Recycled Aggregates and Industrial By-products in Green Concrete

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ABSTRACT

Global concrete production reaches 30 billion tonnes annually, with cement manufacturing (4.0 Gt/yr) emitting ~0.9 t CO_2 per tonne of cement. Construction accounts for ~40% of world energy use and ~35% of greenhouse gases. Concurrently, vast waste streams—~1 Gt/yr fly ash, 0.27–0.32 Gt/yr blast furnace slag, and 3 Gt/yr construction/demolition waste (CDW)—necessitate sustainable solutions. Green concrete addresses these challenges by replacing virgin materials with wastes: recycled concrete aggregates from CDW substitute natural aggregates, and supplementary cementitious materials (fly ash, slag, silica fume, metakaolin) replace part of the cement. This review synthesizes current knowledge on recycled aggregates (sources, properties, concrete performance) and SCMs, examining mechanical strength, durability, environmental/economic benefits, and future challenges. Comprehensive tables compare key findings. With careful mix design, high-volume waste replacements achieve required performance while delivering substantial sustainability gains.

Keywords: **green concrete, recycled aggregate, fly ash, silica fume, metakaolin**

1. *INTRODUCTION*

Concrete is the most used artificial material globally, but its production has major environmental impacts. In 2020, concrete consumption reached about 30 billion tonnes (with ~4.0 billion tonnes of cement). Cement production alone contributes about 8% of global CO_2 emissions and consumes large energy and raw materials. Similarly, construction uses ~40% of world energy and ~35% of GHG emissions. Aggregate mining (concrete's main constituent, ~75% by mass) causes landscape disruption; global extraction is projected to exceed 500 Gt by 2100. At the same time, industry and construction generate vast wastes: ~1 Gt/yr of coal fly ash, ~0.27–0.32 Gt/yr of blast furnace slag, and several gigatonnes of CDW (e.g. >2 Gt in China, ~0.85 Gt in EU). Up to 90% of CDW is theoretically recyclable, and a concrete product can contain recycled aggregates from CDW.

These pressures have led to the concept of green concrete, where recycled waste replaces virgin inputs. In such concretes, natural coarse aggregates (NCAs) are partially or fully substituted by recycled concrete aggregates (RCAs) from CDW, and Portland cement is partly replaced by supplementary cementitious materials (SCMs) like fly ash, ground granulated blast-furnace slag (GGBFS), silica fume, metakaolin, etc. These substitutions can greatly reduce raw material demand, landfill disposal, and CO_2 emissions (each tonne of cement avoided saves roughly a tonne of CO_2). Recent reviews note that such wastes in concrete can yield "considerable benefits in cost, energy efficiency, and environmental impact". This paper reviews the technical state of green concrete: Sections 1–2 detail recycled aggregates and SCMs; Sections 3–4 examine mechanical and durability performance of modified concrete; Section 5 assesses environmental/economic outcomes; and Section 6 discusses remaining challenges and future research. Data and citations come solely from peer-reviewed engineering literature.

1. RECYCLED AGGREGATES IN GREEN CONCRETE

Recycled concrete aggregates (RCAs) are produced by crushing CDW (old concrete, demolished structures) to obtain coarse and fine aggregate for new concrete. This practice conserves natural resources and reduces waste. In a green concrete mix, a fraction (typically 20–50%) of NCAs may be replaced with RCAs, although 100% replacement is sometimes used for non-structural applications. Incorporating RCAs alters the aggregate properties and mix behavior. For example, RCAs retain residual cement mortar from their source concrete (20–56% of mass). This adhered mortar lowers the aggregate's specific gravity (typically 1.91–2.70 g/cm³ for RCAs versus ~2.6–2.8 for natural gravel) and raises water absorption (often 2–15%, significantly above natural aggregate values). Consequently, concrete with RCAs often has lower workability and requires more mixing water or plasticizer. RCAs also have rougher, more angular surfaces, which increases internal friction and reduces initial slump. For example, Zhu et al. observed that RCA concrete showed reduced slump and a more brittle failure mode due to the porous, irregular RCA surface.

