



Original Research Article

Mechanical Properties and Durability of Concrete Composites Incorporating Recycled Concrete Aggregate and Porcelain Aggregate

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ABSTRACT

This study examines the mechanical properties and durability performance of concrete composites in which recycled concrete aggregate (RCA) and porcelain aggregate (PA) partially replace natural coarse aggregates. Five concrete mix designs were prepared: a control mix (M0) made entirely with natural coarse aggregate and four modified mixes (M1 to M4) containing varying proportions of RCA and PA. Experimental tests measured compressive strength, splitting tensile strength, flexural strength, water absorption, depth of water penetration, and sulphate resistance after 28 days of water curing. The results showed that RCA reduces mechanical performance and durability because of its elevated porosity and adhered old mortar, whereas PA improves both properties through its dense, angular, vitrified microstructure. Mix M2 (50% PA replacement) achieved the best performance among all modified mixes, with a compressive strength of 30.1 MPa, splitting tensile strength of 2.80 MPa, flexural strength of 4.85 MPa, water absorption of 3.7%, penetration depth of 17 mm, and sulphate mass loss of 2.1%, all close to the control values. Mix M3 (25% RCA and 25% PA) also delivered acceptable structural and durability characteristics, indicating effective synergy between the two recycled aggregate types. These findings confirm that porcelain waste can serve as a viable and sustainable substitute for natural aggregates, while moderate RCA incorporation remains appropriate for non-critical structural applications. The study provides useful performance-based evidence to support sustainable aggregate selection in concrete infrastructure and advances understanding of hybrid recycled aggregate systems.

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1. INTRODUCTION

The materials base of road, pavement, and structural construction is under sustained pressure as infrastructure demand grows alongside rapid urban redevelopment. Concrete production remains

fundamentally dependent on high-quality natural aggregates, yet the quarrying scale required to meet this demand continues to intensify environmental degradation, landscape disruption, and resource depletion (Mehta and Monteiro, 2014; Kisku *et al.*, 2017). In parallel, construction and demolition activities generate large volumes of waste concrete and ceramic materials, much of which retains substantial mechanical value but is nonetheless directed to landfills (Silva *et al.*, 2014). This widening imbalance between aggregate scarcity and waste material abundance has positioned recycled aggregates not merely as substitutes but as strategic components in the transition toward sustainable and circular construction systems (Tam *et al.*, 2018).

In an ideal construction scenario, concrete composites would simultaneously satisfy three conditions: reliable mechanical performance under service loads, durability under aggressive environmental exposure, and reduced environmental impact through material reuse. Conventional practice largely fulfils the first condition but falls short on the latter two. Natural aggregate extraction remains energy-intensive and environmentally intrusive, while ceramic and concrete wastes accumulate without structured high-value reuse pathways (Pacheco-Torgal and Jalali, 2010; Siddique *et al.*, 2018). Although recycled aggregates have been introduced into cementitious systems, their adoption in durability-sensitive applications remains cautious because of concerns about moisture susceptibility, permeability, and long-term performance stability, particularly for systems incorporating recycled concrete aggregates (Kou and Poon, 2012; Thomas *et al.*, 2013).

Previous research has addressed these shortcomings, though often in fragmented ways. Studies on concrete incorporating recycled concrete aggregate have shown that acceptable compressive strength can be achieved at moderate replacement levels, especially when mix design is carefully controlled or supplementary cementitious materials are introduced to improve the interfacial transition zone (Silva *et al.*, 2014; Pedro *et al.*, 2017). Separately, investigations into porcelain and ceramic waste aggregates have reported favourable mechanical strength, abrasion resistance, and chemical stability, particularly in pavement and flooring applications where surface durability is critical (Senthamarai and Devadas Manoharan, 2005; Anderson *et al.*, 2016). However, these research streams have largely evolved independently, providing limited insight into how recycled concrete aggregate and porcelain aggregate behave when combined within the same composite matrix.

The consequences of this fragmented understanding are both immediate and far-reaching. Directly, uncertainty over strength retention and durability limits the use of recycled aggregates in load-bearing or exposure-critical concrete applications. Indirectly, the construction industry remains locked into a linear resource model, continuing to exploit virgin aggregates while overlooking locally available waste materials that could meaningfully reduce environmental impact (Medina *et al.*, 2014; Gonzalez-Fonteboa *et al.*, 2018). This challenge is especially pronounced in developing regions such as Nigeria, where urban expansion generates significant volumes of demolished concrete and discarded porcelain materials, yet performance-based guidelines for their combined reuse remain scarce (Awoyera *et al.*, 2017).

