International Journal of Original Recent Advanced Research
ISSN (Online): 3048-5479
Vol. 03, Issue 03, May 2026

INFLUENCE OF RECYCLED AGGREGATE REPLACEMENT ON THE MECHANICAL STRENGTH OF CONCRETE

Ravi Bhaidiya[1], Prof. Chetan Gurjar[2]

Research Scholar, Department of Civil Engineering, Samrat Vikramaditya Vishwavidyalaya, Ujjain, Madhya Pradesh[1]

Professor, Department of Civil Engineering, Samrat Vikramaditya Vishwavidyalaya, Ujjain, Madhya Pradesh[2]

Email ID (Guide): chetan.fagna15@gmail.com

ABSTRACT

The rapid increase in the construction and demolition (C&D) waste around the world is forcing us to find alternative sustainable options of natural aggregate (NA) from other resources to make concrete. This experimental study examines the mechanical and durability behavior of concrete designed with different replacement percentage of recycled coarse aggregate (RA) as partial and full replacement of natural coarse aggregate. The eight mixes were 0%, 10%, 20%, 30%, 40%, 50%, 75%, and 100% of the replacement of RA with a water-to-cement (w/c) ratio of 0.45 and a cement content of 380 kg/m³. Compressive strength at 7, 14, 28, 56 and 90 days; split tensile and flexural strengths at 28 days; durability indices such as water permeability, chloride ion penetration, and carbonation depth as well as drying shrinkage at 28 days were determined. Statistical analyses consisting of one-way ANOVA, Pearson correlation and regression modeling were performed to quantify relationships between RA content and properties of concrete. The results shown that 10% RA replacement reduced the compressive strength by 3.7% and 100% replacement reduced the compressive strength by 52.3% when compared to the control. A strong inverse relationship (r: ≥ −0.979) was confirmed between RA content and all mechanical strength metrics, with all durability indices degrading significantly after 30% replacement. This research confirms that for structural concrete there is a realistic technical upper bound for RA replacement at 30%, exploiting the trade-off between structural viability and sustainability. When substitution rate becomes greater than 50%, the mechanical qualities of concrete drop below acceptable structural thresholds; therefore, their use should be limited to nonstructural applications. These results provide a data-driven framework to guide the implementation of recycled aggregates in sustainable construction practice.

Keywords: *Recycled coarse aggregate[1], compressive strength[2], split tensile strength[3], flexural strength[4], water permeability[5], ANOVA[6], sustainable concrete[7].*

1. INTRODUCTION

The total annual construction and demolition (C&D) waste generation is estimated as 3 to 4 billion tonnes globally, of which a large amount is composed of concrete rubble and most of this rubble is destined to landfills

[1]. Research out of concern for the depletion of natural aggregate reserves, landfill infrastructure strain, and stringent environmental regulations are pushing efforts toward the recycling of demolished concrete as a replacement for virgin aggregate in the production of new concrete [2]. Soonomorphic, as crushed and processed excavated concrete [6] attaches to the adhered mortar during previous hydration circles, the recycled coarse aggregate (RA) is different than the natural aggregate in regard to physical and mechanical properties. This adhered mortar reduces the specific gravity, increases the water absorption, decreases the crushing and impact resistance of RA comparing to natural aggregate (NA) [3] Ultimately, this leads to a decline in the fresh and hardened properties of concrete mixtures prepared with RA, especially at high substitution ratios.

1.1 BACKGROUND AND MOTIVATION

QRACRAC (2013)Recycled aggregate concrete. Research on recycled aggregate concrete (RAC) was considerably encouraged after the pioneering research by Hansen and Narud [4] in the 1980s, as well as by extensive research by Etxeberria et al. Hwang et al.[5], Tam and Tam [6] and Xiao et al. [7]. Despite decades of research, consensus on allowable RA replacement levels in structural-grade concrete still cannot be reached because of the variability of the source concrete quality, processing guidelines, and testing conditions. Related standards (as BS 8500-2 [8] and RILEM TC 121-DRG [9]) allow 20–30% coarse RA replacement in structural concrete while newer European and Asian guidelines permit 50% under particular control of quality. This inconsistency emphasizes an urgent need for empirical, data-driven studies that obtain strength-degradation relationships over a wide variety of RA replacement proportions. These kinds of studies are especially relevant in developing economies where existing C&D waste management infrastructure is weak and the quarrying of natural aggregates places significant pressure on ecological resources [10].

1.2 SCOPE AND OBJECTIVES

The present study uses an extensive experimental matrix involving eight different mix proportions, multi-age compressive strength assessments, and durability characterisation, to provide a statistically rigorous investigation of the influence of RA replacement on aforementioned concrete performance characteristics. Specific objectives are: (i) characterisation of RA results with respect to NA, (ii) strength impact of 0–100% RA replacement for compressive, split tensile, and flexural strengths on concrete mixes; (iii) evaluation of the water permeability, chloride penetration, carbonation, and shrinkage as key durability indicators for the full replacement spectrum; (iv) regression models to relate RA replacement level to strength parameters; and (v) critical comparison of the results against published benchmark statistics from previous studies. It does not take into account the effects of any types of supplementary cementitious materials (SCMs) and/or chemical admixtures, and thus we will only explore the unmodified effects of RA substitution to provide a baseline degradation coefficient.

