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Recycled Coarse Aggregate Concrete Incorporating Ground Granulated Blast Furnace Slag: A Review of Workability, Compressive Strength and Mix Proportioning

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Abstract

The combined use of recycled coarse aggregates (RCA) and ground granulated blast furnace slag (GGBS) offers a route to reduce dependence on virgin aggregates and Portland cement in concrete. However, increasing recycled content does not necessarily improve engineering performance. This critical narrative review examines workability, compressive strength and mix proportioning in Portland cement concrete incorporating RCA and GGBS. Selected experimental publications are evaluated alongside foundational studies on aggregate moisture, parent concrete quality and slag reactivity. Evidence is organised by material characteristics, water management, replacement basis, curing age and concrete application. The comparison shows that apparently conflicting findings frequently reflect differences in the reference mixture or experimental controls. Improvements relative to an RCA mixture without slag should not be interpreted automatically as improvements relative to natural aggregate concrete. Similarly, strength development at later ages and resistance to transport of aggressive agents represent different performance outcomes. A comparison framework is proposed using explicit replacement ratios, effective water-to-binder ratio, matched reference mixtures and age-specific strength retention. The reviewed evidence supports performance-based selection of RCA and GGBS contents rather than a universal optimum percentage. Future work should prioritise complete factorial experiments, independent batches, realistic slump retention, traceable aggregate sources and equal-performance environmental assessment. The review provides an interpretive basis for designing and reporting experiments on RCA–GGBS concrete without conflating material substitution, strength recovery and sustainability.

Keywords: recycled coarse aggregate; ground granulated blast furnace slag; recycled aggregate concrete; workability; compressive strength; mix proportioning; critical review.

1 Introduction

Concrete made with recycled coarse aggregate must be evaluated as a composite whose constituents retain part of their previous service history. Replacing a natural stone particle with a particle containing old mortar changes more than the source of the aggregate. Moisture exchange and the condition of the recycled material can influence fresh and hardened performance. Poon et al. [1] investigated air-dried, oven-dried and saturated surface-dry aggregate states, demonstrating the importance of moisture condition for interpreting slump and strength. Etxeberria et al. [2] studied mixtures with 0%, 25%, 50% and 100% recycled coarse aggregate designed to achieve comparable compressive strengths. Their experimental approach illustrates why replacement percentage alone is insufficient to define a concrete mixture.

Source quality provides a second reason for caution. Padmini et al. [3] investigated recycled aggregates obtained from parent concretes of different strengths and aggregate sizes. Chakradhara Rao et al. [4] evaluated field material recovered from a demolished reinforced concrete culvert. These investigations represent different levels of control over the source material. A review concerned with practical mix proportioning must therefore distinguish laboratory-controlled

recycled aggregate from field-derived aggregate rather than treat both as interchangeable evidence.

Ground granulated blast furnace slag introduces an additional variable through the binder. Escalante et al. [5] examined slag reaction under different hydration conditions, while Lothenbach et al. [6] discussed the influence of composition, fineness, reactive phases and solution chemistry on supplementary cementitious material reactions. In the present paper, GGBS and GGBFS refer to ground granulated blast furnace slag used as a binder constituent. They do not refer to air-cooled slag used as aggregate.

The purpose of this review is to explain how RCA and GGBS contents should be interpreted together when evaluating slump and compressive strength. Its contribution is a structured distinction between three questions: whether slag improves a given RCA concrete, whether the combined mixture matches a natural aggregate reference, and whether an acceptable mixture reduces resource use or environmental burden. These questions require different comparisons. A favourable answer to one cannot be used as evidence for all three.

The review addresses four questions. Which material and processing variables most strongly complicate comparisons? Under what conditions does slag incorporation accompany strength recovery or delayed strength gain? Why do studies identify different promising proportions? What minimum reporting and comparison procedures would make future experiments more useful? The emphasis is on interpreting combined substitution in conventional concrete, with modified systems used to clarify the boundaries of transferability.

2 Review approach and scope

2.1 Literature identification

This paper is a focused critical narrative review, not a systematic review or meta-analysis. Literature identification used targeted web searches, publisher article records, accessible abstracts and full text where available, together with institutional publication repositories. Bibliographic details were checked against publisher records, institutional records and DOI registration metadata. Searches combined terms including recycled coarse aggregate, recycled aggregate concrete, ground granulated blast furnace slag, GGBS, GGBFS, workability, compressive strength, moisture state, curing and mix proportioning. Reference checking was completed on 5 November 2026. The selected references span 2001–2026; this range describes the included evidence rather than an exhaustive search window.