A critical knowledge gap therefore persists. While the individual mechanical and durability characteristics of recycled concrete aggregate and porcelain aggregate are reasonably documented, their combined influence on the mechanical performance and durability of concrete composites has not been systematically examined. Existing studies provide limited guidance on optimal replacement ratios, permeability control, or resistance to chemical attack when these two recycled aggregate types coexist within the same matrix (Gonzalez-Fonteboa *et al.*, 2018). Moreover, microstructural explanations linking aggregate characteristics to macro-scale performance outcomes remain underdeveloped for hybrid systems that reflect real construction and demolition waste streams.

The present study addresses this gap by investigating the mechanical properties (compressive strength, splitting tensile strength, and flexural strength) and durability indicators (water absorption, depth of water penetration, and sulphate resistance) of concrete composites incorporating recycled concrete aggregate and porcelain aggregate. The research is guided by composite material theory, in which global

performance is governed by micro-scale interactions at the aggregate-binder interface. It is hypothesised that the dense, vitrified structure of porcelain aggregate may partially offset the porosity-driven weaknesses associated with recycled concrete aggregate, producing a more balanced and resilient composite when replacement levels are appropriately optimised.

2. MATERIALS AND METHODS

2.1. Research Design

This study adopted an experimental research design to systematically investigate the mechanical properties and durability performance of concrete composites incorporating recycled concrete aggregate and porcelain aggregate as partial replacements for natural coarse aggregates. An experimental approach was considered most appropriate because the research objectives required controlled manipulation of aggregate types and replacement levels, alongside direct measurement of strength and durability indicators under standardised conditions. Such a design allows causal relationships between aggregate composition and concrete performance to be established with a high degree of reliability and reproducibility, which is essential for materials-focused research intended for structural and pavement-related applications (Mehta and Monteiro, 2014).

The experimental programme was conducted in a controlled laboratory environment within the Department of Civil Engineering, Taraba State University, Jalindo, Nigeria, between August and November 2025. This setting provided access to standard testing equipment and ensured that specimen preparation, curing, and testing could be carried out in accordance with relevant British and American standards. Conducting the study within a defined time frame under stable laboratory conditions reduced the influence of external environmental variability, thereby enhancing the internal validity of the results. The focus on laboratory-scale testing aligns with established practice in recycled aggregate concrete research, where material behaviour is first evaluated under controlled conditions before field-scale application is considered (Silva *et al.*, 2014; Tam *et al.*, 2018).

2.2. Materials

Ordinary Portland cement of strength class 42.5R, complying with BS EN 197-1, was used as the primary binder throughout the study. It was sourced from a certified local supplier. River sand conforming to Zone II grading under BS 882 was used as the fine aggregate, selected to ensure good workability and consistent particle size distribution across all mixes. Natural coarse aggregate consisted of crushed granite with a nominal maximum size of 20 mm, serving as the reference material in the control mix.

The recycled concrete aggregate was obtained by crushing hardened concrete debris sourced from local demolition waste, while porcelain aggregate was produced from discarded sanitary ware and ceramic tiles. Both recycled aggregate types were processed to achieve a particle size range comparable to that of the natural coarse aggregate and were thoroughly cleaned to remove loose contaminants prior to use. This processing approach is consistent with recommendations in previous studies aimed at minimising variability and improving aggregate quality (Kisku *et al.*, 2017; Gonzalez-Fonteboa *et al.*, 2018).

Given the elevated water absorption typically associated with recycled concrete aggregate, a pre-soaking treatment was applied to both recycled concrete aggregate and porcelain aggregate for 24 hours prior to mixing. This step was necessary to reduce rapid water absorption during mixing and to improve the consistency of the fresh concrete. The decision to apply pre-treatment aligns with established findings that untreated recycled aggregates can adversely affect the effective water-to-cement ratio and, by extension, strength development and durability performance (Kou and Poon, 2012). Potable water free from impurities was used for both mixing and curing. No chemical admixtures were used in any of the five final mix compositions, to ensure that observed performance differences could be attributed solely to changes in coarse aggregate type and proportion.

