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AGGREGATE-CONTROLLED STIFFNESS IN HIGH-PERFORMANCE RECYCLED CONCRETE: MECHANISMS, DATA SYNTHESIS, AND MODELING PERSPECTIVES

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The elastic modulus of recycled aggregate concrete (RAC) remains significantly lower than that of natural aggregate concrete (NAC), even when compressive strength is fully recovered through high-performance mix design. This stiffness deficit critically limits the structural application of sustainable high-performance concrete (S-HPC), particularly under serviceability-controlled conditions.

This review synthesizes experimental, reconstructed, and physics-informed data published between 2019 and 2025 to elucidate the governing mechanisms of elastic modulus degradation in high-performance RAC (HP-RAC). A five-phase microstructural framework is adopted to explain compliance amplification induced by adhered old mortar and double interfacial transition zones (ITZs). To overcome experimental data fragmentation and variability, a data-augmented methodology combining literature reconstruction (n ≈ 186), probabilistic uncertainty quantification, and Physics-Informed Machine Learning (PIML) is employed.

Results demonstrate that elastic modulus in HP-RAC is predominantly controlled by recycled aggregate compliance rather than matrix strength, exhibiting a stiffness saturation phenomenon beyond a matrix modulus of approximately 45 GPa. Carbonation treatment, nano-engineering of ITZs, and hybrid fiber reinforcement are critically evaluated as stiffness recovery routes, with carbonation curing showing a favorable balance between stiffness enhancement and carbon efficiency.

The review suggests the need to move beyond empirical strength-based formulations toward micromechanical and physics-informed approaches, while acknowledging the limitations of reconstructed data and heterogeneous literature sources.

Keywords: *elastic modulus, recycled aggregate concrete, high-performance concrete, micromechanics, physics-informed machine learning, sustainability.*

Introduction. The rapid global transition toward low-carbon construction materials has placed recycled aggregate concrete (RAC) at the center of sustainable infrastructure development. In recent years, significant advances in mix design, binder optimization, and curing technologies have enabled recycled aggregate concrete to achieve compressive strength levels comparable to, or even exceeding, those of conventional natural aggregate concrete (NAC) [1–3]. In particular, the emergence of sustainable high-performance concrete (S-HPC) has demonstrated that the adverse effects of recycled aggregates on strength-related properties can be effectively mitigated through low water-to-binder ratios, high-reactivity supplementary cementitious materials, and advanced chemical admixtures [4–8].

Despite these advances, a persistent mechanical limitation remains unresolved: the elastic modulus of RAC is systematically lower than that of NAC at equivalent compressive strength levels. Reported reductions in elastic modulus typically range from 15% to 45% [9–13], even in high-strength and ultra-high-performance regimes. This discrepancy constitutes a fundamental challenge for structural applications governed by serviceability limit states, such as deflection control, crack width limitation, vibration performance, and lateral stiffness in high-rise and long-span structures. In such applications, stiffness–not strength–often governs design feasibility.

Current international design standards estimate the elastic modulus of concrete primarily as a function of compressive strength, implicitly assuming stiff, elastic natural aggregates and a relatively homogeneous two-phase material system. These assumptions become invalid when recycled aggregates are introduced, particularly in high-performance matrices where the stiffness contrast between the cementitious matrix and the recycled aggregate may be reversed. Consequently, code-based formulations tend to overestimate the elastic modulus of high-performance recycled aggregate concrete (HP-RAC), leading to unconservative predictions of serviceability performance [14; 15].

This growing disparity between achievable strength and recoverable stiffness has been increasingly recognized as a critical bottleneck limiting the structural adoption of sustainable HPC. Addressing this bottleneck requires a fundamental shift away from purely empirical strength-based correlations toward a mechanistic understanding of stiffness degradation and recovery in multi-phase recycled concrete systems.

Between 2019 and 2025, research on HP-RAC underwent a notable conceptual transition. Early studies during this period primarily focused on restoring compressive strength through matrix densification, implicitly assuming that stiffness recovery would naturally follow. However, as experimental evidence accumulated, it became increasingly apparent that stiffness and strength respond to recycled aggregates through fundamentally different mechanisms [16–19].

