

A STUDY ON EMISSION OF EQUIVALENT CARBON DIOXIDE BY PORTLAND CEMENT CONCRETE AND GEOPOLYMER CONCRETE

Suppachai Sinthaworn and Piyanuch Jaikaew*

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Abstract

Concrete for general construction uses ordinary Portland cement as a binder or uses geopolymers as a binder to activate the alkaline properties, which have the potential to significantly reduce emission of equivalent carbon of concrete. This paper presents the results of the assessment of the carbon footprint of ordinary concrete and geopolymers, including related energy activities, by evaluating the carbon dioxide (CO₂-e) emissions from the raw material procurement to the production of ordinary concrete and geopolymer concrete using the life cycle assessment (LCA) method, Cradle to Gate or (Business to Business: B2B). The study found that: The emission value of the general concrete production of 1 cubic meter is equal to 331.45 kg.CO₂-e/m³, from the raw material production process and transportation process amounting to 310.98 kg.CO₂-e/m³ and 20.47 kg.CO₂-e/m³, For 1 cubic meter of geopolymer concrete is equal to 266.37 kg.CO₂-e/m³ and 32.41 kg.CO₂-e/m³, from the raw material production process and transportation process. From the assessment to know the use of all resources to be worthwhile for maximum benefit, to help reduce the amount of greenhouse gases or carbon footprints sustainably.

Keywords: Carbon dioxide; Geopolymer; Cement concrete; Carbon dioxide equivalent (CO₂-e)

Introduction

Concrete is the most widely used construction material globally, with an average annual consumption of approximately 1 cubic meter per person in Gartner, E. (2004). Ordinary Portland Cement (OPC) serves as the primary binder in concrete and is responsible for significant greenhouse gas emissions. OPC production contributes 5–7% of global anthropogenic CO₂ emissions, with the carbon dioxide equivalent

(CO₂-e) ranging from 0.66 to 0.82 kg CO₂ per kilogram of cement in Peng *et al.* (2013) and Li *et al.* (2013). The high CO₂ emissions are primarily associated with the calcination of limestone (CaCO₃) and the energy-intensive processes involved in Flower and Sanjayan (2007). Efforts to mitigate these emissions have focused on the development of alternative binders and optimization of concrete mix designs. Blended

Faculty of Engineering, Department of Civil and Environmental Engineering, Srinakharinwirot University, Ongkharak, Nakhonnayok, Thailand. E-mail: piyanuchj@swu.ac.th

* Corresponding author

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cements, which partially replace OPC with supplementary cementitious materials (SCMs) such as fly ash a byproduct of coal combustion and ground granulated blast furnace slag (GGBFS) a byproduct of steel production - can reduce CO₂ emissions by 13–22%. However, the environmental benefits vary based on local conditions, material sourcing, mix design, transportation distances, and energy sources in Duxson *et al.* (2007). Optimizing concrete formulations is another key strategy. High-performance concrete (HPC) and ultra-high-performance concrete (UHPC) offer enhanced mechanical properties while using less cement, reducing the environmental impact without compromising durability and strength in Habert *et al.* (2010). Geopolymers, first described by Duxson *et al.* (2007), represent a promising alternative to OPC. These materials are formed by activating aluminosilicate-rich precursors (e.g., fly ash, metakaolin) using alkaline solutions such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium or potassium silicate in Barbosa *et al.* (2003). Sodium-based activators are most commonly used due to their lower cost and availability. Geopolymer concrete typically requires elevated-temperature curing (40–80°C) for at least six hours to achieve optimal strength in Van *et al.* (2010). The CO₂-e values for geopolymer concrete are significantly lower than those of conventional OPC-based concrete, with reported reductions ranging from 26-45% to as high as 80% in Habert *et al.* (2011). However, the variability in CO₂-e estimates arises from differences in accounting methodologies - particularly whether the energy-intensive production of alkaline activators and transportation of raw materials are included. Additionally, the curing process's energy demand can substantially impact the overall carbon footprint of geopolymer concrete, a factor often overlooked in previous studies in Scrivener *et al.* (2018). Strategies for Carbon Reduction in Concrete Production, Incorporating geopolymers as a binder can substantially reduce the carbon footprint of concrete. However, the feasibility of large-scale adoption depends on addressing challenges related to material availability, high-temperature curing requirements, and consistent performance in diverse applications. Additionally, transitioning to renewable energy sources (e.g., wind, solar, biomass) and adopting energy-efficient technologies such as heat recovery systems, alternative fuels, and low-carbon clinkers can further reduce the carbon intensity of cement production in Stengel *et al.* (2009).