2.3. Mix Design and Proportions

Concrete mix proportions were developed using the Department of Environment method, targeting a characteristic compressive strength of 25 MPa at 28 days. This strength class was selected to reflect typical requirements for structural and pavement-related concrete in developing regions. Five mix compositions were prepared comprising one control mix with natural coarse aggregate only and four modified mixes incorporating varying proportions of recycled concrete aggregate and porcelain aggregate. Cement content, fine aggregate content, and water-to-cement ratio were kept constant across all mixes so that observed performance differences could be attributed primarily to changes in coarse aggregate composition. Table 1 summarises the mix designations and coarse aggregate proportions used in this study.

Table 1: Mix designations and coarse aggregate proportions used in the study

Mix ID	Natural aggregate (%)	RCA (%)	PA (%)	Description
M0	100	0	0	Control (natural aggregate only)
M1	50	50	0	50% RCA replacement
M2	50	0	50	50% PA replacement
M3	50	25	25	25% RCA and 25% PA blend
M4	0	50	50	50% RCA and 50% PA (full replacement)

2.4. Specimen Preparation, Curing, and Testing

Batching was carried out by weight using a calibrated digital scale, and mixing was performed in a laboratory pan mixer to ensure uniform distribution of materials. Dry constituents were initially mixed before the gradual addition of water, followed by further mixing until a homogeneous consistency was achieved. Fresh concrete was cast into standard steel moulds corresponding to the requirements of each test. Cube specimens measuring 150 mm x 150 mm x 150 mm were prepared for compressive strength and water absorption tests, cylindrical specimens measuring 150 mm x 300 mm were used for splitting tensile strength tests, and beam specimens measuring 100 mm x 100 mm x 500 mm were cast for flexural strength evaluation. Compaction was achieved using a vibrating table to minimise entrapped air and ensure consistent density across specimens.

After casting, specimens were covered to prevent moisture loss and demoulded after 24 hours. All specimens were then cured in water at a temperature of 20 ± 2 degrees Celsius until the designated testing ages of 7, 14, and 28 days. For durability assessment related to chemical attack, selected specimens were exposed to a 5% sodium sulphate solution following an initial 28-day water curing period. This procedure was adopted to simulate aggressive environmental conditions commonly encountered in soils and groundwater, and is consistent with established durability testing protocols (Thomas *et al.*, 2013).

Mechanical testing included compressive strength, splitting tensile strength, and flexural strength measurements conducted in accordance with relevant ASTM and British standards. Durability performance was assessed through water absorption, permeability based on depth of water penetration under pressure, and sulphate resistance evaluated in terms of mass loss and residual compressive strength. To enhance the robustness of the findings, three specimens were tested for each parameter and mix, and results were analysed using descriptive statistics including mean values and standard deviations.

3. RESULTS AND DISCUSSION

3.1. Compressive Strength

The compressive strength results demonstrate a clear and systematic influence of aggregate type on load-bearing capacity. Table 2 presents the compressive strength values at 7, 14, and 28 days for all five

mixes. The control mix achieved a 28-day compressive strength of 32.8 MPa, establishing the benchmark for comparison. Concrete incorporating porcelain aggregate at 50% replacement attained 30.1 MPa, representing only an 8.2% reduction relative to the control, while the blended mix containing 25% RCA and 25% PA reached 29.0 MPa, corresponding to an 11.6% reduction. In contrast, mixes with higher proportions of RCA exhibited more pronounced strength reductions: the 50% RCA mix recorded 28.4 MPa (13.4% reduction) and the full replacement mix of 50% RCA plus 50% PA declined to 26.9 MPa (18.0% reduction).

Table 2: Compressive strength results at 7, 14, and 28 days for all mix compositions

Mix ID	7-day (MPa)	14-day (MPa)	28-day (MPa)	Reduction vs M0 (%)	Description
M0	22.1	28.5	32.8	-	Control
M1	19.4	24.7	28.4	13.4	50% RCA
M2	20.8	26.3	30.1	8.2	50% PA
M3	20.1	25.6	29.0	11.6	25% RCA + 25% PA
M4	18.2	23.1	26.9	18.0	50% RCA + 50% PA

These trends align closely with the established understanding of recycled concrete aggregate behaviour. The reduction in strength associated with RCA is primarily attributed to the presence of adhered old mortar, higher porosity, and weaker interfacial transition zones, which collectively reduce effective stress transfer under compression (Silva *et al.*, 2014; Kou and Poon, 2012). The relatively strong performance of PA mixes supports prior findings that vitrified ceramic materials possess high intrinsic strength, angularity, and low water absorption, which promote improved particle packing and matrix continuity (Senthamarai and Devadas Manoharan, 2005; Anderson *et al.*, 2016). The blended mix results suggest a partial compensatory mechanism in which porcelain aggregate offsets the inherent weaknesses of recycled concrete aggregate, a synergy previously proposed but rarely quantified in combined systems (Gonzalez-Fonteboa *et al.*, 2018).