The review is organised around combined aggregate and binder substitution. Primary publications were used for published findings, and no new cube-test results are introduced. Literature selection was purposive: foundational studies explain material behaviour, while direct and application-specific experiments support the comparative discussion. Database screening totals, duplicate-removal counts and formal risk-of-bias scores are not available for this narrative approach.

2.2 Inclusion boundaries and evidence handling

Priority was given to experimental studies of Portland cement concrete incorporating coarse recycled concrete aggregate and GGBS. Foundational experiments on moisture condition, aggregate source and mixing were included to explain mechanisms and comparison problems. Self-consolidating, fibre-reinforced, lime-activated and mass concrete studies were retained as contextual evidence and are identified separately. Their results were not pooled with conventional binary RCA–GGBS concrete. Alkali-activated slag concrete without a comparable Portland cement binder, slag aggregate concrete and studies involving only recycled fine aggregate were outside the main synthesis.

Detailed mixture quantities or numerical effect sizes are reported only where supported by the accessible source material. Where only an abstract or article preview was accessible, interpretation is

restricted to the stated design and findings. Thus, the review does not provide a complete extraction of all water corrections, admixture dosages or specimen statistics from every cited experiment. This limitation prevents a defensible pooled dose–response model. The tables are an evidence map, not a statistical ranking of studies.

Table 1 Evidence groups and their roles in the review

Evidence group	Representative references	Purpose and boundary
Aggregate and water control	[1], [2], [3], [4], [7]	Explain source, moisture and processing effects; do not establish a GGBS optimum.
Binder reaction	[5], [6]	Explain why slag performance depends on material characteristics and hydration conditions.
Direct RCA and slag experiments	[8], [9], [10], [11], [12]	Provide the main evidence for combined substitution and strength–durability distinctions.
Modified concrete systems	[13], [14], [15], [16], [17]	Supply application-specific context; additional constituents or exposure conditions limit transfer.
Environmental and recent integrated assessment	[18], [19]	Support comparison of engineering performance with environmental objectives.

3 Materials and mechanisms relevant to interpretation

3.1 Aggregate history and moisture exchange

A recycled aggregate specification should describe the actual feedstock, processing route and measured properties. The work of Padmini et al. [3] makes parent concrete quality a relevant explanatory variable, while the field study of Chakradhara Rao et al. [4] demonstrates the value of evaluating material obtained from a real demolished structure. Together, these studies support source traceability as a requirement for interpretation. They do not justify assuming that every recycled aggregate has the same strength penalty or that one source represents construction and demolition waste generally.

Moisture condition must be defined at mixing. Poon et al. [1] associated initial slump with free water and slump loss with aggregate moisture state. For review purposes, this means that a nominally identical water ratio can conceal a different supply of water to the fresh paste. The distinction is particularly relevant when a study reports water absorption measured over one duration but mixes concrete over a much shorter interval. Absorption capacity and water actually absorbed during mixing should not be used as synonymous quantities.

3.2 Slag reaction and the role of curing

GGBS is a latent hydraulic binder constituent whose reaction depends on the surrounding cementitious system. The chemistry review of Lothenbach et al. [6] provides a basis for distinguishing physical particle effects from subsequent chemical reaction. Escalante et al. [5] showed that slag reaction varied with hydration conditions and slag characteristics. Accordingly, two mixtures with the same slag mass fraction need not develop strength at the same rate. Differences in curing temperature, moisture availability and slag reactivity are plausible explanations that should be tested rather than assumed.

The interpretive implication is temporal. A comparison made at an early construction age answers a different question from a comparison made after extended curing. A slag mixture can display continuing strength development without reaching the strength of the reference mixture. Conversely, a mixture that meets a specified later-age requirement may still be unsuitable for an early formwork-removal schedule. A review should report the measured age and reference condition whenever it describes strength recovery.

3.3 Interfaces and processing as interacting variables

Tam et al. [7] proposed a two-stage mixing approach to improve recycled aggregate concrete through changes in the cement slurry distribution and interfacial region. This is evidence that the production sequence is a meaningful experimental variable. It does not show that slag alone produces the same effect. In comparing RCA–GGBS mixtures, the mixing method should therefore be recorded alongside aggregate replacement and binder composition.

