

Carbon-Negative Concretes & Artificial Aggregates

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ABSTRACT

The construction industry is one of the largest contributors to global carbon dioxide emissions, with ordinary Portland cement (OPC) production alone accounting for nearly 7–8% of total anthropogenic CO₂ release. In recent years, the concept of carbon-negative concrete has gained attention as a potential pathway to mitigate climate change while meeting the growing demand for infrastructure. Carbon-negative concretes are designed not only to reduce emissions during production, but also to actively capture and store carbon dioxide over their life cycle. Parallel to this development, artificial aggregates produced from industrial by-products, recycled wastes, and carbonated materials are emerging as sustainable alternatives to natural aggregates, whose extraction causes ecological damage.

This paper presents a comprehensive review of carbon-negative concrete technologies and the role of artificial aggregates in achieving net-negative carbon performance. Various binder systems, including alkali-activated materials, magnesium-based cements, and bio-mediated binders, are discussed in terms of raw materials, processing, mechanical properties, and environmental benefits. Artificial aggregates derived from industrial wastes such as fly ash, steel slag, red mud, and municipal solid waste incineration ash are reviewed with respect to manufacturing techniques, physical properties, and compatibility with carbon-negative binders. Life cycle assessment (LCA) studies reported in literature are critically analyzed to understand the true carbon footprint of these materials. Challenges related to durability, scalability, cost, and standardization are also highlighted. The review concludes that

carbon-negative concretes combined with artificial aggregates offer a promising route toward low-carbon and circular construction, though further research and field-scale validation are required for widespread adoption.

KEYWORDS: *Carbon-negative concrete, artificial aggregates, sustainability, CO₂ sequestration, green construction materials*

INTRODUCTION

Concrete is the most widely used construction material in the world, owing to its versatility, durability, and relatively low cost. However, the environmental burden associated with conventional concrete is significant, primarily due to cement manufacturing and natural aggregate extraction. The calcination of limestone and high-temperature kiln operations during OPC production release large amounts of CO₂. At the same time, excessive mining of river sand and crushed stone leads to depletion of natural resources, riverbank erosion, and biodiversity loss.

In response to these challenges, researchers and industry stakeholders are exploring alternative materials and technologies that can reduce or even reverse the carbon footprint of concrete. The idea of carbon-negative concrete goes beyond carbon-neutrality, aiming to absorb more CO₂ than is emitted during its production and service life. This can be achieved through the use of alternative binders with lower embodied energy, incorporation of industrial by-products, and direct carbon capture through mineral carbonation or bio-based processes.

Artificial aggregates represent another important component in sustainable concrete design. Unlike natural aggregates, artificial aggregates are engineered materials produced from waste or by-product streams. Their use not only conserves natural resources but also diverts waste from landfills. When artificial aggregates are combined with carbon-negative binders, the overall environmental performance of concrete can be substantially improved. This review attempts to integrate these two emerging areas and assess their combined potential for sustainable construction.

CONCEPT OF CARBON-NEGATIVE CONCRETE

Carbon-negative concrete refers to concrete systems that result in a net removal of CO₂ from

the atmosphere over their life cycle. This concept considers emissions from raw material extraction, processing, transportation, construction, use, and end-of-life stages. Achieving carbon negativity typically involves a combination of emission reduction and carbon sequestration mechanisms.

One approach is the replacement of OPC with alternative binders that require lower processing temperatures or utilize waste materials. Alkali-activated materials (AAMs), commonly known as geopolymers, use industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS) activated by alkaline solutions. These binders can reduce CO₂ emissions by 40–80% compared to OPC-based systems. Another approach involves magnesium-based cements, which can absorb CO₂ during curing to form stable magnesium carbonates.

In addition to binder modification, carbon-negative concrete may include processes that actively capture CO₂. For example, CO₂ curing techniques introduce carbon dioxide into fresh or early-age concrete, where it reacts with calcium or magnesium compounds to form carbonates. These reactions not only store CO₂ permanently but may also enhance early strength. Bio-based strategies, such as microbial-induced calcium carbonate precipitation (MICP), are also being investigated, although their large-scale feasibility is still under evaluation.

BINDER SYSTEMS USED IN CARBON-NEGATIVE CONCRETES

1. Alkali-Activated and Geopolymer Binders

Alkali-activated binders are produced by activating alumino-silicate rich materials using alkaline solutions such as sodium hydroxide or sodium silicate. Fly ash, slag, and metakaolin are commonly used precursors. These binders eliminate the need for limestone calcination, significantly reducing CO₂ emissions. Some studies suggest that when industrial by-products are locally sourced, the overall carbon footprint can be further reduced.