3.2. Splitting Tensile Strength

Splitting tensile strength followed a pattern consistent with compressive strength but showed greater sensitivity to aggregate quality. Table 3 presents the 28-day splitting tensile strength values for all mixes. The control mix achieved 3.05 MPa, while porcelain aggregate concrete recorded 2.80 MPa and the blended RCA-PA mix achieved 2.75 MPa. These values represent reductions of less than 10%, indicating that moderate replacement with porcelain aggregate does not significantly impair tensile resistance. Conversely, the RCA-rich mixes exhibited more substantial reductions, with tensile strengths of 2.62 MPa and 2.42 MPa for the 50% RCA and full replacement mixes, respectively.

Table 3: 28-day splitting tensile strength results for all mix compositions

Mix ID	28-day f_{ct} (MPa)	Reduction vs M0 (%)	Standard deviation (MPa)	Description
M0	3.05	-	0.08	Control
M1	2.62	14.1	0.11	50% RCA
M2	2.80	8.2	0.09	50% PA
M3	2.75	9.8	0.10	25% RCA + 25% PA
M4	2.42	20.7	0.13	50% RCA + 50% PA

This behaviour reflects the governing role of the interfacial transition zone in tensile failure. Splitting tensile strength is particularly sensitive to microcracking and bond discontinuities, which are more prevalent in recycled concrete aggregate because of residual mortar and internal flaws (Dilbas *et al.*, 2014). Porcelain aggregate, by contrast, provides a dense, mechanically interlocking interface that improves crack-bridging capacity and limits early crack propagation. The results corroborate observations by Anderson *et al.* (2016), who reported comparable splitting tensile strength between porcelain aggregate concrete and conventional concrete. The findings further demonstrate that even

when RCA is present in the mix, porcelain aggregate can significantly mitigate tensile performance losses, suggesting a practical pathway to blended mixes with acceptable tensile characteristics.

3.3. Flexural Strength

Flexural strength results further reinforce the observed mechanical trends. Table 4 presents the 28-day flexural strength values for all mixes. The control mix achieved 5.25 MPa, while porcelain aggregate concrete recorded 4.85 MPa and the blended RCA-PA mix recorded 4.70 MPa. Although reductions were evident, all values remained within acceptable ranges for pavement and slab applications. The lowest flexural strength, 4.30 MPa, occurred in the full replacement mix, underscoring the cumulative effect of weaker aggregate stiffness and increased microstructural discontinuities.

Table 4: 28-day flexural strength results for all mix compositions

Mix ID	28-day fr (MPa)	Reduction vs M0 (%)	Standard Deviation (MPa)	Description
M0	5.25	-	0.12	Control
M1	4.50	14.3	0.14	50% RCA
M2	4.85	7.6	0.11	50% PA
M3	4.70	10.5	0.13	25% RCA + 25% PA
M4	4.30	18.1	0.15	50% RCA + 50% PA

Flexural behaviour is governed by both tensile capacity and aggregate stiffness. The relatively strong performance of porcelain aggregate mixes aligns with prior studies indicating improved bending resistance due to the ceramic aggregate's rigidity and angular shape (Senthamarai and Devadas Manoharan, 2005; Torkittikul and Chaipanich, 2010). The blended mix results again demonstrate a balanced response, supporting the theoretical premise that hybrid aggregate systems can achieve acceptable flexural performance when aggregate gradation and replacement ratios are appropriately optimised.

3.4. Durability Performance

Durability results reveal a clear divergence between the effects of recycled concrete aggregate and porcelain aggregate. Table 5 presents the water absorption, depth of water penetration, and sulphate mass loss results for all five mixes.