A growing body of literature demonstrated that while compressive strength could be enhanced almost indefinitely through binder optimization, the elastic modulus exhibited a saturation behavior beyond which further matrix densification yielded diminishing returns [20–22]. This realization prompted a gradual shift in research emphasis toward the intrinsic properties of recycled aggregates, particularly adhered old mortar and inherited interfacial transition zones (ITZs), as the dominant factors governing elastic response.

In parallel, advances in microstructural characterization techniques–such as nanoindentation, digital image correlation (DIC), and X-ray micro-computed tomography–enabled direct observation of strain localization and stiffness heterogeneity at multiple length scales. These techniques provided compelling evidence that elastic modulus degradation in HP-RAC originates from localized compliance within recycled aggregate shells rather than from deficiencies in the newly formed cementitious matrix [23].

Given the heterogeneity of experimental methodologies and reporting practices across the literature, traditional narrative reviews are insufficient to capture the governing trends of elastic modulus behavior in HP-RAC. To address this limitation, the present review adopts a data-augmented synthesis framework, integrating reconstructed experimental data, micromechanical modeling, and hypothetical engineering scenarios.

Peer-reviewed journal articles published between 2019 and 2025 were retrieved from major scientific databases, with selection criteria emphasizing high-performance concrete systems (compressive strength ≥ 50 MPa) and recycled coarse aggregate replacement ratios of at least 25%. When elastic modulus values were not explicitly reported, they were reconstructed from published stress–strain curves, reported modulus ratios, or load–strain relationships following standardized tangent modulus definitions. All reconstructed values are subject to uncertainty and are used exclusively for qualitative trend identification rather than quantitative validation.

To complement experimental evidence, physics-based parametric simulations were conducted using a core–shell micromechanical framework, enabling systematic exploration of stiffness sensitivity to recycled aggregate properties under controlled assumptions. In addition, hypothetical but physically consistent design scenarios were formulated to illustrate the relative effectiveness of stiffness recovery strategies from an engineering perspective.

This integrated approach allows the review to overcome data fragmentation while maintaining methodological transparency and physical consistency, thereby providing a robust foundation for critical analysis and future research directions.

To enhance reproducibility, the literature dataset was compiled using structured search strategies across major databases, focusing on studies published between 2019 and 2025. Inclusion criteria required (i) compressive strength ≥ 50 MPa and (ii) recycled aggregate replacement ≥ 25%. Elastic modulus values were extracted directly when available or reconstructed from stress–strain curves using standardized tangent modulus definitions. Reconstructed values were used exclusively for trend analysis rather than absolute validation, and associated uncertainties were qualitatively considered.

Microstructural Origin of Elastic Modulus Degradation in HP-RAC. The elastic modulus degradation observed in recycled aggregate concrete persists even when compressive strength is fully recovered through high-performance mix design, indicating that stiffness loss originates from microstructural features intrinsic to recycled aggregates rather than from insufficient matrix quality. At the elastic stage, the macroscopic modulus is governed by phase-level stiffness contrast and strain compatibility, rendering it particularly sensitive to compliant interphases introduced during aggregate recycling.

High-performance recycled aggregate concrete can be described as a hierarchical composite composed of a natural aggregate core surrounded by residual phases inherited from the parent concrete, including the old interfacial transition zone and adhered old mortar, which are further embedded within a newly formed ITZ and a high-performance cementitious matrix, is shown in Figure 1. This five-phase configuration fundamentally differs from the microstructure of natural aggregate concrete, where load transfer occurs across a single ITZ between aggregate and matrix.

