American Journal of Civil Engineering and Constructions (AJCEC)

ISSN: 3070-0884 (ONLINE)

VOLUME 2 ISSUE 2 (2026)

PUBLISHED BY
E-PALLI PUBLISHERS, DELAWARE, USA

American Journal of Civil Engineering and Constructions (AJCEC)

Volume 2 Issue 2, Year 2026
ISSN: 3070-0884 (Online)
DOI: https://doi.org/10.54536/ajcec.v2i2.8460
https://journals.e-palli.com/home/index.php/ajcec

Recycled Aggregate Concrete: Performance, Durability & Sustainability

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Article Information

Received: June 20, 2026

Accepted: August 29, 2026

Published: September 18, 2026

Keywords

Circular Economy, Construction Demolition Waste, Durability, Interfacial Transition Zone, Life-Cycle Assessment, Recycled Aggregate Concrete, Sustainability

ABSTRACT

Both construction and demolition (C&D) activity and the production of concrete rely on huge amounts of natural sand and gravel. The use of Recycled Aggregate Concrete (RAC) with Recycled Aggregate (RA) from C&D waste could provide a pathway to addressing both pressures simultaneously. This review gathers and aggregates the latest scientific studies (2020-2026) published in the four fields of RAC: mechanical, durability, microstructural and environmental performance aspects. In general, the RAC has lower compressive strength, tensile strength, flexural strength, and bond strength than natural aggregate concrete (NAC), and this strength decrease becomes larger as the RAC replacement ratio rises, as indicated in many studies; about 20-30 percent replacement is considered a practical optimum level between strength retention and utilization of waste, in many reviews. The main reason for this lack is the interfacial transition zone (ITZ) that is present around recycled particles that is more porous and prone to crack because of the presence of the old mortar adhered to it. Also, permeability to chloride, sulfate ions and carbonates can differ, with RAC generally being slightly more permeable than NAC, although treatments of the aggregates like carbonation curing, nano-silica impregnation, and mechanical pre-treatment can significantly reduce the differences. Life-cycle assessment (LCA) studies have always shown that recycled aggregate generates significantly less (typically 50 to 65 percent less) greenhouse gas and requires significantly less (typically 50 to 65 percent less) non-renewable energy than quarrying virgin aggregate, depending on the transport distance and processing method. Limited use of RCA is now incorporated into regulations like BS8500-2, RILEM recommendations, ACI guidance, and a number of national standards, which are conservative, and harmonized quality-classification systems are still being worked out. The review concludes that RAC is a technically possible and environmentally acceptable material at moderate replacement rates, depending on the quality of the aggregates used and the correct treatment or mix-design compensation if necessary.

INTRODUCTION

Background and Rationale

Concrete is the most widely used construction material in the world, and usually contains from 60 to 75 percent natural aggregates (sand and crushed stone). These materials are associated with the pressure of extraction, loss of habitat, emissions from transport, and C&D wastes remaining in landfills. Both these problems can be solved by using Recycled Aggregate Concrete (RAC) in which natural aggregates are replaced by aggregate reclaimed from crushed concrete or from mixed demolition wastes. The interest in RAC has increased significantly over the past 5 years, as a result of policy for circular economy, the tighter regulation of landfill and the national reduction targets on carbon.

Recycled aggregates are commonly available in two categories: Recycled Concrete Aggregate (RCA) which is mostly crushed concrete contaminated with very low content of other C&D waste; and Mixed Recycled Aggregate (MRA) which is a mix of concrete, masonry and other C&D waste materials that are heterogeneous. The properties of the old adhered mortar that remain on the surface of the RCA particles cause it to have higher water absorption, lower density and more variation than natural aggregate, which then contribute to the fresh and hardened concrete properties.

Research Objectives

- A synthesized information of the effects of recycled aggregate type and replacement ratio on the mechanical properties of concrete (compressive strength, tensile strength, flexural strength, bond strength).
- For assessing durability of RAC under chloride ingress, sulfate attack, carbonation and freeze-thaw exposure and effectiveness of the methods of treating the aggregate.
- To conduct review of environmental performance of RAC using life-cycle assessment (LCA) studies, such as GHG emissions and embodied energy.
- To give a summary of the existing regulations and practical challenges for better use of RAC for structural applications.