Table 5: Durability test results at 28 days

Mix ID	Water absorption (%)	Penetration depth (mm)	Sulphate mass loss (%)	Classification
M0 (Control)	3.2	13	1.4	Excellent
M1 (50% RCA)	5.4	28	3.8	Marginal
M2 (50% PA)	3.7	17	2.1	Good
M3 (25% RCA + 25% PA)	4.3	22	2.9	Acceptable
M4 (50% RCA + 50% PA)	6.1	34	4.6	Poor

Water absorption increased markedly with RCA content, reaching 5.4% in the 50% RCA mix and 6.1% in the full replacement mix, while porcelain aggregate concrete exhibited a low absorption value of 3.7%, close to the control value of 3.2%. Similar trends were observed for permeability and sulphate resistance. The 50% PA mix had a penetration depth of 17 mm and a sulphate mass loss of 2.1%, whereas the full replacement mix recorded 34 mm and 4.6%, respectively. These findings are consistent with the dense, low-porosity microstructure of porcelain aggregate and its chemical inertness, which limit moisture ingress and sulphate diffusion (Siddique *et al.*, 2018; Medina *et al.*, 2014). The blended mix M3 achieved intermediate durability values, with a water absorption of 4.3%, penetration depth of 22 mm, and sulphate mass loss of 2.9%, all within acceptable limits for structural applications in

moderately aggressive environments. This outcome supports the proposition that PA can partially compensate for the durability limitations of RCA in blended systems.

3.5. Theoretical Implications and Composite Behaviour

From a theoretical standpoint, the results support composite material theory, which holds that global performance is governed by micro-scale interfacial interactions. Porcelain aggregate enhances matrix continuity and offsets the porous interfacial zones introduced by recycled concrete aggregate, leading to improved mechanical and durability outcomes in blended systems. The interfacial transition zone between the cement paste and RCA particles is typically weaker and more porous than that formed with natural or porcelain aggregates, due to the residual mortar layer that prevents intimate contact between fresh paste and the underlying aggregate. When PA is introduced alongside RCA, the dense ceramic particles occupy void-forming sites within the matrix and improve overall packing density, which reduces the proportion of weak interfacial zones in the composite. This mechanism explains why the blended mixes M2 and M3 consistently outperformed the RCA-only mix M1 across all tested parameters.

4. CONCLUSION

This study investigated the mechanical properties and durability performance of concrete composites incorporating recycled concrete aggregate and porcelain aggregate as partial replacements for natural coarse aggregates, with the objective of evaluating their suitability for sustainable structural applications. Based on the experimental findings, the following conclusions are drawn.

Porcelain aggregate concrete exhibited mechanical performance close to that of the control mix across all three strength parameters, with reductions of less than 10% for compressive, tensile, and flexural strength. Mixes with higher proportions of recycled concrete aggregate experienced more pronounced reductions, particularly in tensile and flexural strength, attributable to weaker interfacial transition zones and greater microcracking. Blended mixtures combining RCA and PA achieved a balanced performance, demonstrating that porcelain aggregate can effectively mitigate the mechanical limitations associated with recycled concrete aggregate, provided replacement levels are appropriately controlled.

Durability assessment showed that porcelain aggregate significantly improved resistance to water absorption, water penetration, and sulphate attack, owing to its dense, low-porosity, and chemically inert structure. In contrast, increasing RCA content led to higher moisture ingress and reduced chemical resistance, reflecting the influence of residual mortar and weaker interfacial transition zones. These findings align with composite material theory and confirm that micro-scale interfacial characteristics govern macro-scale mechanical and durability behaviour.

The study therefore advances theoretical understanding by demonstrating that hybrid recycled aggregate systems can be engineered to achieve acceptable performance through appropriate aggregate selection and proportioning. Mix M2 (50% PA) is recommended for applications requiring durability close to that of conventional concrete, while Mix M3 (25% RCA and 25% PA) offers a practical compromise between sustainability objectives and structural adequacy for moderate-exposure conditions.

While the experimental programme was limited to laboratory-scale testing and short-term curing durations, the findings provide a strong foundation for future research. Further studies should focus on long-term durability, microstructural characterisation using scanning electron microscopy and X-ray diffraction, field-scale validation under realistic service conditions, and the influence of supplementary cementitious materials such as fly ash and silica fume on hybrid RCA and PA concrete. Overall, this research contributes substantial evidence that combining recycled concrete aggregate with porcelain aggregate offers a viable pathway for producing durable, structurally sound, and environmentally responsible concrete, thereby supporting the transition toward circular construction practice..

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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