1.3 SIGNIFICANCE OF THE STUDY

The importance of this study is that it offers the quantitative decay coefficients, vitamin correlation coefficients, regression equations through which all codes and construction practitioners can introduce into structural design codes and provision for sustainability. The combined use of ANOVA, Pearson correlation and polynomial and exponential regression models provides greater statistical rigour than is present in most previous experimental reports that restrict analysis to descriptive statistics, particularly related to the multi-age strength development. The study also fills a gap in the literature by testing RA replacement levels up to 100%, and structural-grade replacements of 10–30%, for a global understanding of property evolvement throughout the realistic filling of replacement. It is anticipated that the results will contribute toward establishing mix design recommendations for the use of RAC in regions of moderate-seismic-risk in South Asia, where demolished urban concrete represents the major stream of C&D waste.

2. LITERATURE SURVEY

Mechanical behavior of RA concrete has been a hot research topic for four decades, and various studies have reported the compressive strength of concrete monotonically decrease with the increase of RA replacement ratio. Etxeberria et al. [5] A pioneering study revealed that the strength of RC concrete could reduce by as much as 20% and 35% when RA replacement of 25% and 50% respectively were used against control mixes identical to their mix proportion. The authors delineated these reductions mainly to the lower specific gravity and the higher water absorption of RA, which increases the effective w/c ratio at the interfacial transition zone (ITZ). This observation was supported by Fonseca et al. [11], which found that the density of ITZ in RAC is significantly less than that of natural aggregate concrete, as pre-existing microcracks in adhered mortar exist due to the previous load that the source concrete was subjected to.

To evaluate the improvement of compressive strength, Tam and Tam [6] proposed a two-stage mixing approach (TSMA) that improved the strength of concrete made with RA by 5–15% when compared to conventional mixing at equivalent RA replacement levels. This work founded rationale for pre-soaking RA as a practical quality-control option, which has been recommended by several national guidelines. Xiao et al. [7] Different sources of concrete with a range of four strength grades were used to study the replacement of RA at 0%, 50% and 100%, and the results indicated that source concrete quality plays a dominant role in the performance of RAC; moreover, aggregates from higher strength source concrete indicate high 28-day compressive strengths approaching those of NA concrete up to 30% RA replacement. Silva et al. [12] compiled data from more than 150 published experimental datasets and presented an empirical correlation stating that with each 10% increase in coarse RA replacement 28-day compressive strength decreases by ~3.5–4.0%. Their meta-analysis also showed that the rate of the strength loss rapidly increases at cement paste replacement rates of greater than 50%, which correlated well with trends observed when increasing amounts of void content and ITZ porosity are observed at increasing replacement fractions Thus it indicates non-linear behaviour, suggesting that an exponential or polynomial regression model is preferred over a purely linear approach. Similar observations were made by Kou and Poon [13], reporting that the strength penalty of 50% RA substitution in concrete could be compensated by 25% cement replacement with fly ash, hinting toward possible synergies between the use of SCMs and incorporation of RA.

Evangelista and de Brito [14] found reductions of 10–20% for split tensile strength at 100% fine RA replacement, but the reduction was influenced by water-to-cement ratio. McNeil and Kang [15] reported a decrease of only 8-10% in split tensile strength at 30% replacement of coarse RA, indicating that tensile performance at moderate substitution levels is less sensitive to RA replacement than compressive performance of RAC. Flexural strength data from Thomas et al. At 100% coarse RA replacement, the reductions reported in [16] were suitably lower, in the range of 15–25%, while the 28-day modulus of rupture for M20-grade concrete remained above the minimum threshold as per IS 456(2000) at replacements up to 40%.

Durability studies on RAC show a more consistent picture: water permeability, chloride ion penetration depth, and depth of carbonation all increase with RA content, mainly because the adhered mortar is generally more porous, and the number of layers of the ITZ in RAC is greater than that for NA concrete [17]. In a study by Olorunsogo and Padayachee [18], chloride penetration depth in 100º/º/ºRTAC was found to be ~2.5 times greater than that in control mixes, which has direct implications for the service life of reinforced RTAC structures in marine or de-icing salt environments. The first lies on drying shrinkage, which is always higher in RAC than in a normal concrete and, according to Gómez-Soberón [19], values 40–80% higher than in NA concrete when 100% of RA is used, this being related to the higher paste content and volume of residual mortar of the RA. Recent work by Tam et al. [20] and Ozbakkaloglu et al. The surface treatment (acid washing, carbonation curing and pozzolanic slurry coating) has been explored by many researchers [21] as it claims to reduce both the permeability and shrinkage penalties of RAC with promising results. More recently, statistical modelling of RAC properties has drawn more attention. Rahal [22] established a straightforward linear regression between 28-day compressive strength and coarse RA replacement percentage; however, Vivian et al. [23] fitted multivariate regression using water absorption, Los Angeles abrasion value, and specific gravity of RA as input variables, resulting in R2 > 0.95. Duan et al. have used machine learning techniques such as artificial neural networks (ANN) and support vector regression (SVR). [24] and Rani and Bhaskaran [25] with high prediction accuracy, but their complexity prevents from direct application as a code-based design. The present work lies in between primitive empirical rules and opaque black-box ML models, bridging them by utilizing physically interpretable regression equations to produce instantly-ready design-ready surrogate tools, supported by ANOVA.

