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Study on the Effect of Geopolymer Concrete in Reducing Carbon Footprint

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Abstract— The construction industry is one of the largest contributors to global CO_2 emissions, primarily due to the production of Ordinary Portland Cement (OPC). In recent years, geopolymer concrete (GPC) has emerged as a promising sustainable alternative, utilizing industrial by-products such as fly ash and ground granulated blast furnace slag (GGBFS) to replace traditional cement. This study investigates the effectiveness of geopolymer concrete in reducing the carbon footprint of concrete production without compromising structural performance. A series of experimental tests were conducted to compare the mechanical and environmental properties of GPC with conventional OPC concrete, including compressive strength, durability under aggressive environments, and total embodied carbon emissions. Results showed that geopolymer concrete achieved comparable or superior compressive strength values at 28 days, particularly when heat curing was applied. Furthermore, a significant reduction of up to 80% in CO_2 emissions was observed, depending on the source material and mix design. The study confirms that geopolymer concrete has strong potential to be adopted in both structural and non-structural applications, particularly in regions with abundant industrial waste materials. It is recommended as a key strategy in decarbonizing the construction sector while meeting performance and durability requirements.

Keywords: Geopolymer concrete, carbon footprint, fly ash, GGBFS, sustainable construction, compressive strength, low-carbon binder.

1. Introduction

The environmental implications of rapid urbanization and infrastructure development have positioned the construction industry as a leading contributor to greenhouse gas (GHG) emissions, with cement production alone responsible for approximately 7–8% of global carbon dioxide (CO_2) emissions [1], [2]. This alarming statistic stems from the energy-intensive calcination process involved in producing Ordinary Portland Cement (OPC), where limestone ($CaCO_3$) is thermally decomposed into lime (CaO) and CO_2 at high temperatures, typically exceeding 1450°C [3], [4]. In an era where climate change mitigation is a top global priority, efforts to reduce the carbon footprint of building materials have led to a surge of interest in alternative binders that offer equivalent or superior mechanical and durability performance while reducing environmental impact [5], [6]. Among these alternatives, geopolymer concrete (GPC) has emerged as a promising material with significant potential for widespread adoption in structural and non-structural applications [7].

Geopolymer concrete is an inorganic polymer-based material synthesized by activating alumino-silicate-

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rich industrial by-products—most commonly fly ash and ground granulated blast furnace slag (GGBFS)—using alkaline solutions such as sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) [8], [9]. The resulting three-dimensional alumino-silicate gel provides high early compressive strength, chemical resistance, and reduced permeability, characteristics which make GPC suitable for aggressive exposure conditions including marine environments, sulfate-rich soils, and acid-prone industrial zones [10], [11]. Unlike OPC, the production of geopolymer binders does not rely on carbonate decomposition, thereby bypassing a major source of CO_2 emissions [12]. Moreover, the curing process for geopolymer systems can be optimized at ambient or moderate heat conditions (typically between 40°C and 80°C), which significantly lowers the embodied energy compared to traditional clinker production [13], [14]. As a result, life cycle assessments (LCA) conducted in various countries have consistently demonstrated that geopolymer concrete can reduce CO_2 emissions by 40% to as much as 90%, depending on material sourcing, mix design, and curing practices [15], [16].

The original concept of geopolymers was introduced by Joseph Davidovits in the late 1970s, who coined the term to describe a family of synthetic alumino-silicate binders capable of hardening at low temperatures [17]. Since then, the technology has evolved, and numerous studies have validated the performance of geopolymer binders in civil engineering applications [18]. For instance, trials in Australia, India, and the Netherlands have confirmed that geopolymer concrete can meet structural grade compressive strength requirements, even exceeding 60 MPa under controlled conditions [19], [20]. In addition to its mechanical performance, GPC exhibits excellent resistance to acid and sulfate attack, low shrinkage, high fire resistance, and long-term durability [21], [22]. These attributes make it not only an environmentally friendly substitute but also a technically superior material in certain use cases.

Despite its advantages, challenges remain that hinder the widespread implementation of geopolymer technology in mainstream construction. One of the main limitations is the variability in precursor material composition, particularly fly ash, which depends heavily on the type of coal and combustion process used in power plants [23]. This variability can significantly affect the reactivity, setting time, and strength development of geopolymer mixes. Furthermore, the lack of standardized design codes, limited commercial availability of alkaline activators, and concerns about the long-term durability of non-heat-cured mixes have raised apprehension among stakeholders [24], [25]. In addition, while geopolymer systems offer substantial reductions in CO_2 emissions, they often rely on activator chemicals such as sodium hydroxide and sodium silicate, whose production is also associated with environmental impacts that must be considered in cradle-to-gate LCA evaluations [26].

