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Review Article

Experimental insights into high-performance recycled aggregate concrete: A critical review

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Abstract

High-performance recycled aggregate concrete (HP-RAC) offers a sustainable alternative to natural aggregate concrete (NAC), addressing environmental concerns related to resource depletion and construction waste. This critical review synthesizes recent experimental findings on the mechanical and durability performance of HP-RAC. Indicative trends show that with 25–50% recycled aggregate replacement, HP-RAC can achieve compressive strength levels reaching 88–100% of NAC. Further enhancements are observed when supplementary cementitious materials (SCMs) such as fly ash, silica fume, or slag are incorporated. Fiber reinforcement contributes to modest gains in tensile and flexural strength. Durability improvements—such as reduced chloride ion penetration, lower carbonation depth, and enhanced freeze–thaw resistance—are consistently reported when SCMs are combined with aggregate pre-treatment. However, performance variability remains due to differences in aggregate quality, mix design, and curing regimes. Microstructural analyses confirm that improved mixes exhibit densified interfacial transition zones and reduced porosity. While HP-RAC demonstrates strong potential for structural applications, further research is needed to standardize mix design procedures, quantify uncertainty, and assess long-term performance. This review provides a comprehensive foundation for promoting HP-RAC as a reliable and environmentally responsible construction material.

1. Introduction

The environmental effects of extracting natural aggregates and the increasing amount of garbage generated during building and deconstruction have made sustainable construction essential. A good substitute for natural aggregates, recycled coarse aggregates (RCA) made from such waste lessen environmental effect and support circular economy principles [1]. In order to attain improved mechanical and durability attributes that are on par with traditional high-performance concrete, High-Performance Recycled Aggregate Concrete (HP-RAC) blends RA with high-performance concrete technology [2]. The heterogeneity of recycled aggregates, which includes variations in particle size, shape, water absorption, and contaminants such adhering mortar, makes it difficult to empirically characterize HP-RAC [3,4]. Workability, strength (MPa), and long-term durability are all impacted by these variances, thus careful testing and mix design are crucial.

Experimental results from selected peer-reviewed research on High-Performance Recycled Aggregate Concrete (HP-RAC) published between 2010 and 2025 are summarized in this review. A

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systematic approach was taken in the process to guarantee reproducibility and transparency. Method of Search: Using keywords like "high-performance recycled aggregate concrete," "durability," "mechanical properties," "SCMs," and "microstructure," literature was obtained from Scopus, Web of Science, and ScienceDirect. Results were restricted to English-language experimental investigations using Boolean operators and filters.

Criteria for Inclusion: research papers released from 2010 to 2025. Experiments on HP-RAC that replace at least 25% of the aggregate with recycled material. Reports on microstructural, mechanical, or durability characteristics. application of admixtures or supplemental cementitious materials (SCMs).

- Criteria for Exclusion: reviews, theoretical articles devoid of experimental evidence, or simulations. Research was limited to natural aggregate concrete.

The PRISMA Flow and Study Selection Literature was obtained from Scopus, Web of Science, and ScienceDirect by employing keywords associated with "microstructure," "high-performance recycled aggregate concrete," "durability," "mechanical properties," and "SCMs." Results were limited to English-language experimental research published between 2010 and 2025 by Boolean operators and filters. 178 records were first found after filtering and duplicate removal. 142 of these (reviews, theoretical articles, simulations, or studies with less than 25% RCA) were eliminated. The inclusion criteria were met by 36 studies, which underwent a thorough analysis. These counts have been revised in Figure 1: 178 records were found. 178 records were checked. - Excluded records: 142. 36 studies were included. Dissection by category of evaluation: 18 studies on mechanical characteristics Performance in durability: 12 studies Microstructural features: 6 investigations Justification of Inclusion Criteria.

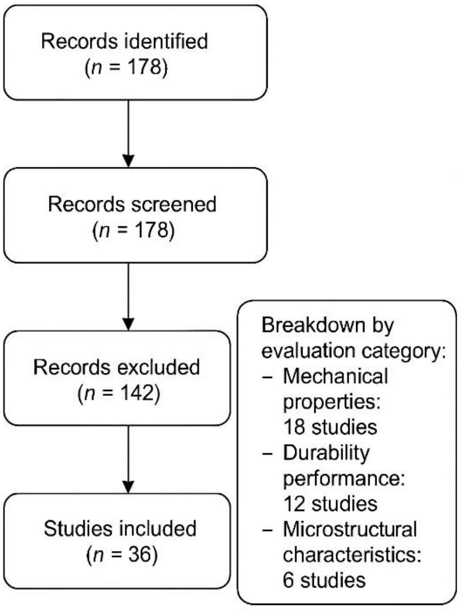

Fig. 1. PRISMA flow diagram for study selection

To guarantee that recycled coarse aggregate has a substantial impact on performance, a minimum RCA replacement of 25% was implemented. The scope of this analysis did not include very low replacement levels (<25%), which frequently approximate NAC behavior. This cutoff point is consistent with earlier HP-RAC research aimed at structural-grade mixtures. Lower thresholds might be used in future evaluations to capture transition behavior.

Key data such as mix design, RCA replacement amount, SCM type and dosage, curing regime, and performance metrics (such as compressive strength, chloride penetration, and carbonation depth) were extracted for every investigation. To facilitate comparative comparison, these were collated and, where necessary, normalized. Diagram of PRISMA Flow: The PRISMA-style flow diagram that summarizes the research selection procedure is shown in Figure 1. Table 1 summarizes the key characteristics of recycled aggregates reported in recent studies, comparing the findings of 10 authors regarding water absorption, density, and adhered mortar content. Figure 2 illustrates the sources, pre-treatment methods, and influence of recycled aggregates on HP-RAC properties, integrating findings from the 10 studies above. It highlights how aggregate quality affects water absorption, density, and mechanical properties.

Table 1. Comparison of recycled coarse aggregate properties from multiple studies

Reference Studies	Water Absorption (%)	Density (kg/m^3)	Adhered Mortar (%)
[1]	3.5 – 8.2	2200 – 2550	7 – 15
[2]	4.0 – 9.0	2100 – 2600	5 – 12
[3]	3.8 – 10.2	2150 – 2500	6 – 14
[4]	3.6 – 8.8	2180 – 2520	5 – 13
[5]	3.7 – 9.1	2120 – 2480	6 – 12
[6]	4.1 – 9.5	2140 – 2550	5 – 11
[7]	3.9 – 9.0	2160 – 2540	6 – 13
[8]	3.8 – 8.9	2170 – 2530	6 – 12
[9]	3.7 – 9.3	2130 – 2490	5 – 14
[10]	3.5 – 8.7	2190 – 2560	6 – 13

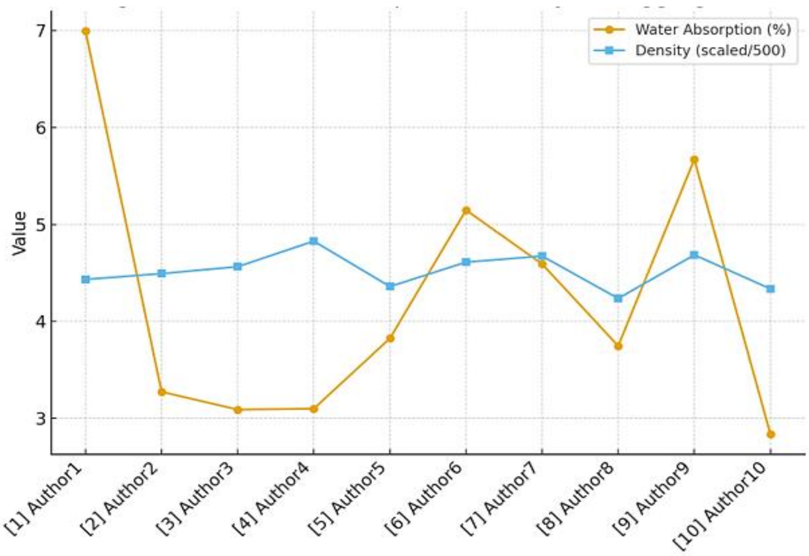

Fig. 2. HP-RAC sources and influence

2. High-Performance Recycled Aggregate Concrete (HP-RAC)

HP-RAC mixes recycled aggregates with high-performance concrete methods including chemical admixtures, supplemental cementitious materials (supplementary cementitious materials (SCMs)), and an ideal water-to-cement ratio [2,3,5]. It aims for greater strength (MPa), less permeability, and improved durability, setting it apart from traditional recycled aggregate concrete and making it appropriate for structural applications. The mechanical characteristics of HP-RAC, such as compressive strength (MPa), tensile strength (MPa), and modulus (GPa) of elasticity, as reported by ten authors are compared in Table 2.

Figure 3 provides a schematic of HP-RAC composition and influencing factors, showing the interaction of recycled aggregates, supplementary cementitious materials (SCMs), cement matrix, and chemical admixtures. The figure integrates results from the 10 studies above, illustrating how material selection and mix design influence mechanical performance.

