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LOW-CARBON FOOTPRINT CONCRETE: SOLUTIONS FOR SUSTAINABLE ARCHITECTURE

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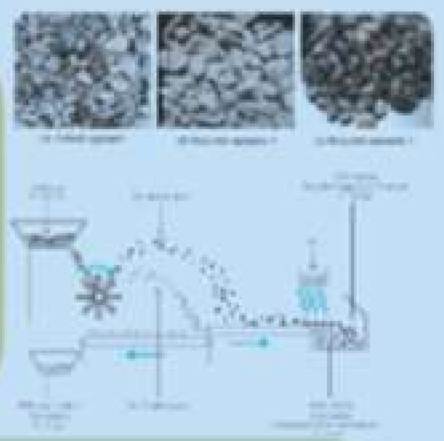
Concrete is the most widely used construction material globally, playing a central role in shaping modern infrastructure. However, its environmental cost is significant: the production of ordinary Portland cement (OPC), the key binder in conventional concrete, is responsible for approximately 8% of global CO_2 emissions. This is due to both the energy-intensive manufacturing process and the chemical release of CO_2 during the calcination of limestone.

As urbanization accelerates and climate targets tighten, the construction industry faces increasing pressure to reduce its environmental impact. This research addresses that challenge by investigating alternative concrete technologies with the potential to dramatically lower carbon emissions. It focuses on the use of geopolymer binders, recycled aggregates, and energy-efficient production techniques, evaluating their performance, sustainability, and architectural applicability through both technical analysis and case studies.

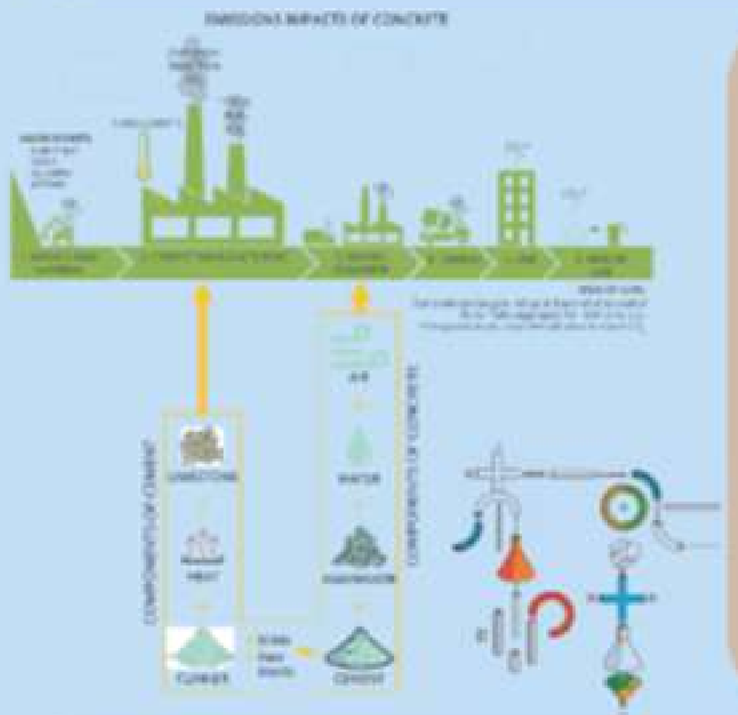


Geopolymer Concrete: Instead of traditional cement, geopolymer binders are made from industrial by-products such as fly ash, ground granulated blast-furnace slag (GGBS), and metakaolin. These materials are activated using alkaline solutions to form a stable, cementitious matrix. Geopolymers offer comparable or superior performance in terms of strength, chemical resistance, and long-term durability. Most importantly, their production emits significantly less CO_2 than OPC.

Recycled Aggregates: Construction and demolition waste (CDW), as well as certain industrial by-products, can be processed into coarse and fine aggregates. These replace virgin materials like sand and gravel, reducing resource extraction and landfill use. Quality control processes – such as sorting, crushing, and contamination removal – are essential to ensure reliable performance in structural concrete applications.

Low-Temperature Production: Traditional concrete often requires high-temperature curing and energy-intensive processing. This research investigates alternatives such as ambient-temperature curing of geopolymer concrete and cold-bonded aggregate production, both of which significantly reduce energy demand during manufacturing.

A comparative Life Cycle Assessment (LCA) methodology was employed to measure the environmental performance of these technologies across multiple criteria, including greenhouse gas emissions, energy use, and resource consumption.



The findings demonstrate that low-carbon concrete technologies can achieve substantial environmental benefits without sacrificing performance. Geopolymer concretes achieved CO_2 emission reductions of up to 80% compared to OPC-based mixes, with equal or improved mechanical properties and durability. These binders also valorize industrial waste, contributing to circular economy goals.

Recycled aggregates were found to perform slightly below natural aggregates in terms of compressive strength, particularly when used in high proportions. However, with proper mix design and processing, recycled aggregates are suitable for many structural and non-structural applications, especially in low- to mid-rise buildings.

Low-temperature curing and cold-bonding techniques also proved effective in reducing energy inputs, especially when integrated with geopolymer systems. Field data from real-world case studies confirmed the long-term performance and aesthetic adaptability of these materials in public buildings, residential architecture, and infrastructure projects across Europe and Asia.

However, several challenges remain. These include the variability in raw material quality, lack of standardized design codes, limited commercial availability, and a general inertia in the construction industry. Cost can also be a barrier, particularly during early adoption phases.

Geopolymer binders, recycled aggregates, and low-energy production methods can together reduce embodied carbon, promote waste valorization, and support the shift toward a circular economy in architecture.

To enable widespread adoption, greater efforts are needed in policy development, building code revision, and supply chain scaling. Future research should focus on hybrid systems, long-term performance monitoring, and the integration of carbon capture or bio-based materials.

The transition to sustainable concrete is no longer a niche innovation – it is a necessary evolution of architectural practice. By embracing alternative materials today, we lay the foundation for the carbon-neutral cities of tomorrow.

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