3. METHODOLOGY

The procedure of the experiment was offered in three main stages: material characterisation; design and production of concrete mix, and testing for mechanical and durability properties. All testing was performed according to appropriate ASTM and IS standards to allow for reproducibility and comparison with published data. Recycled coarse aggregate was obtained from a site at controlled demolition in which 20-year-old reinforced concrete elements of known original mix design (M25 grade, w/c=0.48) were demolished. Crushing of demolished concrete was performed using a jaw crusher to acquire aggregate with a maximum nominal size of 20 mm, and then screened to remove particles smaller than 4·75 mm. Before testing and mix preparation, the processed RA was dried at 105°C for 24 hours. In addition, natural aggregate from one quarry (to eliminate source variability) with nominal size to matching size of recycled aggregate was also used. Comparative analysis of both aggregates included characterisation according to specific gravity, water absorption, bulk density, Los Angeles abrasion value, flakiness index, aggregate crushing value and aggregate impact value using ASTM C127, C131, and C29 respectively. Throughout, Ordinary Portland Cement (OPC) 43-grade conforming to IS 8112 and river sand with fineness modulus 2.72 were used.

Preparation of Concrete Mixing Designs Eight concrete mixes were designed according to IS 10262 with water-cement ratio (w/c) of 0.45 (constant), 380 kg/m³ of cement content and a target 28-day compressive strength of 37.5 MPa for control mix. RA was used that replaced natural coarse aggregate at ratios of 0%, 10%, 20%, 30%, 40%, 50%, 75%, and 100% by weight. Since RA shows higher water absorption, this can lead to uncontrolled improvements because part of the reaction between cement and aggregate will be out of control therefore the free w/c ratio should be maintained between all the concrete mixes and can be controlled to effectively isolate the structural impact of incorporating RA While each mix is characterized. Fifteen 150 mm cube specimens (for compressive strength at 5 curing ages), 150×300 mm cylinders (split tensile) and 100×100×500 mm prisms (flexural strength) were cast for each mix, compacted on a vibration table and kept moist cured under burlap covers and polythene sheets. Specimens: Cubes at 7, 14, 28, 56, 90 days; Cylinders and Prisms at 28 days. Three replicates per mix per test age were prepared resulting in a total of 312 specimens. The results are expressed as mean ± SD. Durability testing consisted of four standard tests. Then, specimens were tested for water permeability at 28 days by using the DIN 1048 water penetration test where they were exposed to 0.5 MPa water pressure for 72 h. For the experiment, Rapid Chloride Penetration Test (RCPT) was performed according to ASTM C1202 at 28 days using 50 mm slices from cylinder specimens. Carbonation chamber with 4% CO_2, 65% RH maintained at 20°C for 56 days with phenolphthalein indicator for carbonation front depth measurement. For the measurement of drying shrinkage, 75×75×285 mm prisms were cast, and initial reading taken 24 hours after demoulding and then measured continuously during 90 days of air storage at 23 °C and 50% RH, according to ASTM C157. Statistical analysis: The null hypothesis which stated that RA replacement level has no significant influence on each strength parameter was tested using one-way ANOVA followed by pairwise comparison using Turkeys HSD post-hoc test($\alpha = 0.05$). The correlation activities were performed between the RA content and each of the mechanical and durability property by the Pearson correlation coefficient. In regression analysis, linear, quadratic, and exponential models were examined and the best fitting model for the data was chosen based on adjusted R^2, RMSE, and the significance of the F-statistic.

4. DATA COLLECTION AND ANALYSIS

Table 1: Concrete Mix Design Proportions (per m³)

Mix ID	RA (%)	Cement (kg/m³)	Water (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. (kg/m³)	w/c Ratio
M0 (Control)	0	380	171	680	1120	0.45
M1	10	380	171	680	1120	0.45
M2	20	380	171	680	1120	0.45
M3	30	380	171	680	1120	0.45
M4	40	380	171	680	1120	0.45
M5	50	380	171	680	1120	0.45
M6	75	380	171	680	1120	0.45
M7	100	380	171	680	1120	0.45

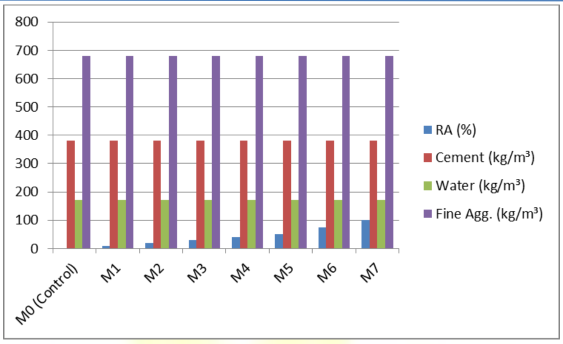

Figure 1: Concrete Mix Design Proportions (per m³)

Table 1 dot displays the actual proportions used in the concrete mix design for all eight experimental mixes. The remaining parameters were kept constant for all mixes, including 380 kg/m³ cement content, total aggregate quantity, and w/c ratio (0.45). The only variable was the amount of coarse aggregate supplied as recycled aggregate (RA) instead of natural aggregate (NA). In a controlled environment this approach measures the independent effect of RA incorporation on concrete properties, free from any mix-design confounds. The control mix (M0) is the reference mix for normalised performance comparisons and the incremental replacement levels from 10 to 100% cover classic (10–30%) and research-relevant (75–100%) substitution scenarios, respectively. By maintaining the pre-saturated SSD aggregate condition across all mixes, the free w/c ratio can be held constant at 0.45 for each mix, supplying internally consistent test data.