1.1 SOURCES AND PRODUCTION OF RCAs

RCAs come from crushed concrete debris, brick, or masonry. To improve quality, RCA production may involve sorting and removing contaminants (wood, glass, etc.), and sometimes processing (e.g. additional crushing of larger particles). The grading of RCAs must meet aggregate specifications; often sieving and blending are needed. Research shows that fine RCAs can meet grading standards similar to natural sand when properly processed. In practice, ASTM and EN standards allow up to ~20–30% RCA in structural concrete, although higher replacement (even 100%) is used in some regions for pavements and blocks. The optimal RCA content depends on the source material and required performance; many studies suggest that keeping RCA under ~30% often avoids large strength or durability penalties.

1.2 EFFECTS ON MECHANICAL PROPERTIES

In general, replacing NCAs with RCAs decreases concrete strength and stiffness. The magnitude of change depends on the replacement level and quality of RCA. As summarized by de Brito et al., compressive strength can be 2.6–43% lower for high-RCA mixes. In one review, up to a 25% reduction was noted when 100% natural coarse aggregate was replaced. Similarly, the concrete's elastic modulus drops (by ~25% at full replacement). Flexural and tensile strengths also diminish; Zhu et al. report flexural strength up to ~15% lower with 100% RCAs. Notably, moderate RCA levels (e.g. 30– 50%) often yield much smaller losses. Mahmood et al. found that in mortar, 50% fine-RCA replacement gave only ~5% reduction in 28-day compressive strength (from ~66.3 to ~63.1 MPa), whereas 100% fine-RCA dropped strength by ~25%. In practice, small strength losses are often offset by higher cement content or admixtures.

RCAs' higher water absorption can also affect strength. Early-age strength may suffer when RCAs suck up mix water. However, that absorbed water can act as internal curing, benefiting later strength gain when pozzolanic SCMs (e.g. fly ash) are present. In fact, combining RCAs with SCMs often improves the composite performance. One study showed that adding fly ash improved workability and mechanical strength of RCA concrete, mitigating the negative effects of the recycled aggregate. For example, Mahmood et al. reported that mixing 30% fly ash (by cement mass) into an RCA mortar yielded the same design strength as a natural-aggregate control. In summary, RCAs tend to reduce strength and stiffness, but moderate RCA use (≤30–50%) and synergistic use of SCMs can limit those losses.

2. INDUSTRIAL BY-PRODUCTS AS SUPPLEMENTARY CEMENTITIOUS MATERIALS

Industrial by-products can partially replace Portland cement, reducing its usage and improving concrete properties. Key SCMs include fly ash (FA) from coal plants, ground granulated blast-furnace slag (GGBFS) from steel mills, silica fume (SF) from silicon metal production, and metakaolin (MK) from calcined kaolin clay. These materials supply latent hydraulic or pozzolanic silica/alumina, reacting with calcium hydroxide in cement to form additional C–S–H gel, thus densifying the microstructure.

2.1 Fly Ash (FA):

Fly ash (usually ASTM Class F or C) is widely used at 15–30% (by weight) of cement. Its spherical particles improve workability and reduce water demand. However, FA reacts slowly: early-age (≤7 day) strength is often lower than OPC concrete, but 28- and 90-day strengths catch up as pozzolanic reactions proceed. Fly ash also refines the pore structure and reduces permeability, greatly improving resistance to sulfate/chloride attack. Importantly, every percent of cement replaced by FA reduces CO_2 emissions (since cement production yields ~0.9 t CO_2/t). note that partial FA replacement "improves durability and contributes to reduction of CO_2 emissions". In mixes with RCAs, FA can mitigate RCA's drawbacks: it improves workability and offset strength loss caused by RCA.

2.2 Blast-Furnace Slag (GGBFS):

GGBFS is a glassy by-product of ironmaking, used as an SCM up to ~50% replacement of cement. Like FA, GGBFS lowers early strength but greatly enhances later strength: for example, adding 15% GGBFS (with 25% recycled aggregate) produced a concrete whose 90-day flexural strength matched the control. In fact, the flexural strength of slag-containing concrete grew ~20% between 28 and 90 days (compared to ~18.6% in the control). The extra strength gain is due to GGBFS's continued hydration and pozzolanic reaction at later ages. GGBFS also markedly improves durability. Its finer cementitious particles fill capillary voids, and its latent reactions consume $Ca(OH)_2$, reducing permeability and shrinkage. For instance, research has shown that adding GGBFS "decreases permeability and increases the chemical stability" of concrete. As with FA, cement replacement with slag cuts embodied CO_2.

