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The Development of Environmentally Friendly Concrete in Sustainable Construction in Indonesia: A Literature Review

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ABSTRACT

The construction industry is one of the significant contributors to carbon emissions, primarily through cement production as the main constituent of concrete. Efforts to reduce the carbon footprint have driven the development of environmentally friendly concrete through the utilization of supplementary cementitious materials and alternative non-cement binders. This study aims to develop a literature synthesis on the advancement of environmentally friendly concrete in Indonesia, to analyze its mechanical performance and durability characteristics, and to evaluate its implications for sustainable construction. The research employs a narrative literature review method, covering national and international publications from 2005 to 2025 relevant to supplementary materials, geopolymer concrete, and sustainability assessment. The findings indicate that the use of fly ash, slag, and silica fume as partial cement replacements can achieve competitive mechanical performance while enhancing resistance to aggressive environmental conditions. Geopolymer concrete also demonstrates significant potential for carbon emission reduction while maintaining adequate structural performance. However, widespread implementation remains constrained by challenges such as variability in material quality, limited technical standards, and industry readiness. This study provides an integrated synthesis of technical and environmental aspects as a foundation for strengthening the adoption of low-carbon concrete in supporting sustainable construction in Indonesia.

INTRODUCTION

The construction sector is one of the principal contributors to global carbon emissions, primarily through cement production as the main constituent of concrete. Portland cement manufacturing generates substantial carbon dioxide emissions due to the calcination of limestone and the intensive consumption of fossil fuel–based energy (Scrivener et al., 2018). Globally, the cement industry is estimated to account for approximately 7–8% of total CO_2 emissions, making it a critical focus within climate change mitigation agendas (IEA, 2022; Andrew, 2019). Beyond carbon emissions, cement production also entails extensive natural resource extraction and high energy consumption, reinforcing the urgency of developing more environmentally friendly construction materials as part of sustainable development strategies (UNEP, 2021).

In Indonesia, concrete is the most widely used construction material in infrastructure projects, buildings, roads, and bridges. The rapid expansion of national infrastructure over the past decade has significantly increased cement and aggregate consumption (BPS, 2023; Ministry of Public Works and Housing, 2022). However, conventional Portland cement–based concrete possesses a high carbon footprint, thereby creating the need for lower-impact alternatives. One widely adopted approach involves partially substituting cement with supplementary cementitious materials (SCMs), such as fly ash, slag, and silica fume (Mehta & Monteiro, 2014; Neville, 2011). National standards, including SNI 7656:2012, have regulated the utilization of fly ash as a supplementary material in concrete mixtures. In the Indonesian construction sector, engineering practices are still largely governed by conventional design approaches and existing national standards, which may limit the integration of innovative materials and technologies into mainstream construction practice (Bastini, Amir, et al., 2026)

The concept of environmentally friendly or green concrete extends beyond carbon emission reduction to encompass resource efficiency, industrial waste utilization, reduced production energy, and enhanced long-term structural durability (Habert et al., 2011; Mehta, 2001). The literature indicates that substituting 15–30% of cement with fly ash can improve long-term compressive strength while reducing concrete permeability through pozzolanic reactions that generate additional calcium silicate hydrate (Mehta & Monteiro, 2014; Prasetyo et al., 2021). Studies conducted in Indonesia further demonstrate that fly ash–based concrete exhibits competitive mechanical performance and improved resistance to sulfate and chloride attacks (Jurnal Teknik Sipil ITB, 2020; Yuliana et al., 2019).

Beyond conventional SCMs, geopolymer concrete based on fly ash and slag has emerged as a low-emission alternative, as it does not rely on Portland cement as the primary binder (Hardjito & Rangan, 2005; Provis & van Deventer, 2014). Geopolymer concrete has been reported to reduce carbon emissions by approximately 40–60% compared to conventional concrete, while achieving comparable or even superior compressive strength under certain conditions (Davidovits, 2011; Turner & Collins, 2013). These developments suggest that innovations in concrete materials are not merely incremental but potentially transformational in reducing the construction sector's carbon footprint.

Nevertheless, the adoption of environmentally friendly concrete in national construction practice continues to face significant challenges. Several studies highlight variability in supplementary material quality, difficulties in mix proportion control, and the absence of comprehensive technical standards as key barriers to widespread implementation (Habert et al., 2011; Provis & van Deventer, 2014). In addition, perceived risks associated with non-conventional materials and limited industry experience influence adoption rates (UNEP, 2021). In Indonesia, existing research is largely experimental, focusing on specific mix designs and mechanical parameters without comprehensively integrating environmental and implementation dimensions.