An interfacial explanation is most useful when it connects an observation to an independent measurement. Strength testing measures the response of the specimen as a whole. A micrograph samples a small region. Neither should be substituted for the other. In the synthesis proposed here, microscopy, microhardness or related measurements support a mechanism only when their sampling locations and corresponding mixtures are identifiable. A claim that every strength increase proves interfacial densification would exceed the available mechanical evidence.

4 Workability of RCA–GGBS concrete

4.1 Initial consistency and consistency over time

Workability should first be separated into the measured fresh property and the time at which it was measured. A single slump value is an initial consistency observation; it does not describe retention during transport or placement. Poon et al. [1] showed why aggregate moisture condition matters for slump loss. A practical comparison should consequently state the elapsed time after water addition, aggregate conditioning, mixing duration and whether subsequent water or admixture was added.

For the same reason, a higher slump should not automatically be attributed to slag. Changes in paste volume, water correction or chemical admixture can alter the result. The proposed interpretation is to identify the experimental control before stating the trend. At fixed effective water content, one examines the response of the material system. At matched target consistency, one examines the additional water or admixture required to achieve an operational condition. Both are legitimate experiments, but they answer different questions.

4.2 Why a universal workability benefit is unsupported

Huo et al. [15] investigated mass concrete containing a binder with 75% GGBFS and recycled aggregates. Their study reported lower slump for the combined high-slag recycled-aggregate condition than for a natural-aggregate slag reference. This finding is a useful counterexample to an unconditional statement that adding GGBS always improves workability. Its application and aggregate configuration must nevertheless be retained when comparing it with ordinary RCA concrete.

Khodair and Bommareddy [13] studied self-consolidating concrete containing RCA and high volumes of fly ash or slag. This concrete category requires its own fresh-performance interpretation. Conventional slump, slump flow, passing ability and segregation resistance are different measurements. A review should not place all of them on a single workability axis merely because the authors describe a mixture as more workable.

Table 2 Controls needed to interpret fresh concrete results

Comparison choice	What it can show	What must be controlled or reported
Fixed effective water-to-binder ratio	Consistency response at a defined available water level	Aggregate moisture, absorption correction and water contained in admixtures.
Matched target slump	Mixture adjustments needed for comparable placement consistency	Actual water, admixture solids and resulting binder ratio.
Repeated measurements after mixing	Consistency retention over the tested interval	Measurement times, retempering and temperature.
Self-consolidating mixtures	Flow, passing and stability performance	Test-specific criteria rather than conversion to ordinary slump.

Table 2 is the comparison framework proposed in this review; it is not a reported dataset. Its purpose is to make the operational meaning of workability explicit before an aggregate or slag effect is inferred. A useful experimental paper would present both the achieved consistency and the quantities needed to obtain it.

5 Compressive strength and the interpretation of combined substitution

5.1 Direct evidence from conventional blended mixtures

Kou et al. [8] compared natural and recycled aggregate concrete incorporating several mineral admixtures. Their reported 55% GGBS replacement reduced compressive strength while improving durability-related performance. This study is important because it separates a favourable transport-related response from a favourable mechanical response. Slag incorporation should therefore not be described as complete strength compensation whenever only durability improves.

Majhi et al. [9] examined a 16-mixture matrix combining RCA levels of 0%, 25%, 50% and 100% with GGBFS levels of 0%, 20%, 40% and 60%. They identified 50% RCA with 40% GGBFS as meeting the desired mechanical properties in their programme. This is a supported example of an acceptable tested combination. It is not evidence that the same proportions maximise strength for every aggregate source, binder or curing regime.

Majhi and Nayak [10] extended examination of GGBFS-based recycled aggregate concrete to bond, durability and microstructural characteristics. Their inclusion of these outcomes broadens the performance question beyond cube strength. Lin and Wu [11] studied slag contents from 0% to 75% and reported reduced strength of recycled aggregate mixtures relative to natural aggregate mixtures, with stronger later-age gains for slag-containing concrete than for corresponding mixtures without slag. The distinction between later gain and absolute strength remains essential.

Ann et al. [12] investigated recycled aggregate concrete incorporating pulverized fuel ash and GGBS. Their findings demonstrate that useful strength and durability responses can be obtained under particular binder conditions. Because different supplementary materials were considered, the review treats their results by mixture identity rather than combining all modified binders into a general slag effect.