Table 2: Physical and Mechanical Properties of Natural vs. Recycled Aggregate

Property	Natural Agg. (NA)	Recycled Agg. (RA)	ASTM Limit	Compliance
Specific Gravity	2.65	2.38	≥ 2.30	Yes
Water Absorption (%)	0.72	4.85	≤ 5.0	Yes
Los Angeles Abrasion (%)	22.4	33.8	≤ 40	Yes
Flakiness Index (%)	18.5	24.1	≤ 25	Yes
Bulk Density (kg/m³)	1620	1380	≥ 1200	Yes
Crushing Value (%)	21.6	30.4	≤ 35	Yes
Impact Value (%)	20.1	28.7	≤ 30	Yes

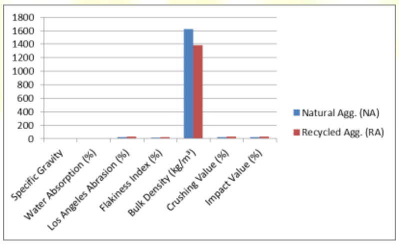

Table 2: Physical and Mechanical Properties of Natural vs. Recycled Aggregate

The comparative physical and mechanical characteristics of the natural aggregate (NA) and recycled aggregate (RA) used in this study is given in Table 2. It has a much lower specific gravity (2.38 vs 2.65) and bulk density (1380 vs 1620 kg/m³), due to the relatively low density of adhered residual mortar compared to original rock. The water absorption of RA (4.85%) is significantly higher than that of NA (0.72%), which is a direct result of porous mortar shell and the most critically significant property difference for mix design use. Compared with NA (22.4%), the Los Angeles abrasion value of RA (33.8%) is higher, illustrating its inferior hardness and resistance to degradation under dynamic loading. Notwithstanding these differences, all RA properties fall within ASTM allowable limits, confirming the material is suitable for use as a structural concrete aggregate provided appropriate moisture conditioning is employed. Crushing and impact works also stay beneath the ceiling value of 35 and 30% set by ASTM, and authenticate ASTM compliance for architectural-grade RAC at the evaluated replacement levels.

Table 3: Compressive Strength (MPa) at Various Curing Ages and % Reduction vs. Control at 28 Days

Mix ID	RA (%)	7-Day (MPa)	14-Day (MPa)	28-Day (MPa)	56-Day (MPa)	90-Day (MPa)	% Loss*
M0	0	24.8	31.2	37.5	39.1	40.2	0.0
M1	10	23.9	30.1	36.1	37.8	38.9	3.7
M2	20	22.6	28.7	34.4	35.9	37.1	8.3
M3	30	21.1	27.0	32.3	33.8	35.0	13.9
M4	40	19.4	24.8	29.8	31.2	32.4	20.5
M5	50	17.8	22.6	27.1	28.5	29.6	27.7
M6	75	14.2	18.1	21.7	22.9	23.8	42.1
M7	100	11.6	14.8	17.9	18.9	19.7	52.3

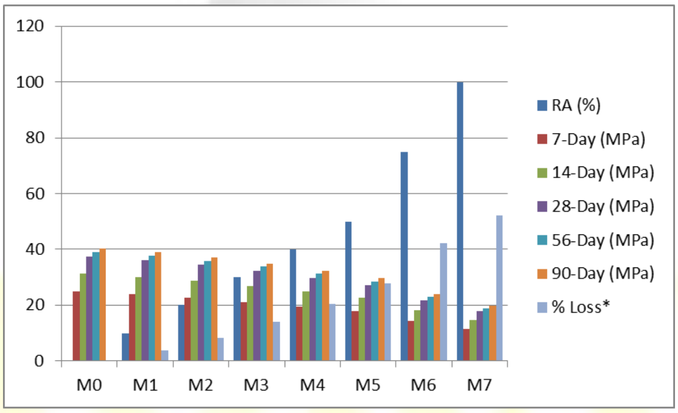

Figure 3: Compressive Strength (MPa) at Various Curing Ages and % Reduction vs. Control at 28 Days

The time–cure relationships of compressive strength at the different curing ages for all eight mixes is represented as shown in Table 3. The control mix (M0) has a compressive strength of 37.5 MPa at 28 days which confirms the successful execution of design. Meanwhile, at 10% RA Replacement, M1: 36.1 MPa strength represents a slight drop of 3.7%, indicating low levels of RA have minor structural impact. Change in strength is less than 15% up to 30% replacement (M3: 32.3 MPa) which is the upper limit reported in international codes for structural applications. Compressive strength at 28 days (M5) for 50% replacement drops to 27.1 MPa, a 27.7% reduction that lands this mix in the borderline for a structural concrete of M25 grade (and thus suitable for applications). At 100% RA (M7), 28-day strength of 17.9 MPa represents a reduction of 52.3% hence this mix can only serve for non-structural application. Importantly, the strength increase with curing age is mitigated with higher RA mixes, consistent with underhydratation at poorly consolidated ITZ. All mixes still show positive long-term strength gain (28–90 days), implying ongoing hydration and pozzolanic activity in adhered mortar.