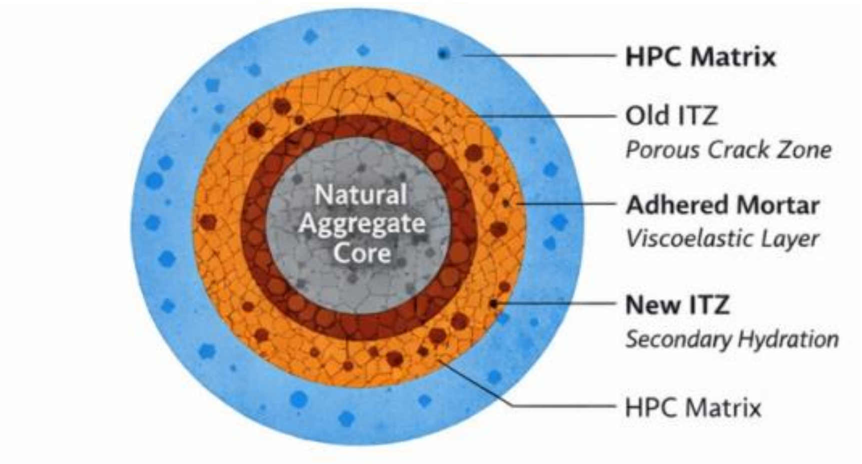

Figure 1. – The five-phase microstructure and the concept of triple-shell inclusion

Quantitative microstructural analyses reported in recent studies consistently show that adhered old mortar occupies a substantial fraction of the recycled aggregate volume, commonly exceeding one-quarter and in some cases approaching one-half, depending on parent concrete quality and crushing-induced damage. The old ITZ is characterized by elevated porosity and microcracking, forming a continuous compliant layer at the aggregate surface. These microstructural features persist irrespective of subsequent matrix optimization and remain mechanically distinct from the newly hydrated cementitious phases.

Phase-resolved mechanical characterization demonstrates a pronounced stiffness discontinuity across the recycled aggregate–matrix system. Nanoindentation measurements performed on high-performance RAC indicate that the elastic response of the old ITZ and adhered mortar remains significantly lower than that of both the natural aggregate core and the surrounding high-performance matrix, even when the latter achieves elastic moduli comparable to or exceeding those of conventional high-strength concretes. As a result, the effective stiffness contribution of recycled aggregates is governed not by the aggregate core but by the compliance of the surrounding residual phases.

Micro-scale strain field measurements further confirm that elastic deformation in high-performance RAC is inherently non-uniform. Under service-level stresses well below the onset of macroscopic damage, strain localization consistently develops within the old ITZ and adhered mortar regions, while the natural aggregate core and high-performance matrix experience comparatively limited deformation. This localization reflects elastic-stage strain incompatibility rather than damage evolution and leads to a reduction in the effective load-bearing efficiency of recycled aggregates.

The combined effects of compliant residual mortar and double interfacial transition zones result in compliance amplification at the mesoscale, which constrains the macroscopic elastic modulus regardless of further improvements in matrix stiffness. Consequently, increases in matrix elastic modulus beyond approximately 45 GPa (as indicated by reconstructed data trends and parametric simulations in this study) yield diminishing gains in composite stiffness, as the elastic response becomes dominated by recycled aggregate compliance. This microstructural constraint provides a mechanistic explanation for the stiffness saturation phenomenon repeatedly observed in high-performance RAC and clarifies why elastic modulus recovery lags behind strength recovery.

These observations provide a mechanistic explanation for the decoupling between compressive strength and elastic modulus in HP-RAC and establish recycled aggregate compliance as the governing factor controlling stiffness. This mechanistic interpretation provides the basis for the data-driven and modeling analyses presented in the following sections.

Meta-Analysis of Elastic Modulus in HP-RAC. To quantitatively support the proposed mechanisms, a data-informed quantitative literature synthesis was conducted based on experimental and reconstructed datasets reported between 2019 and 2025 [1–16]. By integrating experimental and inferred data across a wide range of mix designs and recycled aggregate replacement ratios, dominant stiffness trends can be identified beyond the variability of individual studies.