LITERATURE REVIEW

This review is topical rather than study based. It first examines the classification of recycled aggregates, as well as the reasons for their variability, because most of the mechanical, durability and environmental findings

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presented later in this document are based on this variability. It then examines mechanical performance, the interfacial transition zone (ITZ) and microstructure, durability, environmental/LCA performance, regulation and implementation challenges in sequence, highlighting areas of consensus and differences in studies and explaining why. Individual studies are reported numerically when there is a pattern or a mismatch in the field, but a comparative synthesis and an interpretation of the pattern is deferred to the Results and Discussion section and is included within the context of the interpretation of the review itself.

Classification and Quality of Recycled Aggregates

Aggregate quality is the major factor affecting the performance of RAC, so there are a number of national standards controlling its recycled aggregate composition in order that it can be used for structural concrete. A Recycled Concrete Aggregate (RCA) is defined as material that has 5 percent or less material fines and 0.5 percent or less lightweight material or asphalt content, and 1 percent or less other foreign material content according to British standard BS 8500-2. Based on a systematic review conducted on the literature from the year 2010–2020, it is found that the composition of RCA material is consistent of cleaner concrete waste stream which gives better mechanical result compared with the other waste stream where the composition of concrete is mixed which gives scattered and generally lower mechanical result.

Mechanical Performance

Major conclusion from the most recent reviews is that RAC does not perform as well as natural aggregate concrete (NAC) in compressive, tensile, flexural, bond and shear strength and the magnitude of this reduction correlates closely with the percent of the recycled aggregate by value. Neupane *et al.* (2023) reviewed the applications of RAC structures and reported that the compression strength of RAC made with normal-strength mixes was around a 33 percent reduction from that of NAC, while the compression strength of RAC made with high-strength mixes was around a 27 percent reduction from that of NAC; bond strength between rebar and RAC was reported as approximately 15 percent lower than with comparable NAC, but in a direction and size dependent on rebar diameter. The effect of replacement ratio on the shape of the stress-strain response was also observed by Bai *et al.* (2020) where the peak stress

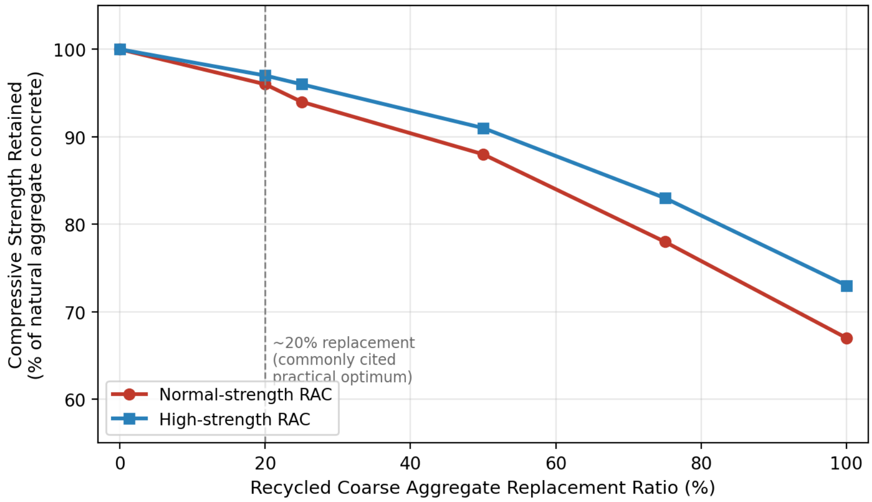

Figure 1: Figure is an illustrative curve synthesized from the ranges reported by the reviewed studies (e.g., Xing *et al.,* 2022; Akbulut *et al.,* 2025) to visualize the general trend; it does not represent raw data from a single experiment

decreases with increase in replacement ratio, but recovers partially with further increase in replacement ratio; the critical replacement ratio was found to vary between 25 and 50 percent of replacement ratio depending on the water-cement ratio used.

Nonetheless, there is a consensus from several reviews about a compromise: Nonetheless, several reviews come to an obvious compromise: Akbulut *et al.* state in a critical review of RAC properties published in 2025 that a 20 percent replacement ratio is a good balance between mechanical properties and the intention of using recycled material, as the reduction in strength at this replacement level is acceptable, while benefits for the environment and waste diversion are still significant. The guidance of the Mineral Products Association (UK) also allows for up to 20 per cent coarse RCA to be automatically adopted without additional testing, with a similar consensus being reached in practice.