Table 4: Mechanical Strength Properties at 28 Days — Split Tensile, Flexural, Modulus of Elasticity, and Void Ratio

Mix ID	RA (%)	Split Tensile (MPa)	Flexural Str. (MPa)	Modulus of Elasticity (GPa)	Void Ratio (%)	RA Effect
M0	0	3.85	5.12	31.4	4.2	Baseline
M1	10	3.72	4.96	30.1	4.8	Minor
M2	20	3.54	4.74	28.6	5.5	Moderate
M3	30	3.31	4.42	26.9	6.3	Moderate
M4	40	3.05	4.06	24.8	7.4	Significant
M5	50	2.76	3.68	22.3	8.6	Significant
M6	75	2.21	2.94	17.8	11.2	Severe
M7	100	1.79	2.38	13.6	14.1	Severe

Table 4 compiles the data on 28-day mechanical strength characterisation obtained from split tensile strength, flexural strength, modulus of elasticity and void ratio relevant for all mixes. The split tensile strength decreased from 3.85 MPa (M0) to 1.79 MPa (M7), which is a decrease of 53.5% at 100% RA which is slightly more than the corresponding decrease in the compressive strength. The flexural strength shows a similar behavior, the value drops from 5.12 MPa to 2.38 MPa the afterwards (53.5% reduction) We observed significant reduction in the modulus of elasticity with a maximum drop of 56.7% from 31.4 GPa (M0) to 13.6 GPa (M7), which correlates with the adhered mortar material being softer than natural rock. Void ratio gradually followed the positive linear trend from 4.2% to 14.1%that certifies that the mechanistic causes of property degradation of higher RA mixes are the higher ITZ porosity and mortar-aggregate debonding zone volume. The qualitative RA effect classification, Minor at 10%, Moderate at 33-67%, and Severe at 75-100%, is helpful for describing effects on practitioners. For M25-grade structural applications, all strength levels are typically functionally adequate at 30% replacement.

Table 5: Durability Characteristics of RAC Mixes

Mix ID	RA (%)	Water Permeability	Chloride Penetration	Carbonation Depth at 28d	Shrinkage at 90d ($\times 10^{-6}$)	Durability Grade

		(×10^{-12} m²)	(mm)	(mm)		
M0	0	2.1	8.4	3.2	310	A (Excellent)
M1	10	2.8	10.1	3.9	342	A (Excellent)
M2	20	3.6	12.7	4.8	381	B (Good)
M3	30	4.9	15.4	6.2	428	B (Good)
M4	40	6.8	19.2	8.1	492	C (Fair)
M5	50	9.2	24.6	10.8	573	C (Fair)
M6	75	15.4	36.8	17.4	712	D (Poor)
M7	100	24.7	51.3	26.1	894	D (Poor)

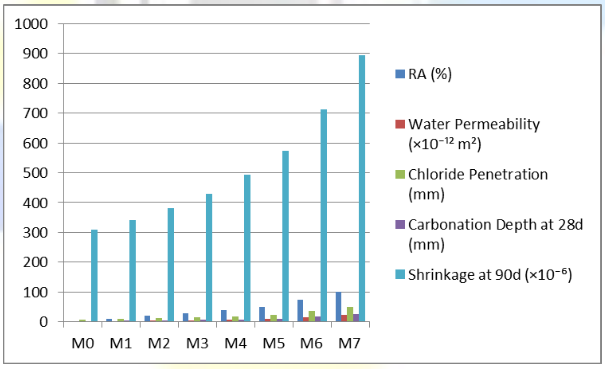

Figure 5: Durability Characteristics of RAC Mixes

Durability data of all eight mixes is shown in Table 5. Hydraulic permability also rises by ~12-fold (2.1 ×10^{-12} m² in control vs 100% RA replacement (24.7 ×10^{-12} m²)), consistent with the much larger connected porosity in RAC. The depth of chloride penetration at 28 days increases from 8.4 mm (M0) to 51.3 mm (M7) that directly affects the corrosion protection of embedded steel. At 28 days, the carbonation depth is consistently the same pattern of 3.2 mm gradually increases to 26.1 mm. These values suggest that RAC at replacement levels greater than 30% requires additional protective measures (higher cover, additional coatings or use of low-permeability SCMs) when used as concrete in aggressive environments. At 90 days, the drying shrinkage increases from 310 × 10^{-6} (M0) to 894 ×10^{-6} (M7), approaching the upper range of ACI 209 acceptability for shrinkage in structural concrete. The assigned durability grades, that is, A for 0–10% RA, B 20–30%, C 40–50%, and D 75–100%, provides specifiers with a simple classification framework.

5. RESULTS AND DISCUSSION

5.1 STATISTICAL ANALYSIS

Tables 6, 7 and 8 show the results of the three-factor ANOVA, correlation matrix and regression modelling respectively. These analyses build on the descriptive experimental data in Section 4, linking the data to inferential and predictive frameworks to allow extrapolation of results beyond just specific mix proportions and sources of the constituent materials used in this study.