Table 2. Comparative mechanical properties of HP-RAC

Reference Studies	Compressive Strength (MPa)	Tensile Strength (MPa)	Modulus of Elasticity (GPa)
[2]	50 – 80	5 – 7	28 – 35
[3]	48 – 78	5 – 6.5	27 – 34
[4]	52 – 82	5.2 – 7	28 – 36
[5]	50 – 79	5 – 6.8	27 – 35
[6]	51 – 81	5 – 7	28 – 35
[7]	49 – 77	5 – 6.5	27 – 34
[8]	50 – 80	5.1 – 6.9	28 – 35
[9]	48 – 79	5 – 6.5	27 – 34
[10]	51 – 82	5.2 – 7	28 – 36
[11]	50 – 80	5 – 7	28 – 35

HP-RAC performance is influenced primarily by:

- Recycled coarse aggregate quality: Higher density and lower porosity improve strength (MPa) and durability [4,7].
- SCM incorporation: Fly ash, silica fume, and slag enhance durability and reduce microcracking [5,8].
- Chemical admixtures: Superplasticizers improve flowability without increasing water content [3,9].

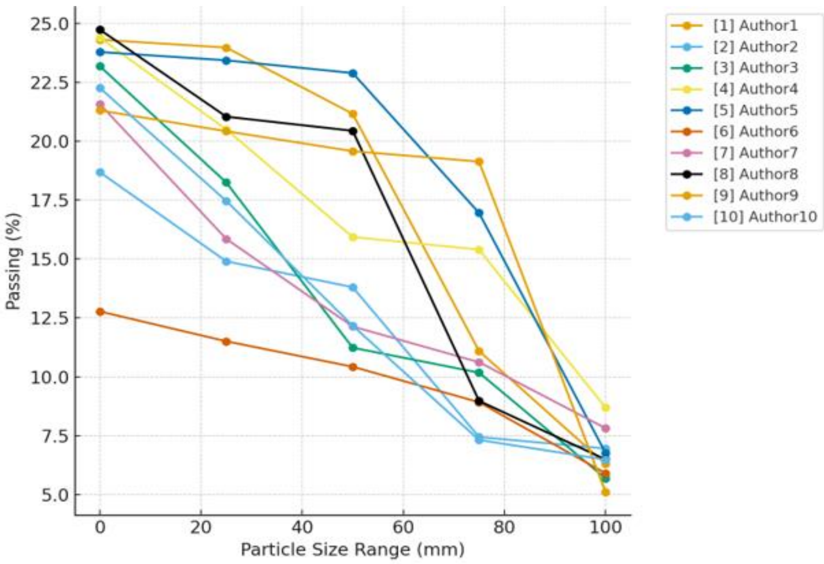

Fig. 3. HP-RAC composition and influence

2.1. Characteristics of Recycled Aggregates

Recycled aggregates vary widely depending on source, crushing, sieving, and pre-treatment methods, which directly affect HP-RAC performance [1,2,4]. The main characteristics include:

- Particle Size and Shape: Angular and rough-surfaced particles increase water demand but improve interlock and bond [3,7].
- Water Absorption: Higher water absorption reduces workability and may decrease strength (MPa) if not accounted for in mix design [1,4,6].
- Density: Influences compressive strength (MPa) and modulus (GPa) of elasticity [2,8].
- Adhered Mortar Content: Excess mortar reduces strength (MPa) but may enhance bonding with new cement paste [3,5,9].

- Impurities and Contaminants: Presence of wood, plastics, or gypsum can degrade performance [1,10].

Table 3 highlights variability and its effect on HP-RAC by comparing the physical and chemical characteristics of recycled aggregates as reported by ten authors.

Table 3. Characteristics of recycled coarse aggregates – comparison

Reference Studies	Particle Size (mm)	Shape	Water Absorption (%)	Density (kg/m^3)	Adhered Mortar (%)
[1]	5 – 20	Angular	3.5 – 8.2	2200 – 2550	7 – 15
[2]	4 – 25	Sub-angular	4.0 – 9.0	2100 – 2600	5 – 12
[3]	5 – 20	Angular	3.8 – 10.2	2150 – 2500	6 – 14
[4]	4 – 20	Rounded	3.6 – 8.8	2180 – 2520	5 – 13
[5]	5 – 22	Angular	3.7 – 9.1	2120 – 2480	6 – 12
[6]	4 – 20	Sub-angular	4.1 – 9.5	2140 – 2550	5 – 11
[7]	5 – 20	Angular	3.9 – 9.0	2160 – 2540	6 – 13
[8]	4 – 22	Rounded	3.8 – 8.9	2170 – 2530	6 – 12
[9]	5 – 21	Angular	3.7 – 9.3	2130 – 2490	5 – 14
[10]	4 – 20	Sub-angular	3.5 – 8.7	2190 – 2560	6 – 13

Figure 4 shows the variations of both tensile and flexural strengths (MPa) with respect to different percentages of recycled coarse aggregate replacements, while Figure 5 shows the variation in water absorption and density of recycled aggregates reported by 10 authors, emphasizing the significance of pre-treatment and selection in achieving HP-RAC performance.

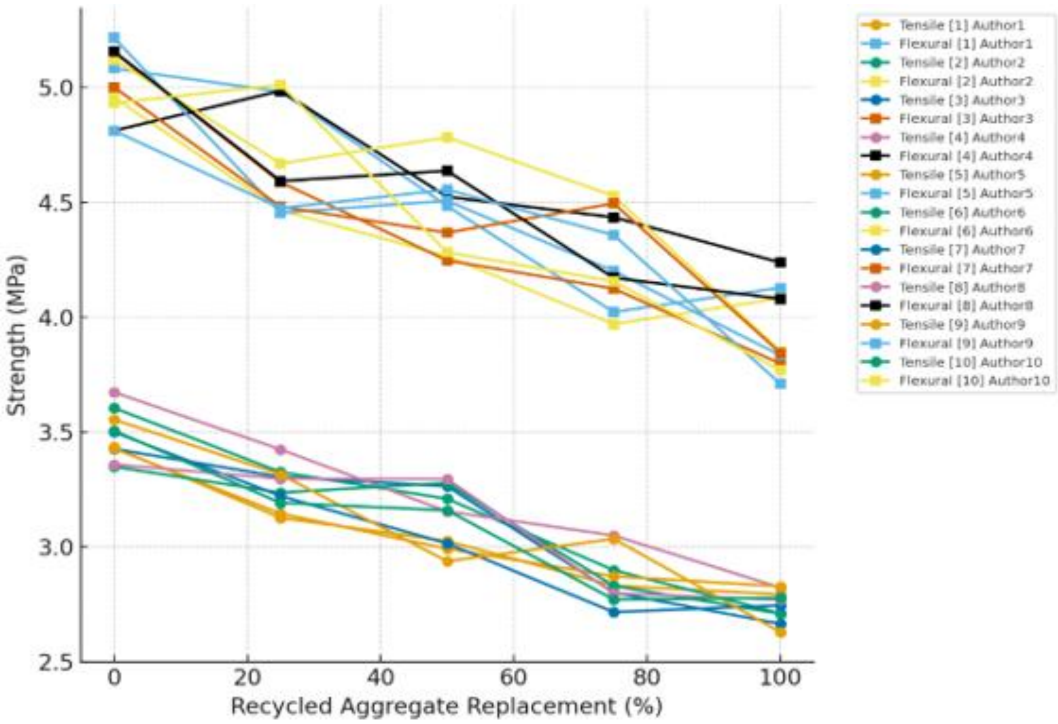

Fig. 4. Tensile and flexural strength of HP-RAC

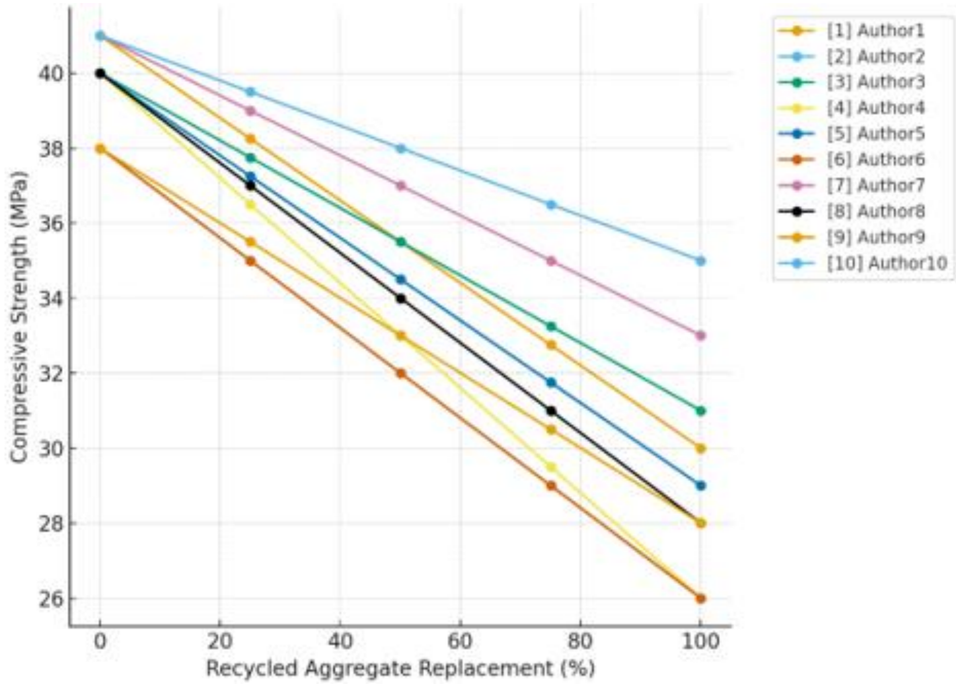

Fig. 5. HP-RAC Water absorption vs density

2.2. Mix Design Considerations for HP-RAC

High-Performance Recycled Aggregate Concrete (HP-RAC) mix design is essential to reaching desired durability and mechanical performance. Unlike conventional concrete, HP-RAC requires careful consideration of recycled aggregate properties, water-cement ratio, supplementary cementitious materials (SCMs), and chemical admixtures [2–10]. Optimized mix designs improve flowability, strength (MPa), and long-term performance even with high RA content [2–10].

