

The Role of Geopolymer Concrete in Achieving Sustainable Development Goals

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ABSTRACT

A sense of safety and comfort is a fundamental right for all people. The United Nations strives to fulfil this through the establishment of 17 Sustainable Development Goals (SDGs). The construction sector plays a significant role in achieving these goals, particularly in the areas of Good Health and Well-being, Clean Water and Sanitation, Decent Work and Economic Growth, Sustainable Cities and Communities, Responsible Consumption and Production, and Climate Action. One key effort in the construction sector is replacing Portland cement with pozzolanic materials. Cement production emits large amounts of carbon dioxide, contributing substantially to global warming. To address this, pozzolanic materials such as fly ash are used as a substitute for cement in the production of geopolymer concrete. Based on compressive strength tests on cylindrical specimens and flexural strength tests on beam specimens, geopolymer concrete demonstrates high potential for structural applications. Its mechanical performance is comparable to that of conventional concrete, making it a promising alternative that supports sustainable development in the construction industry.

Keywords: Cement; Construction; Geopolymer Concrete; Pozzolanic; Sustainable Development Goals

INTRODUCTION

For all people on Earth to enjoy peace, justice, equality, and prosperity, the United Nations (UN) established 17 Sustainable Development Goals (SDGs) at its General Assembly in September 2015, to be achieved by 2030 (Alfathy et al., 2024). Indonesia, as a member of the UN, is participating in the implementation of the SDGs, one of which is by providing legal certainty through the Presidential Regulation of the Republic of Indonesia Number 111 of 2022 concerning the Implementation of the Achievement of the Sustainable Development Goals (Kementerian Sekretariat Negara Republik Indonesia, 2022).

The Sustainable Development Report 2024 states that Indonesia has made significant progress in achieving the SDGs among all upper-middle-income countries. Over five years, from 2019 to 2024, Indonesia's score increased from 64.2 to 69.4, and its ranking improved from 102nd to 78th (J. Sachs et al., 2019; J. D. Sachs et al., 2024). The report also states that, out of 289 indicators, Indonesia has achieved the target for 40% of the indicators and has shown limited progress on 36% of the others, thus demonstrating significant improvement (J. D. Sachs et al., 2024).

Despite progress in some areas and countries, significant gaps remain in achieving the SDGs overall. The world's

primary concern today is climate change—a global challenge that requires a collective response from all countries. Indonesia, as one of the countries most vulnerable to the impacts of climate change, has a significant responsibility to reduce greenhouse gas emissions and increase its resilience to natural disasters related to climate change.

In 2023, efforts to mitigate greenhouse gas emissions became a key focus of the Indonesian government. The global community believes that with the help of science, technology, and innovation, greenhouse gas emissions can be reduced. Therefore, the role of universities—especially those with Faculties of Engineering/Technology or Science—is crucial in reducing greenhouse gas emissions through research, facilitating innovation, leading by example, and collaborating with community partners. In addition to having science, technology, and innovation, reducing greenhouse gas emissions also requires strong institutional support. Institutions engaged in reducing emissions must collaborate and synchronise their actions.

To help the government accelerate the achievement of the TPB/SDGs, the Civil Engineering Study Program at Pelita Harapan University seeks to contribute, one way being by encouraging the use of environmentally friendly and sustainable building materials to reduce greenhouse gas

emissions. One such alternative material is geopolymers, which can be used as a substitute for ordinary Portland cement (Singh & Middendorf, 2020). Geopolymer cement is a byproduct of coal combustion at power plants (PLTU), in the form of fly ash and bottom ash (FABA) (Prayoga & Afla, 2023). The purpose of this study is to examine the extent to which various TPB/SDG goals have been achieved in Indonesia through the use of geopolymer cement as a substitute for ordinary Portland cement.

MATERIALS AND METHODS

Sustainable Development Goals (SDGs)

The use of concrete in Indonesia is increasing in line with the rapid development of housing and infrastructure projects. This is due to several advantages of concrete, such as its high compressive strength and relative stability, high durability, low maintenance requirements, fire resistance, and ease of shaping. The UN General Assembly proposed a set of 17 global Sustainable Development Goals (SDGs) (Figure 1.). The construction industry plays a critical role in supporting the achievement of these goals (Fei et al., 2021). The industry contributes not only to a few but to almost all of the 17 SDGs. One of the key concerns in the construction sector is its significant contribution to greenhouse gas emissions (Arioğlu Akan et

al., 2017). Innovation in building materials that can reduce the carbon footprint contributes directly to sustainability targets.

Therefore, the use of alternative binders to replace cement is a strategic move toward fulfilling the world's SDG commitments.