2.3 Metakaolin (MK):

Metakaolin is produced by calcining kaolin clay, yielding a highly reactive aluminosilicate. It is typically used at 5–20% replacement of cement. MK tends to significantly boost strength and refine microstructure. For example, one study found that 20% MK raised 90-day compressive strength by 33% relative to control. In general, MK concrete often shows higher ultimate strength than plain concrete, although MK increases water demand (workability drops with higher MK content). The fine MK particles produce dense C–S–H and C–A–H gel, enhancing impermeability and durability.

2.4 Silica Fume (SF):

Silica fume is a very fine (mean ~0.1 µm) amorphous SiO_2 byproduct. It is highly pozzolanic and usually used at ~5–15% of cement. SF's extremely small particles (∼100× smaller than OPC grains) greatly fill voids and accelerate C–S–H formation. As a result, SF concrete can achieve very high strength and exceptionally low permeability. Feldman et al. report that SF significantly increases packing density and early strength. The optimal SF content is often ~10–15%; doses above ~20% severely reduce workability unless superplasticizers are used. In summary, SF produces some of the strongest, most durable concretes (e.g. high-strength bridge or marine concretes) due to its ability to densify the microstructure.

3. MECHANICAL PERFORMANCE OF MODIFIED GREEN CONCRETE

This section reviews how recycled aggregates and SCMs affect concrete strength properties. We consider both plain RCA concretes and mixes incorporating SCMs.

3.1 Compressive Strength

Recycled aggregates generally reduce compressive strength relative to natural-aggregate concrete. As noted above, full replacement of NCAs by coarse RCA may cut strength by up to 40%. In practice, partial replacements show less loss: with 50% RCA some studies report only a few percent drop. The strength reduction arises from weaker RCA particles and poorer aggregate–paste bond due to residual mortar. To compensate, RCA concrete mixes often use a higher cement content or include SCMs.

Adding SCMs can offset the strength loss. For example, mixes with both RCA and 30% fly ash have achieved compressive strength equal to conventional mixes. This is because FA contributes to C–S–H formation and also improves workability, indirectly enhancing strength. Similarly, GGBFS helps regain long-

term strength: a mix with 15% slag and recycled sand reached 90-day strength on par with the control. Silica fume and metakaolin further increase strength: their fine particles bridge pores and strengthen the ITZ. In general, binary or ternary mixes (RCA + SCM) can produce concrete with compressive strength comparable to natural mixes, provided replacement levels and curing are optimized.

3.2 Tensile and Flexural Strength

Tensile and flexural (modulus of rupture) strengths also decline with RCA content, though usually less dramatically than compressive strength. De Brito et al. found that flexural strength could drop by up to ~15% when using 100% coarse RCA. Tensile behavior follows a similar trend (since it is strongly linked to interfacial bonding), so RCA concretes are often more brittle under tension. Again, SCMs can compensate: SF and MK accelerate bond development, raising flexural/tensile capacity. For instance, Silva et al. observed that even replacing 10–15% of cement by SF significantly increased both compressive and flexural strength in mortar due to denser microstructure. In summary, RCA reduces all strength metrics, but appropriate SCM use (e.g. SF addition) and curing can restore or enhance tensile and flexural performance.

Table 1. *Effects of recycled aggregates and industrial by-products on green concrete properties (strength, durability, and emissions) based on literature data.*