A gap in the literature is evident in the absence of a systematic synthesis linking mechanical performance, durability, carbon emission reduction, and implementation challenges within a comprehensive analytical framework specific to Indonesia. Many studies emphasize laboratory performance, while broader implications for sustainable construction at the national level remain insufficiently synthesized conceptually (Andrew, 2019; UNEP, 2021). This condition underscores the need for a literature review that integrates both technical and environmental dimensions to provide a holistic perspective on the potential and challenges of environmentally friendly concrete in Indonesia.

Accordingly, this study aims to identify the development of environmentally friendly concrete utilization in Indonesia, analyze the mechanical performance and durability of alternative materials based on the literature, and evaluate their implications for sustainable construction. The novelty of this research lies in the development of an integrated synthesis encompassing technical, environmental, and practical implementation aspects of environmentally friendly concrete within the national context, thereby providing a conceptual foundation for strengthening low-carbon construction policies and practices in Indonesia.

METHOD

This study employs a qualitative approach using a narrative literature review method to develop a comprehensive synthesis of the advancement of environmentally friendly concrete in sustainable construction in Indonesia. This approach was selected because the research aims to integrate scientific findings from experimental, theoretical, and policy-oriented studies without conducting laboratory testing or direct field data collection. A narrative review facilitates analysis of conceptual developments, comparison of material performance, and identification of implementation challenges within a unified conceptual framework (Snyder, 2019).

The literature search was conducted up to December 2025 through national and international scientific databases, including Scopus, ScienceDirect, Google Scholar, as well as the Garuda and SINTA portals for accredited national journals. The keywords consisted of combinations of English and Indonesian terms, such as "green concrete," "geopolymer concrete," "supplementary cementitious materials," "fly ash concrete Indonesia," "beton ramah lingkungan," and "konstruksi berkelanjutan." Boolean operators (AND, OR) were applied to systematically broaden and refine search results in accordance with structured literature review procedures (Kitchenham, 2004).

The reviewed literature was limited to publications from 2005 to 2025 to capture the development of geopolymer concrete and modern supplementary materials, while retaining selected classical references as theoretical foundations in concrete technology. The inclusion criteria comprised: (1) nationally and internationally indexed journal articles addressing environmentally friendly concrete or supplementary cementitious materials; (2) experimental studies reporting mechanical performance and/or durability; (3) publications analyzing environmental aspects such as carbon emission reduction or life cycle assessment (LCA); and (4) relevant national standards or policy documents related to the use of alternative materials. Popular opinion articles and publications lacking technical data or environmental analysis were excluded from the selection process.

The selection procedure involved three primary stages: initial identification based on keywords, screening of titles and abstracts, and full-text review to ensure alignment with the research objectives. The selected literature was then analyzed using a thematic synthesis approach by categorizing findings into three principal themes: (1) the development of alternative material types and proportions in concrete; (2) the mechanical performance and durability of environmentally friendly concrete; and (3) environmental implications and implementation challenges within the national construction context (Thomas & Harden, 2008).

To enhance the credibility and consistency of the analysis, source triangulation was conducted by comparing findings from national and international studies and identifying consistent patterns across the literature. Interpretation was performed analytically to ensure that the resulting synthesis is not merely descriptive but capable of constructing a conceptual framework relevant to the advancement of sustainable construction in Indonesia.

Through this methodology, the study is expected to provide a comprehensive overview of the development of environmentally friendly concrete, evaluate its technical performance, and formulate strategic implications for the adoption of low-carbon materials within the national construction industry.

RESULT AND DISCUSSION

Based on the synthesis of the selected literature, the development of environmentally friendly concrete in Indonesia has demonstrated significant progress over the past two decades. The analysis was structured around three principal focuses: the evolution of alternative materials, evaluation of mechanical performance and durability, and implications for sustainable construction. The findings indicate that material innovation is directed not only toward structural performance enhancement but also toward carbon footprint reduction and resource efficiency.

Development of Alternative Materials in Environmentally Friendly Concrete

The literature indicates that supplementary cementitious materials (SCMs), such as fly ash, slag, and silica fume, are the most extensively studied and applied alternative materials in Indonesia. Fly ash, a by-product of coal-fired power plants, has become the dominant choice due to its relatively abundant availability and favorable pozzolanic properties.

Partial cement substitution with fly ash in the range of 15–30% generally results in compressive strength comparable to or exceeding that of conventional concrete at 28 to 56 days. This improvement is attributed to the pozzolanic reaction between reactive silica in fly ash and calcium hydroxide, producing additional calcium silicate hydrate (C–S–H), which enhances the density of the concrete microstructure.

In addition, the development of geopolymer concrete has shown considerable potential as a Portland cement–free alternative. Fly ash- or slag-based geopolymer concrete utilizes alkaline activators to form a strong inorganic polymer network. The literature reports that geopolymer concrete can achieve high compressive strength within a relatively short period and exhibits good chemical resistance.