However, the production of alkaline activators themselves is energy-intensive, which slightly offsets the environmental benefits. Researchers are therefore exploring alternative activators derived from waste streams. Despite these challenges, geopolymer concretes have shown comparable or even superior mechanical and durability properties compared to OPC concretes.

2. Magnesium-Based Cements

Magnesium-based binders, such as reactive magnesia cement, are gaining interest due to their ability to sequester CO₂ during carbonation curing. Unlike OPC, which emits CO₂ during calcination, magnesium oxide can be produced at lower temperatures. When exposed to CO₂, it forms hydrated magnesium carbonates, locking carbon into a stable mineral form.

The availability of suitable magnesium resources and the kinetics of carbonation remain challenges. Also, long-term durability under aggressive environments needs further investigation. Still, the inherent carbon uptake capability makes magnesium-based systems attractive for carbon-negative applications.

3. Bio-Mediated and Hybrid Binders

Bio-mediated binders use biological processes to induce mineral formation. MICP involves bacteria that precipitate calcium carbonate as a metabolic by-product. While this technology is still at an experimental stage, it offers a low-energy route to mineral formation. Hybrid systems combining small amounts of OPC with bio-based or geopolymer components are also being explored to balance performance and sustainability.

ARTIFICIAL AGGREGATES: SOURCES AND PRODUCTION METHODS

Artificial aggregates are engineered materials developed to substitute natural coarse and fine aggregates in concrete. Their production is generally based on industrial by-products, recycled wastes, or specially processed materials, allowing control over properties such as particle size distribution, density, porosity, strength, and water absorption. Compared to natural aggregates, artificial aggregates offer the advantage of consistency in quality and the opportunity to integrate carbon capture or waste utilization within their manufacturing process.

1. Industrial By-Product Based Aggregates

Industrial by-products have been widely investigated as raw materials for artificial aggregate production due to their abundance and low cost. Fly ash aggregates are among the most extensively studied. These aggregates are commonly manufactured using pelletization techniques followed by sintering or cold bonding. In the sintering method, fly ash pellets are heated at high temperatures to achieve strength and durability; however, this process is energy-intensive. Cold bonding, on the other hand, involves the use of cementitious or alkali-activated

binders to harden the pellets at ambient or slightly elevated temperatures. This approach significantly reduces energy consumption and greenhouse gas emissions, making it more suitable for sustainable construction.

Steel slag aggregates represent another promising alternative, particularly for applications requiring high strength and abrasion resistance. Steel slag contains hard crystalline phases that contribute to superior mechanical performance. Nevertheless, issues related to volumetric instability caused by free lime and free magnesia must be carefully addressed through aging, stabilization, or controlled processing before use. Properly treated steel slag aggregates have shown satisfactory performance in concrete pavements and structural applications.

Red mud, a highly alkaline waste generated during alumina production, has also been explored for artificial aggregate manufacture. Its utilization helps mitigate the serious environmental concerns associated with large-scale disposal. Red mud-based aggregates are typically produced by mixing with binders such as cement, lime, or geopolymer precursors followed by pelletization. While promising results have been reported in terms of strength, concerns regarding alkalinity, leaching of heavy metals, and long-term durability require thorough evaluation before large-scale implementation.

2. Carbonated Artificial Aggregates

Carbonated artificial aggregates are an emerging class of sustainable aggregates that integrate CO₂ sequestration into their production process. In this method, freshly formed aggregates made from fly ash, slag, or other calcium- or magnesium-rich materials are exposed to controlled concentrations of carbon dioxide. CO₂ reacts with reactive oxides to form stable carbonate compounds, leading to densification of the aggregate structure.

Carbonation curing not only improves the mechanical strength and dimensional stability of aggregates but also results in permanent storage of carbon dioxide in mineral form. Studies have shown that carbonated aggregates exhibit reduced water absorption and enhanced resistance to crushing compared to non-carbonated counterparts. From a sustainability perspective, these aggregates function both as construction materials and as carbon sinks, contributing directly to carbon-negative concrete systems. However, optimization of carbonation conditions and assessment of long-term performance remain areas of active

research.

3. Recycled and Waste-Derived Aggregates

Recycled and waste-derived aggregates are produced from construction and demolition waste, plastic waste, municipal solid waste incineration ash, and other discarded materials. Recycled concrete aggregates are obtained by crushing and processing demolished concrete elements, enabling partial replacement of natural aggregates. Although these aggregates support circular economy principles, their higher porosity and variability in composition often result in lower strength and increased water demand in concrete.

