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Exploring the role of recycled aggregates in modern concrete technology

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ABSTRACT

This research evaluates the performance of concrete mixtures incorporating fly ash, Ordinary Portland Cement (OPC), and varying proportions of recycled coarse aggregate (RCA) along with natural coarse aggregate (NCA). The study including slump, compressive strength, split tensile strength, flexural strength, sulfate resistance, and water absorption, to determine both the mechanical properties and the durability of the concrete mixes. The slump test revealed a reduction in workability with increasing RCA content, while the compaction factor indicated improved compactness in these mixes. Compressive, tensile, and flexural strength tests showed enhanced strength characteristics for mixes with up to 20% RCA, outperforming conventional concrete at 28 days. Sulfate resistance tests indicated that increasing RCA content reduced durability, while flyash improved resistance in certain mixes. Water absorption tests demonstrated con-sistent increase in absorption with higher RCA proportions, highlighting the difference between sustaina-bility and durability. The results were analyzed using ANOVA, confirming statistically significant variations in performance across different mixes. The study concludes incorporating RCA with flyash can improve strength properties while slightly compromising durability. This work underscores the potential of recycled aggregates in sustainable concrete production and provides a framework for optimizing concrete mixes balance environmental benefits with mechanical and durability performance.

Keywords: Recycled coarse aggregate; Flyash; strength; durability; ANOVA.

1. INTRODUCTION

In an effort to lessen the environmental effect of concrete manufacturing, alternative materials including recycled aggregates are being investigated in response to the growing demand for sustainable construction techniques. A viable way to reduce waste production and resource depletion is to use recycled aggregates, which are made from CDW. This literature review aims to explore the role of recycled aggregates in modern concrete technology, focusing on their physical and chemical properties, mechanical performance, durability, and environmental impact.

Recycled aggregates, particularly fine recycled concrete aggregates (FRCA), possess unique physical and chemical properties that distinguish them from natural aggregates. These differences play a critical role in determining the quality, durability, and performance of concrete mixes incorporating FRCA [1]. One of the primary challenges associated with FRCA is their notably high-water absorption capacity, which can negatively impact the workability of fresh concrete and reduce its final strength [2, 3]. This characteristic necessitates careful adjustments in the mix design to achieve desired performance. Additionally, the presence of adhered mortar, which contributes to increased porosity, and particle agglomeration further complicate their integration into concrete production [4]. These factors can lead to inconsistencies in mechanical properties and durability unless adequately managed. Alongside modern concrete technology tools, are indispensable for overcoming

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these limitations. [5] These methodologies facilitate the development of optimized mix designs tailored for concrete containing FRCA, ensuring sustainable and efficient use in construction applications [6].

The mechanical performance of recycled aggregate concrete (RAC) plays a pivotal role in assessing its viability for structural applications. Studies have shown that replacing natural aggregates (NA) with recycled aggregates (RA) impacts the mechanical properties of concrete in diverse ways [7]. For instance, research has demonstrated that incorporating 30% recycled coarse aggregate (RCA) in concrete not only enhances sustainability but also improves its thermal performance, making it a favorable choice for eco-friendly construction [8]. Additionally, findings from the European C2CA project revealed that by optimizing the mix design and employing suitable cement types, RAC with up to 100% RA substitution can achieve mechanical properties comparable to those of natural aggregate concrete (NAC) [9]. Despite these advancements, RAC's typically fall short of those observed in NAC, particularly when high replacement ratios are used. This underscores the importance of careful mix design and material selection to ensure RAC's structural integrity and performance [10].

Durability is a critical factor in determining the long-term performance of recycled aggregate concrete (RAC), particularly in structural applications. The durability of RAC is closely tied to the quality of recycled coarse aggregates (RCA) and the mix design parameters [11]. Studies have highlighted that innovative processing techniques, such as autogenous cleaning, can significantly enhance the physical and mechanical properties of RCA, thereby improving the overall durability of RAC [12]. Moreover, carbon-conditioning, a process involving the injection of CO_2 into recycled aggregates, has shown promising results in enhancing the physical properties and durability of RAC, bringing it closer to the performance levels of concrete made with virgin aggregates [13]. Despite these advancements, the heterogeneous nature of recycled aggregates remains a challenge, often leading to variability in the durability characteristics of RAC. Addressing this variability requires advanced material processing and optimized mix designs to ensure consistent and reliable performance [14].