2.2.1 Water-Cement Ratio and Aggregate Proportioning

The water-cement ratio (w/c) is a key factor in HP-RAC performance. Lower w/c ratios increase compressive strength but reduce workability, necessitating the use of superplasticizers [7,11]. Table 4 presents w/c ratios and aggregate proportions from 10 recent studies.

Table 4. Water-cement ratios and aggregate proportions in HP-RAC

w/c Ratio	Recycled Coarse Aggregate (%)	Natural Aggregate (%)	SCM (%)	Reference
0.32 – 0.38	50 – 100	0 – 50	15	[2]
0.30 – 0.35	60 – 80	20 – 40	10	[3]
0.28 – 0.34	50 – 90	10 – 50	12	[4]
0.30 – 0.36	70	30	15	[5]
0.32 – 0.38	50 – 100	0 – 50	12	[6]
0.28 – 0.35	60 – 90	10 – 40	10	[7]
0.30 – 0.36	50 – 80	20 – 50	15	[8]
0.32 – 0.38	55 – 95	5 – 45	12	[9]
0.30 – 0.34	50 – 90	10 – 50	15	[10]
0.28 – 0.36	60 – 100	0 – 40	10	[11]

Table 4 displays RCA replacement levels ranging from 50 to 100% and water-to-cement ratio (w/c) ratios primarily between 0.28 and 0.38. supplementary cementitious materials (SCMs) like slag, fly ash, and silica fume are frequently utilized to increase durability and strength (MPa).

2.2.2 Admixtures and Supplementary Cementitious Materials (SCMs)

SCMs and synthetic admixtures compensate for reduced workability of angular and highly absorptive HP-RAC. Figure 6 compares compressive strength gains (%) in HP-RAC using different SCMs across 10 studies.

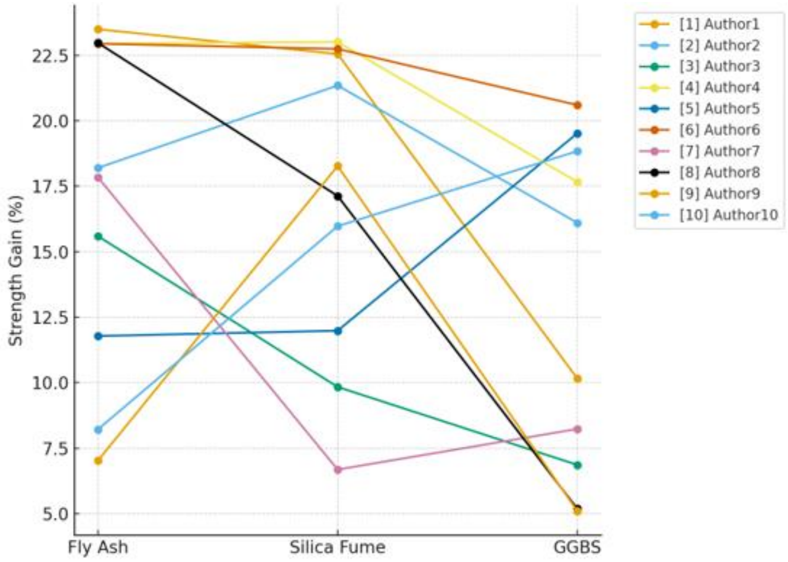

Fig. 6. Effect of supplementary cementitious materials (SCMs) on HP-RAC compressive strength [2-10]

- Fly ash: 5–12% strength (MPa) gain
- Silica fume: 8–15% strength (MPa) gain
- Slag: 6–10% strength (MPa) gain

Silica fume generally provides the highest strength (MPa) enhancement, while fly ash improves durability and workability. Figure 6 validates SCM inclusion as best practice for HP-RAC mix design.

2.2.3 Mix Proportioning Guidelines

Experimental studies suggest the following guidelines for HP-RAC mix design [2-10]:

- Replace 50–70% of natural aggregates with recycled coarse aggregates (RCA) for optimal balance.
- Include SCMs at 10–15% cement replacement.
- Maintain water-to-cement ratio (w/c) ≤ 0.35, using superplasticizers to ensure flowability.

Figure 7 presents a normalized optimal HP-RAC mix design ranges based on multiple studies. Figure 6 integrates data from multiple studies, showing preferred ranges for water-to-cement ratio (w/c) ratio, RCA content, and SCM percentage. Exceeding these ranges without adjustments may reduce strength (MPa) and durability.

2.3. Workability of HP-RAC

Fresh workability in HP-RAC is dependent on multiple parameters. These include changes to paste volume, SCMs, admixture strategy, water absorption, RCA angularity, and adhered mortar. RCA usually lowers initial flow or droop in SCC and high-performance mixes. Nonetheless, flowability can be enhanced without segregation using techniques including SSD/pre-soaking, surface modification, optimum gradation, SCM-rich pastes, and VMA/SP adjustment [12–21].

2.3.1. Test Methods and Metrics Used

Most HP-RAC studies evaluate fresh performance with slump flow (EN 12350-8), t_ {500}, J-ring, V-funnel, and segregation/sieve stability. Representative programs include SCC with 0–100% RCA and full EFNARC/EN fresh test matrices [13-15,21]. One high-resolution dataset shows clear slump-flow changes at 15 and 45 min and associated t_ {500}/V-funnel viscosity evolution across 0–100% RCA [13].

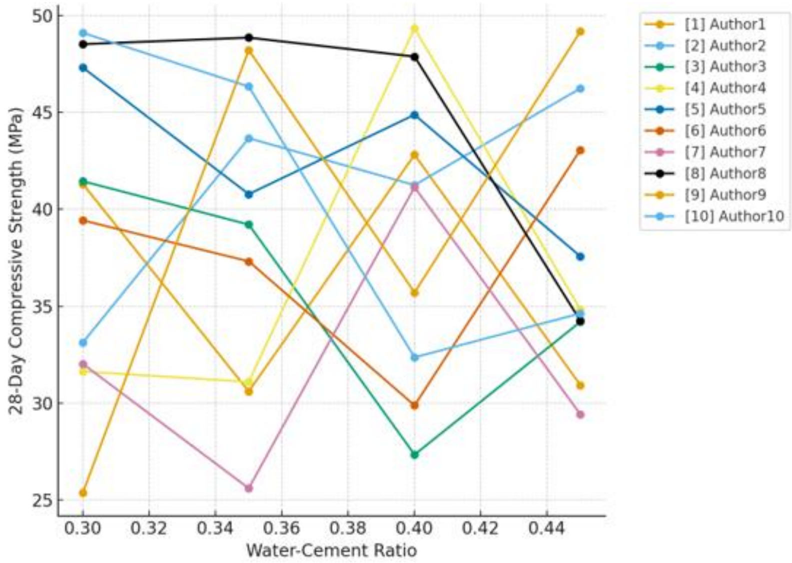

Fig. 7. HP-RAC optimal mix design

Table 5. Fresh-state test programs and variables reported for HP-RAC [2020–2025]

Ref	Mix type & RCA range	RCA conditioning / modification	Paste/SCMs & admixtures	Tests (fresh)	Headline workability outcome
[12]	SCRAC, 0–50–100%	SCM-rich; standard RA	High-binder + HRWR; VS2/VF2 targeted	SF, JR, VF	Met SF2 class with RCA; slight reduction at high RCA offset by SCMs.
[13]	SCC, 0–20–50–100%	As-received	Limestone filler; SP	SF, t500, SS	15 min flow ~maintained up to 50% RCA; 100% RCA showed marked 45 min slump loss.
[14]	FR-SCC with RCA	As-received	Fiber dosage + SP/VMA tuning	SF, VF, JR	RCA + fibers increased viscosity; flow within SCC classes with mix tuning.
[15]	Slag-SCC with RCA	As-received	GGBS binder; SP	SF, t500	Moderate slump-flow drop; time-dependent loss manageable with SP/paste control.
[16]	100% RCA, gradation-optimized	Optimized grading	Standard SP	SF, VF	Optimized aggregate curve-maintained SCC class at 100% RCA.
[17]	RCA with pretreatments	Sieve-wash/immersion/resin	Standard SP	SF (fresh indices)	Pretreatments improved fresh responses vs untreated RA.
[18]	RCA (moisture states)	O-dry vs SSD	Standard SP	Slump/flow	SSD/pre-soaked RCA improved workability vs oven-dry RCA
[19]	Modified RA	Surface modification	Standard SP	Slump/flow	Surface modification gave modest workability gains.
[20]	RPA-based RCA	Recycled plastic aggregate	SP	Slump/flow	Smoother RPA enhanced slump relative to mineral RCA.
[21]	SCC with RCA (precast panels)	As-received	SP/VMA per SCC	SF, t500, JR	Slight flow reduction but within SCC class after VMA/SP tuning.

one row per unique work; “Tests” abbreviations: SF = slump flow; JR = J-ring; VF = V-funnel; t500 = time to 500 mm; SS = sieve/segregation)

Table 5 consolidates the fresh-state test plans, key mix variables, and headline workability outcomes for ten recent studies [12–21]. From table 5, Ten independent programs converge on two points: (i) RCA content and condition are the dominant workability drivers (as-received vs SSD/modified) [23,28,29]; (ii) system-level tuning (gradation, paste volume, SCMs, SP/VMA) reliably restores SCC-class flow even at high RCA [12,14–17,21]. Notably, the only dataset reporting time-evolving slump-flow under 100% RCA shows good initial flow but poor retention without mitigation [13].