Figure 1. Seventeen Sustainable Development Goals

Geopolymer Concrete

The basic ingredients for making concrete are cement, coarse aggregate, fine aggregate, and water. Indonesia is the largest producer and consumer of cement in Southeast Asia. At the global level, Indonesia is the 6th largest producer. Indonesia's cement production in 2023 was around 66 million metric tons (China Research and Intelligence, 2024). However, cement production is not environmentally friendly (Mehta, 2001). Various efforts are being made to reduce cement use, such as minimising combustion energy in the production process or using alternative materials with similar adhesive capabilities to cement in concrete. Several studies (Benhelal et al., 2013; Nielsen & Glavind, 2007; Ralli & Pantazopoulou, 2021;

Wibowo et al., 2024; Widjajakusuma et al., 2022) suggest the use of waste materials as substitutes for cement, such as fly ash, rice husk ash, palm oil ash, steel slag, microsilica, and metakaolin ash.

A study by Widjajakusuma et al. (2022) examined the mechanical characteristics of fly ash-based geopolymer concrete, including compressive strength, tensile strength, and flexural strength, and compared them with concrete made from Portland cement. The results showed that the average compressive strength of the geopolymer concrete reached 38.2 MPa, which is 13% lower than that of normal concrete. However, this value is still acceptable as a substitute for Portland cement-based concrete. The study found that the average flexural strength of

geopolymer concrete reached 22.9 kN·m, which is relatively better than that of normal concrete. This indicates that the bonding between geopolymer concrete and reinforcing steel is superior to that of normal concrete. The setting time of geopolymer concrete is approximately 30–60 minutes, whereas that of normal concrete is around 1–2 hours. The workability of geopolymer concrete is lower than that of normal concrete, but it is still sufficient to form blocks, as demonstrated in this study. Based on the study's results, geopolymer concrete can be recommended as an alternative material for construction.

RESULTS AND DISCUSSION

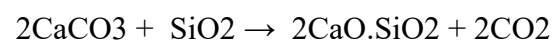
This study discusses how the transition from Portland cement to fly ash-based geopolymer paste can support various SDGs. One of the primary objectives of the SDGs is to limit the global average temperature increase to a maximum of 2°C, with the ultimate goal of achieving a temperature rise of no more than 1.5°C. Geopolymer cement has a lower carbon footprint than Portland cement—around 60% to 80% lower (Benhelal et al., 2013). Additionally, the use of fly ash waste as a pozzolanic material reduces pollution, utilises resources more efficiently, and promotes a circular economy.

The first discussion focuses on how reducing the use of Portland cement can

help achieve several SDGs. The high carbon footprint of Portland cement production can be attributed to the following factors.

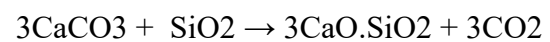
The burning of limestone and silica produces cement. Chemically, the result of the burning process is dicalcium silicate, as shown in the following reaction:

- Reaction (1)



and tricalcium silicate:

- Reaction (2)



Reactions (1) and (2) indicate that the production of 1 ton of cement emits approximately 0.545 tons of CO₂. Additionally, burning 1 ton of clinker requires around 1,800 MJ of energy and produces 0.4 tons of CO₂ (Rashad & Zeedan, 2011). Meanwhile, transporting raw materials results in CO₂ emissions of about 0.1 tons (Benhelal et al., 2013). Therefore, the total emissions from producing 1 ton of cement amount to approximately 1 ton of CO₂ (Benhelal et al., 2013; Yu et al., 2019). Technical and managerial inefficiencies can further increase emissions. Overall, the cement industry contributes about 5% to 7% of global annual CO₂ emissions (Benhelal et al., 2013).

Thus, replacing ordinary Portland cement with geopolymer cement can help reduce emissions and support Goal 13 of the

SDGs: "Take urgent action to combat climate change and its impacts."

The production of 1 ton of cement also consumes natural resources. Around 2.8 tons of non-renewable raw materials, such as limestone and clay, are required to produce 1 ton of cement (Guo et al., 2010). Therefore, using geopolymers helps conserve natural resources and aligns with Goal 12.2 of the SDGs: "By 2030, achieve sustainable management and efficient use of natural resources."

Concrete production also requires a large volume of water, as it serves both as a cement hydrator (approximately 25% of the cement weight) and as a lubricant for aggregates. Additionally, water is essential for curing. According to SNI 03-6861.1-2002, only clean water is allowed in concrete production (Badan Standardisasi Nasional, 2002). Although no exact data exist, it is estimated that the concrete industry consumes around 1 trillion litres of clean water annually (Mehta, 2001).

Recent studies (Cahyadi et al., 2022; Danareksa Research Institute, 2023) have highlighted that clean water supply remains a global concern, including in Indonesia. This is due to extreme climate change and increasing water pollution in rivers, lakes, and streams. The only practical large-scale solution is to use water resources more efficiently.

Thus, replacing Portland cement with geopolymers can significantly reduce the use of clean water and support SDG Target 6.4: "By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity" (Kementerian Sekretariat Negara Republik Indonesia, 2022).

The second discussion examines how the use of fly ash-based pozzolanic cement contributes to achieving the SDGs. The use of fly ash significantly supports the concept of a circular economy, which is based on three key principles: eliminating or reducing waste and pollution, increasing the value of waste by converting it into materials or products, and regenerating natural resources. The circular economy has great potential to support several SDG goals.

