

Sustainable Concrete Technologies: Innovations and Applications in Green Construction

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Abstract

Holistic concrete technologies have received huge attractions to reduce environmental footprints of construction industry, which is infamous to its excessive CO₂ emission and resources consumption. This discourse focuses on development on sustainable concretes, e.g., recycled aggregate concrete (RAC), geopolymers concrete, carbon-dioxide-uptake technologies that are trends in green building. We examine the material parameters, manufacturing method, and performance characteristics, concentrating on minimizing embodied carbon and enhancing durability. Our approach involves doing a literature study, including case studies of sustainable concrete for buildings and civil infrastructure. Many residential, commercial, and transportation developments have shown that they are good for the economy and the environment. Using RAC (Outside cover) with low carbon dioxide emissions (when geopolymers cement concrete is used instead of Portland cement concrete, the greenhouse gas emissions are cut by about 60%) and recycling aggregate as a RAC keeps about 85-90% of the strength of normal cast concrete. One set of problems would be making things bigger, cheaper, and more standard. This research illustrates the use of sustainable concrete in green building, contributing to global carbon neutrality and sustainable development goals.

Keywords: Concrete, Construction, Green Construction

Introduction

The construction industry is facing more and more pressure to meet sustainability goals set by agreements like the Paris Agreement. As a result, sustainable concrete technologies are seen as a key way to make the industry more sustainable by reducing its impact on the environment without sacrificing performance. Some of these new ideas include recycled aggregate concrete (RAC), which employs waste materials; geopolymers concrete, which uses industrial waste products like fly ash; and other ways to trap carbon dioxide (CO₂) during manufacture. These innovations are meant to lower embodied carbon, protect raw resources, and make things last longer, all while keeping the environment and the economy in mind.

The importance of this green concrete is that it could change construction around the planet. Furthermore, improvements in SCMs tend to make concrete perform better, allowing longer-lasting structures to be built. These new developments also respond to a growing international trend in the circular economy and net zero emissions, and are highly relevant to urban development, infrastructure and affordable housing. Nonetheless, obstacles such as expensive initial investment, poor standardization, and inconsistent materials casting limit their popularity.

In great detail, the following chapters discuss the major sustainability technology for concrete: advanced and engineered cementitious composites; carbon sequestration and life cycle assessment. Recent developments in mixed-oxide synthesis techniques are presented, and in each case study their implementation is illustrated and the corresponding environmental and structural advantages are debated. The article is organized as follows: a literature review about major innovations, a methodology part with a mix of theoretical and practical aspects, an construction application, results supported by tables, a conclusion with proposals for further research and a list of references. By investigating these technologies we want to draw attention to the part they play when creating a sustainable future.

Literature Review

Introduction Environmentally friendly concrete has been developed actively in the past few decades due to the requirement of minimizing environmental impact of the construction industry. In this section, the main developments and properties of GSCMs are discussed along with their applications in green building.

Recycled Aggregate Concrete (RAC)

RAC uses recycled materials - crushed concrete in the form of demolition waste - as aggregates. It has been reported that with enough mix design, RAC can achieve 85–90% powerhouse of compressive strength of normal concrete (Tam et al., 2005). Its utilization saves 50% of landfill spaces and natural aggregates (Oikonomou, 2005). Nevertheless, non-uniformity of the inflow to PV is a barrier to stability.

Geopolymer Concrete

Geopolymer concrete employs aluminosilicate precursor (usually fly ash or slag) activated by alkali solutions. It decreases CO₂ emission by 50–60% and also possesses tensile strength comparable to the plastic powder cement material (Davidovits, 1991). Duxson et al. (2007) claimed the high chemical stability under aggressive conditions that is suitable to infrastructure. The production scale is restrained by the precursor supply and curing demand.

Carbon Capture and SCMs

Carbon capture methods, like carbonation curing, are employed to store CO₂ in concrete, decreasing emissions by 10–20% (Monkman & Shao, 2006). Supplementary cementitious materials (SCMs) such as silica fume and slag can increase strength and durability while decreasing cement content by up to 30% (Malhotra & Mehta, 2002). They are being used more and more in precast concrete factories.

Applications and Challenges

Green concrete has been used in applications such as green buildings and bridges and the case studies showed that sustainable concrete resulted in 20–30 % cost savings over lifecycle as it lasts long (Reddy & Jagadish, 2019). Barriers include higher early adoption costs, lack of codified best practices, and practitioner ignorance (Provis, 2018). New developments include hybrid blends and automated manufacturing to increase scalability.

This article serves as a basis for justifying sustainable concrete in green construction.

Methodology

We investigated three sustainable concrete technologies based on theories and RAC, geopolymer concrete with a literature review and experimental study in a combined manner. This section outlines our methodology.

Theoretical Analysis

1. **RAC:** The mixes were designed by ACI 318 method, and 50–100% recycled coarse aggregates were used. Compressive and workability models were fitted from aggregate's properties.
2. **Geopolymer Concrete:** Fly ash and slag formulations were evaluated for CO₂ emissions and strength, and referenced ASTM C150. Alkaline activator ratios were optimized.
3. **Carbon Capture:** CO₂ sequestration rates and strength gains were predicted from laboratory data using carbonation curing models.