Table 3 Selected experimental evidence relevant to combined RCA and GGBS use

Study	System or tested levels	Supported interpretation
Kou et al. [8]	Mineral-admixture comparison; 55% GGBS condition	Durability improvement and compressive-strength recovery are distinct outcomes.
Majhi et al. [9]	RCA 0/25/50/100%; GGBFS 0/20/40/60%	A factorial matrix supports comparisons within the tested material system.
Majhi and Nayak [10]	RCA with GGBFS; bond and microstructure included	Mechanical acceptance should be related to the intended structural function.
Lin and Wu [11]	Slag 0/15/30/45/60/75%; natural and recycled aggregate	Later-age gain does not necessarily mean parity with the natural aggregate reference.
Ann et al. [12]	Recycled aggregate with PFA or GGBS	Binder identity must remain explicit when interpreting modified concrete.
Majhi and Nayak [14]	High-volume slag and RCA with lime activation	Activation changes the binder system and prevents simple transfer to binary blends.
Huo et al. [15]	Mass concrete with 75% GGBFS binder	High-slag application context changes the relevant performance priorities.
Ahmad et al. [16]	RCA, GGBS and steel fibres	Observed gains belong to a multicomponent system.
Tung et al. [17]	GGBS recycled concrete after elevated temperature	Residual strength is exposure-specific evidence.
Chaitanya et al. [19]	Staged RCA investigation with 20/25% GGBS	A selected combination need not establish a full RCA–GGBS response surface.

5.2 Appropriate reference mixtures

A central synthesis of this review is that at least three reference questions should be distinguished. The first compares the combined mixture with natural aggregate concrete containing Portland cement only. The second compares it with RCA concrete containing no slag. The third compares it with natural aggregate concrete having the same slag content. These comparisons isolate different practical effects. Reporting only the strongest-looking comparison can create an impression of synergy without demonstrating it.

Let f(r,s,t) denote the mean compressive strength measured at age t, where r is the RCA fraction and s is the GGBS fraction. The following ratios are proposed as reporting indices, not fitted predictive models:

$$R_N(t) = f(r,s,t) / f(0,0,t) \quad (1)$$

$$R_G(t) = f(r,s,t) / f(r,0,t) \quad (2)$$

$$R_A(t) = f(r,s,t) / f(0,s,t) \quad (3)$$

R_N measures performance relative to the conventional reference. R_G measures the change associated with slag at the selected RCA level. R_A measures the change associated with RCA at the selected slag level. Ratios above unity indicate higher mean strength only for the specified comparison. They do not establish statistical significance, compliance with a characteristic-strength requirement or environmental superiority. The matched reference should use the same

specimen geometry, testing age and curing procedure.

5.3 Testing an interaction rather than assuming synergy

The term synergy is stronger than simultaneous use. A mixture containing both materials may be acceptable even if their effects are independent or partly adverse. For a controlled factorial design, an additive interaction contrast can be defined as:

$$I(t) = f(r,s,t) - f(r,0,t) - f(0,s,t) + f(0,0,t) \quad (4)$$

A positive I indicates that the combined response exceeds the sum of the two individual changes on this strength scale. Its interpretation depends on the chosen scale and design controls. Confidence intervals and independent batch replication are needed before a non-zero interaction is asserted. A multiplicative or logarithmic analysis would test a different definition. This review proposes the contrast to improve experimental reasoning; it does not calculate it from incomplete literature observations.

5.4 Curing age and strength development

An age-development ratio can complement the reference ratios: $G(t2,t1) = f(r,s,t2)/f(r,s,t1)$, where t2 is later than t1. This ratio describes gain within the same mixture. It should be presented beside, rather than substituted for, R_N at both ages. For example, a mixture can show a larger age-development ratio because its earlier strength was lower. The engineering decision still depends on whether the required strength is achieved when it is needed.

The selection of test ages should follow the intended construction use. Early-age measurements address handling and construction scheduling. Later-age measurements address continued development under the specified curing regime. A study cannot claim that longer curing will restore a missing result merely because slag reaction is time-dependent. Missing observations should remain missing, and a fitted trend should be labelled as prediction rather than measurement.