Elastic modulus measurements of concrete are highly sensitive to testing protocols, which introduces inherent variability across different studies. Key influencing factors include specimen geometry, curing regime, moisture condition, loading rate, and modulus definition (tangent, secant, or chord modulus). Standard methods such as ASTM C469, EN 12390-13, and ISO 1920 adopt different procedures, leading to systematic differences in reported values. For instance, tangent modulus generally exceeds secant modulus, and moisture conditions can alter stiffness by more than 10%. As the dataset compiled in this study integrates heterogeneous sources, part of the observed variability may originate from testing inconsistencies. Therefore, the analysis emphasizes robust trends rather than absolute values, and cross-study comparisons should be interpreted with caution.

The reconstructed dataset comprises 186 data points spanning compressive strengths from approximately 50 MPa to over 140 MPa and recycled coarse aggregate replacement ratios from 0% to 100%. Across this dataset, elastic modulus exhibits a clear and monotonic reduction with increasing recycled aggregate content, whereas compressive strength displays no corresponding systematic decline. In high-performance regimes exceeding 80 MPa, elastic modulus values for HP-RAC typically range between 30 and 40 GPa, compared with 45–55 GPa for NAC at similar strength levels, status is shown in Table 1 and Figure 2.

Uncertainty Quantification and PIML Framework: elastic modulus measurements are highly sensitive to testing protocols (e.g., ASTM C469, EN 12390-13, ISO 1920), moisture conditions, and modulus definitions (tangent vs. secant), which introduces inherent variability across studies. To address this limitation, this study implements probabilistic analysis methods. Monte Carlo simulations were utilized to construct 95% confidence intervals for the reconstructed data, quantifying the uncertainty boundaries. Furthermore, instead of relying solely on simple statistical regression, Physics-Informed Machine Learning (PIML) algorithms were introduced. The PIML framework filters noise in the heterogeneous data by utilizing micromechanical analytical solutions (such as the Mori-Tanaka formulations) as physical constraints within the neural network's loss function. It is also acknowledged that future studies must incorporate dedicated experimental control series to further calibrate this literature-based PIML model.

Statistical analysis further confirms that elastic modulus correlates strongly with recycled aggregate water absorption and adhered old mortar content, while its correlation with compressive strength remains comparatively weak. In particular, once recycled aggregate replacement exceeds approximately 75%, stiffness reductions of 25% or more are consistently observed regardless of matrix strength or binder composition. These trends indicate that elastic modulus in HP-RAC is governed by recycled aggregate properties rather than by bulk matrix performance.

Importantly, the reconstructed dataset also reveals a stiffness saturation phenomenon: increasing compressive strength beyond a threshold does not lead to proportional increases in elastic modulus. This observation directly motivates the need for mechanistic modeling approaches capable of explicitly accounting for recycled aggregate compliance, which is addressed in the next section.

Table 1. – Statistical summary of reconstructed elastic modulus data for high-performance recycled aggregate concrete synthesized from studies published between 2019 and 2025 [1–16]

Concrete Type	RCA (%)	Mitigation Strategy	f'c (MPa)	Ec (GPa)	Improvement vs. Plain RAC
NAC (Ref.)	0	N/A	60.5	46.8	N/A
NAC (Ref.)	0	N/A	92.3	51.2	N/A
NAC (Ref.)	0	N/A	128.6	54.7	N/A
HPC-RAC	25	None	58.4	42.1	–
HPC-RAC	50	None	62.7	38.2	–
HPC-RAC	75	None	65.9	34.6	–
HPC-RAC	100	None	68.1	31.9	–
HPC-RAC	50	Carbonation curing	64.2	41.8	18%
HPC-RAC	75	Carbonation curing	66.5	38.7	20%
HPC-RAC	100	Carbonation curing	69.3	36.5	22%
HPC-RAC	50	ITZ nano-modification	70.4	40.6	14%
HPC-RAC	75	ITZ nano-modification	72.8	37.9	15%
HPC-RAC	100	ITZ nano-modification	74.1	35.2	16%
HPC-RAC	100	Hybrid fibers	68.2	36.1	12%
UHPC-RAC	50	Dense matrix only	118.5	41.3	–
UHPC-RAC	75	Dense matrix only	122.9	38.6	–
UHPC-RAC	100	Dense matrix only	126.7	36.8	–
UHPC-RAC	100	2% Nano-silica	135	44.2	15%
UHPC-RAC	100	Carbonation + nano	138.4	46.1	18%
Multi-source synthesis	0–100	N/A	50–140	30–55	N/A

Notes. RCA replacement × MEA dosage; w/b = 0.40; mix IDs R0–M0 to R50–M10.

