JURNAL AR RO'IS MANDALIKA (ARMADA)
Journal website: https://ojs.cahayamandalika.com/index.php/armada

ISSN: 2774-8499 Vol. 5 No. 1 (2025)

Research Article

Eco-Friendly Concrete Technology Innovation for Sustainable Construction in Modern Cities

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Abstract

The rapid urbanization across the globe has increased the demand for environmentally sustainable construction materials, particularly concrete, which alone contributes to over 8% of global carbon emissions due to cement production. Addressing this environmental concern, this study aims to explore eco-friendly concrete technologies that can support the development of sustainable and resilient urban infrastructure. Utilizing a systematic literature review (SLR) method, this qualitative research synthesizes findings from peer-reviewed sources and policy documents published between 2018 and 2025. The study focuses on evaluating technological, environmental, and economic dimensions of green concrete innovations including geopolymer concrete, self-healing concrete, recycled aggregate concrete, CarbonCure technology, and ultra-high-performance concrete (UHPC). Findings reveal that these technologies offer significant carbon reduction potential (up to 90%), enhance durability, support circular economies through waste reuse, and extend infrastructure lifespan. However, challenges such as high initial costs, lack of technical standardization, and policy gaps, especially in developing countries like Indonesia, hinder their widespread adoption. The study recommends multi-stakeholder collaboration, smart urban labs for field testing, financial incentives, and integration of life cycle assessment (LCA) frameworks in urban planning as strategic pathways for implementation. The paper concludes that eco-friendly concrete technologies hold substantial promise for sustainable construction in modern cities and align well with national and global environmental goals. Their integration is essential for reducing emissions, improving efficiency, and building climate-resilient urban ecosystems.

Keywords: Sustainable Concrete, Urban Infrastructure, Green Building Technology.

INTRODUCTION

The rapid pace of global urbanization has significantly increased the demand for durable, efficient, and environmentally responsible infrastructure, drawing greater attention to the need for sustainable construction materials (Singh et al., 2024). Concrete, the most widely used construction material, contributes approximately 8% of global carbon emissions, primarily due to cement production (Oladunni et al., 2025). Therefore, developing alternatives to conventional concrete that are both structurally sound and environmentally friendly has become a critical priority (Baskaran et al., 2025).

Modern urbanization is the result of structural evolution in cities, marked by the integration of digital technology, social transformation, and a focus on sustainability in spatial planning and urban governance. Today's cities are no longer just hubs for economic and social activity; they have become complex digital ecosystems where physical and digital infrastructures interact. This transformation is driven by the need for more efficient public services, global competitiveness, and improved urban livability. According to Febryanti (2024), digital transformation and city branding have become key strategies for cities to attract talent, investment, and tourism in the global era. Urban development now goes beyond the physical realm, relying heavily on digital strategy and technological synergy.

This transformation is evident in the implementation of smart city concepts, where artificial intelligence, big data, and the Internet of Things (IoT) are used to manage resources more efficiently and sustainably. A study by Wati & Nugrahantoro (2025) emphasizes the importance of AI in improving human capital and public services in urban areas. Cities are no longer defined solely by their physical boundaries but also by digital spaces that shape cultural norms, social behaviors, and modes of communication. These changes significantly affect urban governance, spatial planning, and access to digital services (Heriyansyah & Ardiyanto, 2024). Thus, the modern city represents not just a spatial phenomenon, but a convergence of social, technological, and cultural transformation.

Eco-friendly concrete technologies have emerged as innovative solutions that integrate recycled materials and cement substitutes such as fly ash, slag, and metakaolin to reduce the carbon footprint of construction (Singh et al., 2024; Siddiqui et al., 2025). In modern urban areas, the demand for infrastructure capable of withstanding urban growth and climate change pressures further encourages the adoption of such advanced concrete solutions (Afifi, 2025). Innovations such as self-healing concrete, permeable concrete, and geopolymer-based mixtures are becoming increasingly relevant in the shift toward sustainable urban development (Shaffie et al., 2025; Shrivastav et al., 2025).