6 Mix proportioning and performance-based selection

6.1 Replacement definitions and available water

For a binary binder, a transparent mass-based definition is $s = m_{GGBS}/(m_{OPC} + m_{GGBS})$, while the RCA fraction is $r = m_{RCA}/(m_{RCA} + m_{NCA})$, with both aggregate masses expressed on the same moisture basis. If GGBS is added to a fixed cement mass, the resulting fraction must be calculated explicitly. A statement such as 40% slag addition relative to cement is not equivalent to 40% replacement of total binder. Additional binders must appear in the denominator when present.

Mass replacement and volume replacement also answer different proportioning questions. The concrete yield should be checked by the absolute volumes of the constituents using a consistent density and moisture basis. Otherwise, changing aggregate type or binder content can change paste volume or aggregate packing inadvertently. For a review, the appropriate response is to flag an unclear definition rather than silently convert it using an assumed density.

An effective water-to-binder ratio should identify the water considered available to the paste. Its estimation needs aggregate moisture, absorbed water, added water and water contributed by liquid admixtures. Because absorption during mixing is time-dependent, any correction method should state its test duration and assumptions. The present review does not prescribe a single universal absorption correction: it proposes that the correction be explicit and applied consistently to the compared mixtures.

6.2 Selecting a feasible mixture rather than a universal optimum

A practical mixture should first satisfy its acceptance constraints. These can include consistency at placement, strength at the specified

age and any exposure-specific requirements. Among feasible candidates, resource use, cost and environmental performance can then be compared. Maximising RCA or slag content without checking feasibility can select a mixture that does not meet the intended use. Maximising measured mean strength can instead select an unnecessarily binder-rich mixture. Neither objective alone defines the preferred concrete.

This review proposes a decision sequence: characterise materials; establish a reference; control available water and mixture yield; test an RCA–GGBS matrix; assess fresh performance and age-specific strength; then compare environmental and economic indicators for the feasible candidates. Application-specific verification follows before a structural recommendation. The sequence is a synthesis for organising experiments and should not be read as a substitute for a concrete design standard.

Table 4 Minimum reporting set for a comparable RCA–GGBS experiment

Domain	Required information	Interpretive purpose
Recycled aggregate	Source, processing, grading, density, absorption and mixing moisture	Distinguish source effects from replacement effects.
Binder	Cement identity, slag characteristics, total binder mass and replacement definition	Separate replacement, addition and altered binder dosage.
Proportioning	Constituent quantities, moisture basis, yield and available-water correction	Detect changes in paste volume and effective water ratio.
Production	Mixing sequence, duration, admixture product and dosage basis	Identify processing and admixture confounding.
Fresh testing	Test method, measurement time, temperature and any retempering	Separate initial consistency from retention.
Hardened testing	Geometry, age, curing, loading method, replicates and independent batches	Establish a valid comparison and uncertainty estimate.
Decision criteria	Reference mixtures, required performance, cost and environmental boundaries	Identify what acceptable or optimum means.

7 Application boundaries and sustainability implications

7.1 Modified systems should remain identifiable

Majhi and Nayak [14] investigated high-volume slag and RCA with a lime activator. Their reported promising combination included 50% RCA, 60% GGBFS and 7% lime. This result belongs to an activated system; it should not be used as a recommended binary Portland cement–slag proportion without lime. Activation introduces a further material, dosage definition and production requirement.

Ahmad et al. [16] included steel fibres alongside RCA and GGBS and reported improvements for a selected multicomponent mixture. Such evidence is relevant to fibre-reinforced concrete but does not isolate the effect of slag. Tung et al. [17] examined residual mechanical performance after elevated temperatures and reported favourable residual

performance at a particular GGBS level. A post-heating result cannot establish ambient-temperature strength or general fire suitability. Exposure protocol and reference condition remain part of the finding.

7.2 Environmental performance requires a matched functional basis

Marinković et al. [18] found that the environmental comparison of natural and recycled aggregate concrete depended on transport distances and modes. This undermines a blanket assumption that recycled content always lowers impact. Chaitanya et al. [19] integrated mechanical, microstructural, environmental and economic assessment in a recent Indian study. Their staged programme introduced GGBS at a selected RCA level; its conclusions should be interpreted within that design rather than as an exhaustive exploration of every combined level.