Fine recycled aggregate is treated far more cautiously than coarse recycled aggregate in the literature. Aggregate particles smaller than about 150 micrometres substantially increase water demand and drying shrinkage, so fine RCA below 2 mm is used only sparingly, and several standards leave its use to project-specific specification rather than blanket approval.

The Interfacial Transition Zone (ITZ) and Microstructure

The interfacial transition zone (ITZ), a thin, porous zone of hydration products around each aggregate particle is the main cause of mechanical shortfall of RAC. There is

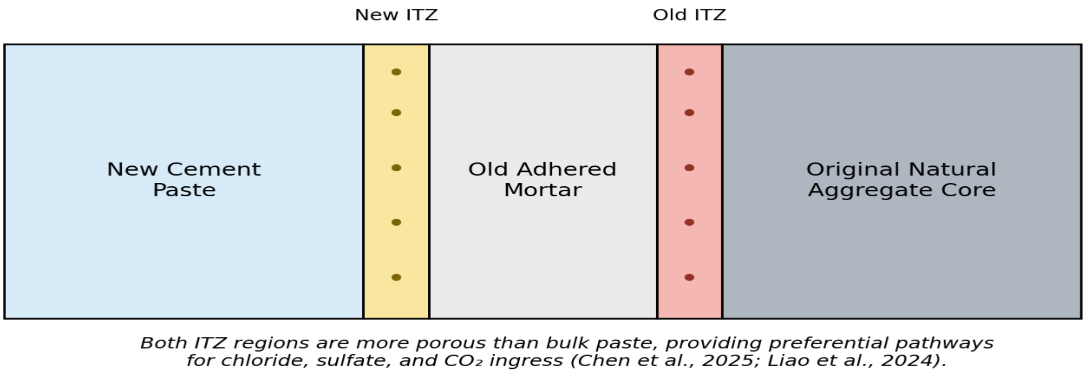

Figure 2: Schematic Illustration of the New and Old Interfacial Transition Zones (ITZs) in Repaired Mortar

one ITZ in natural aggregate concrete which is between the virgin aggregate and the new cement paste. A second, typically weaker ITZ is formed in RAC, however, between the old adhered mortar and the new cement paste, as shown schematically in Figure 3 and has been described in the literature as a 'double ITZ'. Within this zone, Chen, Zhang, and Yan (2025) found porosities up to 30 percent greater in RAC products than in natural aggregate concrete, which accounts for a significant amount of the macro-scale strength and durability issues that have been observed.

Durability Performance

Resistance to chloride and sulfate. The above mentioned porous ITZ is the main reason for multiple studies indicating that untreated RAC is more susceptible to chloride penetration, sulfate-induced expansion and carbonation than NAC. The authors Chen *et al.* (2025) performed dry-wet cycling tests on recycled fine aggregate concrete with three different strength grades, and concluded that lower strength mixes (approx. 20 MPa) experienced over 60 per cent strength reduction after 70 cycles of performance, while a 60 MPa mix of the same concrete type actually gained strength from the exposure, proving strength and density of the base mix to be more important in driving durability than the presence of recycled aggregate. The sulfate-resistance results from this body of work did not take into consideration the effect of adding RCA to the concrete; an independent long-term field study indicated that, if partially submerged in sulfate-contaminated soil, the sulfate resistance of the concrete was not significantly affected by the presence of RCA.

Carbonation and freeze-thaw. It has been reported that the carbonation depth of recycled coarse aggregate concrete is up to 2.5 times that of similar NAC concrete under similar exposure conditions, due to the more porous ITZ facilitating carbon dioxide to travel through the concrete. A study performed on using permeable crystalline treatment on to the coarse aggregate found that as higher percentages of RCA were replaced with the coarse aggregate, the freeze-thaw resistance also decreased. Another study performed found that when the coarse aggregate was impregnated with these crystalline materials, the freeze resistance and carbonation resistance were measurably higher than the untreated coarse aggregate.