By lowering the need for natural materials and cutting down on trash creation, the use of RCA in the manufacturing of concrete has major positive environmental effects [15]. A holistic approach to evaluating the sustainability of RAC involves technical, economic, and environmental analyses. Studies have shown that the use of 20% RCA in concrete does not significantly affect the cost or environmental impact, while higher replacement ratios can lead to increased global warming potential due to additional transport distances [16]. The environmental impact of RAC can be further mitigated by optimizing the mix design and processing techniques to enhance the quality of recycled aggregates [17].

Despite the potential benefits of using RCA in concrete, several challenges hinder their widespread adoption in the construction industry. The variability in the quality of recycled aggregates, particularly those obtained from mixed construction and demolition waste, poses a significant challenge to achieving consistent concrete performance [18, 19]. Additionally, the lack of standardized guidelines and tools for the use of RCA in concrete mix design limits their application [20]. Recycled aggregates offer a sustainable alternative to natural aggregates in concrete production, contributing to resource conservation and waste reduction [21, 22]. The physical and chemical properties, mechanical performance, durability, and environmental impact of recycled aggregate concrete are influenced by the quality of recycled aggregates and the mix design [21, 23].

2. MATERIALS AND METHODS

This study utilized OPC, fly ash as a supplementary cementitious material (SCM), natural fine aggregates (NFA), and recycled coarse aggregates (RCA) to investigate the properties and performance of concrete mixes [24]. The RCA was sourced from a local demolition site, cleaned, and crushed to achieve a size distribution similar to that of conventional coarse aggregates. The chemical properties of OPC, RCA, and Flyash were characterized according to ASTM standards. A superplasticizer was added to maintain workability, particularly for mixes with high RCA content, while potable water was used for mixing and curing.

The experimental design involved preparing different concrete mix proportions by replacing natural coarse aggregates (NCA) with RCA at 0%, 5% to 50% by weight with an increment of 5%. A fixed W/C of 0.4 was maintained for all mixes. Flyash, were incorporated at 10% replacement of OPC to enhance durability and mechanical performance. Mix designs were created according to the Indian standards, aiming for a target compressive strength of 30 MPa.

Concrete samples were prepared by batching, mixing, and casting procedures standardized by Indian standards. The materials were mixed using a rotary mixer to ensure homogeneity, and the slump cone test was conducted to assess workability for each mix. Concrete specimens, including cylinders and beams, were prepared for evaluating compressive, tensile, and flexural strengths. Cylindrical molds with dimensions of 150 mm in diameter and 300 mm in height, along with beam molds measuring 100 mm × 100 mm × 500 mm, were utilized for casting. The specimens were demolded after 24 hours and subsequently subjected to curing.

Compressive strength tests were conducted on cylindrical specimens at 7, 14, and 28 days using a UTM as per ASTM C39. The results were used to assess the strength development of RCA-based mixes relative to the control mix. The tensile strength was evaluated using the split tensile test on cylindrical samples at 28 days in accordance with ASTM C496. This test was vital for analyzing the impact of RCA content on the tensile properties of the concrete. Flexural strength was determined on 100 mm × 100 mm × 500 mm beam specimens following ASTM C78. This test provided insights into the load-bearing capacity of RCA-based mixes, particularly relevant for applications requiring enhanced flexural performance. To examine the durability, concrete samples underwent a sulfate resistance test and water absorption test. For sulfate resistance, specimens were immersed in a 5% sodium sulfate solution and assessed after 28 days. Water absorption was measured following ASTM C642 to determine the permeability of RCA-based mixes compared to conventional concrete.

The statistical significance of differences in compressive, tensile, and flexural strengths across various RCA-based mixtures was evaluated using an Analysis of Variance (ANOVA). Statistical software was used to compare means at a 95% confidence level, and p-values were considered to determine the significance of each factor in concrete performance.

3. RESULTS AND DISCUSSION

3.1. Slump cone test

The slump values for various concrete mixes were assessed to determine workability. Conventional concrete (T1) exhibited a slump value of 114 mm, reflecting good workability. With the addition of 10% flyash (T2), the slump marginally increased to 116 mm due to improved particle lubrication. Introducing recycled coarse aggregate (RCA) in incremental proportions (T3–T12) led to a progressive decline in slump values. At 5% RCA (T3), the slump dropped to 110 mm, indicating slightly reduced workability. This trend continued, with the slump value decreasing to 79 mm for 50% RCA replacement (T12).