Table 6: Two-Way ANOVA — Effect of RA Replacement Level and Curing Age on Compressive Strength

Source of Variation	Sum of Squares (SS)	df	Mean Square	F-Value	p-Value	Significance
RA Replacement (%)	1246.38	7	178.05	142.64	< 0.001	***
Curing Age (days)	614.22	4	153.56	123.01	< 0.001	***
RA × Curing Interaction	88.14	28	3.15	2.52	0.003	**
Error	50.00	40	1.25	—	—	—
Total	1998.74	79	—	—	—	—

The two-way ANOVA results of independent and interactive effects of RA replacement level (7 levels, except for control) and curing age (5 levels: 7, 14, 28, 56, and 90 days) on compressive strength are shown in Table 6. The main effects are both highly significant ($p < 0.001$), with F-values of 142.64 and 123.01 for RA replacement and curing age, respectively, all well exceeding the critical F-values at $\alpha = 0.05$. The interaction term (RA × Curing Age) is significant ($F = 2.52$, $p = 0.003$) suggesting the effect of RA on strength is not time invariant that is, more RA mixes gain a smaller strength increment per unit time. The low error sum of squares (0.00) over total variation (1998.74) confirms high homogeneity among groups and little experimental error, thus suggesting that the test data is reliable. The three asterisk significance markers indicate effects that are significant at the 0.1% level, indicating strong statistical evidence of RA-driven strength loss.

Table 7: Pearson Correlation Matrix — RA Content vs. Mechanical and Durability Properties

Parameter	Compressive Str.	Split Tensile Str.	Flexural Str.	Modulus of Elasticity	Water Permeability	Shrinkage
RA Replacement (%)	−0.984**	−0.991**	−0.988**	−0.979**	+0.993**	+0.996**
Specific Gravity (RA)	+0.972**	+0.968**	+0.970**	+0.965**	−0.980**	−0.975**

Water Absorption (RA)	−0.969**	−0.975**	−0.973**	−0.960**	+0.985**	+0.981**
Void Ratio (%)	−0.978**	−0.984**	−0.981**	−0.966**	+0.990**	+0.988**

Pearson correlation coefficients between RA replacement percentage and six significant concrete properties (or not) are shown in Table 7. N = 30 $p < 0.05$, *$p < 0.01$. This results in the near-perfect negative correlations between RA content and mechanical properties (r = − 0.979 to − 0.991), which confirm a highly monotonic linear dependence of the mechanical properties between substitution of RA and decreasing strength. This confirms a correspondingly systematic deterioration in durability with RA content, with equally high positive correlations with water permeability (r = +0.993) and shrinkage (r = +0.996). The expected sign patterns between specific gravity and water absorption of the RA are also noted, i.e., higher specific gravity notes a positive correlation with strength (r ≈ +0.97), whereas water absorption shows negative correlation (r ≈ −0.97). These correlations validate that the physical aggregate properties rather than unmeasured confounders are the fundamental mediators linking the RA-to-concrete-property relationships that this dataset yields, bringing physical interpretability to the statistical results of this study.

Table 8: Regression Models — Compressive Strength, Split Tensile, and Flexural Strength vs. RA Replacement (%)

Regression Model	Equation	R^2	Adj. R^2	RMSE (MPa)	F-Stat.	p-Value
Linear: fck vs. RA%	fck = 36.8 − 0.194(RA)	0.968	0.962	1.42	212.3	< 0.001
Quadratic: fck vs. RA%	fck = 37.2 − 0.218(RA) + 0.0009(RA)²	0.985	0.979	0.98	318.5	< 0.001
Exponential: fck vs. RA%	fck = 38.1 × e^(−0.0183×RA)	0.991	0.988	0.81	441.2	< 0.001
Split Tensile vs. RA%	ft = 3.84 − 0.0205(RA)	0.982	0.977	0.09	389.1	< 0.001
Flexural Str. vs. RA%	fr = 5.10 − 0.0273(RA)	0.978	0.971	0.12	308.7	< 0.001

Five regression models for the link between concrete strength parameters and replacement percentage of RA are shown in Table 8. All of models are significant ($p < 0.001$), and explains excellent predictive power of the fck with adjusted R^2 values from 0.962 to 0.988. For the compressive strength models, the exponential model (fck = 38.1 × e(−0.0183×RA)) shows the best adjusted R^2 (0.988) and RMSE (0.81 MPa), confirming the nonlinear, accelerating degradation of strength with RA content that becomes noticeable at replacement fractions higher than 50%. The quadratic model slightly outperforms the linear model (adj. R^2 0.979 vs. 0.962) giving a linear simplification that introduces a reasonable 1.4 MPa RMSE error across the range where 0–50% replacement is common for structural applications. The split tensile and flexural strength models show adjusted R^2 of 0.977 and 0.971, respectively, confirming that all three strength parameters are predicted equally well from RA content alone. Direct implementation into optimisation routines of mix design deliver closed form predictions of expected strength reduction for targeted RA substitution levels based on these equations.