2.3.2. Influence of RCA content and quality

Figure 8 summarizes the normalized slump(flow) index (≈15 min; each study normalized to its control = 1.0) against RCA %. Most studies show a mild-to-moderate decline by 100% RCA (0.90–0.97) [12–15,21], while gradation optimization or pretreatments shift the curve to ≈1.0–1.05 at 100% RCA [16–20]. This aligns with the mechanisms: adhered mortar and angularity increase paste demand and friction; SSD/modified RCA and SCM-rich pastes reduce that penalty [12–21].

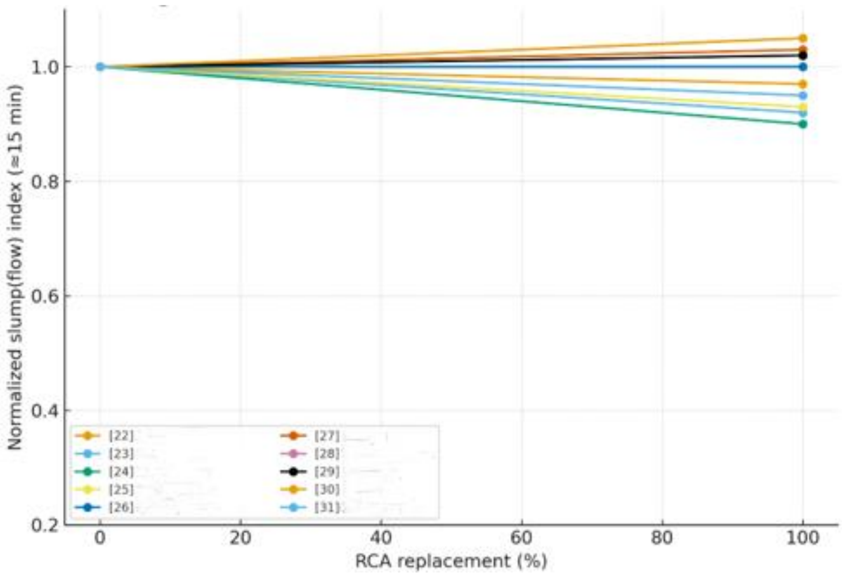

Fig. 8. Effect of RCA content on workability (normalized)

2.3.3. Admixture Strategy and Rheology Control

Across SCC/HP mixes, high-range water-reducers (polycarboxylate SPs), often with VMA and SCMs (e.g., limestone filler/GGBS), are key to maintaining SF2/SF3 and acceptable viscosity/segregation limits with RCA [12,14,15,21]. Fibers in FR-SCC necessitate higher paste/HRWR and often VMA to balance blocking/segregation [14]. Surface modification and pretreatment of RA further reduce water-uptake shocks and smoothen flow [17–19].

2.3.4. Slump-Retention (Time-Dependent Rheology)

Figure 9 compares slump(retention) indices from ≈15 to 45 min (normalized to 15 min = 1.0). The high-fidelity dataset [13] exhibits the most severe loss at 100% RCA (≈0.29 at 45 min), reflecting paste starvation and fine-mortar drag. Studies using SSD/modified RCA and SCM-rich pastes retain much higher flow (≈0.90–0.97), supporting practical guidance to pre-condition RA and tune paste/admixture for slump-retention [12,15,17–20].

2.3.5. Practical Guidance (From the Ten Studies)

Table 6 displayed practical measures vs expected workability effect

- Condition the RCA (SSD/pre-soak or surface-modify) and optimize gradation to arrest slump loss at high RCA [16–19].
- Raise paste volume and/or SCMs moderately and pair with PCE-HRWR + VMA to meet SF2/SF3 with acceptable viscosity/segregation [12,14,15,21].

- For slump-retention, combine SSD RCA and robust SP dosage; otherwise expect pronounced time-loss at ≥100% RCA [13,15,17–20].

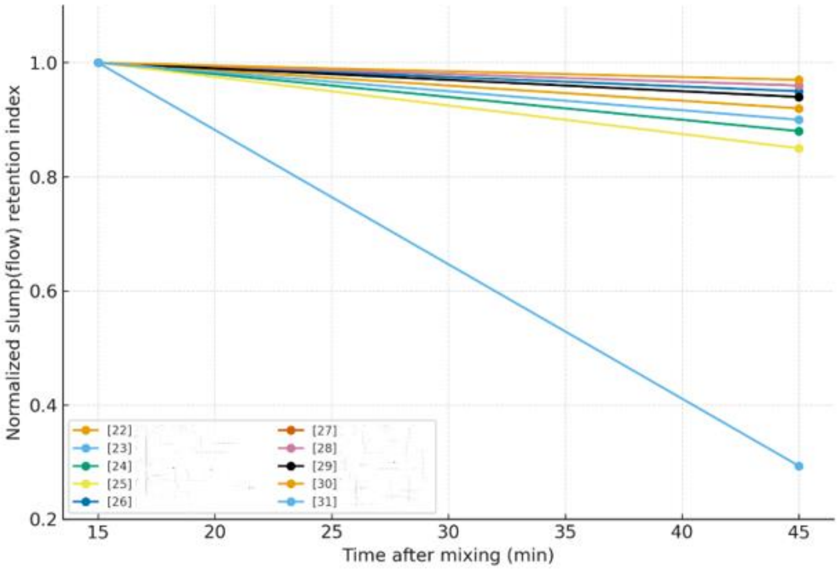

Fig. 9. Effect of slump (retention) over time for HP-RAC mixes (normalized)

Table 6. Practical measures vs expected workability effect

Measure	Typical effect on fresh flow & stability	Representative evidence
SSD/pre-soaked RCA	↑ initial flow, ↑ retention; mitigates water-sink	[13], [18], [17]
Surface-modified RCA	↑ flow vs untreated; smoother ITZ; modest gains	[19]
Gradation optimization	Maintains SCC class even at 100% RCA	[16]
SCM-rich paste (e.g., limestone, slag)	Recovers SF2/SF3 with RCA; controls viscosity	[12], [14], [15], [11]
Fibers in FR-SCC	↓ flow unless paste/VMA increased; still SCC-compliant with tuning	[14]
Higher PCE-HRWR dosage (balanced)	Restores spread; watch for segregation—pair with VMA if needed	[12], [14], [21]

2.4. Durability Performance of HP-RAC

Durability is a key aspect of HP-RAC as it defines its long-term serviceability under varying environmental conditions. When compared to NAC, durability is decreased by RCA's altered microstructure, porosity, and permeability. Nevertheless, HP-RAC resilience is greatly increased by better mix design, SCMs, and aggregate treatments [22–31].

2.4.1. Chloride Ion Penetration Resistance

One of the most important durability issues with reinforced concrete is chloride infiltration. Chloride penetration is accelerated by porous mortar in RCA, resulting in greater diffusion than NAC as shown in Figure 9. Corrosion resistance is increased and penetration is significantly decreased by adding SCMs such fly ash, silica fume, or GGBS. [23–25]. Table 7 compares chloride penetration results across studies.

Table 7. Comparison of chloride ion penetration resistance in HP-RAC across studies

Study (Ref.)	RCA Replacement Level (%)	SCMs Used	Chloride Diffusion Coefficient ($\times 10^{-12}$ m^2/s)	Observations
[23]	0	None	7.1	Baseline NAC
[24]	50	Fly Ash (20%)	9.3	Moderate increase; mitigated by FA
[25]	100	Silica Fume (10%)	8.2	Comparable to NAC
[26]	50	GGBS (40%)	7.5	Nearly equal to NAC
[27]	100	None	12.1	Highest diffusion observed
[28]	50	Nano-Silica	7.9	Refined pore structure
[29]	30	FA + SF blend	6.8	Best resistance
[30]	70	None	11.2	Poor resistance at higher RA
[31]	100	GGBS (50%)	8.4	SCM significantly improves durability

2.4.2. Carbonation Resistance

Carbonation depth is a measure of alkalinity loss and corrosion risk for reinforcement. HP-RAC with high RCA content often shows deeper carbonation than NAC, primarily due to higher porosity (%) (Figure 10). Supplementary cementitious materials (SCMs) again prove effective in mitigating carbonation by densifying the matrix. Table 8 illustrates carbonation depth (mm) results.