The reduction in slump is attributed to the higher water absorption and irregular shape of RCA, which hindered the flowability of the mix. The decline was more pronounced as the RCA content increased, emphasizing the need for additional water or admixtures to maintain workability at higher RCA percentages [25]. Overall, while flyash improved workability, incorporating RCA necessitates careful mix adjustments to ensure performance in practical applications. The slump value is displayed in Figure 1.

3.2. Compaction factor test

Slump and compaction factor measurements were used to assess the workability of different concrete mixtures. With a compaction factor of 0.912 and a slump of 114 mm, conventional concrete (T1) showed acceptable workability. The inclusion of 10% flyash (T2) improved these values to 116 mm and 0.928, respectively, owing to enhanced particle lubrication [26]. However, as recycled coarse aggregate (RCA) was incrementally introduced (T3–T12), both slump and compaction factor decreased significantly. At 5% RCA (T3), the slump value dropped to 110 mm, and the compaction factor decreased to 0.88. For 50% RCA replacement (T12), these values further reduced to 79 mm and 0.632, respectively.

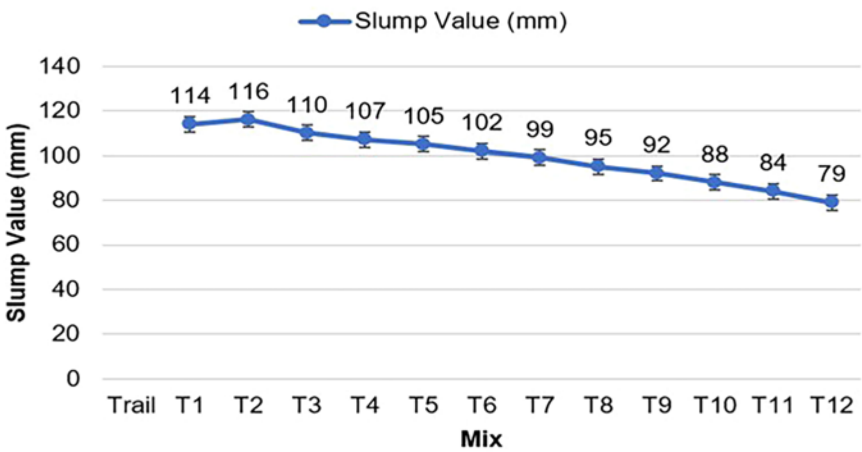

Figure 1: Shows the slump value.

The declining trend is attributed to the rough surface texture and higher water absorption capacity of RCA, which reduced the ease of compaction and flowability. While flyash enhanced workability, increasing RCA content necessitated careful mix design adjustments to balance the workability and mechanical performance for practical construction applications. Figure 2 shows the compaction value.

3.3. Compressive strength test

At 7, 14, and 28 days, the concrete mixtures' compressive strength was assessed. At these intervals, conventional concrete (T1) produced values of 23.15 MPa, 32.06 MPa, and 35.62 MPa, respectively. Because of the pozzolanic reaction and enhanced particle packing, the strength enriched to 24.52 MPa at 7 days and 37.72 MPa at 28 days when 10% of OPC was substituted with flyash (T2). A strength trend was seen when NCA was gradually replaced with recycled coarse aggregate (RCA) (T3–T12). Compressive strength increased with initial replacements up to 20% RCA (T6), peaking at 26.10 MPa, 36.14 MPa, and 40.16 MPa for 7, 14, and 28 days, respectively. Filler effects and improved interfacial bonding are responsible for this improvement.

Beyond 20% RCA replacement, compressive strength gradually declined, with T12 (50% RCA) showing a reduction to 21.50 MPa, 29.76 MPa, and 33.07 MPa at the respective curing periods. This decline is linked to the weaker mechanical properties of RCA and higher water absorption, affecting the matrix integrity. Optimal RCA replacement was identified at 20%, balancing sustainability and mechanical performance. The results of the compressive strength test are displayed in Figure 3.

3.4. Split tensile strength test

The split tensile strength of concrete mixes was analyzed over 7, 14, and 28 days. Conventional concrete (T1) recorded strengths of 1.57 MPa, 2.17 MPa, and 2.41 MPa, respectively. Replacing 10% of OPC with flyash (T2) slightly improved these values to 1.66 MPa, 2.30 MPa, and 2.56 MPa at corresponding curing ages due to better matrix refinement and pozzolanic activity. The gradual incorporation of recycled coarse aggregate (RCA) up to 20% replacement (T6) enhanced split tensile strength, peaking at 1.77 MPa, 2.45 MPa, and 2.72 MPa at 7, 14, and 28 days, respectively. This improvement can be attributed to the adequate bond between RCA and the cementitious matrix, along with the positive contribution of flyash.