Plastic waste aggregates, typically produced by shredding and melting waste plastics, offer the benefit of low density and diversion of plastic from landfills. However, poor bonding with cementitious matrices and reduced stiffness limit their use mainly to non-structural or lightweight applications. Aggregates derived from municipal solid waste incineration ash present another option, though strict treatment and testing are required to address leaching and durability concerns.

Overall, while recycled and waste-derived aggregates significantly contribute to waste management and resource conservation, careful material characterization and quality control are essential to ensure reliable performance, particularly in structural concrete applications.

PROPERTIES OF CARBON-NEGATIVE CONCRETES WITH ARTIFICIAL AGGREGATES

The performance of concrete incorporating carbon-negative binders and artificial aggregates depends on mix design and curing conditions. In general, compressive strength values comparable to conventional concrete (25–40 MPa) have been reported. Artificial aggregates often exhibit higher water absorption, which may affect workability and durability if not properly addressed.

Durability studies indicate satisfactory resistance to sulphate attack and chloride penetration, particularly for geopolymer-based systems. Carbonated aggregates may contribute to internal curing, improving long-term performance. However, freeze–thaw resistance and long-term carbonation behavior require further research.

ENVIRONMENTAL IMPACT AND LIFE CYCLE ASSESSMENT

Life cycle assessment is a critical tool for evaluating the true sustainability of carbon-negative concretes. Many studies report significant reductions in global warming potential when OPC is replaced with alternative binders and natural aggregates with artificial ones. In some cases, net-negative CO₂ emissions have been claimed, particularly when industrial wastes and CO₂ curing are combined.

However, LCA results vary widely depending on system boundaries, data sources, and assumptions. Transportation distances, energy sources, and end-of-life scenarios play a major role. Therefore, standardized LCA methodologies are needed for fair comparison.

Table 1. Comparison of Conventional Concrete and Carbon-Negative Concrete

Parameter	Conventional OPC Concrete	Carbon-Negative Concrete
Binder type	OPC	Geopolymer / Mg-based
CO ₂ emission	High	Low to negative
Aggregate type	Natural aggregates	Artificial aggregates
Resource consumption	High	Reduced
Sustainability	Moderate	High

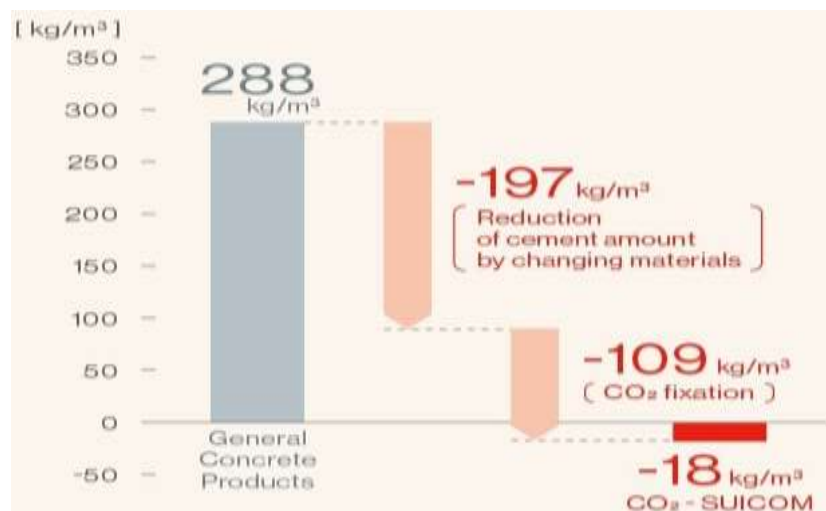


Figure 1: Conceptual Life Cycle of Carbon-Negative Concrete

CHALLENGES AND FUTURE PERSPECTIVES

Despite promising results, several challenges hinder the widespread adoption of carbon-negative concretes. These include limited availability of industrial by-products in some regions, lack of design codes and standards, and uncertainty regarding long-term performance. Economic factors also play a role, as some alternative binders and processing techniques may be costlier at present.

Future research should focus on field-scale demonstrations, durability testing over extended periods, and development of region-specific solutions. Policy support and incentives can accelerate adoption by encouraging low-carbon construction practices.

CONCLUSION

Carbon-negative concretes combined with artificial aggregates represent a significant step toward sustainable and climate-resilient construction. By reducing emissions, sequestering CO₂, and utilizing waste materials, these systems address multiple environmental challenges simultaneously. Although technical and economic barriers remain, ongoing research and innovation are steadily improving feasibility. With appropriate standardization and industry acceptance, carbon-negative concrete has the potential to transform the construction sector and contribute meaningfully to global carbon reduction goals.

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