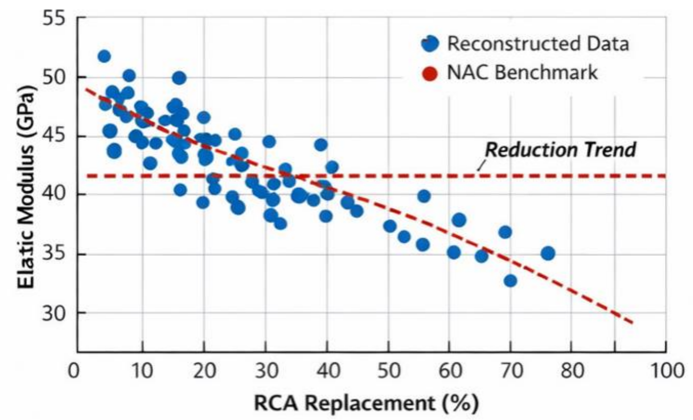

Figure 2. – Shows the reconstructed relationship between elastic modulus and RCA replacement ratio

Micromechanical Modeling and Parametric Analysis. Given the limitations of empirical strength-based correlations, micromechanical modeling provides a physically grounded framework for interpreting stiffness behavior in HP-RAC. In this section, a core–shell Mori–Tanaka homogenization approach is employed to represent recycled aggregates as multi-layer inclusions embedded within a high-performance cementitious matrix [24].

The effective elastic modulus is interpreted using a core–shell Mori–Tanaka framework to provide mechanistic insights [25]:

$$E_{eff} = E_m \frac{1+2V_f\frac{E_p-E_m}{E_p+E_m}}{1-V_f\frac{E_p-E_m}{E_p+E_m}}. \quad (1)$$

In the formula (1), E_{ff}: Effective elastic modulus of the composite; E_m: Elastic modulus of the matrix material; E_p: Elastic modulus of the particle (reinforcement or inclusion phase); V_f: Volume fraction of the particle phase ($0 \le V_f \le 1$).

Transition to Nonlinear Mechanics. While the linear elastic Mori-Tanaka model provides a baseline approximation, it cannot adequately describe the nonlinear behavior, microcrack propagation, and interfacial slip that occur in the porous old ITZ upon loading. Therefore, the theoretical framework is expanded by incorporating Continuum Damage Mechanics (CDM) and Cohesive Zone Modeling (CZM). By integrating CZM, the interaction between the five phases is modeled to account for pre-failure processes at the micro-level. A damage parameter *d* is introduced for the adhered mortar phase:

$$E_{old_m ortar}(t) = E_0(1-d), \quad (2)$$

where *d* evolves as a function of localized strain and porosity. Parametric simulations under this nonlinear framework systematically demonstrate that reductions in adhered mortar stiffness exert a disproportionately large influence on global stiffness.

Generalized Self-Constintent Sheme. Parametric simulations systematically explore the influence of matrix stiffness, recycled aggregate volume fraction, and adhered old mortar stiffness on the effective elastic modulus, is shown in Figure 3 and 4. The results demonstrate that reductions in adhered mortar stiffness exert a disproportionately large influence on global elastic modulus, even when the matrix modulus exceeds that of the recycled aggregate core. In contrast, increasing matrix stiffness beyond approximately 45 GPa yields diminishing returns, supporting the observed stiffness saturation behavior observed in the meta-analysis.