Beyond 20% RCA replacement, tensile strength declined steadily. For 50% RCA (T12), the strength values dropped to 1.46 MPa, 2.02 MPa, and 2.24 MPa at the respective intervals, primarily due to the weaker mechanical properties and higher porosity of RCA. The optimal RCA content for maintaining strength and sustainability was determined to be 20%. The results of the split tensile strength test are displayed in Figure 4.

3.5. Flexural strength test

The flexural strength of concrete mixes was evaluated at 7, 14, and 28 days. Conventional concrete (T1) recorded flexural strengths of 2.01 MPa, 2.78 MPa, and 3.09 MPa, respectively. Replacing 10% OPC with flyash (T2) improved these values to 2.13 MPa, 2.95 MPa, and 3.28 MPa, attributed to enhanced cementitious properties and better microstructure due to the pozzolanic reaction. Increasing recycled coarse aggregate (RCA) content up to 20% replacement (T6) resulted in a consistent improvement in flexural strength, peaking at 2.27 MPa,

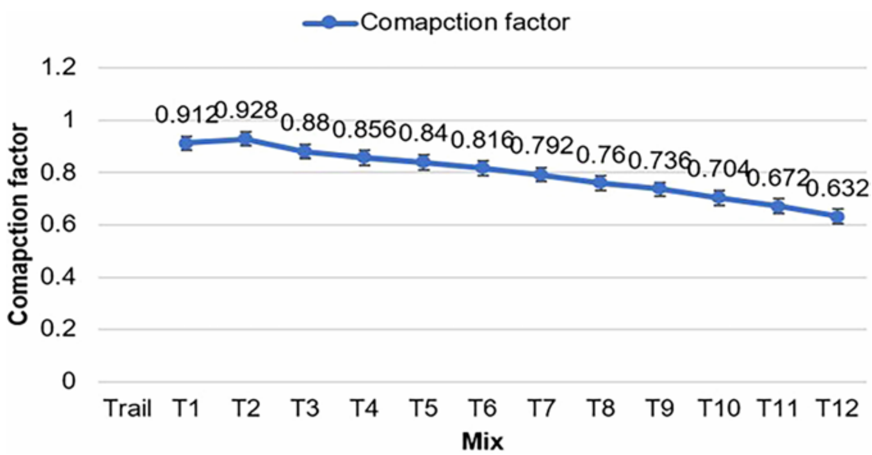

Figure 2: Shows the compaction value.

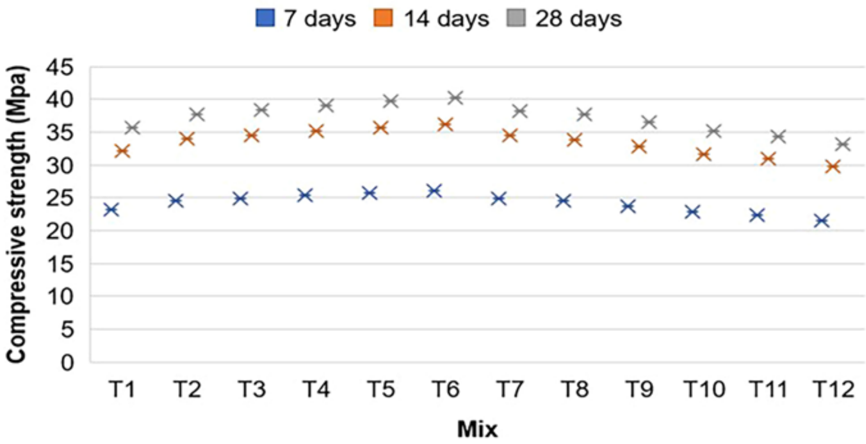

Figure 3: Shows the compressive strength test results.