Material	***Effect on Strength***	***Effect on Durability***	***Environmental Impact***
Recycled Coarse Aggregate	*Compressive strength ↓ about 3–43% as RCA content increases; elastic modulus ↓ (~25%). Flexural strength ↓ up to ~15% at 100% RCA.*	*Increases porosity and permeability (lower slump, more microcracks), which can raise water absorption and carbonation. However, at ≤30% RCA the durability loss is modest.*	*Saves natural aggregates (less quarrying); reduces CDW landfill. May slightly increase cement demand (if strength loss compensated).*
Fly Ash (FA)	*Early-age strength ↓ (slower hydration); later-age strength comparable or ↑ with sufficient curing. May slightly increase long-term strength.*	*Lowers permeability and refines pore structure, improving chloride and sulfate resistance. Reduces alkali-silica reaction.*	*Each % cement replaced cuts ~1% of cement's CO_2; FA is a waste reuse. Improves sustainability.*
Ground Granulated Slag (GGBFS)	*Early strength ↓ relative to OPC, but long-term strength ~equal or higher. 15–25% replacement often reaches control strength at 90 days.*	*Improves concrete density and reduces shrinkage. Lowers permeability substantially, enhancing durability to chemicals.*	*Byproduct use reduces cement output by the same amount, saving CO_2. Utilizes steelmaking waste.*
Metakaolin (MK)	*Generally increases strength; e.g. 20% MK gave +33% 90-day compressive strength. Doses >10% can significantly boost early strength.*	*Fills voids and accelerates cement hydration, improving impermeability. Enhances resistance to chloride/corrosion.*	*Repurposes clay (an abundant raw material); allows lower cement use (CO_2 saving).*

Silica Fume (SF)	*Dramatically increases strength; optimal ~10–15% replacement. Very fine SiO_2 particles produce very high early and ultimate strength.*	*Virtually eliminates capillary pores, giving superior durability. SF concretes have very low permeability and high chemical resistance.*	*Recycles Si/ferroalloy industry waste; reduces cement need. Very high energy content though, so logistics key.*

4. DURABILITY CONSIDERATIONS

Durability refers to concrete's resistance to environmental attack (permeation, corrosion, etc.). Both recycled aggregates and SCMs strongly influence durability, often in opposite ways.

4.1 Permeability and Water Absorption

Using RCA tends to make concrete more permeable. The adhered mortar and RCAs' porosity create more capillary voids and weaker ITZs. Studies show RCA concrete typically has higher water absorption and chloride ingress than all-natural concrete. For example, Zhang et al. report that the RCA–paste interface has higher porosity and diffusion coefficients, allowing deeper carbonation and chloride penetration. In general, the more RCA used, the higher the capillary porosity and permeability. However, this effect is moderate at low replacement levels: replacing NCAs with up to ~30% RCA yields only a small increase in permeability. The RCA's higher absorption can also provide internal curing water for ongoing hydration, which is beneficial when SCMs like fly ash are used. In contrast, SCMs usually enhance durability by refining the pore structure. Fly ash, GGBFS, and silica fume all produce additional C–S–H gel that fills voids and reduces connected porosity. For instance, adding GGBFS is reported to "decrease the permeability" of concrete, and SF's nano-particles pack tightly with cement to block micro-channels. In combined mixtures, SCMs can largely offset the RCA-induced porosity. Experimental reviews show that ternary blends (e.g. 10% SF + 20–30% FA) yield very low water absorption and high resistance to chloride and sulfate ingress. Overall, RCA concrete requires attention to mix design (e.g. lower w/b ratio, SCM addition) to maintain durability.

4.2 Resistance to Aggressive Agents

The modified pore structure affects resistance to carbonatation, chloride, and sulfate. RCA concrete without SCM is generally more vulnerable: increased porosity accelerates carbonation and chloride diffusion, potentially reducing rebar protection. Several studies note deeper carbonation depths and faster chloride penetration in high-RA mixes compared to control, although values vary widely among tests. Nevertheless, adding SCMs greatly improves resistance. Fly ash and GGBFS reduce free $Ca(OH)_2$ and refine capillaries, thereby lowering the rate of carbonation and chloride ingress. For example, combining GGBFS with FA has been shown to outperform single-SCM mixes in sulfate resistance. Silica fume is particularly effective against sulfate attack and chloride penetration due to its near-complete pore blockage. In one review, even a small SF dose (5%) drastically cut porosity. In practice, meeting durability requirements often means using binary or ternary SCM mixes and ensuring adequate curing. For freeze-thaw and shrinkage, SCMs also help by densifying the matrix, though proper air entrainment may still be needed for severe climates. In summary, RCA by itself tends to degrade durability, but SCMs generally reverse or exceed those losses. A conservative design employs low w/b ratios and substantial SCM (e.g. FA+GGBFS or FA+SF) in RCA concrete, which has been shown to match the durability of conventional concrete.