Aggregate treatment methods. Since untreated RCA quality is the most important, there has been an increasing amount of research on pre-treatment of recycled aggregate prior to incorporation. About 15 percent, respectively over 30 percent, of the SPT were lowered by carbonation, respectively, carbonation combined with

Table 1: Selected mechanical and durability findings from recent RAC literature (2022-2025

Study / Source	Aggregate / Treatment	Replacement or Dosage	Key Reported Effect
Piccinali *et al.* (2022)	RCA vs. Mixed Recycled Aggregate (MRA)	Systematic review, 2010-2020	RCA more homogeneous and better suited to structural use than MRA
Neupane *et al.* (2023)	RCA, general	Normal- and high-strength mixes	~33% lower compressive strength (normal strength); ~27% lower (high strength); ~15% lower bond strength vs. NAC
Akbulut *et al.* (2025)	RCA, various ratios	0-100%	~20% replacement identified as practical optimum across studies reviewed
Bai *et al.* (2020)	RCA	0, 25, 50, 100%	Peak stress initially decreases then partially recovers; transition ratio shifts with w/c ratio
Chen, Zhang & Yan (2025)	RCA + carbonation / 2% nano-silica	Nano-silica 2% by cement weight	ITZ porosity up to 30% higher than NAC; nano-silica cuts sulfate penetration depth >30%, raises strength ~15% after exposure

Liao *et al.* (2024)	RCA + permeable crystalline material	0, 50, 100% replacement	Freeze-thaw and carbonation resistance decline with replacement ratio; crystalline treatment improves both
Chen, Adama *et al.* (2025)	Recycled fine aggregate concrete (RFAC)	20, 40, 60 MPa mix grades	20 MPa mix lost ~60% strength after 70 sulfate cycles; 60 MPa mix gained ~2.5% strength
Oikonomopoulou *et al.* (2022)	RCA with adhered-mortar removal	Various replacement levels	Sharper 90/365-day strength gain; drying shrinkage reduced ~15%; mass loss reduced ~10%

nano-silica (2 percent by cement weight), correlates Chen, Zhang and Yan (2025). Oikonomopoulou *et al.* (2022) in their study on mechanically treated RCA that adhered mortar was partially removed before mixing, reported some better gains in 90-day and 365-day compressive strength than was achieved for untreated RCA mixes, and a 'shrinkage-controlling' effect on the drying strain (by nearly 15 per cent) and mass loss (by about 10 per cent) in comparison with the reference mix.

Summmary of Reported Mechanical and Durability Findings

Environmental Performance and Life-Cycle Assessment

The most common approach to calculate the environmental cost of recycled aggregate (RA) substitution is to use life-cycle assessment (LCA), usually carried out in accordance with the framework of the International Organization for Standards (ISO) 14040/14044. Based on a cradle-to-gate assessment in two Portuguese regions, Dias et al (2021) found the greenhouse gas emissions from recycling coarse aggregate (ca) were 65 per cent lower than the emissions from the production of natural aggregate (na), while the use of non-renewable energy (nre) was 58 per cent lower. In Chinese case studies compiled by Ma *et al.* (2025), comparable magnitude reductions (around 65 percent for carbon emissions) are reported, but recycling plants used at the far end of the waste as opposed to mobile crushing plants, as well as the distance to the concrete plant, can significantly alter the results.

In a closed loop CE-LCA study carried out by Ding *et al.* (2016) in China, they have stated that the use of recycled aggregate with the use of supplementary cementitious material (SCM) significantly amplifies the environmental advantages in both the NAC and RAC, with the two greatest contributors being the cement content and the transportation distance. Recent machine-learning generated LCA studies from Lv, Mu, Du, Song, and Niu have also presented the possibility for a 'passive' removal of carbon dioxide during storage by carbonation of the old mortar coating and thus make a portion of the total emissions between the lace and the concrete in place. In a critical review of RAC LCA methodology Xing, Tam, Le, Hao, and Wang (2022) highlight the continued shortcomings in the field: the majority of published works focus on only part of the life cycle (cradle-to-gate), but not all the way to gate-to-gate, and the many published studies fail to clearly report on the method used to allocate the material flow between the recycled and virgin streams, making direct