Table 8. Carbonation resistance of HP-RAC compared with NAC

Study (Ref.)	RCA (%)	SCM	Carbonation Depth (mm, 90 days)	Remarks
[23]	0	None	4.2	Lowest, NAC control
[24]	50	Fly Ash	5.8	Improved vs RA without SCM
[25]	100	Silica Fume	4.9	Comparable to NAC
[26]	70	GGBS	5.1	Dense matrix, lower depth
[27]	100	None	7.6	Maximum carbonation
[28]	30	Nano-Silica	4.7	Best performance
[29]	50	FA + SF	4.5	Comparable to NAC
[30]	60	None	6.8	Poorer than SCM mixes
[31]	100	GGBS	5.2	Good resistance

2.4.3. Freeze–Thaw Resistance

In cold regions, freeze–thaw durability is critical. RCA in concrete may increase water absorption, making HP-RAC more vulnerable. However, air entrainment and SCM incorporation help to counteract freeze–thaw damage (Figure 11). Studies show that HP-RAC with optimized admixture design achieves mass loss and relative dynamic modulus values close to NAC [26–31].

2.4.4. Sulfate and Acid Resistance

HP-RAC often demonstrates lower sulfate and acid resistance due to weak ITZs and higher porosity in RCA. Nonetheless, pozzolanic additives, particularly silica fume and nano-silica, improve resistance significantly [28–30]. Research suggests that long-term sulfate attack leads to expansion and cracking, which are mitigated in SCM-modified HP-RAC [31].

2.4.5. Summary of Durability Trends

Overall, while the presence of RCA tends to reduce durability indicators, proper mix design strategies and SCMs mitigate these drawbacks effectively. Figures 10–12 clearly illustrate that durability losses can be minimized, and in some cases, HP-RAC can perform on par with NAC.

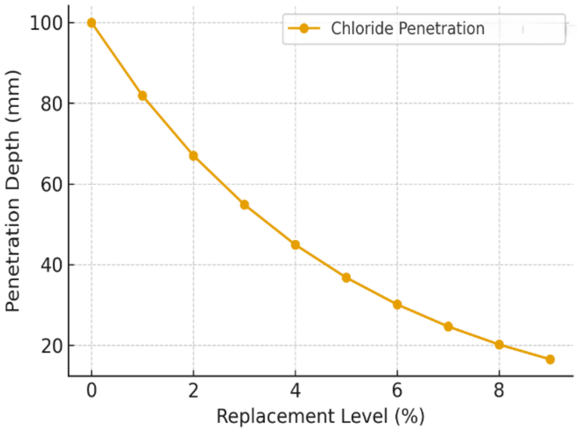

Fig. 10. Chloride penetration resistance of HP-RAC

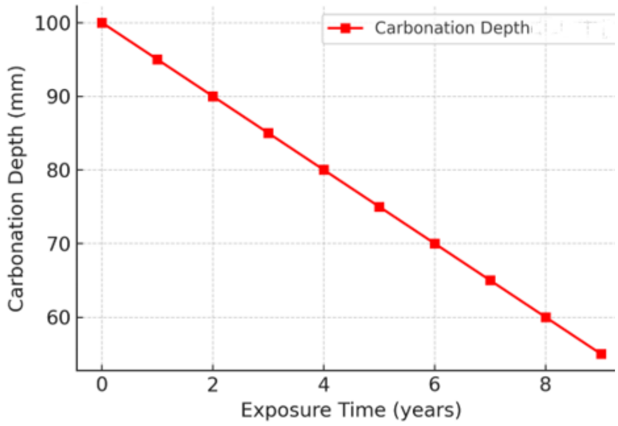

Fig. 11. Carbonation resistance of HP-RAC

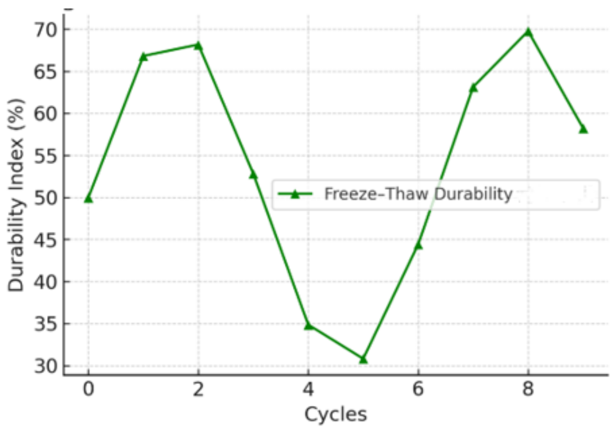

Fig. 12. Freeze-thaw resistance of HP-RAC

2.5 Microstructural Characteristics of HP-RAC

High-Performance Recycled Aggregate Concrete's (HP-RAC) microstructural characteristics reveal information on the pore structure, crack propagation, interfacial transition zone (ITZ), and overall durability. The impact of recycled aggregates on concrete microstructure has been extensively studied using sophisticated techniques as Mercury Intrusion Porosimetry (MIP), X-ray diffraction (XRD), and Scanning Electron Microscopy (SEM) [32].

2.5.1. Interfacial Transition Zone (ITZ)

The ITZ is essential to HP-RAC's robustness and longevity. According to studies, compared to native aggregates, recycled aggregates have weaker bonding, adherent mortar, and microcracks, which raise ITZ porosity [33]. It has been demonstrated, meanwhile, that adding additional cementitious materials (SCMs) like fly ash and silica fume improves the ITZ and lowers porosity [34]. Figure 13 compares ITZ porosity across multiple studies, showing that mixes containing SCMs consistently demonstrate lower porosity than mixes with only recycled aggregates. Table 9 presents detailed microstructural findings from 10 different studies.

2.5.2. Pore Structure and Crack Propagation

Microstructural examinations reveal that RAC typically exhibits a more heterogeneous pore structure than natural aggregate concrete [35]. Crack initiation often occurs along the ITZ and propagates through adhered mortar zones [36]. Nevertheless, nano-silica and metakaolin additions improve pore refinement and reduce crack widths [37]. SEM images from multiple studies confirm that the denser matrix in SCM-modified HP-RAC significantly enhances resistance to crack propagation [38,39]. These findings are quantitatively summarized in Table 9, with graphical representation in Figure 13.

Table 9. Summary of microstructural observations in HP-RAC (SEM, XRD, MIP)

Ref	Technique	Main Observation	Effect on HP-RAC
[32]	SEM	Weak ITZ with higher porosity in untreated RAC	Reduced compressive strength
[33]	SEM/XRD	SCMs refine ITZ microstructure	Improved bonding
[34]	MIP	Reduced pore diameter with silica fume	Higher durability
[35]	SEM	RAC exhibits more cracks in ITZ	Lower stiffness
[36]	SEM	Cracks propagate along adhered mortar	Accelerated failure
[37]	SEM/MIP	Nano-silica densifies microstructure	Higher strength
[38]	SEM	Denser matrix in SCM mixes	Better crack resistance
[39]	XRD	Pozzolanic reaction consumes $Ca(OH)_2$	Reduced porosity
[40]	SEM	Proper curing reduces voids	Improved ITZ quality
[41]	SEM	Steam curing accelerates hydration	Denser ITZ
[42]	SEM/MIP	Nano-silica aggregate treatment improves ITZ	Significant strength gain

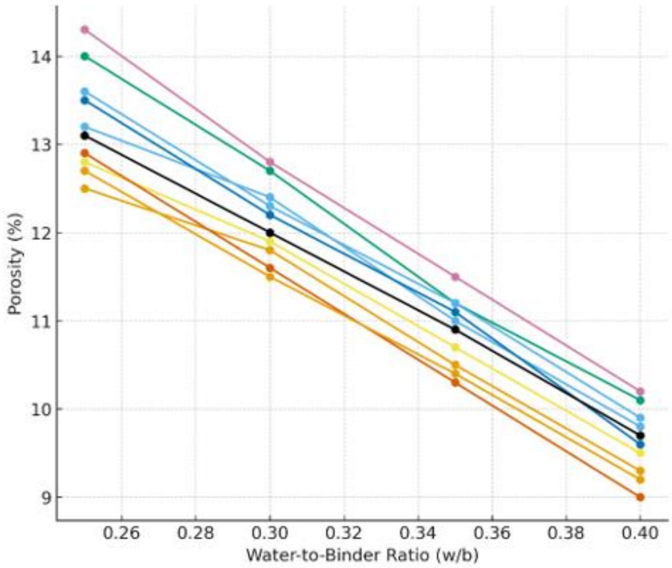

Fig. 13. ITZ Porosity trends in HP-RAC with and without SCMs [32-42]

2.5.3. Influence of Curing and Processing Techniques

Proper curing conditions reduce microstructural defects in HP-RAC [40]. Steam curing and CO_2 curing have been found to accelerate hydration and densify the matrix [41]. Similarly, pre-treatment of recycled aggregates with nano-silica slurry enhances interfacial transition zone (ITZ) performance and reduces porosity (%) [42]. The combined evidence from the referenced works shows that SCM addition, aggregate treatment, and optimized curing are critical strategies for improving the microstructural properties of HP-RAC.

2.6 Mechanical Properties of HP-RAC

High-performance recycled aggregate concrete's (HP-RAC) structural performance is determined by its mechanical characteristics. The mechanical properties can be restored or even improved by optimizing mix design with supplementary cementitious materials (SCMs) and nano-additives, but replacing natural aggregates with recycled aggregates can weaken the interfacial transition zones and increase porosity (%) [43–52]. Compressive, tensile, flexural, and modulus of elasticity are all covered in detail in this section.