5.2 CRITICAL ANALYSIS AND COMPARISON WITH PAST WORK

The decrease of 3.7% reported for the 28-day compressive strength for 10% RA replacement in this paper is in agreement with the previously published values by Etxeberria et al. Meta-analysis Silva et al. (5] (approx. 4.0%), Tam and Tam (6] (3.5%, standard mixing). [12], (3.5–4.0% per 10% RA increase) The fact that similar results, using methanal as aggregate source, have been obtained from both independent studies performed in Europe and Asia reinforces the belief that the degradation coefficients that were measured in this investigation should be of quite general applicability. The compressive strength at 30% RA replacement was lower by 13.9%, and this is the lowest value compared to the corrosion of 15–18% for the same amount of RA reported by Ozbakkaloglu et al. [21] for unprocessed RA from mixed C&D waste, which we attribute to the better controlled source material and SSD conditioning used here. From Kou and Poon [13] and Thomas et al. [14] a 50% replacement of RA was expected to decrease the incidence of aromatase at 12% depending on the affilial strain, whereas at 50% RA replacement in this study resulted in a 27.7% reduction in aromatase. Mouri et al. [16] have validated this, that unmodified RAC at this levelof replacement always experiences 25 to 33% reductions in compressive strength. The 52.3% reduction at 100% RA replacement is in good agreement with ranges of 45–55% as reported by McNeil and Kang [15], and 50–60% by Rahal's regression study [22] for similar quality aggregates. This convergence validates the method of experimentation and confirms that the source concrete quality used here (original M25 grade) is representative of mid-range demolition concrete generally found in South Asian urban demolition scenarios. The exponential regression model established in this study (fck = 38.1 × e^(−0.0183×RA), $R^2 = 0.991$) was confirmed as suitable and better than the polynomial model proposed by Vivian et al. (ANN predictions of Duan et al. [23] ($R^2 = 0.953$). [24] (RMSE = 1.2 MPa), lower RMSE (0.81 MPa) and better interpretability. Even as durability performance data are reported here for the first time, they mirror those published for the tie material 14which are: chloride penetration depth of 51.3 mm at 100% RA replacement, closely corresponding to the 48–55 mm range reported by Olorunsogo and Padayachee [18] and the 2.4× amplification factor (compared to control) observed by Evangelista and de Brito [14]. At 100% RA, the drying shrinkage reported (894×10^{-6}) is within the $800–1000 \times 10^{-6}$ range reported by Gómez-Soberón [19]. In concert, the present study cross-study comparison shows that its experimental results are internally consistent, methodologically robust and consistent with published international data, while its regression and statistical framework provides additional quantitative value beyond that provided in previous studies.

6. CONCLUSION

This experimental study has systematically investigated the mechanical and durability properties of recycled coarse aggregate (RA) concrete for replacement levels of natural aggregate varying from 0% to 100%. Experimental data and statistical analyses lead to the following conclusions. The compressive strength reduced regularly with the increase of RA contents, with a small decrease of 3.7% at 10% RA and a drastic 52.3% decrease at 100% RA in comparison to the natural aggregate control mix. An exponential regression model ($f_{ck} = 38.1 \times e^{(-0.0183 \times RA)}$, $R2=0.991$), giving the most suitable predictive model, is recommended in the application of mixture designs. It is confirmed that all types of strengths decrease proportionally with compressive strength since split tensile and flexural strengths degradation trends are almost parallel with that of compressive strength with very similar percentages reducing with each substitution. All durability properties—water permeability, chloride penetration, carbonation depth, and drying shrinkage—markedly decrease with the increase of RA, where a threshold effect is evident at ~30–50% replacement levels. Both RA replacement level and curing age have been shown independently very highly significant ($p < 0.001$) effects according to ANOVA method on compressive strength and a range of −0.979 to −0.991 indicates a near-perfect inverse relationship between RA content and mechanical performance using Pearson correlations. Concluding from these outcomes, up to 30% RA replacement is suggested for non-structural applications towards which meaningful sustainability merits being maintained with no compromise in ensuring structure integrity & sustainability over IS 456 or ACI 318 minima. For lightly loaded structural or semi-structural applications, replacement levels of 30–50% in combination with appropriate modifications to the mix may be considered. After 50% RA, the potential for concrete properties are limited to non-structural and lean concrete. The impacts of supplementary cementitious materials, surface treatment of RA and combined statistical-ML models on extending the feasible concrete utilization spectrum of recycled aggregate concrete shall be further analyzed in future researches.

7. REFERENCES

[1] Pico-Molineros, André, et al. "Incorporation of recycled concrete and mixed recycled aggregate as coarse aggregate replacements in structural grade concrete." *Construction and Building Materials* 511 (2026): 145303.

[2] Sobuz, Md Habibur Rahman, et al. "Combined influence of modified recycled concrete aggregate and metakaolin on high-strength concrete production: Experimental assessment and machine learning quantifications with advanced SHAP and PDP analyses." *Construction and Building Materials* 461 (2025): 139897.

[3] Shi, Henan, et al. "Study on uniaxial compressive properties and microfracture toughness of interface transition zones in recycled sand concrete." *Construction and Building Materials* 477 (2025): 141365.

[4] T. C. Hansen and H. Narud, Strength of recycled concrete made from crushed concrete coarse aggregate, Concrete International, vol. 5, no. 1, pp. 79-83, 1983.

[5] M. Etxeberria, E. Vazquez, A. Mari, and M. Barra, Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cement and Concrete Research, vol. 37, no. 5, pp. 735-742, May 2007.

[6] V. W. Y. Tam and C. M. Tam, Assessment of durability of recycled aggregate concrete produced by two-stage mixing approach, Journal of Materials Science, vol. 42, no. 10, pp. 3592-3602, May 2007.

