in recycled aggregates derived from higher-strength parent concrete. However, the disparity in these properties between the parent concrete and RAC diminished as the concrete strength increased. Kumar et al. [6] furthered the understanding of RAC by examining the incorporation of supplementary cementitious materials (SCMs) such as silica fume, ground granulated blast furnace slag (GGBFS), and mechanically recycled fines into RCA. Their study demonstrated that substituting cement with SCMs significantly improved the compressive, tensile, and durability performance of RAC. Notably, RCA with mechanically recycled fines exhibited performance comparable to GGBFS, while M-Fines, a byproduct of RCA processing, showed potential as an SCM. These findings underscored the feasibility of utilizing optimized RCA with SCMs in structural concrete, thereby contributing to sustainable construction practices.

Additional studies addressed the challenges of residual mortar in RCA. For instance, Muhammad et al. [7] analyzed the influence of bonded mortar and proposed predictive tools to assess RCA-based concrete. In a related review, Verian et al. [8] evaluated various strategies to enhance RCA concrete, including advanced mixing techniques, the use of SCMs, 0.1M HCl acid treatment, adding 8% extra cement, limiting RCA content to 50%, soaking RCA in water for 30 days to fully hydrate adhered mortar, and adding fibres. Structural performance assessments also affirmed that RCA can be employed in load-bearing applications, though reductions in cracking moments and stiffness must be accounted. In exploring the structural performance of RCA in concrete elements, a study [9] found that while RCA-based structural components exhibited higher midspan deflections under service loads and reduced cracking moments, the ultimate moment capacity was only moderately affected. This suggests that RCA remains a viable material for structural concrete. Wang et al. [10] demonstrated that mechanical rubbing and acetic acid treatment improve RCA's compressive strength. Karthik et al. [11] found that ultra-fine fly ash (UFFA) concrete required only 50% of the high-range water reducer needed for silica fume concrete, while maintaining similar early strengths and durability. UFFA enhanced workability, long-term strength, and durability. Yike et al. [12] concluded that ultrafine composite mineral admixtures from fly ash offer promising solutions for sustainable construction. Maeijer et al. [13] emphasized that UFFA's impact on durability depends on both type and replacement levels. Fernando et al. [14] studied the composite effects of fly ash, silica fume, and rice husk ash in high-strength RAC using a 4^2 factorial experimental design. The study varied UFFA replacement (0%, 5%, 10%, 15%) and RCA content (0%, 33%, 66%, 100%). Using ANOVA and Tukey's test [15], they statistically analyzed compressive, split tensile, and flexural strengths. The best performance was recorded at 7.5% UFFA and 50% RCA. Workability was assessed using slump tests.

Hamada et al. [16] investigated dry and wet milling of fly ash to enhance pozzolanic activity. The life cycle cost analysis indicated that wet-milled FA not only improved the performance characteristics of the material but also significantly reduce CO_2 emissions and production costs when compared to OPC. Chavan et al. [17] who utilized Life-365 software to evaluate quaternary blended concrete's long-term cost efficiency and resistance to chloride ingress in coastal conditions. Results indicated improved service life and reduced maintenance, demonstrating SCMs' role in durable infrastructure. Elizah et al. [18] tested the flexural behavior of under-reinforced RC beams with partial cement replacement by fly ash. Beams with 20% fly ash showed higher crack resistance and load-bearing capacity, especially in beams with 50–70% reinforcement deficiency. Ojha et al. [19] tested a treated C&DW-based coarse RCA by 500 revolutions in the Los Angeles machine without abrasive charge. Treated RCA showed better specific gravity, lower water absorption, and improved mechanical and durability properties, supporting its complete replacement of natural aggregate in concrete. Poonam and Singh [20] optimized concrete incorporating blast furnace slag aggregate and recycled concrete sand using response surface methodology (RSM). This statistical approach enabled efficient waste utilization without significantly compromising performance. Saleh et al. [21] advocated using locally available, recycled, or rapidly renewable materials to reduce the environmental footprint of construction. This practice supports green building initiatives and contributes to climate change mitigation goals. Finally, Hamad et al. [22] examined the role of fly ash in ultra-high-performance concrete (UHPC), finding that its inclusion significantly delayed signs of acid and sulphate attacks by increasing matrix density. However, the presence of adhered mortar in RCA often leads to reduced strength, higher porosity, and compromised durability in recycled aggregate concrete (RAC). To address these drawbacks, researchers are investigating the use of supplementary cementitious materials (SCMs) to enhance RCA performance. UFFA, due to its fine particle size and high pozzolanic reactivity, improves workability, compressive strength, and durability. Despite the progress in evaluating RCA and UFFA individually, there is limited research combining these materials in a single concrete mix. Moreover, studies utilizing statistical optimization techniques to identify the most effective combination of RCA and UFFA and quantify their interactive effects on mechanical performance is less. Accordingly, the specific objectives of this study were to: (i) Examine the mechanical behavior of environmentally sustainable concrete mixes prepared by partially replacing natural coarse aggregates with Recycled Concrete Aggregates (RCA) and Ordinary Portland Cement with Ultra-Fine Fly Ash (UFFA). (ii) Evaluate the influence of different RCA (0%, 33%, 66%, and 100%) and UFFA (0%, 5%, 10%, and 15%) substitution levels on concrete characteristics using statistical methods, including Analysis of Variance (ANOVA) and regression modelling; and (iii) Determine the optimal blend that achieves both mechanical performance and ecological viability for potential structural applications**.**

2. Materials and Methods

2.1 Materials Used

2.1.1 Cement

Ordinary Portland Cement (OPC) of 53 grade conforming to the IS standards was used in this investigation. The cement was tested for various properties according to the relevant IS code, and the specific gravity of the cement was 3.1, void ratio was 1.0, porosity was 0.33, Unit weight was-1440 kg/m^3.

