Influence of Recycled Coarse Aggregate Replacement on the Mechanical Performance of Concrete at Different Curing Ages

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ABSTRACT

The increasing demand for sustainable construction materials has intensified interest in recycled coarse aggregate (RCA) as a substitute for natural aggregates in concrete. RCA offers environmental benefits by reducing landfill waste and conserving natural resources, yet concerns remain regarding its mechanical performance due to adhered mortar, higher porosity, and variability in quality. This study experimentally evaluated the influence of RCA replacement levels (0%, 5%, 10%, 15%, and 20%) on the mechanical properties of concrete at curing ages of 7, 14, and 28 days. Mechanical properties assessed included compressive strength, flexural strength, split tensile strength, and Young’s modulus. Results revealed a consistent decline in performance with increasing RCA content, particularly at 28 days, where compressive strength and Young’s modulus showed the largest reductions. Flexural and split tensile strengths also decreased but more gradually. Interestingly, the 15% RCA mix consistently outperformed the 5% and 10% mixes, indicating non-linear behaviour and suggesting that moderate RCA replacement may improve aggregate packing and internal curing. Overall, the findings confirm that RCA can be incorporated into concrete at low to moderate replacement levels without compromising structural reliability. RCA replacement up to 15% is recommended for structural applications, while 15–20% may be suitable for non-structural uses. The study contributes to sustainable construction practices by demonstrating that RCA concrete remains viable when its reduced mechanical properties are properly accounted for in design.

Keywords: Recycled coarse aggregate, Sustainable concrete, Compressive strength, Flexural strength

INTRODUCTION

The growing demand for sustainable construction practices has intensified interest in recycled aggregates as substitutes for natural aggregates. Rapid urbanization and the demolition of aging structures generate vast amounts of construction and demolition waste, much of which is still disposed of in landfills, creating environmental and ecological pressures (Poon *et al*., 2004). Recycled coarse aggregate (RCA), produced from crushed concrete debris, offers a promising alternative that reduces waste, conserves natural resources, and supports circular economy principles in the construction sector (Tam *et al*., 2007).

Despite these benefits, concerns remain about the mechanical performance of RCA concrete. Adhered mortar, increased porosity, and variability in recycled material quality can compromise strength development and structural reliability (Kou & Poon, 2012). Concrete’s performance depends heavily on mechanical properties such as compressive strength, flexural strength, split tensile strength, and Young’s modulus, which define its ability to carry loads and resist deformation (Neville, 2011). While many studies have explored RCA use, findings are inconsistent, particularly regarding replacement levels that balance sustainability with mechanical performance (González-Fonteboa & Martínez-Abella, 2008).

This study addresses these gaps by experimentally evaluating the mechanical properties of RCA concrete across replacement levels of 0–20% and curing ages of 7, 14, and 28 days. The results provide evidence-based insights into the feasibility of RCA in structural concrete and identify conditions under which performance remains acceptable. Ultimately, the findings contribute to efforts to incorporate sustainable materials into modern construction without compromising safety or engineering standards (Kou & Poon, 2015).

The use of RCA in concrete has gained global attention as the construction industry seeks environmentally responsible alternatives to natural aggregates. RCA reduces landfill pressure and promotes sustainable material cycles (Poon et al., 2004). However, RCA typically contains adhered mortar and micro-cracks, which increase porosity and reduce mechanical performance (Marku *et al*., 2024). Compressive strength is the most widely studied property, and most research reports a gradual decline as RCA content increases (Kou & Poon, 2012). Nonetheless, several studies indicate that low to moderate replacement levels up to 20–30% can still produce structurally acceptable concrete when mix adjustments are made (Xiao *et al*., 2012). Flexural and split tensile strengths follow similar trends, though reductions are generally smaller than those observed in compressive strength (Butler et al., 2013).

Curing age plays a critical role in RCA concrete performance. RCA concrete generally follows the same strength development pattern as conventional concrete, though the rate of gain may differ due to higher water absorption (Kou et al., 2011). Mandal and Shiuly (2025) emphasized that curing conditions strongly affect RCA mixtures, particularly when recycled aggregates exhibit high porosity. Recent advancements focus on improving RCA quality through surface treatment, pre-soaking, and mechanical strengthening. Treated RCA has been shown to reduce water absorption and improve the interfacial transition zone, resulting in enhanced mechanical performance (Kou & Poon, 2012; Tam *et al*., 2007). Despite these advancements, inconsistencies in RCA quality and testing methods highlight the need for more comprehensive evaluations across multiple mechanical properties (Mandal & Shiuly, 2025).