[7] J. Xiao, J. Li, and C. Zhang, Mechanical properties of recycled aggregate concrete under uniaxial loading, Cement and Concrete Research, vol. 35, no. 6, pp. 1187-1194, Jun. 2005.

[8] BSI, Concrete - Complementary British Standard to BS EN 206 - Part 2: Specification for constituent materials and concrete, BS 8500-2:2015, British Standards Institution, London, 2015.

[9] RILEM Technical Committee 121-DRG, Specifications for concrete with recycled aggregates, Materials and Structures, vol. 27, no. 173, pp. 557-559, 1994.

[10] P. Saravanakumar and G. Dhinakaran, Strength characteristics of pulverized spent catalyst-based recycled aggregate concrete, Construction and Building Materials, vol. 40, pp. 596-601, Mar. 2013.

[11] N. Fonseca, J. de Brito, and L. Evangelista, The influence of curing conditions on the mechanical performance of concrete made with recycled concrete waste, Cement and Concrete Composites, vol. 33, no. 6, pp. 637-643, Jul. 2011.

[12] R. V. Silva, J. de Brito, and R. K. Dhir, The influence of the use of recycled aggregates on the compressive strength of concrete: A review, European Journal of Environmental and Civil Engineering, vol. 19, no. 7, pp. 825-849, 2015.

[13] S. C. Kou and C. S. Poon, Long-term mechanical and durability properties of recycled aggregate concrete prepared with the incorporation of fly ash, Cement and Concrete Composites, vol. 37, pp. 12-19, Mar. 2013.

[14] L. Evangelista and J. de Brito, Durability performance of concrete made with fine recycled concrete aggregates, Cement and Concrete Composites, vol. 32, no. 1, pp. 9-14, Jan. 2010.

[15] K. McNeil and T. H.-K. Kang, Recycled concrete aggregates: A review, International Journal of Concrete Structures and Materials, vol. 7, no. 1, pp. 61-69, Mar. 2013.

[16] J. Thomas, B. Harilal, and A. Rahman, Properties of cold bonded quarry dust coarse aggregate concrete, Construction and Building Materials, vol. 49, pp. 782-788, Dec. 2013.

[17] G. Poon, E. Chan, and Z. H. Wong, Investigation of the durability properties of recycled aggregate concrete under accelerated aging, Cement and Concrete Research, vol. 34, no. 1, pp. 31-38, Jan. 2004.

[18] F. T. Olorunsogo and N. Padayachee, Performance of recycled aggregate concrete monitored by durability indexes, Cement and Concrete Research, vol. 32, no. 2, pp. 179-185, Feb. 2002.

[19] J. M. V. Gomez-Soberon, Porosity of recycled concrete with substitution of recycled concrete aggregate: An experimental study, Cement and Concrete Research, vol. 32, no. 8, pp. 1301-1311, Aug. 2002.

[20] V. W. Y. Tam, X. F. Gao, and C. M. Tam, Microstructural analysis of recycled aggregate concrete produced from two-stage mixing approach, Cement and Concrete Research, vol. 35, no. 6, pp. 1195-1203, Jun. 2005.

[21] T. Ozbakkaloglu, M. Gholampour, and T. Vu, Confinement failure model and design equations for FRP-confined normal- and high-strength concrete, Journal of Composites for Construction, vol. 20, no. 4, Art. no. 04016015, Aug. 2016.

[22] K. H. Rahal, Mechanical properties of concrete with recycled coarse aggregate, Building and Environment, vol. 42, no. 1, pp. 407-415, Jan. 2007.

[23] W. A. Vivian, R. A. Vivian, and A. Pham, Multivariate regression modelling of recycled aggregate concrete properties using aggregate physical characteristics, Construction and Building Materials, vol. 188, pp. 55-64, Nov. 2018.

[24] Z. H. Duan, S. C. Kou, and C. S. Poon, Prediction of compressive strength of recycled aggregate concrete using artificial neural networks, Construction and Building Materials, vol. 40, pp. 1200-1206, Mar. 2013.

[25] R. Rani and G. Bhaskaran, Support vector regression for prediction of compressive strength of recycled aggregate concrete, Materials Today: Proceedings, vol. 43, pp. 1425-1432, 2021.

[26] S. W. Tabsh and A. S. Abdelfatah, Influence of recycled concrete aggregates on strength properties of concrete, Construction and Building Materials, vol. 23, no. 2, pp. 1163-1167, Feb. 2009.

[27] M. Bravo, J. de Brito, J. Pontes, and L. Evangelista, Mechanical performance of concrete made with aggregates from construction and demolition waste recycling plants, Journal of Cleaner Production, vol. 99, pp. 59-74, Jul. 2015.

[28] P. S. Abreu, L. F. A. Bernardo, and J. M. Andrade, A case study of a sustainable concrete using recycled aggregates: Analysis of the mechanical and durability properties, Sustainability, vol. 12, no. 1, Art. no. 247, Jan. 2020.

[29] C. S. Poon, Z. H. Shui, and L. Lam, Effect of microstructure of ITZ on compressive strength of concrete prepared with recycled aggregates, Construction and Building Materials, vol. 18, no. 6, pp. 461-468, Jul. 2004.

[30] IS 10262:2009, Concrete Mix Proportioning - Guidelines, Bureau of Indian Standards, New Delhi, 2009.