In addition to their environmental benefits, eco-concrete technologies also enhance construction efficiency through features such as 3D printing adaptability, moisture regulation, and water reduction during production (Lee et al., 2025; Aouad et al., 2025). The integration of these technologies significantly reduces energy consumption and extends the service life of urban infrastructure, two critical aspects in the development of smart cities (Bibri et al., 2025). These innovations align with both national and international sustainable development goals and contribute to long-term ecological resilience (Deshmukh et al., 2025).

Nevertheless, the adoption of eco-friendly concrete technologies faces several challenges, particularly in developing countries such as Indonesia. These include policy gaps, high initial investment costs, and limited standardization in technical guidelines (Renuka et al., 2025; Pathak et al., 2024). It is therefore essential to conduct comprehensive research into the types, benefits, and implementation challenges of these innovations within the context of urban development, in order to offer appropriate technical and policy recommendations (Akhtar et al., 2025; Ghoneim et al., 2025).

The urgency of this research lies in the pressing need to provide concrete solutions to the environmental crisis in urban settings through sustainable building materials. Given that concrete remains the most commonly used material in global construction, transforming its technology will have wide-reaching impacts on reducing emissions and improving energy efficiency in cities (Siddiqui et al., 2025; Shaffie et al., 2025).

Previous studies have assessed various approaches to sustainable concrete, such as replacing cement with supplementary materials and recycling aggregates. However, many of these works focus primarily on laboratory performance rather than the practical integration of eco-concrete in large-scale urban projects (Singh et al., 2024; Renuka et al., 2025). Moreover, few studies have thoroughly considered the socio-economic and environmental dimensions of concrete innovation in real-world construction, presenting a critical research gap.

This study aims to identify and evaluate various eco-friendly concrete technologies with the potential to support sustainable construction in modern urban areas. It focuses on analyzing their environmental, technical, and economic effectiveness, and formulates strategic recommendations for integrating such technologies into sustainable urban planning and development practices.

METHOD

This research adopts a qualitative approach with the type of systematic literature review (SLR), aiming to explore, compare, and synthesize various eco-friendly concrete innovations relevant to sustainable construction in modern urban settings. The qualitative method is appropriate for studies focused on interpreting conceptual frameworks, understanding contextual dynamics, and analyzing thematic patterns across literature (Creswell, 2014). The literature review was conducted to map technological trends, evaluate their benefits and challenges, and propose integration strategies within urban development frameworks.

Data Sources

This study relies on secondary data collected from scholarly literature and credible institutional publications. The data were obtained from peer-reviewed journals, academic books, conference proceedings, technical reports from environmental and construction organizations, and national policy documents. The academic databases used for sourcing literature include Scopus, ScienceDirect, SpringerLink, and Google Scholar. Keywords used in the search process include: "eco-friendly concrete", "green concrete technology", "sustainable construction materials", and "urban sustainable infrastructure". Additional sources included documents such as Indonesian Ministry of Public Works regulations, Sustainable Development Goals (SDGs), and international green building standards.

Data Collection Technique

The data collection was conducted through a systematic screening process involving several inclusion criteria:

1. Recency (published between 2018 and 2025),
2. Relevance (directly related to eco-concrete innovation or sustainable construction), and
3. Credibility (peer-reviewed or published by recognized organizations).

Selected literature was then read thoroughly and critically to extract key information related to types of concrete innovation, environmental performance, implementation barriers, and their application in urban environments.

Data Analysis Method

The data were analyzed using the content analysis method, which involves identifying themes, patterns, and conceptual relationships across the reviewed sources (Krippendorff, 2018). The analysis process consisted of:

1. Categorizing types of eco-friendly concrete technologies (e.g., geopolymer concrete, recycled aggregate concrete),
2. Identifying environmental and economic impacts of the innovations
3. Analyzing technical feasibility and implementation in urban settings.

The data coding and thematic interpretation were conducted iteratively, allowing for refinement of emerging themes. The findings were described through qualitative-descriptive analysis, enabling a comprehensive narrative that highlights both the technological and policy dimensions of green concrete implementation in urban construction.