2.1.2 Fine Aggregates

Locally available sand, free from clay, salt, and organic impurities, was utilized as a fine aggregate. The sand was tested for properties such as specific gravity and bulk density in accordance with IS 2386-1963[23]. Fineness modulus of fine aggregate was 2.933 and the given sand belonged to "ZONE-1" as per IS 383-2016 [24].

2.1.3 Coarse Aggregate

Locally sourced, machine-crushed angular granite served as the coarse aggregate. Its properties included a fineness modulus of 8.17, specific gravity of 2.81, bulk density of 1601 kg/m^3, a void ratio of 0.76, and porosity of 0.431

2.1.4 Superplasticizer

CONPLAST SP 430 was used, and a mini-cone slump test was performed to determine the compatibility of the superplasticizer. Based on the flow of the cement in the various mixes above, we found that 0.75% SP gave the best result when ultrafine fly ash was added to the cement.

2.1.5 Water

Freshly potable water was used for both mixing and curing.

2.1.6 Ultra-Fine Fly Ash

UFFA, derived from Class F fly ash, was sourced from M/s Dirk (India) Pvt. Ltd., Nashik. It had a top particle size below 10 μm and an average diameter ranging from 2–4 μm. Table 1 presents its physical and chemical properties.

Table 1. Physical properties and Chemical composition of Ultra-fine fly ash (as given by supplier)

Chemical composition		Physical properties	
Constituents	Weight %	Presentation	Finely divided dry powder
Silicon dioxide (SiO_2)	50	Color	Greyish White
Calcium oxide (CaO)	5.5	Bulk Weight	0.65 ton/ m^3
Magnesium oxide (MgO)	4.5	Specific Density	2.3
Sodium oxide (Na_2O)	2	Loss of Ignition	<2.5 %
Sulphur oxide (SO_3)	1.5	Particle Size	Zero retention on 45μ sieve, <0.25 % retained on 25μ sieve
		Particle Shape	Spherical

Preparation of Recycled Aggregate: Demolished concrete of the same grade was collected and crushed into smaller pieces. The pieces were crushed using a jaw crusher and further processed using a Los Angeles machine. The crushed material was sieved to collect aggregates passing through a 20 mm sieve and retained on a 4.75 mm sieve. The recycled aggregates were thoroughly washed, dried, and prepared for further use. The water absorption of recycled concrete aggregate was found to be1.56%, and the specific gravity was 2.506.

2.2 Methods

2.2.1 Consistency Test IS: 4031- 1998 [25]

Table 2 mentions the tests conducted on cement mortar. As the percentage of UFFA increased, the weight of water required decreased and the standard consistency percentage also decreased with higher UFFA content, indicating improved workability and reduced water demand due to the filler effect and fineness of UFFA and improved pozzolanic activity. The standard consistency also followed a similar trend, where an increase in UFFA improves workability and reduces water demand, suggesting that UFFA can effectively improve the efficiency of cementitious materials by reducing the water requirements while maintaining the desired consistency.

2.2.2 Initial Setting Time

The replacement of cement with ultra fine fly ash (UFFA) affected the initial setting time of the cement paste. At 0% and 5% UFFA replacements, the initial setting time remained constant at 50 min. However, as the replacement percentage increased to 7.5%, the initial setting time decreased to 40 min, indicating a noticeable acceleration in the setting process. With further increases in UFFA replacement to 10% and 15%, the initial setting time decreased further to 40 and 33 min, respectively, suggesting a continued trend of faster setting. This reduction in the initial setting time with a higher UFFA content may be attributed to the increased fineness of UFFA, which enhanced the hydration reactions and pozzolanic activity, leading to faster strength gain and reduced setting times. The results demonstrate that UFFA requires careful consideration to balance the initial setting time requirements for any field-specific requirements.

2.2.3 Compressive and Flexural Strength of Cement Mortar

Refer to the Table 2 the flexural strength of the hydraulic cement mortar was determined according to ASTM C 348 [26].

2.2.4 Workability of Concrete

Slump test performed and results were shown in Fig. 1. Workability improved with increasing UFFA content, especially in mixes with RCA.

2.2.5 Determination of Compressive Strength

Tests on 150 mm and 100 mm cubes at 28 days. UFFA improved compressive strength even in RCA mixes (Figures 2, 3). Size effect observed and correction factor (K = 0.835) derived.

2.2.6 Determination of Split tensile Strength

Cylindrical specimens (100 mm diameter × 200 mm length) were tested for split tensile strength at 28 days of curing. The strength results were plotted in Fig. 4.

Table 2. Tests on cement mortar

% of UFFA	Standard consistency %	Initial setting time (minutes)	Compression strength of cement mortar cubes of 70mm size with w/c ratio of 0.5 in MPa	Flexural strength of cement mortar prisms of 40x40x160mm long in MPa
0%	32.50	50	35.63	5.60
5%	31.75	50	36.59	5.88
7.5%	30.00	45	37.60	6.16
10%	29.75	40	37.88	6.44
15%	28.75	33	37.69	6.72

2.2.7 Determination of Flexural Strength

Flexural strength was tested on prisms of 100mmx100mmx500mm long using two-point loading test and the results are plotted in Fig.5. Maximum strength observed at 15% UFFA in both mortar and concrete (Figure 5).