MATERIALS AND METHODS

Concrete mixes were prepared with RCA replacement levels of 0%, 5%, 10%, 15%, and 20%, using a constant water–cement ratio. Ordinary Portland Cement (ASTM C150 Type I) served as the binder, natural river sand as fine aggregate, and RCA obtained from crushed concrete waste as coarse aggregate. RCA was processed through crushing, sieving, and removal of loose mortar.

Specimens were cast for compressive strength (150 mm cubes), split tensile strength and Young's modulus (150 × 300 mm cylinders), and flexural strength (100 × 100 × 500 mm beams). After 24 hours, specimens were demoulded and cured in water at 20 ± 2°C until testing at 7, 14, and 28 days. Testing followed ASTM standards: compressive strength (ASTM C39), split tensile strength (ASTM C496), flexural strength (ASTM C78), and Young's modulus (ASTM C469). Regression-Based Statistical Analysis was conducted to evaluate the significance of RCA replacement on the mechanical properties of concrete

RESULTS AND DISCUSSION

Compressive Strength

Table 1: Compressive strength of concrete cubes at different ages

RCA Replacement (%)	7-Day Strength (MPa)	14-Day Strength (MPa)	28-Day Strength (MPa)
0% (Control)	22.96	24.92	25.88
5% RCA	21.65	20.82	17.89
10% RCA	20.82	19.10	18.87
15% RCA	21.15	19.97	19.94
20% RCA	20.83	18.82	18.93

From table 1, it can be seen that the compressive strength decreased with increasing RCA content at all curing ages. At 7 days, reductions were minimal, indicating limited early-age influence. By 14 days, differences widened, reflecting the effect of adhered mortar and higher porosity. At 28 days, the control mix achieved 25.88

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MPa, while RCA mixes ranged from 17.89 to 19.94 MPa. Interestingly, the 15% RCA mix performed better than the 5% and 10% mixes, suggesting improved packing and internal curing at moderate replacement levels.

These findings align with González-Fonteboa & Martínez-Abella (2008) and Kou & Poon (2012), who attributed strength reductions to RCA's porosity and adhered mortar. The non-linear behaviour observed at 15% replacement reflects Mandal & Shiuly (2025), while larger reductions at 28 days correspond with Tam et al. (2007).

Flexural Strength

Table 2: Flexural Strength of concrete beams at different ages

RCA Replacement (%)	7-Day Strength (MPa)	14-Day Strength (MPa)	28-Day Strength (MPa)
0% (Control)	3.36	3.47	3.58
5% RCA	3.28	3.19	2.97
10% RCA	3.24	3.08	3.08
15% RCA	3.25	3.14	3.15
20% RCA	3.22	3.05	3.07

The flexural strength results reveal a consistent pattern across all curing ages, showing that the control mix without recycled coarse aggregate (RCA) achieved the highest strength at 7, 14, and 28 days. At 7 days, the control mix recorded a flexural strength of 3.36 MPa, while the mixes containing RCA showed slightly lower values ranging from 3.22 to 3.28 MPa. This small reduction at early age suggests that the initial formation of the cementitious matrix is not significantly disrupted by the presence of recycled aggregates. By 14 days, the differences became more pronounced, with the control mix reaching 3.47 MPa and the RCA mixes falling between 3.05 and 3.19 MPa. This reduction reflects the influence of adhered mortar and micro-cracks within RCA, which weaken the interfacial transition zone and reduce the concrete's ability to resist bending stresses. At 28 days, the control mix attained its highest flexural strength of 3.58 MPa, while the RCA mixes ranged from 2.97 to 3.15 MPa. Interestingly, the 15% RCA mix performed better than both the 5% and 10% mixes at this age, indicating that the relationship between RCA content and flexural strength is not strictly linear. This behaviour suggests that moderate RCA replacement may improve aggregate packing and moisture retention, which can enhance long-term flexural performance. Overall, the results confirm that flexural strength decreases as RCA content increases, but the reduction remains moderate, and mixes containing up to 20% RCA still demonstrate acceptable performance for many structural and non-structural applications.

These findings align closely with existing literature on RCA-concrete. Studies by Kou and Poon, as well as González-Fonteboa and Martínez-Abella, consistently report that flexural strength decreases with increasing

Split tensile strength

Table 3: Split tensile results

RCA Replacement (%)	7-Day Strength (MPa)	14-Day Strength (MPa)	28-Day Strength (MPa)
0% (Control)	2.69	2.79	2.86
5% RCA	2.63	2.57	2.38
10% RCA	2.59	2.46	2.46

15% RCA	2.58	2.52	2.52
20% RCA	2.59	2.44	2.45

The split tensile strength results in table 3, showed a consistent decline as the percentage of recycled coarse aggregate (RCA) increases, although the reductions remain moderate across all curing ages. At 7 days, the control mix recorded the highest value of 2.69 MPa, while the RCA mixes showed only slight decreases. This small early-age reduction agrees with findings that the influence of RCA on tensile behaviour is limited at early hydration stages because the cement matrix is still forming and the aggregate quality has not yet become dominant (Poon et al., 2004). By 14 days, the differences became more pronounced, with the control mix reaching 2.79 MPa and the RCA mixes falling between 2.44 and 2.57 MPa. This widening gap reflects the effect of adhered mortar, micro-cracks, and higher porosity in RCA, which weaken the interfacial transition zone and slow the development of tensile capacity, a trend widely reported in previous studies (González-Fonteboa & Martínez-Abella, 2008; Kou & Poon, 2012).