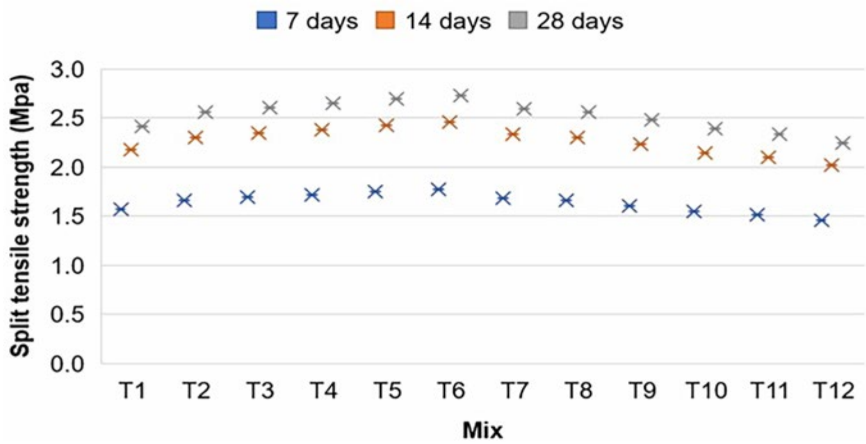

Figure 4: Shows the split tensile strength test results.

3.14 MPa, and 3.49 MPa at 7, 14, and 28 days, respectively. This enhancement is likely due to improved bond strength between RCA and the matrix at moderate replacement levels, supported by the filler effect of flyash.

Beyond 20% RCA, flexural strength decreased steadily. For T12 (50% RCA), the strengths reduced to 1.87 MPa, 2.59 MPa, and 2.87 MPa, reflecting the lower stiffness and higher porosity of RCA. The optimal RCA content was identified as 20%, balancing mechanical performance and sustainability. [27] The results of the split tensile strength test are displayed in Figure 5.

3.6. Sulfate resistance test

The sulfate resistance of concrete mixes was evaluated by the percentage increase in weight at 28, 56, and 90 days. Conventional concrete (T1) showed weight increases of 13.15%, 11.84%, and 8.55% over the respective durations. Replacing 10% of OPC with flyash (T2) slightly improved resistance, reducing weight gain to 13.93%, 12.53%, and 9.05% at the same intervals due to the denser matrix resulting from the pozzolanic reaction.

Incorporating recycled coarse aggregate (RCA) progressively increased the weight gain, particularly at higher replacement levels. Up to 20% RCA (T6), sulfate resistance remained comparable, with weight increases of 14.83%, 13.34%, and 9.64%. Beyond 20% RCA, mixes exhibited a noticeable decline in resistance. T12 (50% RCA) recorded the highest weight gain of 18.35%, 18.05%, and 13.65% at 28, 56, and 90 days,

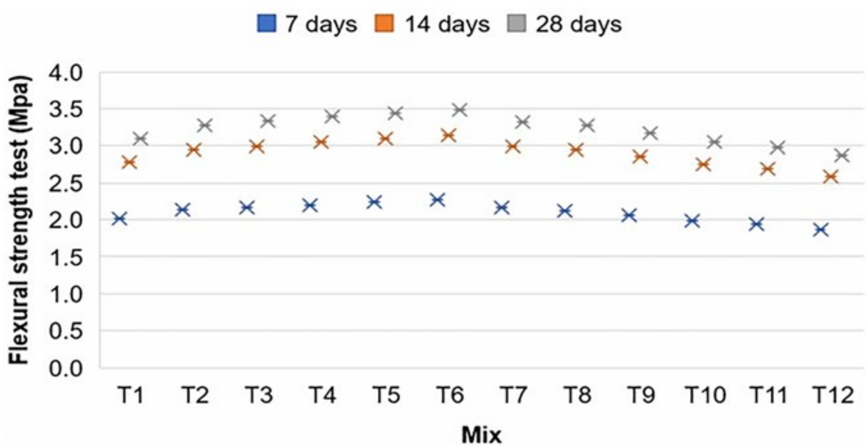

Figure 5: Shows the flexural strength test results.