2.2.8 Factorial Design – Methods and Approach

4^2 full factorial design with 16 mixes (UFFA: 0–15%, RCA: 0–100%). ANOVA, regression, and Tukey's test used for statistical analysis (Equations 2–4). Mix A17 used for validation.

2.2.9 Concrete Mixing Procedure

Mixing was carried out in a 40-liter laboratory pan mixer. Dry materials (coarse aggregate, fine aggregate, and cement) were first blended, followed by gradual addition of 75% of the mixing water. The remaining water was mixed with the superplasticizer and added subsequently. The mixture was then mixed thoroughly and cast in molds. Table 3 outlines the concrete mix proportions and Table 4 states the Nomenclature of the concrete mixes prepared. To check the consistency of results the following random mix was prepared (Table 5).

Table 3. Concrete mix design - M40 grade as per IS:10262:2019 [27]

Cement	Coarse Aggregates	Fine Aggregates	water
440 kg/m^3	1086 kg/m^3	701 kg/m^3	190 kg/m^3

Table 4. Nomenclature of the concrete mixes prepared.

Mix	UFFA %	RCA %	Mix	UFFA %	RCA %	Mix	UFFA %	RCA %	Mix	UFFA %	RCA %
A1	0	0	A5	5	0	A9	10	0	A13	15	0
A2	0	33	A6	5	33	A10	10	33	A14	15	33
A3	0	66	A7	5	66	A11	10	66	A15	15	66
A4	0	100	A8	5	100	A12	10	100	A16	15	100

Table 5. Mix used for checking the consistency of work

S. No.	Mix	Cement %	UFFA %	RCA %	Slump in mm	28-days compression strength (MPa) for 150mm cubes	28-day compression strength (MPa) for 100mm cubes	Split tensile strength MPa	Flexural strength MPa
17	A17	92.5	7.5	50	110	41.33	52.56	4.17	6.80

3. Results and discussion

3.1 Compressive and Flexural Strength of Cement Mortar

In terms of strength of cement mortar, both compressive and flexural strengths improved with UFFA replacement. Compressive strength peaks at 10% replacement, achieving 37.88 MPa, while flexural strength steadily increases, reaching a maximum of 6.72 MPa at 15% UFFA. These improvements demonstrate the potential of UFFA for enhancing the mechanical properties of cement mortars. Overall, replacing cement with up to 15% UFFA improves sustainability and performance, although higher percentages may require adjustments to setting and workability conditions based on specific application needs the same was also reported by Roychand et al. [28]

3.2 Workability of Concrete

The slump flow values were shown in Fig 1. The results showed that varying the RCA and UFFA contents affected the concrete workability. A higher UFFA enhanced the workability at 0%, 33%, and 66% RCA. With 100% RCA, UFFA significantly improved workability. Increasing UFFA from 5% to 15% consistently enhanced the slump across the RCA contents, suggesting that UFFA acts as a lubricant. Overall, 15% UFFA was optimal, maintaining desirable workability in mixes with highly recycled aggregate.

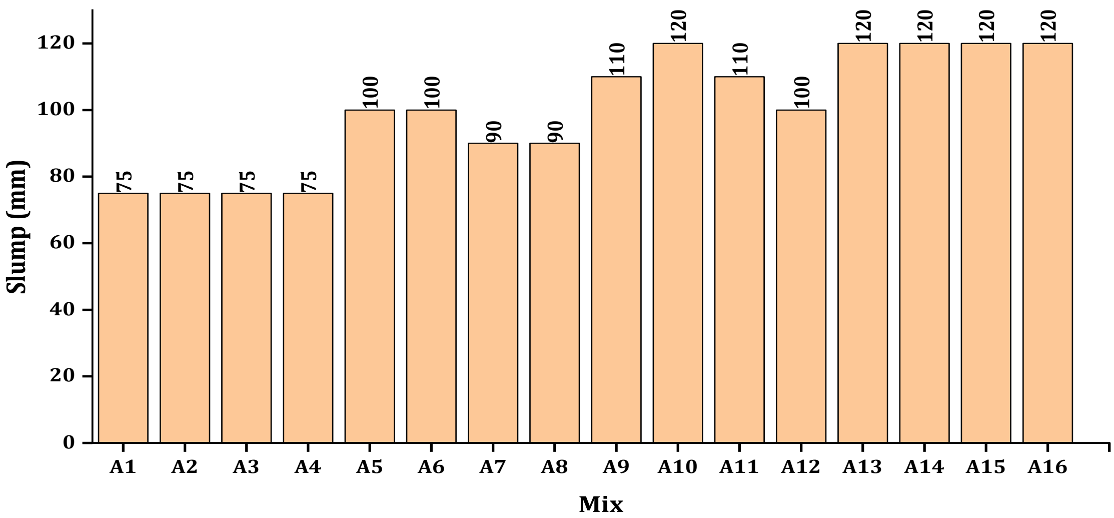


Fig. 1. Slump flow of UFFA and RCA freshly mixed concrete

3.3 Compressive Strength on Concrete Cubes

3.3.1. 150 mm Cubes

The strength of concrete improved consistently with UFFA additions, achieving a maximum of 49.06 MPa in the mix with 15% UFFA and 0% RCA. However, increasing RCA led to a decrease in compressive strength due to the weaker and more porous nature of the recycled aggregates. The highest strength among RCA-containing mixes was observed for Mix A16 (15% UFFA and 100% RCA) (Fig.2).