However, variability in fly ash quality across different sources in Indonesia presents challenges in maintaining consistent performance. This suggests that, despite rapid material development, quality control and standardization remain critical issues.

Mechanical Performance and Durability

From a mechanical perspective, the synthesis indicates that fly ash–substituted concrete often exhibits lower early-age compressive strength (e.g., at 7 days), but demonstrates significant strength gain at later ages due to ongoing pozzolanic reactions. This behavior reflects a distinct strength development pattern compared to conventional concrete.

In terms of durability, SCM-based concrete generally shows improved resistance to permeability and chloride ion penetration. The denser microstructure formed through secondary reactions enhances resistance to sulfate attack and reinforcement corrosion. These findings support the premise that environmentally friendly concrete not only reduces carbon emissions but also potentially extends structural service life.

Geopolymer concrete also demonstrates strong resistance to high temperatures and aggressive environments. Nevertheless, its sensitivity to curing conditions and alkaline activator composition requires more stringent technical control compared to conventional concrete.

Overall, the literature suggests that in terms of structural performance and durability, environmentally friendly concrete exhibits competitive—if not superior—characteristics under certain conditions.

Implications for Sustainable Construction in Indonesia

From a sustainability perspective, the adoption of environmentally friendly concrete contributes directly to reducing clinker consumption, thereby lowering carbon emissions within the construction sector. Several studies indicate that substituting 20–30% of cement with fly ash can significantly reduce embodied carbon without compromising structural performance.

Beyond emission reduction, the utilization of industrial by-products such as fly ash and slag supports circular economy principles within the construction sector. This aligns with sustainable development objectives promoting resource efficiency and waste minimization.

However, widespread implementation of environmentally friendly concrete in Indonesia continues to face structural and technical barriers. One of the primary challenges is the variability in supplementary material quality, particularly fly ash and slag, which are highly dependent on raw material sources and industrial production processes. Inconsistencies in chemical and physical properties may affect concrete performance, necessitating stricter quality control mechanisms. Furthermore, the absence of comprehensive technical standards specifically regulating mix proportions, testing procedures, and applications of environmentally friendly concrete limits large-scale implementation.

Additionally, the national construction industry tends to exhibit conservative attitudes toward non-conventional materials, largely due to concerns regarding long-term performance risks and limited practical experience. This issue is compounded by the limited integration of life cycle assessment (LCA) in project planning stages, meaning that the environmental benefits of environmentally friendly concrete are not fully accounted for in technical and economic decision-making processes. These conditions indicate that, although the technical and environmental potential of environmentally friendly concrete is highly promising, the transition toward low-carbon construction requires stronger policy support, reinforcement of national standards, and enhanced technical capacity and literacy within the construction industry.

Overall, the literature review demonstrates that the development of environmentally friendly concrete in Indonesia is currently in a transitional phase—from experimental research toward limited implementation. From a technical standpoint, alternative materials such as fly ash and geopolymer binders exhibit competitive mechanical performance and durability. From an environmental perspective, their contributions to carbon emission reduction and industrial waste utilization are significant.

However, the principal challenges lie in standardization, material quality consistency, and industry readiness. Therefore, the successful adoption of environmentally friendly concrete depends not only on technological innovation but also on the integration of regulatory frameworks, policy support, and national construction practices.

CONCLUSION

Based on the synthesis of the literature, the development of environmentally friendly concrete in Indonesia has demonstrated significant progress over the past two decades, particularly through the utilization of supplementary cementitious materials such as fly ash, slag, and silica fume, as well as the advancement of geopolymer concrete. These alternative materials have been shown to exhibit competitive mechanical performance and, in certain conditions, enhanced durability compared to conventional concrete. From a technical perspective, the incorporation of supplementary materials functions not only as a partial cement replacement but also contributes to microstructural refinement, thereby improving long-term durability performance.

From a sustainability standpoint, the adoption of environmentally friendly concrete has considerable potential to reduce clinker consumption and significantly lower carbon emissions within the construction sector. The utilization of industrial by-products as supplementary materials further supports circular economy principles and promotes resource efficiency. Nevertheless, the transition toward low-carbon construction in Indonesia continues to face challenges, including variability in material quality, the absence of comprehensive technical standards, and limited industry readiness to widely adopt non-conventional materials.

Overall, this study affirms that environmentally friendly concrete holds substantial potential as a strategic solution for advancing sustainable construction in Indonesia. Its successful implementation requires the integration of technological innovation, strengthened regulatory frameworks and national standards, and enhanced capacity within the construction industry. Through such an integrated approach, environmentally friendly concrete can become a key component in reducing the construction sector's carbon footprint and promoting more sustainable infrastructure development.

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