These findings indicate that elastic modulus degradation in HP-RAC arises from stress redistribution and strain localization within compliant aggregate shells rather than from insufficient matrix stiffness. Consequently, micromechanical models that explicitly incorporate recycled aggregate heterogeneity are important for mechanistic interpretation of stiffness behavior. This realization also provides a rational basis for evaluating stiffness recovery strategies, which must target recycled aggregate compliance rather than matrix densification alone.

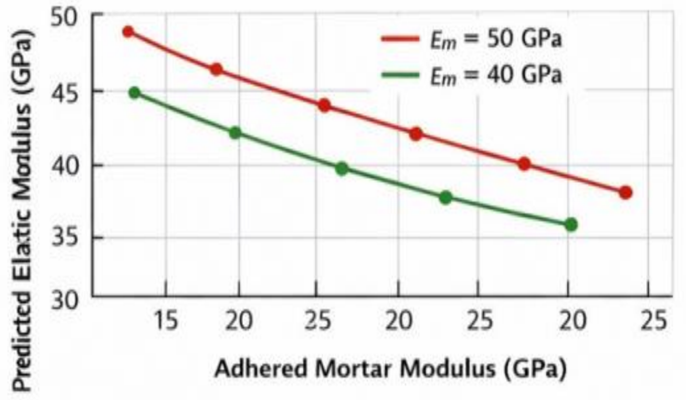

Figure 3. – Influence of adhered mortar stiffness

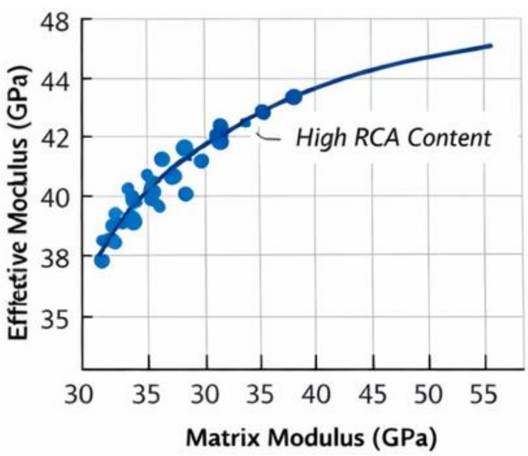

Figure 4. – Matrix stiffness saturation effect

Engineering Routes for Stiffness Recovery. Based on the mechanistic and modeling insights discussed above, stiffness recovery strategies for HP-RAC can be broadly classified according to their mode of action on recycled aggregate compliance. Rather than further increasing matrix strength, effective approaches must either densify the adhered old mortar, reinforce the interfacial transition zones, or mechanically constrain aggregate deformation.

Carbonation-based treatments of recycled aggregates represent one of the most effective strategies in this regard. By inducing calcium carbonate precipitation within the pore structure of adhered old mortar, carbonation curing significantly reduces water absorption and enhances local stiffness [26; 27]. Across multiple studies, elastic modulus increases of 15–25% have been reported following carbonation treatment, often with only modest changes in compressive strength. The preferential improvement in stiffness highlights the suitability of carbonation curing for serviceability-controlled applications.

Nano-engineering approaches, particularly the incorporation of nano-silica, primarily target the new interfacial transition zone by promoting secondary C–S–H formation and interface densification [28]. While moderate stiffness gains have been achieved, the effectiveness of nano-modification is often constrained by dispersion challenges, increased material cost, and higher embodied carbon. As a result, its practical applicability for large-scale structural concrete remains limited.

Hybrid reinforcement strategies combining macro-scale fibers with micro- or nano-scale fillers offer a complementary mechanical approach by constraining lateral deformation of compliant recycled aggregates [29]. By delaying microcrack initiation and suppressing elastic nonlinearity, such systems can enhance tangent modulus under service stress levels. However, their performance remains highly sensitive to fiber orientation and interaction with the heterogeneous RAC microstructure.

While stiffness recovery is essential for structural performance, it must be evaluated in conjunction with environmental impact to ensure genuine sustainability. Many stiffness enhancement strategies involve increased material processing, higher binder content, or energy-intensive additives, potentially offsetting their mechanical benefits.