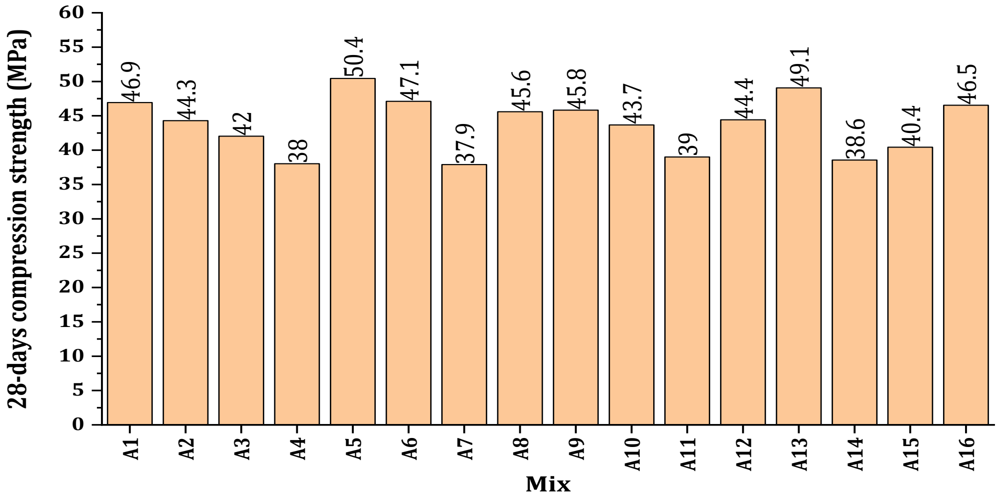


Fig. 2. Compressive strength of 150mm size cubes containing UFFA and RCA mixes after 28d of curing

3.3.2. 100 mm size cubes

The compressive strength results of the 100 mm cubes are similar to those of the 150 mm cubes. The A13 mix (15% UFFA and 0%RCA) achieved the highest strength of 59.64 MPA while the A14 strength was the highest among the RCA-based concrete mixes (Fig.3).

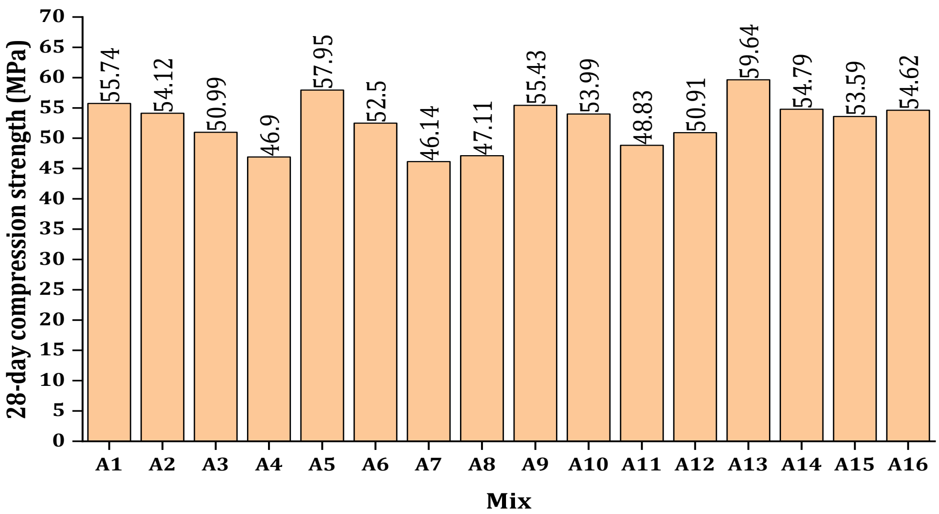


Fig. 3. Compressive strength of 100mm size cubes containing UFFA and RCA mixes after 28d of curing

3.3.3 Effect of the Size of The Cube on Compressive Strength of Concrete

Figures 2 and 3 indicate that the size of the cube influences the test results. In general, the 100 mm cube tends to provide higher strength than the 150 mm cube. Larger cubes may possess flaws and weak zones, which lead to reduced strength. From the test results, it is observed that 100 mm cubes consistently report higher strengths than 150 mm cubes in the range of 1.15 to 1.25. An empirical relationship suggests that the strength of 100 mm cubes is approximately 10-20% higher than 150 mm size cubes. A simple correlation of;

$$CS_{150} = k \times Cs_{100} \tag{1}$$

where CS_{150}: compressive strength of 150mm cubes; CS_{100}: compressive strength of 100mm cubes.

In general, the factor K is typically ranges between 0.8 to 0.9 and from the data it is observed that Mix A14 and A8 are not in line with the equation, which may be due to improper compaction, aggregates distribution. and the constant obtained is 0.835 after the removal of outliers which is in consistent with Yi et al [29]. The compressive strength of 150 mm cubes can be reliably estimated using an average ratio of 0.835.

3.4 Split Tensile Strength

Tensile strength improved with increasing UFFA content in all mixes. The maximum value of 4.75 MPa was recorded in Mix A15, comprising 15% UFFA and 66% RCA. This illustrates UFFA's role in improving tensile resistance, even when RCA-induced weaknesses are present. In mixes without RCA, the peak tensile strength was 4.09 MPa at 15% UFFA (Fig.4).