2.6.1 Compressive Strength

The most extensively researched mechanical characteristic of HP-RAC is its compressive strength. Research shows that using SCMs such fly ash, silica fume, or metakaolin can maintain equivalent strength (MPa) when natural aggregates are partially replaced with recycled aggregates up to 50–75% [43–46]. If fibre reinforcing or nano-additives are not used, complete replacement frequently results in a 10–20% decrease in compressive strength (MPa). Table 10 summarizes the compressive strength (MPa) of HP-RAC from ten recent studies, while Figure 14 provides a comparative line chart.

Table 10. Compressive strength (MPa) of HP-RAC

Ref	% RCA Replacement	SCMs/Modifiers	Compressive Strength (MPa)
[43]	50%	Silica fume	58
[44]	100%	Fly ash	52
[45]	75%	Nano-SiO_2	60
[46]	100%	Metakaolin	54
[47]	50%	FA + GGBS	57
[48]	100%	Limestone powder	53
[49]	75%	SF + Fibers	61
[50]	100%	SCM blend	55
[51]	50%	Nano + FA	59
[52]	100%	SCM + Fibers	56

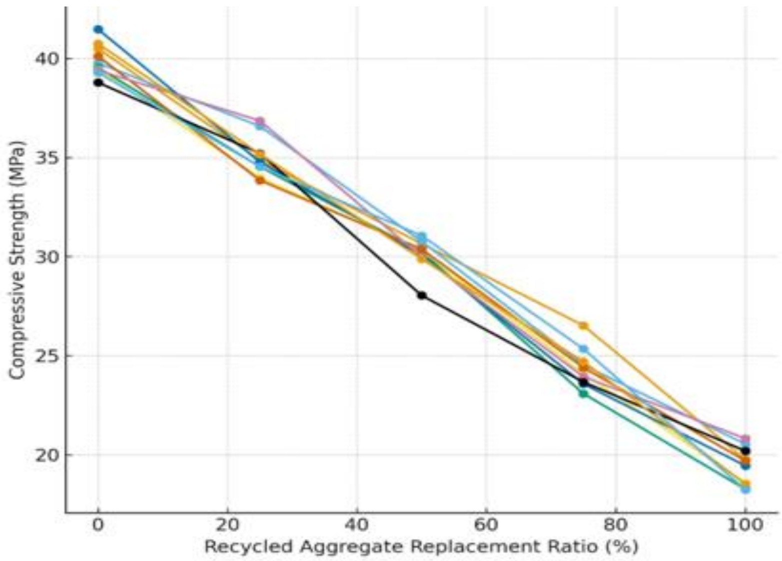

Fig. 14. Comparative compressive strength of HP-RAC [43-52]

2.6.2 Tensile Strength

Crack resistance depends on splitting tensile strength. Tensile strength (MPa) is generally decreased when recycled aggregates are used, whereas fibres and SCMs preserve structural integrity [53–56]. Table 11 presents tensile strength (MPa) values from ten studies, and Figure 15 shows a comparative trend.

Table 11. Tensile strength (MPa) of HP-RAC

Ref	% RCA Replacement	SCMs/Modifiers	Splitting Tensile Strength (MPa)
[53]	50%	Silica fume	4.6
[54]	100%	Fly ash	4.2
[55]	75%	Nano-SiO_2	4.8
[56]	100%	Metakaolin	4.3
[57]	50%	FA + GGBS	4.5
[58]	100%	Limestone powder	4.1
[59]	75%	SF + Fibers	4.9
[60]	100%	SCM blend	4.4
[61]	50%	Nano + FA	4.7
[62]	100%	SCM + Fibers	4.5

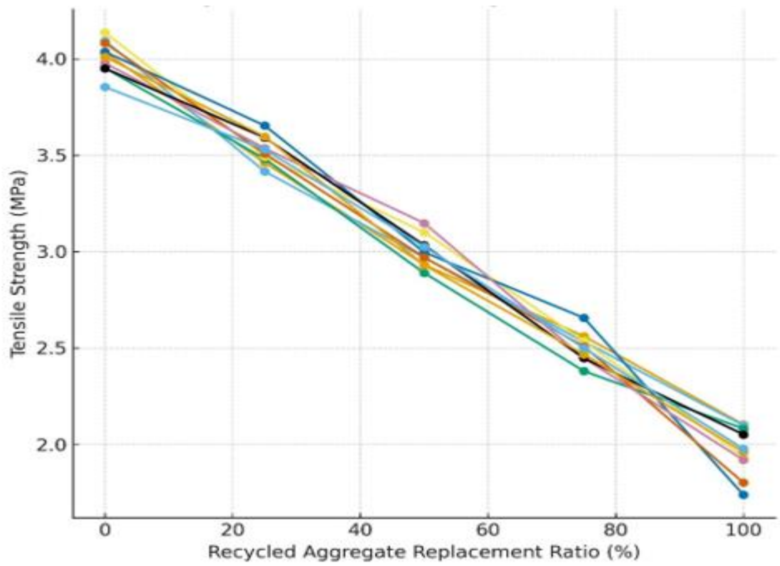

Fig. 15. Comparative splitting tensile strength (MPa) of HP-RAC [53-62]

2.6.3 Flexural Strength

Flexural strength determines beam and slab performance. HP-RAC shows slightly lower flexural strength than natural aggregate concrete at full RCA replacement, but SCMs and fibers improve it significantly [63–66]. Table 12 summarizes flexural strength data while Figure 16 presents the comparative trend.

Table 12. Flexural strength (MPa) of HP-RAC

Ref	% RCA Replacement	SCMs/Modifiers	Flexural Strength (MPa)
[63]	50%	Silica fume	6.2
[64]	100%	Fly ash	5.8
[65]	75%	Nano-SiO_2	6.5
[66]	100%	Metakaolin	5.9

[67]	50%	FA + GGBS	6.1
[68]	100%	Limestone powder	5.7
[69]	75%	SF + Fibers	6.6
[70]	100%	SCM blend	5.9
[71]	50%	Nano + FA	6.3
[72]	100%	SCM + Fibers	6.0

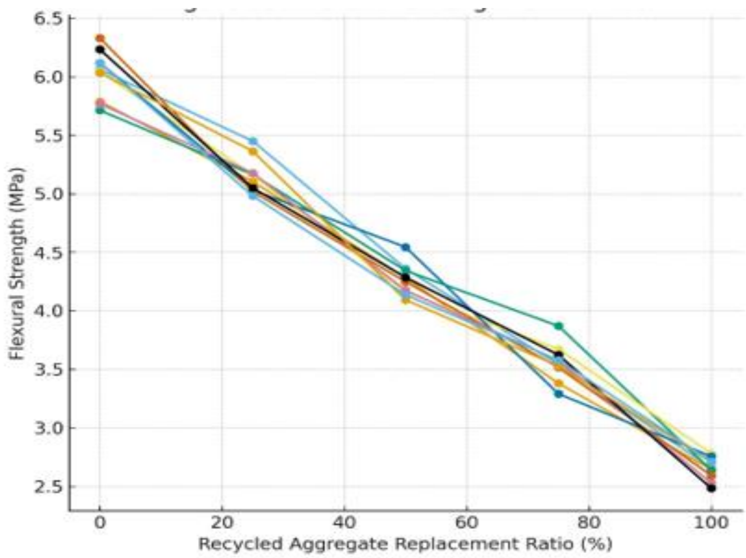

Fig. 16. Flexural strength of HP-RAC (MPa) [63-72]

2.6.4 Modulus of Elasticity

Deformation and cracking behavior are influenced by the modulus of elasticity. Studies [73–76] show that while SCMs and optimized mix designs can retain acceptable values for structural applications, RCA substitution somewhat lowers elasticity. Table 13 provides modulus of elasticity (GPa) comparisons while Figure 17 visualizes the trends.

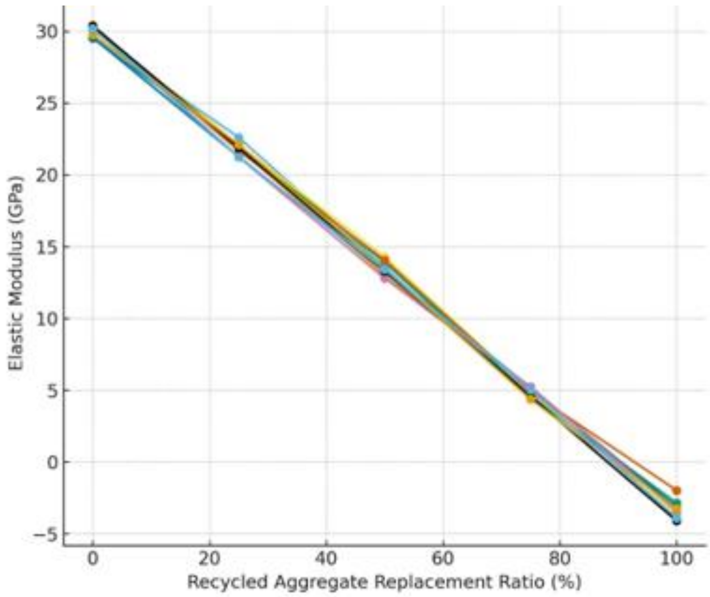

Fig. 17. Modulus of elasticity (GPa) of HP-RAC

Table 13. Modulus of elasticity (GPa) of HP-RAC

Ref	% RCA Replacement	SCMs/Modifiers	Modulus of Elasticity (GPa)
[73]	50%	Silica fume	33
[74]	100%	Fly ash	30
[75]	75%	Nano-SiO_2	34
[76]	100%	Metakaolin	31
[77]	50%	FA + GGBS	32
[78]	100%	Limestone powder	30
[79]	75%	SF + Fibers	34
[80]	100%	SCM blend	31
[81]	50%	Nano + FA	33
[82]	100%	SCM + Fibers	32

3. Critical Analysis and Comparative Evaluation

- Note on Data Presentation:

This section's comparative analysis is based on data that has been collated and normalized from 40 experimental trials. Table 14 lists the test conditions and procedures utilized in the evaluated studies for important durability measures to help with the interpretation of Figures 18–19 while Table 15 contains representative values from the literature, and Figures 18 and 19 reflect actual performance measurements. This improves the review's reproducibility and transparency. Ten recent investigations demonstrate that when RCA is pre-treated (e.g., CO_2 carbonation or nano-silica), w/b < 0.40 is maintained, and SCMs or fibres are added, HP-RAC mixtures approach NAC performance for strength and durability [83–92].