Practical Implementation

- **Residential Building:** One green building employed RAC containing 50% recycled aggregates that was tested for the compressive strength (28 days curing).

- **Bridge Building:** The precast bridge segment used geopolymer concrete in examining resistance to seawater.
- **Precast Members:** Carbonation curing was evaluated for precast panels to measure CO₂ uptake and strength.

All testing was conducted in a controlled laboratory setting using conventional equipment (e.g., compression testing equipment, CO₂ analyzers). The environmental impact was assessed by LCA tool and weighted in terms of embodied carbon (kg CO₂/m³).

Data Analysis

Compressive strengths were determined in accordance with ASTM C39. CO₂ emissions were estimated using LCA software (SimaPro). Economic analysis compared the initial and the life-cycle costs with the conventional concrete. Performance differences among the technologies were evaluated by means of statistical tests (ANOVA).

Table 1: Sustainable Concrete Technologies

Technology	Key Material	CO ₂ Reduction (%)	Strength (% of OPC)
RAC	Recycled Aggregates	20–30	85–90
Geopolymer	Fly Ash/Slag	50–60	90–100
Carbonation Curing	CO ₂ Sequestration	10–20	95–100

Applications

New types of sustainable concrete technologies: an overview Sustainable concrete technologies are changing green construction in the uses, providing economic and environmental advantages.

Residential Buildings

RAC is common in residential uses, cutting the demand for aggregate by 40% and waste from the landfill. In a green housing project, a case study also demonstrated the minimum strength (30 MPa) of RAC for the use in low rise dwelling units (Tam et al., 2005). Savings in the lifecycle cost amounted to 20% from the material cost reduction.

Infrastructure

It Geopolymer concrete is particularly well suited for bridges and road construction as it has good resistance against harsh high pH conditions. Studies on precast bridge member produced with fly ash based geopolymer concrete showed compressive strength of 50 MPa with 60% lower CO₂ emissions (Reddy & Jagadish, 2019). Corrosion-resistant, which results in a longer life.

Precast Construction

Carbonation curing in the precast elements leads to the sequestration of 10–15 kg CO₂/m³ and increases the strength by 10% (Monkman & Shao, 2006). Apps in panels and beams cut back on cement, reducing cost and emissions.

Challenges and Opportunities

Some challenges are the initial costs escalate for geopolymer concrete and inconsistency in RAC quality. Opportunities include combinations of sustainable concrete with modular construction, and the establishment of global standards so that properties are exchanged with uniformity.

Table 2: Application Performance

Application	Technology	Strength (MPa)	CO ₂ Emissions (kg/m ³)
Residential	RAC	30	200
Bridge	Geopolymer	50	150
Precast Panels	Carbonation Curing	40	180

Results

Our study on sustainable concrete technologies reveals their performance, efficiency, and environmental advantage from case studies and theoretical analysis.

Material Performance

The compressive strength of RAC with 50% recycled aggregate, 85% ordinary Portland cement (OPC) concrete is up to 30 MPa. Geopolymer concrete achieved 50 MPa, similar to OPC but with 60% less CO₂ (150 kg/m³ vs 400 kg/m³ for OPC). Carbonation curing sequestered 13 kg CO₂/m³ with a strength of 40 MPa, 95% OPC.

Environmental Impact

The results of LCA indicated that RAC decreased embodied carbon by 25% (200 kg CO₂/m³). Geopolymer concrete had a 62% lower emissions of 150 kg/m³ when compared with OPC. Carbonation curing reduced emissions by 15% and also improved the durability. Statistical analyses (ANOVA) verified that emission reductions are significant ($p < 0.01$) for all technologies.

Economic Benefits

The LCC analysis demonstrated 20–30% savings for RAC and geopolymer concrete, owing to their lesser maintenance and material expenses. Geopolymer concrete had a 10% higher initial cost but was cost saving over 20 years.

Table 3: Environmental and Cost Metrics

Technology	CO ₂ Emissions (kg/m ³)	Initial Cost (\$/m ³)	Lifecycle Savings (%)
RAC	200	80	20
Geopolymer	150	100	30
Carbonation Curing	180	90	25

Discussion

The outcomes demonstrate the potential of sustainable concrete to reduce emissions and save costs while preserving structural performance. For infrastructure, geopolymer concrete reigns supreme and RAC is best suited for the residential industry. Challenges include uniform mix designs and scaling up manufacture. It is yet to be improved on automation and world scale standards.

Conclusion

The idea that the building industry has a big impact on the environment and ecology may be lessened by using sustainable concrete technologies like recycled aggregate concrete, geopolymer concrete, and carbonation curing. This is one of the biggest reasons why green construction is so popular. This is further supported by GOL Residential case studies of infrastructure and precast applications that demonstrate 20–30% reductions in life-cycle costs and environmental advantages that meet global sustainability goals. But it isn't utilized more often because to problems including high starting prices, uneven materials, and codes that don't suit everyone.

More research is required to look at the best mix design, how to automate the manufacturing process, and how to make progress on worldwide standards to increase geometric scaling capabilities. If these problems can be solved, sustainable concrete technologies would really change the way buildings are built. They would make Carbon Neutrality and Circular Economy projects and advancements possible, and they would provide long-lasting, useful structures for the future.

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