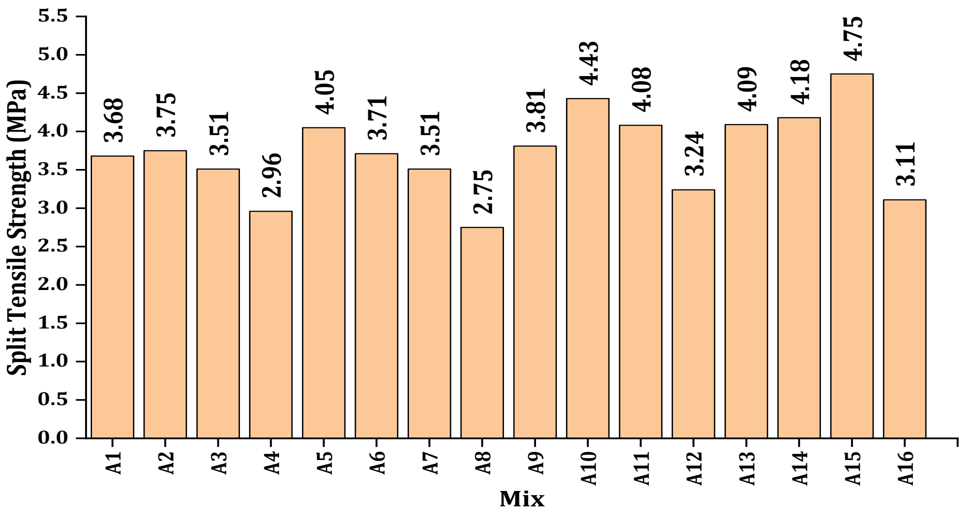


Fig. 4. Split Tensile strength of UFFA and RCA mixes after 28d of curing

3.5 Flexural Strength

For the 0% RCA mixes, the A13 mix with 15% UFFA attained a strength of 8MPa. The mixes with RCA again showed a decrease in flexural strength following a similar trend, and the mixes with 10% UFFA, 15%UFFA, and 33% RCA had the highest strengths (Fig.5).

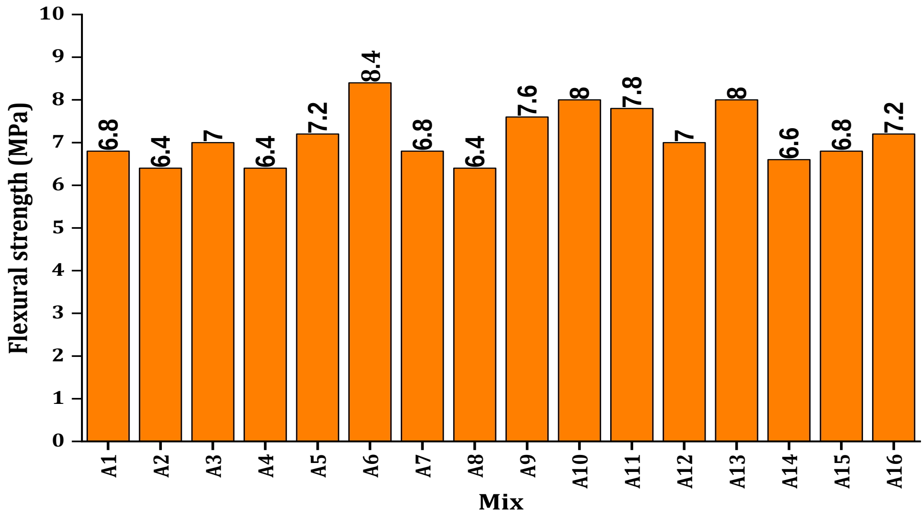


Fig. 5. Flexural strength of UFFA and RCA mixes after 28d of curing

3.6 Comparative Analysis of Flexural Strength in Mortar and Concrete Prisms

The flexural strength of mortars differs from that of concrete owing to the composition and presence of aggregates (Table 2). The flexural strength of mortar prisms ranges from 5.60MPa to 6.72MPa due to gradual increase of UFFA and the maximum strength is observed at 15%

replacement of cement by UFFA indicating improved pozzolanic activity. For concrete prisms strength varies from 6.40MPa to 8.4MPa with the highest strengths observed for 5% UFFA and 33% RCA. This improvement can be attributed to the densification of the ITZ and better particle packing owing to UFFA. It was concluded that the incorporation of UFFA positively influences the flexural strength of both mortar and concrete, with concrete exhibiting higher values owing to the presence of coarse aggregates.

3.7 Impact of UFFA and RCA on Strength Parameters

3.7.1 UFFA Replacement

The replacement of cement with UFFA improved both the compressive and tensile strengths by densifying the microstructure and enhancing the pozzolanic reaction. The flexural strength showed significant improvement owing to the UFFA, which may be attributed to the improvement in the bond and reduced porosity.

3.7.2 RCA Inclusion

The presence of RCA reduces the overall strength owing to weaker aggregates and higher porosity and water absorption, while the presence of UFFA offsets this reduction by improving the matrix-aggregate bond-reduced water demand.

3.8 Statistical Analysis

3.8.1 Slump Flow of Fresh Concrete

Slump values for each concrete mix were evaluated and statistically analyzed using regression models to assess the influence of RCA and UFFA. At a 5% significance level ($\alpha = 0.05$), only factors with p-values $\leq \alpha$ were considered statistically significant (Fig.1). The regression model for slump flow (Eq. 2) and Pareto diagrams (Fig.6) identified UFFA as the dominant factor, with minimal impact from RCA content. The model exhibited a high goodness-of-fit (R^2 = 0.9552), and validation using Mix A17 (7.5% UFFA, 50% RCA) resulted in only an 8.85% deviation from measured slump values, confirming the accuracy of the predictive equation. SF_{28} corresponds to the slump flow in millimeters; X_1 is the percentage of % RCA, and X_2 is the percentage of ultrafine fly ash replacing the Portland cement of the mixture.