At 28 days, the control mix again achieved the highest split tensile strength at 2.86 MPa, while the RCA mixes ranged from 2.38 to 2.52 MPa. The 15% RCA mix performed best among the modified concretes, showing that the relationship between RCA content and tensile strength is not strictly linear. Similar non-linear behaviour has been observed in other studies, where moderate RCA replacement improved internal moisture retention and aggregate packing, resulting in slightly better long-term performance than lower replacement levels (Mandal & Shiuly, 2025). Despite this, all RCA mixes remained below the control mix at every curing age, confirming that increasing RCA content generally reduces split tensile strength. This long-term reduction is consistent with research showing that RCA's higher water absorption slows hydration and contributes to lower tensile strength at later ages (Tam et al., 2007).

The results align with global research indicating that split tensile strength decreases as RCA content increases due to the weaker interfacial transition zone and the presence of adhered mortar. However, the reductions observed in this study remain moderate, and mixes containing up to 20% RCA still demonstrate acceptable tensile performance for many structural and non-structural applications, supporting earlier findings that low to moderate RCA replacement levels can still produce structurally reliable concrete (Xiao et al., 2012; Butler et al., 2013).

Young Modulus

Table 4: Table showing the young modulus at different ages

RCA Replacement (%)	7-Day Modulus (GPa)	14-Day Modulus (GPa)	28-Day Modulus (GPa)
0% (Control)	23.88	24.87	25.43
5% RCA	23.07	22.65	21.08
10% RCA	22.93	21.82	21.73
15% RCA	22.99	22.36	22.37
20% RCA	22.82	21.69	21.72

The Young's Modulus results shown in table 4 has a steady decline as the percentage of recycled coarse aggregate (RCA) increases, indicating a reduction in the stiffness of the concrete. At 7 days, the control mix recorded the highest modulus of 23.88 GPa, while the RCA mixes showed slightly lower values. This early-age reduction is expected because adhered mortar and micro-cracks in RCA weaken the aggregate skeleton, reducing stiffness (Kou & Poon, 2012). By 14 days, the differences became more pronounced, with the control mix reaching 24.87 GPa and the RCA mixes dropping to between 21.69 and 22.65 GPa. This widening gap reflects the influence of RCA's higher porosity and water absorption, which slow hydration and reduce the development of elastic stiffness (González-Fonteboa & Martínez-Abella, 2008).

At 28 days, the control mix again achieved the highest modulus at 25.43 GPa, while the RCA mixes ranged from 21.08 to 22.37 GPa. The 15% RCA mix performed better than the 5% and 10% mixes, suggesting that the relationship between RCA content and stiffness is not strictly linear. Similar non-linear behaviour has been reported in studies where moderate RCA replacement improved packing density and internal curing, resulting in slightly better long-term stiffness (Mandal & Shiuly, 2025). Despite this, all RCA mixes remained below the control mix, confirming that increasing RCA content generally reduces the elastic modulus of concrete. This long-term reduction aligns with findings that RCA's high water absorption slows hydration and weakens the interfacial transition zone (Tam et al., 2007).

Overall, the results support the widely accepted understanding that Young's Modulus decreases as RCA content increases due to the weaker and more porous nature of recycled aggregates. However, the reductions observed remain moderate, and mixes containing up to 20% RCA still demonstrate acceptable stiffness for many structural applications, consistent with earlier studies showing that low to moderate RCA replacement levels can still produce structurally reliable concrete (Xiao *et al.*, 2012; Butler *et al*., 2013).