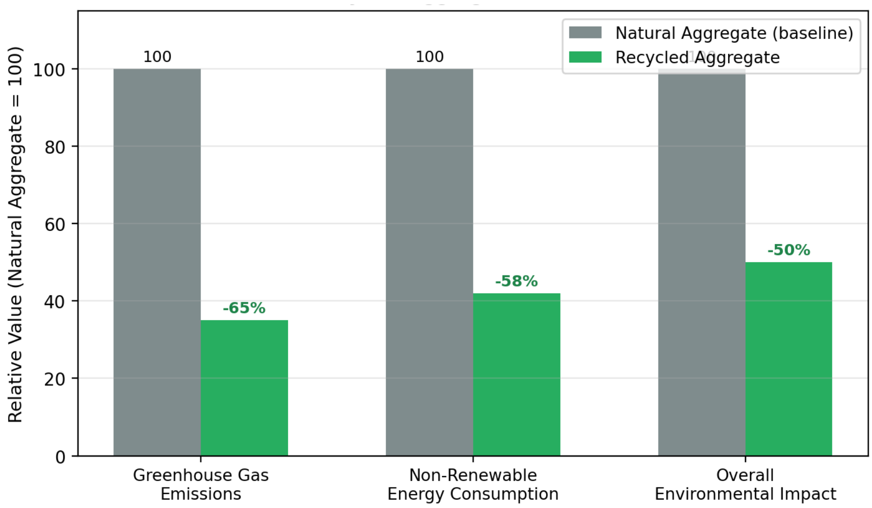

Figure 3: Environmental Performance Comparison: Natural vs. Recycle aggregate Production

Table 2: Reported environmental performance indicators for recycled aggregate production and use

Indicator	Reported Reduction vs. Natural Aggregate	Source Context
Greenhouse gas emissions (aggregate production)	Up to ~65%	Dias *et al.* (2021); Ma *et al.* (2025)

Non-renewable energy consumption	Up to ~58%	Dias *et al.* (2021)
Overall environmental impact (vs. crushed stone)	Up to ~50%	Dias *et al.* (2021)
Largest emission contributors (concrete-level, not aggregate-only)	Cement content & transport, not aggregate source itself	Ding, Xiao & Tam (2016)
Carbon sequestration during RCA storage	Partial offset via carbonation of adhered mortar	Lv *et al.* (2026)

comparisons between studies difficult.

They conclude that using recycled concrete aggregate (RCA) instead of landfilling it can help to reduce energy consumption by up to 85 percent and the associated use of landfill space, and report on a comparative LCA that shows energy consumption for RAC is about 35 to 42 percent less per cubic metre when compared to natural aggregate concrete, depending on maximum aggregate size used, but that RAC actually consumes 24 to 26 percent more energy per cubic metre than natural aggregate concrete, with a slight increase in acidification potential that is not often reported in other studies.

Regulatory Standards and Industry Practice

National (regional) standards for the use of recycled aggregate have evolved independently and whilst a number of standards have now allowed for the use of RAC in structural applications, most are rather conservative. The United Kingdom has enacted a directive in BS 8500-2 that permits up to 20 per cent of the coarse natural aggregate of specified concrete grades RC20/25 through RC40/50 to be automatically substituted with coarse RCA that meets the standards. This is extended to higher levels of replacement as specified in the project. RILEM's TC121-DRG recommendations, DIN 4226-100 in Germany and similar standards in Denmark, Spain, Switzerland, Belgium and the Netherlands are the parallel regional efforts; the U.S. ACI Committee 318 states that the quality of the RCA can be influenced by the strength of the original concrete, the amount of contamination and the crushing and recovery method used. The Japanese distinction is between lower quality Class L material (which can only be used for backfill and levelling applications), and higher quality Class H material which can be used sin normal structural concrete in both the JIS A5021 and A5023 specifications.

One aspect that is common to all of these systems is that the design codes for reinforced RAC members, such as shear and flexural capacity equations derived from codes like GB50010, ACI 318-19 and Model Code 2010, are generally conservative when directly applied to RAC because they were calibrated using test data from NAC. The conservatism helps ensure safety margins and may underestimate the actual capacity of well-controlled RAC mixes, hence the continued research interest in RAC specific design requirements instead of an overall safety reduction of NAC design equations.

Practical Implementation Challenges

Variability in the quality of the aggregates: The quality of the aggregate can differ between source demolition sites, at the source of the concrete and its original strength and depending on the method of crushing; consistent mix design is difficult unless there is a strong regime in place to provide aggregate classification and testing.