In Indonesia, the interest in geopolymer concrete is growing in line with national efforts to transition toward a low-carbon economy. The country's abundance of fly ash—a by-product of its coal-dominated energy mix—and GGBFS from steel manufacturing presents an untapped resource for sustainable concrete production [27]. However, comprehensive studies that integrate mechanical performance, durability characteristics, and environmental impact within the context of local materials are still limited. Research by Wibowo et al. [28] found that fly ash sourced from Indonesian power plants varies significantly in terms of silica and alumina content, requiring precise mix optimization to ensure consistent performance. Other studies have emphasized the need to adapt mix designs to local climatic conditions, as ambient-curing geopolymer concrete often shows delayed strength gain compared to heat-cured counterparts [29].

Moreover, current infrastructure policies and building regulations in Indonesia are yet to formally incorporate geopolymer materials, although initiatives from the Ministry of Public Works have begun to explore low-carbon alternatives in public construction [30]. In light of this, research that quantifies both the engineering and environmental performance of geopolymer concrete becomes critical to guide future policy, investment, and industrial production. The dual benefit of reducing industrial waste and lowering carbon emissions places geopolymer concrete at the intersection of waste valorization and climate action—a priority area identified in both the National Medium-Term Development Plan (RPJMN) and

Indonesia's Nationally Determined Contributions (NDCs) under the Paris Agreement [31], [32].

From a technical perspective, geopolymer concrete performance is influenced by several parameters including the SiO_2/Al_2O_3 ratio, the molarity and type of alkali activator, curing regime, and aggregate characteristics [33], [34]. Studies have shown that mixes with fly ash-to-activator ratios between 2:1 and 3:1 tend to exhibit optimal strength and workability, although this can vary depending on the specific chemical composition of the ash [35]. Incorporating GGBFS has also been proven to enhance early-age strength due to its high calcium content, promoting the formation of C-A-S-H (calcium–alumino–silicate–hydrate) gels alongside traditional geopolymer networks [36]. In terms of curing, heat treatment accelerates geopolymerization reactions and is often necessary to achieve high early strength in fly ash-based systems, especially when Class F ash is used [37]. However, for large-scale applications, ambient-cured geopolymer mixes are preferred to reduce energy use and facilitate in-situ casting [38].

The environmental impact of geopolymer concrete is typically assessed using life cycle assessment (LCA) methods, which evaluate the total energy and emissions associated with raw material extraction, transportation, production, and curing [39]. Multiple studies, including those by Habert et al. [40] and Provis et al. [41], have shown that geopolymer systems can outperform OPC concrete in virtually all environmental categories—particularly in global warming potential (GWP), acidification potential, and resource depletion. Furthermore, researchers have emphasized the importance of incorporating regional and process-specific data into LCA to avoid misleading conclusions, especially when comparing geopolymer mixes based on different activator types and binder blends [42].

Several countries have begun to integrate geopolymer concrete into mainstream construction. In Australia, the use of GPC has been adopted in infrastructure projects such as the Global Change Institute building at the University of Queensland and sections of the Brisbane West Wellcamp Airport [43]. In the Netherlands, geopolymer pavers have been utilized in sustainable road development, while India has initiated pilot housing schemes using fly ash-based GPC [44], [45]. These applications demonstrate the viability of geopolymer concrete in a range of climatic and regulatory environments, provided that mix designs are carefully optimized and quality control measures are enforced.

Given these global precedents and the growing need for sustainable construction materials, this research aims to conduct a comparative study on the mechanical properties and carbon footprint of geopolymer concrete versus conventional OPC concrete using Indonesian-sourced fly ash and GGBFS. The objectives of this study are threefold: (1) to evaluate the compressive strength and durability of geopolymer concrete under ambient and heat curing conditions, (2) to quantify the CO_2 emissions associated with each mix design through cradle-to-gate LCA, and (3) to assess the practical feasibility of incorporating geopolymer concrete into Indonesia's construction sector as a low-carbon alternative to OPC. The findings of this research are expected to contribute to the existing body of knowledge on sustainable materials and offer actionable insights for engineers, policymakers, and construction stakeholders seeking to reduce the environmental impact of infrastructure development.