$$SF_{28} = 77.99 - 0.0602 * X_1 + 4.5 * X_2 - 0.1 * X_2^2 \quad (2)$$

3.8.2 Compressive strength at 28 days

A second regression model (Eq. 3) was developed to analyze compressive strength of 150 mm cubes.

$$Y_{28} = 48.37 - 0.2418\, X_2 - 0.001915 * X_2^2 \quad (3)$$

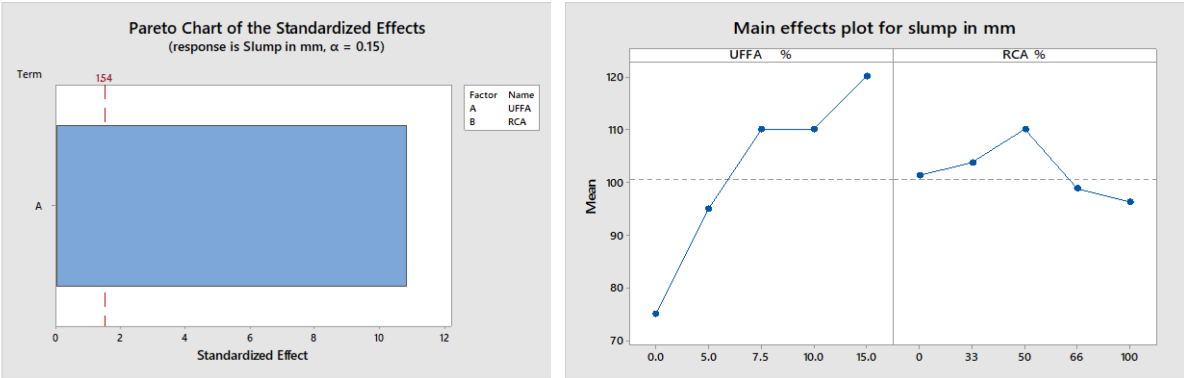
Y_{28} corresponds to the compressive strength at 28 d in MPa, X_1 is the percentage of ultrafine fly ash replacing Portland cement, and X_2 is the % RCA of the mixture.

Table 6. Test for validation and predicted values for A17

	Slump flow in mm	Compressive strength of 150mm cube (MPa)	Split tensile strength (MPa)
Experimental value (MPa)	110	41.33	4.17
Predicted value (MPa)	103	31.49	5.85
% error	6.43%	23.8%	40.28%

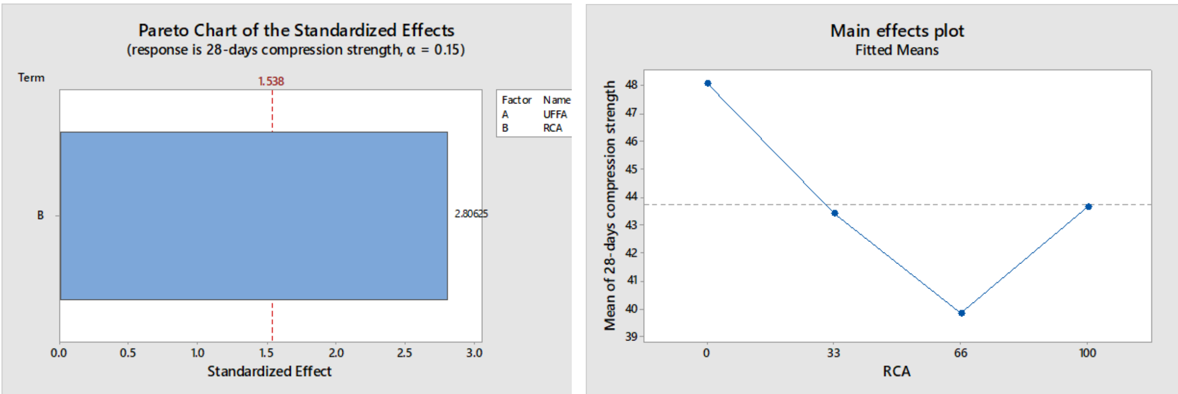
The R^2 value, which accounted for 53.29% of the data variability, was significant (p<0.1 for the compressive strength measured at 28 d. Model validation was conducted using the A17 mixture, which included 7.5% UFFA and 50% RCA. As shown in Table 6, The model was validated using Mix A17, with a deviation of 23.85% from experimental values (Fig. 2 and 3).

Analysis of the Pareto diagrams for 28-day compressive strength (Fig. 7) showed that the percentage of recycled concrete aggregate (RCA) was the most influential factor. The main effects plot revealed that compressive strength decreased as the RCA content increased. Notably, at 100% RCA replacement, the beneficial effect of ultra-fine fly ash (UFFA) on compressive strength became more evident.



(a) (b)

Fig. 6. Pareto Diagram main effects plot of slump flow (a) Pareto Diagram, (b) Main Effects plot



(a) (b)