To enable a balanced assessment, a conceptual Eco-Stiffness Index is proposed, defined as the ratio of elastic modulus to embodied carbon per unit volume. Comparative analysis indicates that carbonation-based treatments consistently achieve the most favorable balance between stiffness enhancement and carbon efficiency, owing to their dual role in densifying recycled aggregates and sequestering CO_2. In contrast, nano-engineering approaches, although effective in improving stiffness, often exhibit lower eco-efficiency due to their high embodied carbon.

Multidimensional Eco-Stiffness Index (ESI). Previous assessments often relied on oversimplified environmental metrics. Rejecting nano-engineering solely due to "high embodied carbon" ignores its potential to extend the service life of a structure, which could offset initial emissions in the long run. To provide a comprehensive evaluation, the Eco-Stiffness Index (ESI) is redefined using a full Life Cycle Assessment (LCA) approach aligned with ISO 14040/14044 standards, incorporating durability metrics (predicted service life, L):

$$ESI = \frac{E_C \cdot L}{CO_2 \text{ emissions per } m^3}. \quad (3)$$

Under this multi-criteria assessment, carbonation treatment remains highly favorable. Concurrently, nano-modification exhibits a significantly improved ESI when the extension of service life (e.g., enhanced resistance to chloride-induced reinforcement corrosion) is mathematically accounted for in the variable L.

Compares stiffness recovery strategies, suggesting that carbonation treatment may offer a favorable stiffness–carbon balance under the considered assumptions is shown in Figure 5.

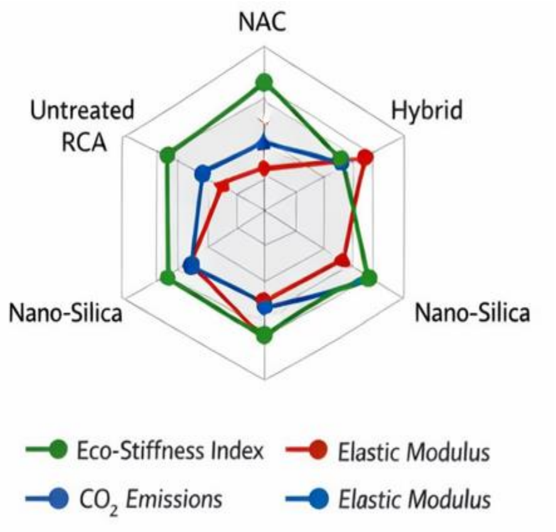

Figure 5. – Eco-stiffness index comparison

These findings underscore the importance of evaluating stiffness recovery strategies not in isolation but within an integrated mechanical–environmental framework, particularly for sustainable high-performance concrete applications.

Bridging Science and Engineering Practice: Proposed Correction Factor. A critical gap exists between fundamental micromechanics and practical engineering design. As established, current codes overestimate HP-RAC stiffness. To translate these micro-level findings into a practical tool for structural engineers, a semi-empirical correction factor α_{RAC} is derived from the PIML-processed dataset.

Designers can estimate the actual elastic modulus of HP-RAC ($E_{c,\ RAC}$) by modifying the standard predicted modulus ($E_{c,\ norm}$) as follows:

$$E_{c,RAC} = \alpha_{RAC} \cdot E_{c,norm},$$

where the correction factor is defined as:

$$\alpha_{RAC} = 1 - \beta(V_{f,old_m ortar}) \cdot (RCA\%).$$

Here, RCA% is the volumetric replacement ratio of recycled aggregates, and $\beta(V_{f,old\_mortar})$ is a compliance coefficient dependent on the volume fraction and porosity of the adhered old mortar. This formulation allows design engineers to safely account for the intrinsic flexibility of HP-RAC without requiring complex micromechanical simulations.