Increased water absorption: Water absorption is increased by using adhered old mortar in RCA, thus higher mixing water allowances are required or use of superplasticizers are needed to ensure workability and control the effective water-cement ratio.

Cost and logistics of treatment: There are additional processing steps and costs involved in aggregate treatments like carbonation curing or impregnation with nano-silica to enhance RAC performance that may diminish economic benefits of re-using waste material.

Fragmented regulation: Lack of an international, harmonised RCA quality classification standard is slowing adoption as designers in many jurisdictions have to use the conservative design equations based on the NAC or hire for project specific testing.

There is limited long-term field data: Multi-decadal field testing, such as the sulfate-soil test (described above), to confirm laboratory extrapolation is still relatively scarce and needs to be expanded.

MATERIALS AND METHODS

This review is a synthesis of the literature and not an original laboratory study. Sources were identified by making use of structured keyword searches in peer-reviewed journals, review papers and standard documentation, published for the most part in the last ten years (2020-2026) together with a small number of earlier foundational studies cited by the more recent papers. To identify quantitative mechanical or durability data, or environmental data, from peer-reviewed studies, and to identify more recently published systematic or critical reviews that synthesized a significant number of primary studies. Results are presented in a thematic way, in sections mechanical performance, microstructure, durability, environmental/ LCA performance, and regulatory practice, and they are presented comparatively, because they were not presented as a detailed study-by-study description.

This is similar to the strategy that is followed in recent RAC review papers, which is to identify convergence in findings, to quantify the magnitude of the effect that is typical in the field (e.g., percentage change of strength per replacement ratio) and to draw attention to gaps (e.g., a lack of long-term field verification or varying LCA allocation approaches) where new experimental data would be useful.

RESULTS AND DISCUSSION

Discussion and Synthesis

The literature, taken as a whole, offers a clear message: At high replacement levels, property-for-property, recycled aggregate concrete (RAC) is technically less desirable than natural aggregate concrete (NAC); however, the disadvantage is controllable, predictable, and correctable at moderate replacement levels. The mechanical strength deficit, increased permeability and accelerated carbonation and chloride/sulfate attack in independent studies have a common cause due to the presence of the ITZ around particles obtained from recycling. What is encouraging from a research perspective is this mechanistic consistency, i.e., interventions based on improving the quality of ITZ (by increasing the carbonation of aggregates, by adding nano-silica to the cement, by removing adhered mortar or by modifying the cement with SCM) commonly have a simultaneously positive effect on mechanical as well as durability properties.

The environmental case is arguably much more uniform and compelling than the mechanical case, as multiple and independent regional studies have shown greenhouse gas and energy savings to be broadly similar (50 to 65 percent reduction in the aggregate production alone). But the reviewed LCA literature indicates that these aggregate savings can be negated at the whole concrete level if the re-use is carried out at a distance, with high transport distances, energy used in concrete processing and when not accompanied by the use of SCM to reduce the actual binder in the concrete.

Practically, when a number of independent reviews have recommended a replacement ratio around 20 per cent as being in the 'low-risk' range, and the UK's automatic replacement ratio is exactly the same for designated concrete classes, it appears to be a defendable level of replacement ratio to begin with when sustainability is considered, with higher replacement ratios still possible but needing some aggregate treatment, mix-design compensation or validation testing at the project level.

CONCLUSION

The use of recycled aggregate concrete is a viable option to reduce virgin materials and construction and demolition waste, but cannot be used as a natural aggregate concrete without engineering consideration. The loss of mechanical strength and durability is the major mechanism and tied to the porosities at the particles' interfaces, and this loss increases with the replacement ratio. At the present time, a replacement ratio of approximately 20 percent, consistent with a number of regulations, appears to provide the optimum tone retention/sustainability benefit balance for use in routine structures; ratios exceeding 20 percent can be accomplished through targeted aggregate treatment (such as carbonation, nano-silica impregnation, or mechanical mortar removal) and mix-design modifications. Results from the life-cycle assessment (LCA) always point to RA as the preferred material for production with benefits varying significantly depending on the logistics of transporting the material and binder used. Long-term field verification of accelerated laboratory durability testing, development of harmonized international aggregate-quality classification systems, provisions for structural design of RACs, and not conservative adaptations of natural-aggregate-concrete design equations, should be encouraged and incorporated in future work.

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