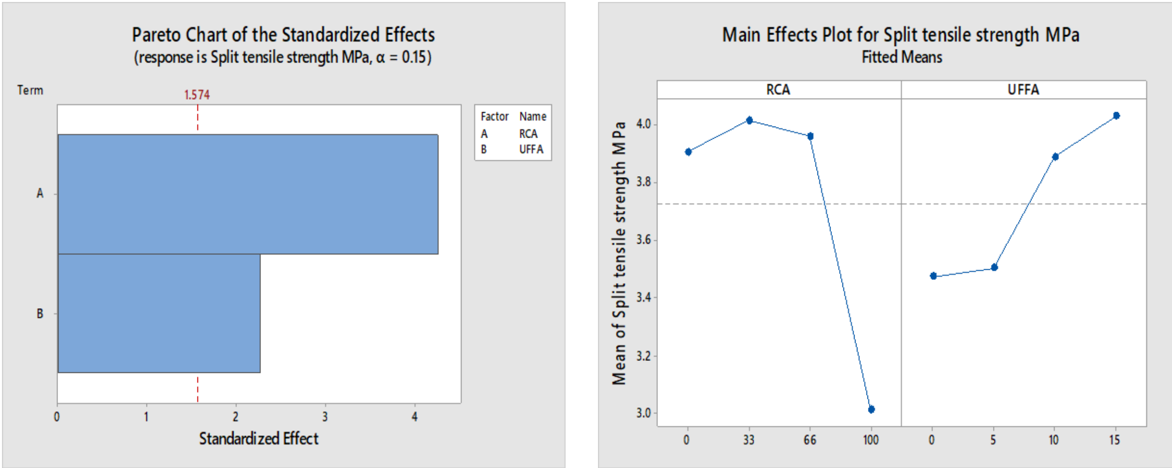
Fig. 7. Pareto Diagram and main effects plot of the 150mm cube compressive strength at 28 days (a) Pareto Diagram, (b) Main Effects plot

3.8.3 Split Tensile strength

Eq. 4 presents the regression models used to represent the effects of the studied factors on the Split tensile strength of concrete at 28 d. Corresponding to the split tensile strengths at 28 d in MPa, X_1 is the percentage of RCA, and X_2 is the percentage of ultrafine fly ash replacing the Portland cement of the mixture.

$$S_{28} = 3.564 + 0.0154 * X_1 + 0.0411 * X_2 - 0.000236 * X_1^2 \quad (4)$$

The proportion of data variability explained by R^2 was 0.7932 ($p<0.1$) for the 28 days Split tensile strength. The models were validated using the A17 mixture containing 7.5% UFFA and an RCA factor of 50%. The equation adequately represented the experimental results of split tensile strength, although the difference between the experimental mean values and the model-predicted values was 40.28% at 28 days. The value of the split tensile strength was small; hence, the observed variance appeared very large.



(a) (b)

Fig. 8. Pareto Diagram and main effects plot of the Split Tensile strength at 28 days (a) Pareto Diagram, (b) Main Effects plot

By analyzing the Pareto diagrams of the split tensile strength at 28 days (Fig. 8), it was observed that the RCA percentage was the most influential factor for the split tensile strength and later the UFFA. From the main effects plot, as the percentage of UFFA increased, the split tensile strength increased, and as the RCA percentage increased, the strength decreased.

3.8.4 Statistical Analysis Using Tukey's Simultaneous Tests

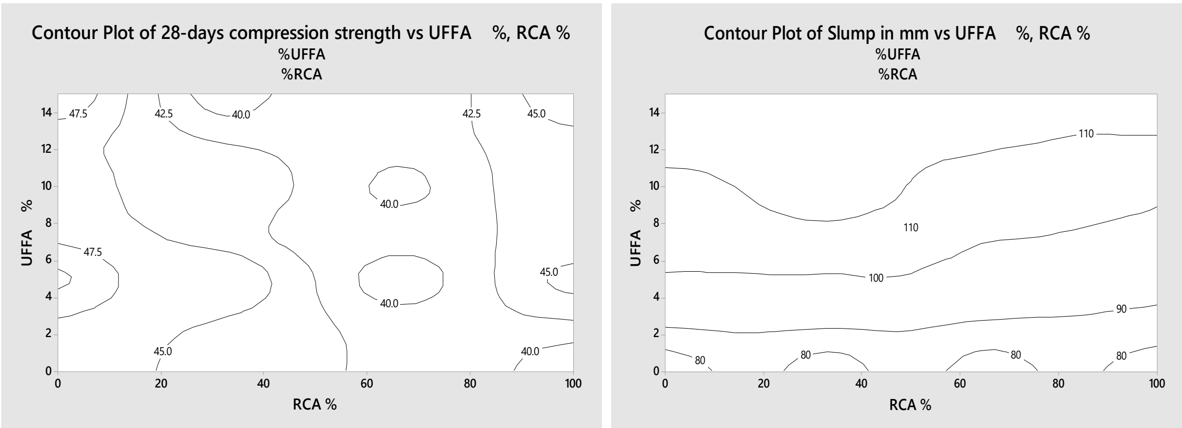
The Tukey test for 28-day compressive strength (Table 7) subdivided the mixtures into five statistically similar groups. Group A1 included concrete mixes with RCA content ranging from 0% to 100%.

Table 7. Results of Tukey Simultaneous Tests for Differences of Means

Concrete Containing RCA only					
Difference of Levels	SE of Difference	95% CI	T-Value	Adjusted P-Value	Significant or Not
28-days comp - RCA %	21.6	(-59.7, 45.9)	-0.32	0.759	Not significance
Concrete Containing UFFA only					
28-days comp - UFFA %	3.39	(32.27, 48.86)	11.96	0	Significance
Concrete Containing Control vs RCA and UFFA					
28-days comp - UFFA %	9.05	(11.55, 56.48)	3.76	0.002	Significant
RCA % - UFFA %	9.05	(28.24, 73.16)	5.6	0	Significant
RCA % - 28-days comp	9.05	(-5.78, 39.15)	1.84	0.175	Not Significant
Concrete Containing RCA only vs RCA and UFFA					
28-days comp - UFFA %	6.92	(17.82, 51.78)	5.03	0	Significant
RCA % - UFFA %	6.92	(41.85, 75.81)	8.5	0	Significant
RCA % - 28-days comp	6.92	(7.06, 41.02)	3.47	0.004	Significant
Concrete Containing UFFA only vs RCA and UFFA					
28-days comp - UFFA %	9.27	(11.29, 56.80)	3.67	0.002	Significant
RCA % - UFFA %	9.27	(17.00, 62.50)	4.29	0	Significant