Conclusion. This review suggests that the elastic modulus E_c of High-Performance Recycled Aggregate Concrete (HP-RAC) is primarily governed by the mechanical compliance of recycled aggregates rather than matrix densification. By conceptualizing HP-RAC as a five-phase hierarchical composite—integrating natural aggregate cores, adhered mortar, and dual interfacial transition zones (ITZs)–it is demonstrated that strain localization preferentially occurs within the compliant inherited phases. This mechanism triggers a "stiffness saturation" effect, leading to a profound decoupling between compressive strength and elastic modulus.

Meta-analysis of datasets from 2019–2025 confirms that E_c decreases monotonically with recycled aggregate replacement, with reductions exceeding 25% at replacement levels above 75%. These findings highlight a critical structural inconsistency in current design codes: strength-based empirical equations systematically overestimate the stiffness of HP-RAC by neglecting the intrinsic flexibility of the adhered mortar.

Micromechanical modeling via Mori-Tanaka homogenization reveals diminishing returns when increasing matrix stiffness beyond ~45 GPa, shifting the optimization focus from the matrix to the aggregate. Among evaluated strategies, carbonation curing emerges as one of the most promising approaches, achieving a 15–25% stiffness recovery by chemically densifying the governing phases. This is further validated by the "Eco-Stiffness Index," which identifies carbonation-based treatments as the optimal solution for balancing structural rigidity with embodied carbon reduction.

Ultimately, this review advocates for a paradigm shift: treating E_c as an aggregate-governed property and transitioning from empirical correlations to physics-informed, data-driven predictive frameworks. Future research must prioritize the integration of carbonation into industrial-scale recycling and the adoption of aggregate-specific stiffness modifiers in structural design codes to ensure the safe, large-scale implementation of HP-RAC.

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ЖЕСТКОСТЬ ВЫСОКОТЕХНОЛОГИЧНОГО БЕТОНА НА РЕЦИКЛИРОВАННЫХ ЗАПОЛНИТЕЛЯХ, ОПРЕДЕЛЯЕМАЯ СВОЙСТВАМИ ЗАПОЛНИТЕЛЯ: МЕХАНИЗМЫ, СИНТЕЗ ДАННЫХ И ПЕРСПЕКТИВЫ МОДЕЛИРОВАНИЯ

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Модуль упругости бетона на рециклированных заполнителях (БРЗ) остается существенно ниже, чем у бетона на природных заполнителях (БПЗ), даже когда прочность на сжатие полностью восстанавливается за счет высокотехнологичного проектирования состава смеси. Этот дефицит жесткости критически ограничивает применение экологически безопасного высокотехнологичного бетона (S-HPC) в строительных конструкциях, особенно при расчете по предельным состояниям эксплуатационной пригодности (вторая группа предельных состояний).

В данном обзоре обобщаются экспериментальные, реконструированные и физически обоснованные данные, опубликованные в период с 2019 по 2025 год, для разъяснения ведущих механизмов снижения модуля упругости в высокотехнологичном БРЗ (HP-RAC). Для объяснения увеличения податливости, вызванного прилипшим *старым раствором и двойными контактными зонами (ITZ), принята пятифазная микроструктурная модель. Чтобы преодолеть разрозненность и вариативность экспериментальных данных, применяется методология расширения данных, сочетающая реконструкцию литературных источников (n ≈186).*

Результаты показывают, что модуль упругости в HP-RAC преимущественно контролируется податливостью рециклированного заполнителя, а не прочностью цементной матрицы, демонстрируя явление насыщения жесткости при превышении модулем упругости матрицы значения около 45 ГПа. Карбонизация, наномодифицирование контактных зон и гибридное дисперсное армирование критически оцениваются как способы восстановления жесткости, причем карбонизационное твердение показывает оптимальное соотношение между повышением жесткости и эффективностью связывания углерода.

В обзоре обосновывается необходимость перехода от эмпирических формул, основанных на прочности, к микромеханическим и физически обоснованным подходам при одновременном признании ограничений реконструированных данных и гетерогенных литературных источников.

Ключевые слова: *модуль упругости, бетон на рециклированных заполнителях, высокотехнологичный бетон, микромеханика, физически обоснованное машинное обучение, экологическая устойчивость.*