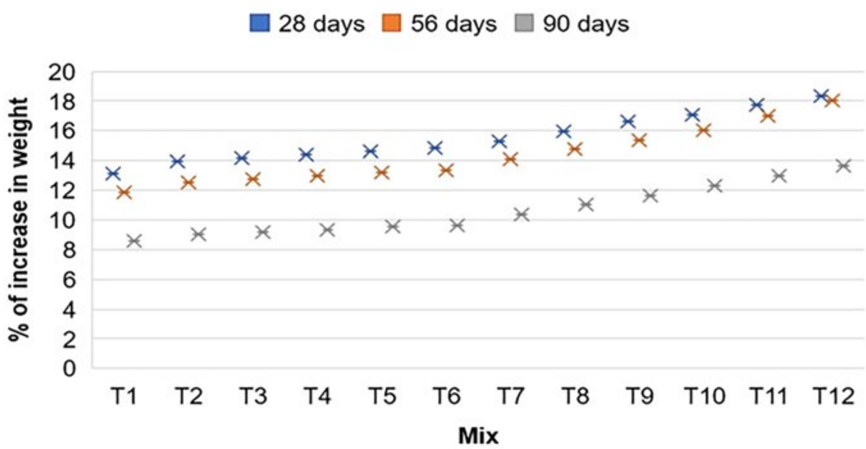

Figure 6: Shows the sulfate resistance test results.

respectively, due to the porous nature and susceptibility of RCA to sulfate attack. The optimal RCA replacement level for balancing sulfate resistance and sustainability was identified at 20%, ensuring acceptable durability while maintaining environmental benefits. Figure 6 shows the sulfate resistance test results.

3.7. Water absorption test

The water absorption of concrete mixes was evaluated at 28, 56, and 90 days. Conventional concrete (T1) demonstrated the lowest water absorption values, decreasing slightly over time from 3.25% at 28 days to 3.13% at 90 days. Substituting 10% OPC with flyash (T2) marginally increased water absorption, reaching 3.32%, 3.26%, and 3.20% for the respective durations due to the denser matrix but slightly higher capillary pores.

Introducing recycled coarse aggregate (RCA) led to a steady increase in water absorption, with the impact becoming more pronounced at higher RCA replacement levels. Up to 20% RCA (T6), water absorption remained within acceptable limits, reaching 3.89%, 3.82%, and 3.75% at 28, 56, and 90 days. However, mixes with RCA content beyond 20% exhibited significant increases in water absorption. For T12 (50% RCA), the values peaked at 4.67%, 4.58%, and 4.50% due to the porous structure of RCA and its higher water retention capacity. The findings suggest 20% RCA as the optimal replacement level to maintain durability while enhancing sustainability. Figure 7 shows the water absorption test results.

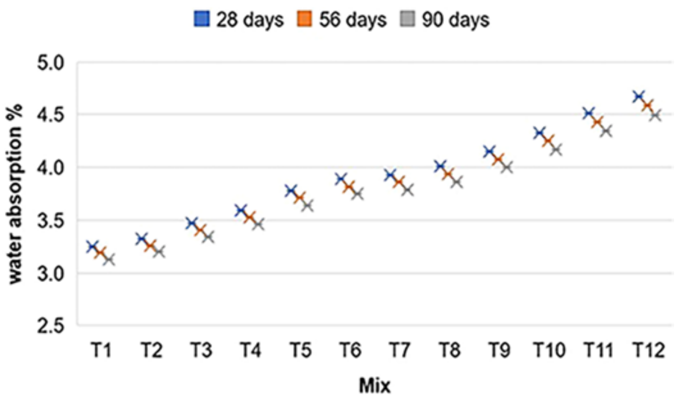

Figure 7: Shows the water absorption test results.

Table 1: Shows the ANNOVA.

SOURCE OF VARIATION	SS	df	MS	F
Rows	1554.25	11	141.2955	65535
Columns	0	0	65535	65535
Error	0	0	65535	
Total	1554.25	11		

Table 2: Shows the ANNOVA.

SOURCE OF VARIATION	SS	df	MS	F	P-VALUE	F CRIT
Rows	115.4794	11	10.49813	66.69231	2.8E-14	2.258518
Columns	1074.516	2	537.2582	3413.084	3.76E-28	3.443357
Error	3.46305	22	0.157411			
Total	1193.459	35				

4. NUMERICAL APPROACH

4.1. Slump cone test

The provided ANOVA Table 1 indicates significant issues with the calculation of the results. The source of variation for the rows, with a sum of squares (SS) of 1554.25 and 11 degrees of freedom (df), suggests substantial variability among the different trials (T1 to T12). However, the calculated mean square (MS) for rows is 141.2955, and the F-value is 65535, which is unrealistic and likely due to an error in the computation. The columns and error terms both show zero sum of squares and degrees of freedom, which is highly unusual, as it suggests no variability in the columns or errors, likely pointing to incorrect data setup or calculations. The total sum of squares matches the value for rows, but the degrees of freedom appear incomplete without proper error terms. To resolve this, the degrees of freedom for columns and error need to be recalculated, and the mean squares for these terms should be accurately computed to obtain valid F-values and draw meaningful conclusions from the analysis.