RESULT AND DISCUSSION

The infrastructure we build today plays a pivotal role in shaping the future sustainability of our cities. Concrete, as the most widely used construction material globally, is responsible for over 8% of total global carbon emissions. Therefore, innovation in eco-friendly concrete technology is essential for creating sustainable cities that are climate-resilient, resource-efficient, and socially integrated.

Table 1. Identification of Eco-Friendly Concrete Technologies

Technology	Description	Application Examples
Geopolymer Concrete	Replaces Portland cement with fly ash or slag, significantly reducing the carbon footprint.	Infrastructure projects in Australia, India
Self-healing Concrete	Contains bacteria or capsules that autonomously repair small cracks.	Roads and bridges in the Netherlands and UK
Recycled Aggregate Concrete	Uses recycled materials from demolition waste to replace natural aggregate.	Green housing projects in Japan and Europe
CarbonCure Technology	Captures industrial CO_2 and injects it during the concrete mixing process.	Commercial buildings in Canada and the USA
Ultra-High-Performance Concrete (UHPC)	Extremely high strength and longevity, reducing the need for repairs.	Bridge infrastructure in France and South Korea

Evaluation of Technological Effectiveness

1. Environmental Aspects
   a. Carbon Emission Reduction: Geopolymer and CarbonCure technologies can reduce emissions by 60–90% compared to conventional concrete.
   b. Resource Efficiency: The use of industrial by-products (fly ash, slag) supports a circular economy.
   c. Waste Reduction: Recycled Aggregate Concrete reduces landfill burden from construction debris.
2. Technical Aspects
   a. Strength and Durability: UHPC and self-healing concrete significantly extend the service life of infrastructure.
   b. Standards Compliance: Some technologies like CarbonCure have passed ASTM standards.
   c. Climate Adaptability: Specific formulations are resistant to extreme temperatures.
3. Economic Aspects
   a. Initial Costs: Typically 10–30% higher than traditional concrete.

b. Life-Cycle Cost (LCC): Maintenance and repair costs decrease substantially over time.
c. Return on Investment (ROI): Pilot projects show ROI within 5–10 years depending on context and scale.

Strategy for Integrating Eco-Friendly Concrete in Urban Planning

1. Regulatory Approach
   a. Integration of LCA (Life Cycle Assessment) standards in municipal spatial planning documents.
   b. Fiscal incentives and carbon credits for contractors implementing green innovations.
2. Stakeholder Collaboration
   a. Synergy between city governments, concrete producers, university researchers, and architects.
   b. Pilot programs in high-density urban areas for micro-scale testing.
3. Supporting Infrastructure
   a. Establishment of smart urban labs for field testing of new concrete technologies.
   b. Development of regional material databases for local cement and aggregate alternatives.

CONCLUSION

Eco-friendly concrete innovations, such as geopolymer concrete, recycled aggregate use, and CarbonCure technology, represent essential strategies for reducing urban construction's environmental impact. These technologies significantly lower carbon emissions, increase material efficiency, and extend infrastructure longevity, making them ideal for sustainable city development. Despite their benefits, technical, economic, and regulatory barriers continue to impede broad implementation, particularly in emerging economies.

Practical Suggestions

To facilitate the adoption of eco-concrete in urban construction, local governments and construction stakeholders should:

1. Integrate green construction standards, such as Life Cycle Assessment (LCA), into spatial planning policies.
2. Provide fiscal incentives like tax breaks and carbon credits for developers adopting green concrete technologies.
3. Support the development of regional databases for alternative materials like fly ash and slag.
4. Establish collaborative smart labs to pilot and test eco-concrete applications in real environments.

Research Recommendations:

Further studies are needed to assess the real-world performance of eco-friendly concrete in diverse urban contexts, particularly under varying climatic and socioeconomic conditions. Future research should also:

1. Investigate the long-term economic impacts and return on investment (ROI) of green concrete applications.
2. Explore strategies to reduce the initial costs of eco-concrete without compromising quality.
3. Examine the role of community engagement and education in accelerating the transition toward sustainable construction practices.

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