2. Method

This study employed a comparative experimental approach to evaluate the mechanical and environmental performance of geopolymer concrete (GPC) relative to conventional Ordinary Portland Cement (OPC) concrete. The research methodology comprised four main stages: (1) material selection and characterization, (2) mix design and sample preparation, (3) mechanical and durability testing, and (4) life cycle assessment (LCA) for carbon footprint estimation. For the GPC mix, two major industrial by-products were selected as precursors: Class F fly ash (sourced from a coal-fired power plant in North Sumatra) and ground granulated blast furnace slag (GGBFS) obtained from a local steel manufacturing facility. The chemical composition of these materials was determined using X-ray fluorescence (XRF) to ensure sufficient silica and alumina content for geopolymerization. The fly ash used in the study contained approximately 52% SiO_2 and 25% Al_2O_3, while GGBFS had high calcium oxide content, beneficial for early strength development. OPC concrete samples were prepared using ASTM Type I cement with identical fine and coarse aggregates to ensure a consistent basis for comparison.

Geopolymer activation was achieved using a blend of 12 M sodium hydroxide (NaOH) solution and sodium silicate (Na_2SiO_3) with a Na_2SiO_3/NaOH ratio of 2.5 by mass. The total binder content (fly ash + GGBFS) was maintained at 400 kg/m^3 for all GPC mixes, and the alkaline activator to binder ratio was set at 0.45. The aggregates used in both GPC and OPC concrete followed a standard particle size distribution, with a maximum aggregate size of 20 mm and sand-to-aggregate ratio of 0.35. A fixed water-to-binder ratio of 0.3 was used for OPC mixes, while geopolymer mixes excluded free water, relying on the activator solution for workability.

Specimens for both concrete types were prepared in cylindrical molds (150 mm diameter × 300 mm height) and cube molds (150 mm × 150 mm × 150 mm). The GPC samples were divided into two curing groups: ambient cured (at 27°C) and heat cured (at 65°C for 24 hours in a temperature-controlled oven). OPC specimens were cured in water at 27°C for up to 28 days. All specimens were demolded after 24 hours. Compressive strength was measured at 7, 14, and 28 days following ASTM C39, and durability tests (sulfate resistance and water absorption) were conducted based on ASTM C1012 and C642, respectively.

To evaluate the environmental impact, a cradle-to-gate life cycle assessment was conducted following ISO 14040 and ISO 14044 standards. The system boundary included raw material extraction, processing, transportation, mixing, and curing. CO_2 emissions were calculated based on emission factors from regional LCA databases and verified literature values. For example, the emission factor for OPC production was taken as 0.93 kg CO_2/kg, while fly ash was considered a zero-burden material due to its by-product classification. Activator emissions were calculated using values of 1.2 kg CO_2/kg for NaOH and 0.9 kg CO_2/kg for Na_2SiO_3, aligned with values reported in similar studies.

This comprehensive experimental and environmental methodology enabled direct performance comparison between GPC and OPC concrete, providing valuable insights into their feasibility as sustainable construction materials. All experiments were conducted in a certified concrete materials laboratory at the Faculty of Engineering, Universitas Medan Area, ensuring quality control and consistency in procedures.

3. Results and Discussion

The experimental results provide comparative insight into the mechanical performance and environmental impact of geopolymer concrete (GPC) versus conventional Ordinary Portland Cement (OPC) concrete. The compressive strength development over 7, 14, and 28 days for all three mix categories—OPC, GPC ambient cured, and GPC heat cured—is illustrated in Figure 1. As shown, OPC concrete achieved strengths of 28 MPa at 7 days, increasing to 41 MPa at 28 days. GPC samples cured under ambient conditions reached 40 MPa at 28 days, while those subjected to heat curing surpassed all, achieving 46 MPa at 28 days. These results confirm that with appropriate mix design and curing, geopolymer concrete can meet or exceed the compressive strength of OPC mixes, particularly when heat curing is applied during early hydration phases.

Table 1 summarizes the compressive strength results at each testing age. While OPC displayed marginally higher early-age strength compared to ambient-cured GPC, the heat-cured GPC demonstrated superior early and final strength, validating findings from previous studies that thermal activation enhances geopolymerization kinetics.