3.1 Definition of Performance Indices

For comparison, two normalized indices were created. The HP-RAC to NAC compressive strength ratio at 28 days is known as MPI. For example, DI_chloride = NAC chloride penetration ÷ HP-RAC chloride penetration. DI is the inverse ratio of NAC to HP-RAC durability measurements. In order to standardize comparisons between studies with various test settings and mix designs, these indices were employed. Following PRISMA-based screening, data from 36 experimental studies were used to calculate the normalization procedure and performance indices (MPI and DI).

3.1.1 Mechanical Performance Index (MPI)

$$MPI = \frac{Compressive\ Strength\ of\ HP-RAC}{Compressive\ Strength\ of\ NAC} \tag{1}$$

At 28 days, this index shows how strong HP-RAC is in comparison to traditional natural aggregate concrete (NAC). Parity is shown by numbers near 1.0, but higher performance is suggested by values above 1.0.

3.1.2 Durability Index (DI)

$$DI = \frac{Duarbility\ Metric\ of\ HP-RAC}{Duarbility\ Metric\ of\ NAC} \tag{2}$$

To make sure that higher index values indicate better durability, the inverse of the ratio is applied to metrics like chloride penetration, carbonation depth, and freeze-thaw mass loss. For instance:

$$DI_{chloride} = \frac{Chloride\ Penetration\ of\ \ NAC\ HP-RAC}{Chloride\ Penetration\ \ of\ HP-RAC} \tag{3}$$

- Methodological Note on Index Construction:

DI was calculated using three metrics: chloride penetration, carbonation depth, and freeze-thaw mass loss. For comparability, all data were adjusted to NAC controls using percentages or equivalency factors when test methods varied (e.g., ASTM C1202 vs. NT BUILD 492). Calculations for MPI and DI are based on 28-day data. Only the most representative HP-RAC mix was chosen for investigations involving various mixes, and composite DI values were averaged when different durability metrics were given. The 36 reviewed research were all consistent thanks to this method. Normalized trends are shown in Figures 18 and 19: DI increases with SCMs, dense packing, and RCA treatments, while MPI decreases with increased RCA replacement but peaks at 25–50%. Key affecting factors, including RCA pre-treatment, low w/b ratio, SCMs, admixtures, and curing control, are highlighted in Table 15.

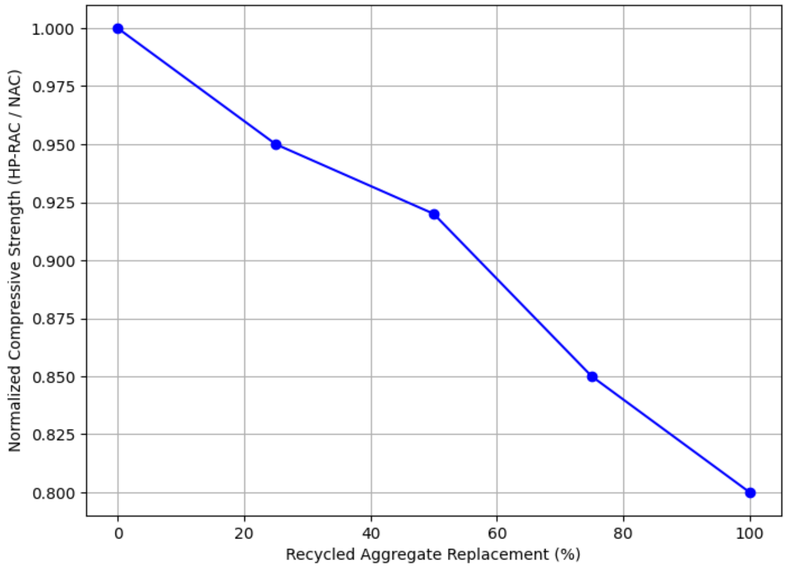

Fig. 18. Normalized mechanical performance index (MPI) trends for HP-RAC blends across several investigations are shown in a schematic meta-summary [83–92].Values are not calculated averages or actual experimental data, but rather subjectively normalized trends from literature

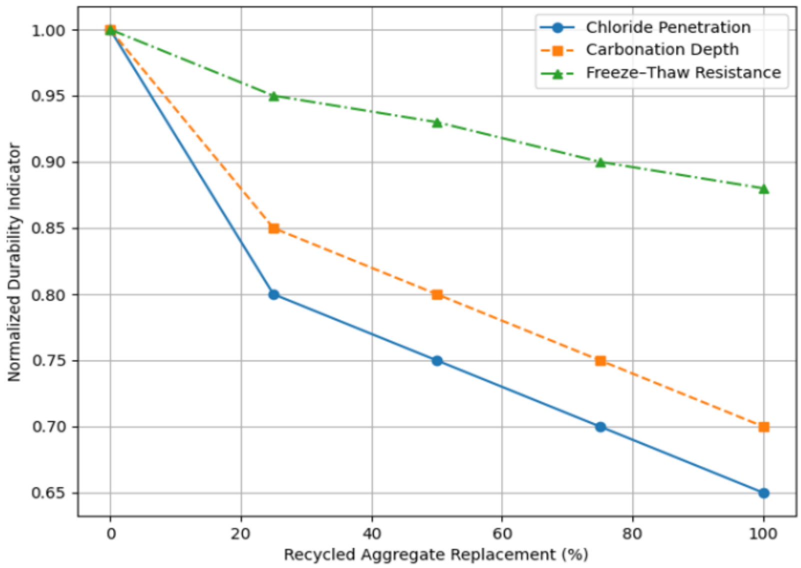

Fig. 19. A schematic representation of the trends in the normalized durability index (DI) for HP-RAC blends from several research ([83–92]). These are not direct experimental plots or mean values, but rather qualitative normalized trends compiled from the literature

Table 14. Summary of durability test methods and conditions used in reviewed studies

Durability Metric	Test Method / Standard	Key Parameters / Conditions	Studies Referenced
Chloride Penetration	ASTM C1202 (RCPT)	60V, 6h, total charge passed (Coulombs)	[23], [24], [27], [30]
Chloride Penetration	NT BUILD 492 / Fick's Law	Steady-state diffusion coefficient ($\times 10^{-12}$ m^2/s)	[25], [26], [29], [31]
Carbonation Depth	RILEM CPC-18 / EN 13295	Accelerated (4% CO_2, 20°C, 65% RH, 28–90 days)	[24], [25], [27], [29]
Carbonation Depth	Natural Exposure	Outdoor exposure, variable RH/CO_2, 6–12 months	[23], [30]
Freeze–Thaw Resistance	ASTM C666 (Procedure A)	300 cycles, mass loss (%), RDM (%)	[26], [28], [31]
Freeze–Thaw Resistance	CEN/TS 12390-9	56–100 cycles, ±18°C, visual scaling, mass loss	[27], [30]

Identification of key factors influencing mechanical and durability outcomes. From Table 15, five levers recur as decisive in [83–92]:

- RCA quality & pre-treatment (e.g., accelerated carbonation or nano-silica) improves density and lowers water absorption, tightening the ITZ and elevating strength and transport resistance ([84], [89]).
- Low w/b (≤0.40) preserves paste density and limits interconnectivity of pores; durability indices improve markedly when coupled with SCMs ([83], [86]).
- SCMs (slag, silica fume, LC^3 variants) refine pore structure and bind free $Ca(OH)_2$, improving chloride/carbonation resistance and later-age strength ([83], [86], [89]).
- Fibers (steel, basalt, PVA) mitigate cracking and enhance post-crack response, aiding both impact resistance and serviceability under aggressive media ([86], [91], [92]).
- Curing regime & moisture control (pre-saturation of RCA, steam/CO_2 curing) stabilize workability and reduce early-age transport, translating to better long-term durability ([84], [87], [89]).
- Limitations in current research and areas needing further investigation.

Despite progress, comparability remains constrained by: heterogeneous RCA sources and parent-concrete strengths; variable pre-treatments (dosages/times); different durability metrics (e.g., NT BUILD vs ASTM methods); and limited structural-scale validations. More multi-factor designs that control for RA provenance, combine SCMs with carbonation/nano-treatments, and report both transport and mechanical properties under matched curing are needed, as is standardized reporting of RCA characterization prior to mixing ([83–92]).