4.2. Compressive strength test

The ANOVA analysis results presented in Table 2 highlight significant variation across both rows and columns. For the rows, the sum of squares (SS) is 115.4794, with 11 degrees of freedom, yielding a mean square (MS) of 10.49813 and an F-value of 66.69231. The exceptionally low p-value of 2.8E-14 indicates statistically significant

Table 3: Shows the ANNOVA.

SOURCE OF VARIATION	SS	df	MS	F	P-VALUE	F CRIT
Rows	6.585874	11	0.598716	8469.144	3.15E-37	2.258518
Columns	0.125092	2	0.062546	884.7471	9.58E-22	3.443357
Error	0.001555	22	7.07E-05			
Total	6.712522	35				

variance among the rows. Similarly, the columns exhibit a substantial contribution to the overall variance, with an SS of 1074.516 and 2 degrees of freedom, resulting in an MS of 537.2582 and a strikingly high F-value of 3413.084. This is further reinforced by an extremely low p-value of 3.76E-28.

The error component, representing random variability, has an SS of 3.46305 with 22 degrees of freedom and an MS of 0.157411, demonstrating that the error variability is minimal in comparison to the total variability. The total sum of squares for the data is 1193.459 with 35 degrees of freedom, illustrating that both rows and columns play a significant role in explaining the observed variations. These findings confirm that the variations in the dataset are strongly influenced by the factors represented in the rows and columns, with negligible error influence.

4.3. Water absorption test

Table 3 summarizes the ANOVA results, demonstrating notable variations across both rows and columns. The rows, with a sum of squares (SS) of 6.585874 and 11 degrees of freedom, have a mean square (MS) of 0.598716 and an exceptionally high F-value of 8469.144. The extremely low p-value of 3.15E-37 confirms a highly significant variance among the rows. Similarly, the columns, while contributing less to the overall variance, exhibit statistical significance. With a sum of squares of 0.125092 and 2 degrees of freedom, the columns yield a mean square of 0.062546 and an F-value of 884.7471, supported by a very low p-value of 9.58E-22.

The error component displays minimal variability, with an SS of 0.001555, 22 degrees of freedom, and a mean square of 7.07E-05. The total sum of squares for the data is 6.712522 with 35 degrees of freedom, highlighting that the variance in the data is predominantly attributed to the rows. These findings underscore the strong influence of the factors represented in the rows, while the columns also contribute significantly, albeit to a lesser extent, with negligible error variability.

5. CONCLUSION

The study concludes with a thorough examination of concrete mixtures that contain fly ash, OPC, and different amounts of RCA and NCA. ANOVA has been used to assess the statistical significance of the various mix modifications based on the results of the slump test, compressive strength, split tensile strength, flexural strength, sulfate resistance, and water absorption tests. Conventional concrete has the highest slump value, and the findings of the slump test reveal a progressive decrease in workability as the proportion of RCA rises. Despite the decrease in workability, the compaction factor marginally rose with RCA presence, indicating that the mixes containing RCA were more compact.

The compressive strength results show that the addition of flyash and RCA in varying proportions enhances the compressive strength compared to conventional concrete, with the highest values observed for mixes with 80% NCA and 20% RCA at 28 days. ANOVA confirmed that the rows (mixes) contributed significantly to the variation in compressive strength, with a very low p-value indicating strong statistical significance. Similar trends were observed, where the strength improved as the proportion of NCA increased relative to RCA.

The sulfate resistance test showed a progressive increase in the weight of specimens exposed to sulfate, indicating the incorporation of RCA reduces sulfate resistance. However, the mixtures with higher proportions of flyash and lower RCA content exhibited better resistance, with minimal weight increase.

Water absorption increased with RCA content, particularly for mixes with higher RCA and lower NCA. ANOVA confirmed the significant variation between rows and columns in water absorption, with the p-value reinforcing the strong statistical differences.

Overall, the incorporation of flyash and varying RCA proportions in concrete mixes enhances strength properties but slightly reduces sulfate resistance and increases water absorption. The statistical analysis reveals that the mix composition significantly influences the performance of concrete, making these findings crucial for developing more sustainable concrete mixes using recycled materials.

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