RCA % - 28-days comp	9.27	(-17.05, 28.46)	0.62	0.813	Not Significant

Statistical analysis using Tukey's simultaneous tests revealed several key insights into the influence of recycled concrete aggregate (RCA) and ultra-fine fly ash (UFFA) on the compressive strength of concrete. Concrete containing only RCA showed no significant difference in the 28-day compressive strength, indicating that RCA alone does not notably improve the strength performance. In contrast, concrete with only UFFA exhibited a statistically significant improvement, highlighting UFFA's positive contribution of UFFA to compressive strength. When comparing the control concrete with mixtures containing both RCA and UFFA, the presence of UFFA led to a significant increase in strength, whereas the effect of RCA alone remained statistically insignificant. The combination of RCA and UFFA consistently demonstrated improved performance compared with RCA-only mixes, with all comparisons showing significant differences, affirming the beneficial role of UFFA when used alongside RCA. Furthermore, although both the UFFA-only and RCA+UFFA mixtures showed enhanced performance, the data suggest that the improvement in compressive strength is primarily driven by UFFA, as RCA's individual contribution of RCA to strength remained statistically insignificant in multiple comparisons. Overall, the inclusion of UFFA significantly enhanced the mechanical properties of concrete, particularly when used in conjunction with RCA.



(a) (b)

Fig. 9. Outline graph in function of % UFFA and % RCA (a) Compressive strength at 28days (b) Slump flow

For better visualization of the factor effects (%UFFA and % RCA), outlining graphs were created for the compressive strengths at 28 days and slump flow tests (Fig.9). It can be observed that an increase in the UFFA content contributes to obtaining concrete with higher resistance and increased flow, while a reduced compressive strength and flow due to the RCA increment was observed.

3.8.5 Comparison with Previous Studies

The results of this study align with and extend the findings of previous research on the incorporation of recycled concrete aggregates (RCA) and ultra-fine fly ash (UFFA) in concrete. For instance, Shaikh [3] reported a 5% improvement in compressive strength using 10% UFFA in RCA-based concrete, whereas in this study, compressive strength improved by up to 7% with 15% UFFA and 0% RCA and an 18% increase in split tensile strength was observed at 15% UFFA and 66% RCA. The flexural strength trends in both mortar and concrete also corroborate the enhancement observed by Elizah et al. [18], where fly ash incorporation improved crack resistance and load-bearing capacity. However, this study goes further by applying full factorial design and statistical analysis (ANOVA, regression, and Tukey tests) to quantify the interactive effects of UFFA and RCA, a methodological advancement over many prior works. Moreover, while studies such as Karthik et al. [11] and Maeijer et al. [13] emphasized the benefits of UFFA on durability and water demand, this research confirms that UFFA not only improves workability but also offsets the strength loss caused by RCA. Therefore, this work fills a significant gap in literature by establishing statistically validated optimal combinations for structural-grade sustainable concrete.

4. Conclusions

The experimental study showed that incorporating ultrafine fly ash (UFFA) and Recycled Concrete Aggregates (RCA) into concrete significantly improves the mechanical performance while enhancing sustainability. The consistency test had shown that as the UFFA content increased from 0% to 15%, the standard consistency percentage decreased from 32.5% to 28.75%, indicating improved workability and reduced water demand. Similarly, the initial setting time was reduced from 50 min to 33 min, showing an accelerated hydration process owing to the fine particle size and enhanced pozzolanic reactivity of UFFA.

In the cement mortar tests, compressive strength peaked at 37.88 MPa with 10% UFFA, while flexural strength improved steadily to 6.72 MPa at 15% UFFA. The slump test indicated a 60% enhancement in workability, with values increasing from 70 to 110 mm, particularly benefiting mixes with high RCA content. For 150 mm concrete cubes, the highest compressive strength (49.06 MPa was observed at 15% UFFA and 0% RCA. An optimal balance of strength and sustainability was achieved with 7.5% UFFA and 50% RCA, yielding 41.33 MPa. The inclusion of RCA led to a compressive strength reduction of up to 15%; however, but UFFA addition of UFFA recovered approximately 5–10% of that loss.

In the test results of 100 mm cubes, the compressive strength reached 59.64 MPa for 15% UFFA and 0% RCA, with results consistently 15–25% higher than those from 150 mm cubes. A correction factor of 0.835 was established to relate the cube sizes. The split tensile strength increased from 3.68 MPa to 4.09 MPa with 15% UFFA in the absence of RCA and the highest strength of 4.75 MPa was recorded with 15% UFFA and 66% RCA, marking an 18% improvement over control mixes. For concrete prisms, flexural strength increased up to 8.4 MPa with 5% UFFA and 33% RCA, while mortar prisms showed a 20% increase from 5.60 MPa to 6.72 MPa as UFFA content increased.

Statistical analysis confirmed that UFFA was the most influential factor affecting strength and workability, whereas RCA had a consistently negative but moderate effect. The regression models produced R^2 values of 0.9552 for slump, 0.5329 for compressive strength and 0.7932 for split tensile strength, validating their predictive utility using Mix A17 using 7.5% UFFA and 50% RCA.

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