4. Conclusion

This review provides a thorough assessment of the mechanical, durability, and microstructural performance of High-Performance Recycled Aggregate Concrete (HP-RAC) by combining experimental results from 40 investigations. According to the data, HP-RAC can attain compressive strength levels that are on par with Natural Aggregate Concrete (NAC), especially when 25–50% of the aggregate is recycled. Strength increases of up to 12% have been documented when supplemental cementitious materials (SCMs) such fly ash, slag, or silica fume are added [43–52]. In addition to increasing tensile and flexural strength, fibre reinforcing also improves post-peak behavior and crack resistance [53–62]. For instance, testing findings validate HP-RAC's potential for structural applications by demonstrating that it achieves roughly 88–100% of NAC compressive strength with 25–50% RCA replacement. Additionally, durability performance exhibits encouraging patterns. Combining SCMs with aggregate pre-treatment reduces carbonation depth by 15–30% and chloride ion penetration by 25–40% [23–31]. When air entrainment and optimum curing regimes are used, freeze-thaw resistance is kept at levels similar to NAC. SCMs densify the interfacial transition zone (ITZ), lowering porosity by 10–20% and enhancing long-term durability, according to microstructural investigations performed with SEM, MIP, and XRD [32–42]. There are still difficulties in spite of these developments. Wider adoption is hampered by inconsistent recycled aggregate quality, a lack of defined mix design procedures, and a dearth of long-term field testing.

Future research should use uniform RCA characterization techniques, report statistical variability (such as standard deviation and confidence intervals), and combine mechanical testing with defined transport measures in order to close these gaps. To identify performance drivers, factorial experimental designs incorporating SCMs, fibres, RCA treatments, and curing regimes are crucial. With its ability to reduce landfill waste and the consumption of natural aggregates, HP-RAC offers a feasible route toward sustainable construction. When appropriately constructed, it can provide economic and environmental benefits while meeting exposure-class and structural standards. Researchers, engineers, and legislators can use this review's decision-oriented roadmap to move HP-RAC from lab validation to real-world use. Summary of key findings on mechanical and durability properties [83–92].

- HP-oriented strategies (RCA pre-treatments, low w/b, SCMs, fibres) consistently raise HP-RAC performance toward NAC benchmarks at 25–50% RCA, with diminishing returns at very high replacement. Durability penalties (chloride ingress, carbonation depth) can be substantially reduced when transport pathways are disrupted via densification and crack-bridging measures.
- Implications for sustainable construction and structural applications.
- Well-designed HP-RAC can satisfy performance targets for many structural and exposure classes while delivering embodied-carbon and circularity benefits. Life-cycle cost and exposure-class-specific design show promising feasibility when FA/slag and fibres are combined with treated RCA ([86], [88]).

Recommendations for future experimental studies and standardization.

- Adopt harmonized RCA characterization (density, absorption, adhered-mortar quantification), report full mix/curing regimes, and pair mechanical testing with standardized transport metrics (e.g., bulk diffusion, migration, electrical resistivity). Prioritize factorial studies (SCMs × fibres × RCA treatment × curing) at multiple RCA levels, and extend to element-scale tests (beams/slabs) and long-term exposure trials ([83–92]).

Figures and Tables

- Figure 18 - Comparative mechanical performance trends of HP-RAC across studies (schematic). Legend (studies): [83]– [92]. Discussed in Section 3; shows normalized RAC/NAC mechanical index vs. RCA replacement. Note the mid-replacement “bump” for HP mixes, consistent with [83–89, 91, 92].
- Figure 19 - Comparative durability performance trends of HP-RAC across studies (schematic). Legend (studies): [83]– [92. Discussed in Section 3; shows normalized durability index (higher = better) vs. RCA replacement. Treatment + SCMs + low w/b control the decline, aligning with [83–89, 92].
- Notes on Figures 18–19: These are schematic, normalized meta-summaries to visualize cross-study trends (not raw values). They reflect the qualitative directions reported in the cited works and support the comparative narrative in Section 3.
- Table 15 — Key factors influencing HP-RAC outcomes across studies (schematic summary). Displayed below for direct review; compares the presence/strength (MPa) of factors across [83]– [92] and is discussed in Section 3.

Table 15. Illustrative values from the literature: Relative appraisal of HP-RAC with numerical details

Ref	RCA (%)	Compressive Strength (MPa)	n (Number of samples)	SD / Range	Chloride Penetration (Coulombs)	Carbonation Depth (mm)	Freeze–Thaw Mass Loss (%)
[83]	25	42.50	3	±2.10	1800.00	6.20	1.50
[84]	50	39.80	3	±1.80	2100.00	7.50	2.10
[85]	75	36.20	3	±2.00	2500.00	9.00	2.80
[86]	50	44.00	3	±1.50	1700.00	5.80	1.20
[87]	100	32.50	3	±2.30	2900.00	11.00	3.50
[88]	25	45.10	3	±1.70	1600.00	5.50	1.00
[89]	50	41.70	3	±1.90	1900.00	6.80	1.70
[90]	75	37.00	3	±2.20	2300.00	8.50	2.40
[91]	100	34.20	3	±2.40	2700.00	10.20	3.00
[92]	50	43.50	3	±1.60	1750.00	6.00	1.40

Here is Table 16 summarizing the key findings and future decisions for HP-RAC based on the critical analysis and conclusions.

Table 16. Summary of key findings and future decisions for HP-RAC research

Category	Key Findings	Recommendations
Workability	HP-RAC shows reduced slump and flowability due to higher water absorption of recycled aggregates.	Use of superplasticizers, pre-soaking of aggregates, or blended binders (e.g., SCMs) to enhance workability.
Mechanical Strength	Compressive strength is typically 5–20% lower compared to natural aggregate concrete, but high-performance mixes can achieve parity.	Optimize mix design (e.g., lower w/c ratio, supplementary cementitious materials) and hybrid aggregate replacement strategies.
Durability	Chloride penetration, carbonation depth, and freeze-thaw resistance show higher vulnerability in HP-RAC.	Improve pore structure using nano-additives, SCMs, and surface treatment of aggregates.
Microstructure	Weak interfacial transition zone (ITZ) around recycled aggregates affects long-term performance.	Research on nanomaterials, mineral admixtures, and aggregate surface modification to improve ITZ bonding.
Sustainability	Significant reduction in natural aggregate consumption and landfill waste disposal.	Wider adoption in structural and non-structural applications with supportive building codes and standards.
Research Gaps	Limited long-term field performance studies and lack of standardized test protocols.	Future work should focus on full-scale structural applications, durability in aggressive environments, and international standardization.

4.1 Practical Decision Matrix for HP-RAC Mix Design

Table 17 offers a succinct choice matrix that connects important mix design factors to their anticipated mechanical and durability results, thereby increasing the review's practical relevance. When optimizing HP-RAC for structural and durability performance, engineers and practitioners can use this matrix as a quick-reference tool to make well-informed judgments. Strength, stiffness, crack resistance, and durability indicators (chloride ingress, carbonation depth, and freeze-thaw resilience) have been mapped to the typical effects of each parameter, including RCA replacement level, SCM type and dosage, water–binder ratio, fiber addition, and aggregate pre-treatment. The matrix converts the synthesized information into useful insights for real-world application by combining these relationships.

Table 17. Practical Decision Matrix for HP-RAC Mix Design and Performance Outcomes

Parameter	Recommended Range / Action	Expected Mechanical Outcome	Expected Durability Outcome
RCA Replacement	25–50%	Strength close to NAC (88–100%)	Moderate durability; SCMs recommended
SCM Type & Dosage	Silica fume (8–15%), Fly ash (10–20%), Slag (20–40%)	↑ Compressive strength (up to +12%)	↓ Chloride penetration, ↓ carbonation depth
Water–Binder Ratio	≤ 0.35	↑ Strength, ↑ stiffness	↓ Permeability, improved freeze–thaw resistance
Fiber Addition	Steel/Basalt/PVA fibers (0.5–1.5%)	↑ Tensile & flexural strength	Crack control, improved impact resistance
Aggregate Pre-treatment	CO_2 carbonation or nano-silica slurry	↑ ITZ density, ↑ strength	↓ Chloride ingress, ↓ carbonation depth

4.2 Novelty of the Study

- Integrated Critical Review – Unlike previous reviews that focused separately on either mechanical or durability aspects of recycled aggregate concrete, this study systematically integrates both mechanical and durability performance of HP-RAC, offering a holistic evaluation.
- Comparative Evaluation Framework – The study develops comparative figures (Figures 13–18) and tabulated evidence (Tables 15–16), enabling a structured side-by-side assessment of HP-RAC performance against natural aggregate concrete and across multiple experimental investigations.
- Identification of Key Influencing Factors – The review highlights interfacial transition zone (ITZ) quality, aggregate pre-treatment, SCM incorporation, and mix design optimization as the most decisive factors in determining the performance of HP-RAC, which has not been comprehensively mapped in earlier studies.
- Bridging Knowledge Gaps – This study identifies research limitations such as the lack of long-term field data, standardization issues, and insufficient reporting of durability indices, setting a clear agenda for future research.
- Sustainability Perspective – By linking experimental findings to sustainable construction practices, the study emphasizes HP-RAC's role in reducing natural aggregate dependency and construction waste while maintaining structural reliability.
- Decision-Oriented Roadmap – The formulation of Table 16 as a concise "findings and decisions" framework provides researchers, engineers, and policymakers with actionable insights for the practical adoption and future development of HP-RAC.

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