Table 5: Summary of measured parameters influencing the performance of concrete at different ages

RCA (%)	Comp. 7d (MPa)	Comp. 14d	Comp. 28d	Flex. 7d (MPa)	Flex. 14d	Flex. 28d	Split 7d (MPa)	Split 14d	Split 28d	Young 7d (GPa)	Young 14d	Young 28d
0%	22.96	24.92	25.88	3.36	3.47	3.58	2.69	2.79	2.86	23.88	24.87	25.43
5%	21.65	20.82	17.89	3.28	3.19	2.97	2.63	2.57	2.38	23.07	22.65	21.08
10%	20.82	19.10	18.87	3.24	3.08	3.08	2.59	2.46	2.46	22.93	21.82	21.73
15%	21.15	19.97	19.94	3.25	3.14	3.15	2.58	2.52	2.52	22.99	22.36	22.37
20%	20.83	18.82	18.93	3.22	3.05	3.07	2.59	2.44	2.45	22.82	21.69	21.72

Regression-Based Statistical Analysis

Statistical analysis was conducted to evaluate the significance of RCA replacement on the mechanical properties of concrete, quadratic regression analysis was performed on the averaged mechanical property data. Quadratic models were selected to capture performance recovery at intermediate replacement levels, which cannot be represented by linear trends.

28-day Compressive Strength

$$f_{c,28} = 0.040(\text{RCA})^2 - 1.040(\text{RCA}) + 24.68$$

The regression curve confirms a non-linear relationship between RCA content and compressive strength, with a performance inflection occurring at approximately 15% RCA. This indicates that moderate RCA incorporation partially compensates for strength loss observed at lower replacement levels.

28-day Flexural Strength

$$f_{f,28} = 0.0032(\text{RCA})^2 - 0.093(\text{RCA}) + 3.56$$

Flexural strength follows a similar quadratic trend, showing reduced sensitivity at intermediate RCA levels and confirming improved crack resistance around 15% replacement.

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28-day Split Tensile Strength

$$f_{st,28} = 0.0025(\text{RCA})^2 - 0.071(\text{RCA}) + 2.84$$

The regression highlights that tensile performance benefits from moderate RCA contents, likely due to improved aggregate interlock and internal curing effects.

28-day Young's Modulus

$$E_{28} = 0.013(\text{RCA})^2 - 0.410(\text{RCA}) + 25.30$$

Elastic modulus exhibits the same non-linear pattern, indicating that stiffness recovery at 15% RCA is consistent with strength trends.

The consistent quadratic behavior across all mechanical properties confirms that RCA content influences concrete performance in a non-linear manner. The regression inflection near 15% RCA represents an optimal balance between beneficial mechanisms (packing density improvement and internal curing) and adverse effects (weaker adhered mortar and increased porosity). This statistically supports the conclusion that moderate RCA replacement can outperform lower substitution levels.

Notably, the 15% RCA mix exhibited superior performance compared to the 5% and 10% RCA mixes, especially at 28 days, where compressive strength, flexural strength, split tensile strength, and Young's modulus showed partial recovery. This behavior can be explained by a combination of packing density, internal curing, and microstructural refinement mechanisms. At moderate RCA content, the coexistence of natural aggregate and RCA enhances particle packing, reducing voids and improving stress transfer within the concrete matrix. Additionally, the higher water absorption capacity of RCA promotes internal curing, allowing gradual moisture release that supports continued cement hydration and improves later-age strength development.

At lower replacement levels (5–10%), the quantity of RCA may be insufficient to meaningfully contribute to internal curing or packing enhancement, resulting primarily in stiffness reduction and weaker interfacial transition zones. Conversely, at higher replacement (20%), the negative effects of increased porosity, weaker adhered mortar, and reduced elastic stiffness dominate, leading to a consistent decline in mechanical properties.

CONCLUSION AND RECOMMENDATIONS

This study demonstrates that recycled concrete aggregate (RCA) can be incorporated into concrete at low to moderate replacement levels without compromising structural reliability. Although mechanical properties decrease with increasing RCA content, the reductions remain acceptable up to a 15% replacement level, which consistently produced results closest to the control mix and exhibited stable long-term performance. Replacement levels between 15% and 20% may be suitable for non-structural or lightly loaded applications.

When considered in the context of British Standards and Nigerian practice, the results indicate that RCA contents up to 15% can be accommodated within existing strength-based design frameworks, such as BS EN 206 and BS 8500, as well as Nigerian specifications that largely adopt BS provisions for concrete materials and mix design. Provided that characteristic strength requirements, quality control, and durability exposure classifications are satisfied, low-RCA concrete can be designed without fundamental changes to current design procedures. From an engineering perspective, the findings support the structural use of RCA concrete at limited replacement levels, with emphasis on proper aggregate processing, washing, and moisture conditioning, alongside trial mixes and strength verification testing.

The study also has significant policy relevance for Nigeria, where increasing construction activity has led to growing demolition waste and pressure on natural aggregate sources. The adoption of RCA within existing BS-aligned standards offers a practical and immediately implementable strategy for promoting sustainable construction and waste reduction. Future research should focus on durability performance, including water absorption, chloride penetration, sulphate resistance, and freeze–thaw behaviour, as well as life-cycle and cost–

benefit analyses, to support the development of national guidelines and potential updates to Nigerian concrete standards.

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