Fly ash and bottom ash (FABA), which are by-products of coal combustion in power plants, are examples of such waste. In 2019, FABA production reached approximately 8.3 million tons and is expected to continue rising with economic and population growth. Dry fly ash can cause respiratory irritation when inhaled and may release hazardous elements such as lead, arsenic, or mercury into groundwater, resulting in secondary pollution.

Utilising fly ash as a cement substitute is a form of circular economy and can contribute to several SDGs, including Goal 3 (Good Health and Well-being), Goal 8 (Decent Work and Economic Growth), Goal 11 (Sustainable Cities and Communities), and Goal 12 (Responsible Consumption and Production).

Research on geopolymer concrete at the Civil Engineering Study Program of Universitas Pelita Harapan began with the development of a suitable mix design. The molarity of the sodium hydroxide (NaOH) solution affects compressive strength, setting time, and workability. Higher NaOH concentration results in higher compressive strength but also accelerates setting time and decreases workability—and vice versa. After identifying a mix design that could yield a compressive strength of 25–40 MPa, further research explored the effect of admixtures to slow down the setting time. One challenge of geopolymer concrete is its short setting time (30–60 minutes) compared to that of normal concrete (60–120 minutes). Certain types of admixtures were found to increase both workability and setting time.

Another factor affecting compressive strength is the curing method. While traditional concrete is typically cured by surface wetting, research shows that geopolymer concrete cured at elevated temperatures (such as in ovens or steam

chambers) exhibits higher early-age strength. However, recent findings suggest that while high-temperature curing accelerates the chemical reaction, it does not significantly affect long-term compressive strength compared to curing at room temperature.

Material homogeneity is also crucial in achieving optimal results. In the preparation of geopolymer concrete, sodium hydroxide flakes are typically dissolved in water and allowed to stand for 24 hours to achieve a homogeneous solution. A study investigating the use of freshly mixed (non-aged) sodium hydroxide showed lower compressive strength, confirming the importance of a homogeneous alkaline solution.

High compressive strength is critical in structural materials. Therefore, additional research explored mix designs that incorporate materials rich in silica, alumina, and calcium, such as palm kernel shell ash, rice husk ash, kaolin, iron powder, and marble powder. These additions were found to enhance compressive strength when used in the right proportions.

Further studies involved flexural testing of geopolymer concrete beams with dimensions of $125 \times 200 \times 1600$ mm to evaluate their potential as structural elements. Other research examined the effect of fibre-reinforced polymer (FRP) reinforcement, the impact of direct and

indirect burning, and indirect tensile strength.

Scanning electron microscope (SEM) tests were conducted on several specimens to analyse microstructural characteristics. The results showed that compressive strength correlates with crack width and frequency. Early-age specimens (Figure 2.) displayed different crack patterns compared to specimens aged 56 days (Figure 3.), due to the continued pozzolanic reaction over time.

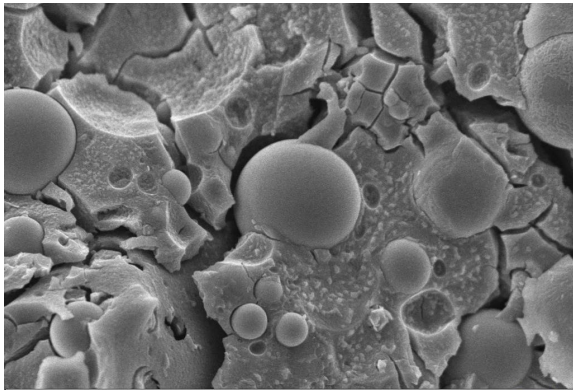


Figure 2. Scanning electron microscopy results of 7-day-old geopolymer concrete

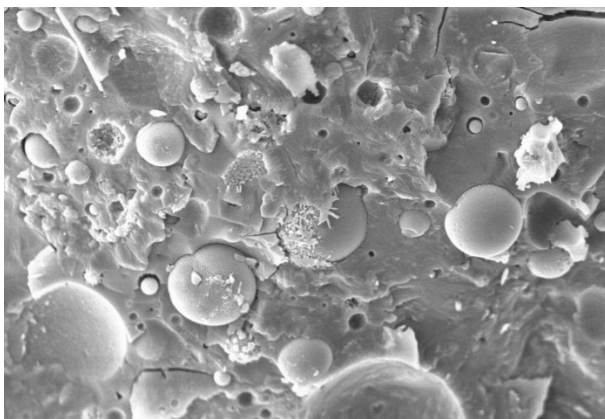


Figure 3. Scanning electron microscopy results of 56-day-old geopolymer concrete

CONCLUSION

The use of fly ash-based cement as a substitute for Portland cement supports

the achievement of several SDG targets, including Goal 3 (Good Health and Well-being), Goal 6 (Clean Water and Sanitation), Goal 8 (Decent Work and Economic Growth), Goal 11 (Sustainable Cities and Communities), Goal 12 (Responsible Consumption and Production), and Goal 13 (Climate Action). To enable the widespread use of fly ash-based cement as a commercial construction material, it is essential to establish technical standards (such as SNI) that ensure compliance with all structural and non-structural concrete requirements for building applications.

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