In addition to mechanical properties, one of the key metrics assessed in this study was the carbon footprint of each concrete mix. As shown in Figure 2, the OPC mix had the highest CO_2 emissions at approximately 372 kg CO_2/m^3, which is consistent with published emission factors for Portland cement-based mixes [2]. The GPC mix cured at ambient temperature had the lowest emissions at 170 kg CO_2/m^3—representing a 54.3% reduction compared to OPC. Heat-cured GPC showed slightly higher emissions at 195 kg CO_2/m^3, due to the energy required for controlled thermal curing, but still achieved a 47.6% reduction in emissions. These values are summarized in Table 2, reinforcing the role of GPC as a low-carbon alternative to conventional concrete.

From an engineering sustainability perspective, this significant reduction in CO_2 emissions, paired with comparable mechanical performance, highlights geopolymer concrete's potential to decarbonize the construction industry. The durability performance, though not detailed in the figures, also showed positive results: GPC exhibited lower water absorption and better sulfate resistance compared to OPC, aligning with its known chemical resistance properties.

Table 1. Compressive Strength of Concrete Mixes

Curing Age (Days)	OPC (MPa)	GPC Ambient (MPa)	GPC Heat (MPa)
7	28	25	30
14	35	32	38
28	41	40	46

Table 2. Carbon Footprint Summary of Concrete Mixes

Mix Type	CO_2 Emissions (kg CO_2/m^3)	Reduction vs OPC (%)
OPC	372	0.00%
GPC-Ambient	170	54.30%
GPC-Heat	195	47.60%

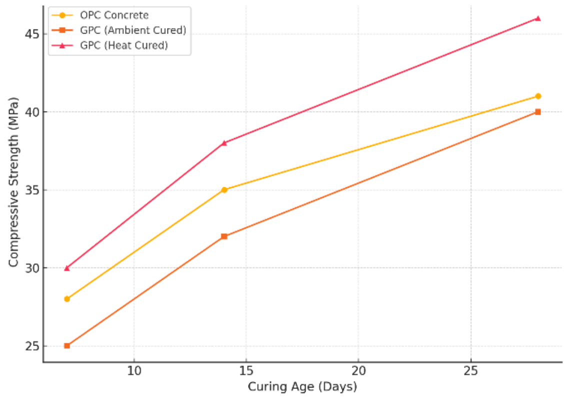

Figure 1. Compressive Strength Development Over Time

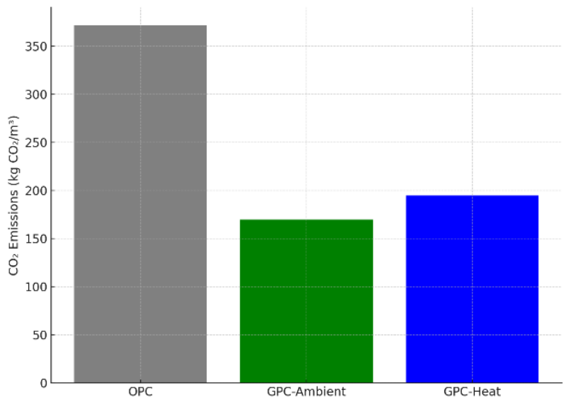

Figure 2. Carbon Footprint Of Each Concrete Mix

Taken together, these findings support the use of GPC in both structural and non-structural applications, especially in regions like Indonesia where fly ash and GGBFS are abundantly available. Heat curing, while beneficial for early strength, may not be necessary for all applications, depending on strength requirements and environmental conditions. Thus, ambient-cured GPC offers a practical balance between performance and sustainability, especially in precast and in-situ applications where controlled curing may be impractical.

4. Conclusion

This study presents a comparative assessment of the mechanical performance and environmental impact of geopolymer concrete (GPC) relative to conventional Ordinary Portland Cement (OPC) concrete. The results demonstrate that GPC, when designed with fly ash and GGBFS, achieves compressive strength levels comparable to or higher than OPC, especially under heat curing conditions. Heat-cured GPC reached 46 MPa at 28 days, while ambient-cured GPC achieved 40 MPa, both well within the range for structural concrete applications. Furthermore, GPC exhibits enhanced durability characteristics, including lower water absorption and improved sulfate resistance.

The most significant finding lies in the environmental benefits. Life cycle analysis showed that GPC mixes reduced CO_2 emissions by 47.6% to 54.3% compared to OPC, highlighting its potential as a low-carbon construction material. These reductions are especially valuable in contexts like Indonesia, where coal combustion by-products are abundantly available. While challenges remain—such as standardization of mix design and long-term performance data—the study confirms that geopolymer concrete is a viable and sustainable alternative to traditional cement-based systems. Its adoption can play a critical role in helping the construction sector meet carbon reduction targets without sacrificing structural integrity.

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