The proposed environmental comparison begins with equal engineering function. A per-cubic-metre inventory is useful, but two cubic metres of different concretes are not necessarily equivalent if their strength, service conditions or required member sizes differ. At minimum, a comparison should state the required grade, assessment boundary, transport assumptions and treatment of slag and recovered aggregate burdens. Any change in cement needed to retain performance belongs in the inventory.

A screening index such as embodied impact divided by compressive strength may help compare candidates within a tightly controlled programme, but it is not a complete structural life-cycle assessment. It omits the influence of geometry, exposure, service life and maintenance unless those are modelled separately. Likewise, local cost savings should use delivered material prices and processing requirements. Neither a nominal replacement percentage nor a laboratory strength result can supply missing cost or environmental data.

8 Research gaps and proposed experimental priorities

The most useful next step is stronger comparability rather than another isolated optimum. The following priorities are proposed from the limitations identified in this review. They are research recommendations, not claims that no previous study has addressed the relevant subject.

Table 5 Research priorities and testable questions

Priority	Testable question	Suggested approach
Source transferability	Does a promising combination retain performance across RCA sources?	Repeat a common matrix across traceable sources and compare source-by-mixture effects.
Water and retention	Do apparent workability gains survive realistic placement delays?	Measure moisture and absorption; test consistency at defined elapsed times.
Joint response	Is the combined strength response interactive?	Include natural/Portland, RCA-only, slag-only and combined controls with independent batches.
Age dependence	Is strength gain sufficient at the required construction age?	Report early and later ages with matched curing and age-specific reference ratios.
Robust selection	Is the selected mixture stable to normal material variation?	Vary moisture or grading within measured ranges and evaluate feasibility.
Equal-performance benefit	Are resource, cost and impact gains retained after engineering constraints?	Use complete quantities, delivered costs, transport scenarios and sensitivity analysis.

Independent batches deserve particular attention. Several specimens from one batch provide information about within-batch testing variation; they do not by themselves characterise production variability across batches. A future experiment should distinguish these levels and avoid treating repeated specimens as independent material production events. Where resources constrain the matrix, the resulting limits should be reported rather than compensated for with an excessively flexible regression.

A defensible response-surface study also needs observations across the intended factor space. Predictions between tested levels are interpolations; predictions beyond them are extrapolations. Neither creates experimental evidence at an untested replacement ratio. If an intermediate percentage is proposed from a fitted curve, confirmation batches should test it directly. This is especially relevant when a small set of slag percentages is used to claim a precise optimum.

9 Limitations of the review

The review is selective and interpretive. It does not claim comprehensive retrieval across bibliographic databases, does not quantify publication bias and does not pool effect sizes. Access varied between full articles, abstracts and previews, so the depth of extraction is not uniform. The evidence map includes different concrete categories to clarify boundaries rather than establish a single numerical trend. These choices permit a focused treatment of RCA–GGBS mix proportioning but limit conclusions about the distribution of all published results.

The mathematical indices and reporting framework are proposed analytical tools. They have not been validated here as predictive models or acceptance standards. The review also does not establish compliance with current regional codes, conduct a new life-cycle assessment or report new experimental measurements. A journal requiring a systematic review would need a separate reproducible database search, documented screening and a fuller extraction process.

10 Conclusions

The reviewed literature supports evaluating RCA and GGBS as interacting components of a defined concrete system. Replacement percentages become meaningful only when the material source, moisture condition, binder basis, effective water ratio and curing conditions are known. The main conclusions are as follows.

First, a reported improvement must identify its reference. Strength recovery relative to RCA concrete without slag is different from parity with natural aggregate concrete. Neither comparison alone demonstrates synergy. Second, later strength gain should be reported alongside absolute strength at the required age. A large development ratio cannot establish that the construction requirement has been achieved.

Third, workability is time- and method-dependent. Initial slump, retained slump and self-consolidating flow should remain distinct outcomes. Fourth, acceptable combined replacement levels are specific to the tested materials and constraints. The evidence does not justify one universal GGBS or RCA optimum. Fifth, environmental and economic benefits need measured mixture quantities, transport and cost assumptions, and an equivalent engineering function.

Future experimental research should use matched controls, complete observation records and independent batches. The reference ratios, interaction contrast and reporting matrix proposed here provide a practical way to organise that work. Their central purpose is to separate feasible material substitution from unsupported claims of universal performance improvement.

Data availability

No new experimental dataset was generated. The evidence discussed is available through the

publications listed in the references. The comparison framework and equations are analytical proposals developed in this review.

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