5. ENVIRONMENTAL AND ECONOMIC BENEFITS

The chief motivation for green concrete is sustainability: reducing resource depletion, emissions, and costs. Both recycled aggregates and SCMs contribute significant environmental benefits. Using RCAs avoids new aggregate extraction and reduces CDW disposal. As pointed out by Fagiolo et al., substituting RCAs "preserves and reduces the extraction of natural resources" while minimizing waste. Likewise, every tonne of cement replaced by fly ash, slag or other SCM saves approximately 0.9 tonnes of CO_2. Studies confirm that SCM substitution can cut the carbon footprint of concrete substantially. For example, Silva et al. note that *partial FA replacement "contributes to the reduction of CO_2 emissions". Life-cycle assessments consistently show that RCA+SCM concrete requires far less embodied energy and emits far less greenhouse gas than OPC–NCA concrete of equal performance. Economically, green concrete can lower material and waste-management costs. RCA and by-products are often cheaper than virgin inputs (sometimes free or even with negative cost if users pay to take waste). Using slag in road concrete, for instance, "eliminates disposal costs" of the slag and even saves on processing. In municipal budgets, diverting CDW from landfills to concrete adds value. Da Silva et al. emphasize that adding wastes "can bring considerable benefits in costs, energy efficiency, and environmental benefits". However, there are some trade-offs: RCA processing and SCM handling can require additional logistics. Overall, most analyses find cost parity or savings: the reduced cement and aggregate costs often outweigh any added processing costs.*

6. CHALLENGES AND FUTURE DIRECTIONS

Despite the promise, several challenges slow the widespread use of green concrete. Quality control of RCAs and by-products is paramount but difficult. RCAs are heterogeneous; their strength and absorption vary with source and processing. This leads to variability in concrete properties, making designers cautious. As reported by de Brito et al., the literature still shows "no congruence" among studies, and so RCA concrete is generally limited to low-demand applications. Standards in many countries restrict RCA content for structural concrete. High-absorption RCA may also require mix adjustments to avoid freeze-thaw or drying shrinkage problems. SCMs have more established use, but challenges remain in ensuring consistent supply and quality. Some industries (e.g. steel, power) regulate or stockpile fly ash and slag, but availability of premium grades can fluctuate. Also, replacing large cement fractions with SCMs may compromise early strength or constructability, requiring careful curing and admixtures. Silica fume and metakaolin are effective but expensive or less available than FA/GGBFS.

For future progress, standardized guidelines are needed. Development of RCA processing (e.g. repeated crushing to remove mortar, treatment to reduce absorption) can improve reliability. Research should refine mix design rules for RCA+SCM systems, including optimal water/binder ratios and admixture dosages. Field demonstrations and long-term monitoring of green concrete structures will build confidence. Incorporating life-cycle analysis (LCA) into concrete design is essential: studies recommend that LCA include recycling steps to fully capture benefits. Emerging topics include use of nano-material additives, biopolymers, or geopolymer binders in combination with recycled components. In summary, while green concrete is technically feasible, overcoming variability and regulatory hurdles will be crucial. Continued research, material characterization, and code updates are needed to allow these sustainable materials to reach their full potential.

7. CONCLUSION

Recycling construction wastes into concrete can significantly reduce the industry's environmental footprint. Recycled concrete aggregates and industrial SCMs (fly ash, slag, silica fume, metakaolin, etc.) can be used to produce green concrete with satisfactory performance. RCAs lower compressive and tensile strength (2–40% loss at high replacement) due to adhered mortar, but up to ~30% replacement often has minimal impact. SCMs can compensate for these losses: for example, adding 30% fly ash to an RCA concrete recovered full strength, and 10–15% silica fume or 20% metakaolin markedly increase strength. Durability can also be maintained: SCMs refine pores and mitigate the permeability increase caused by RCAs. Critically, using these wastes cuts CO_2 emissions and saves resources. The main obstacles remain quality control, variability of waste materials, and lack of specific standards, which currently limit green concrete to less-demanding uses. Nonetheless, with optimized mixtures and better regulations, recycled aggregates and by-products offer a viable path to more sustainable concrete. It is anticipated that future advances (e.g. improved RCA treatment, new SCM sources, and integrated life-cycle design) will further enhance the performance and acceptance of green concrete.

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