Materials and Methods

Scope of the System

The defined as the CO₂-e emissions (kg CO₂-e/kg) resulting from the activities required to produce 1 cubic meter of concrete, is the constant measure used in this study to compare different types of concrete produced with conventional binders and geopolymers. The scope of the CO₂ emissions study for producing 1 cubic meter of conventional concrete is summarized in Figure 1(a), detailing activities associated with CO₂ emission sources, including energy use, raw material transportation and production, and concrete manufacturing. Similarly, the scope of the CO₂ emissions study for producing 1 cubic meter of geopolymer concrete is summarized in Figure 1 (b).

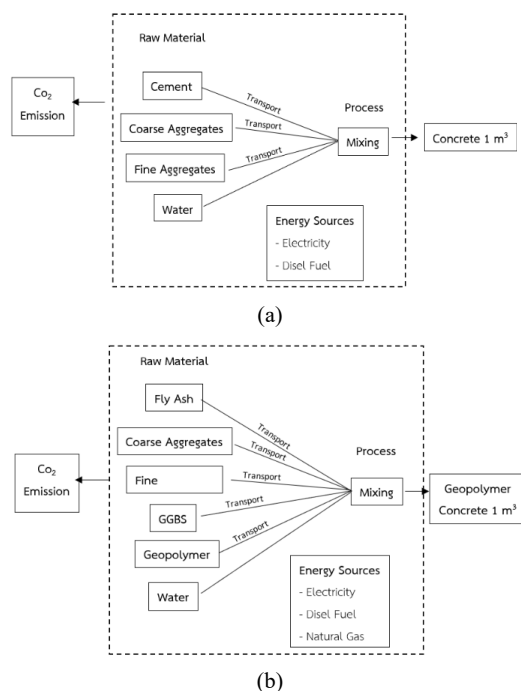


Figure 1. (a) Scope of CO₂ emissions for producing 1 cubic meter of conventional concrete. (b) Scope of CO₂ emissions for producing 1 cubic meter of geopolymer concrete

Methodology

The calculation of CO₂ emissions follows the guidelines for the Carbon Footprint Assessment of Products, as outlined by the Greenhouse Gas

Management Organization in Public Organization (2020). The assessment is based on the following equations:

$$CFP = \sum_{i=1}^n GHGi \quad (1)$$

$$GHGi = \text{Activity data} \times \text{Emission Factor}_i \quad (2)$$

Where: CFP is the carbon footprint of the product (kg CO₂-e).

GHGi is Greenhouse gas emissions for each activity (kg CO₂-e)

Activity data on specific activities. Emission factor is the coefficient for greenhouse gas emissions (kg CO₂-e per unit of activity data).

GWP (Global Warming Potential) is the warming potential of CO₂ (GWP₁₀₀ = 1), as shown in Table 1. To estimate the CO₂-e emissions from producing 1 cubic meter of concrete with a compressive strength of 20 MPa at 28 days, the following approach;

Table 1. Information on the transportation distance of various types of raw materials

Raw Material	Type of Truck	Distance (km)	
		(1)	(2)
Cement	Semi-truck 18 wheel	80	-
	Truck 4 wheel	-	15
Coarse Aggregates	Semi-truck 18 wheel	98	-
	Truck 6 wheel	-	5
Fine Aggregates	Semi-truck 18 wheel	92	-
	Truck 6 wheel	-	5
Fly Ash	Semi-truck 18 wheel	614	-
	Truck 4 wheel	-	65
GGBS	Semi-truck 18 wheel	221	-
	Truck 4 wheel	-	38
Sodium hydroxide	Pickup Truck 4 wheel, solid box	-	80
Sodium silicate	Pickup Truck 4 wheel, solid box	-	80

Raw Material Production: CO₂ emissions from raw material production are calculated as:

$$\text{Emissions} = \text{Quantity of raw material} \times \text{Emission factor for raw material production}$$

Raw Material Transportation: CO₂ emissions from raw material transportation are calculated as:

$$\text{Transportation emissions} = \text{Outbound emissions} + \text{Inbound emissions}$$

Where:

$$\text{Outbound emissions} = \text{Load weight} \times \text{Distance} \times \text{Emission factor for outbound transport}$$

$$\text{Inbound emissions} = \frac{\text{Load weight}}{\text{Maximum load capacity}} \times \text{Distance} \times \text{Emission factor for inbound transport}$$

For this analysis, large and small trucks are assumed to carry full loads outbound and return empty. By aggregating CO₂ emissions from each activity, the total carbon footprint for producing 1 cubic meter of concrete is determined. Large and small trucks are assumed to carry full loads outbound and return empty.

Considerations and assumptions

The calculation scope includes activities related to raw material sourcing, production, and concrete manufacturing for 1 cubic meter of concrete. Additional considerations focus on the potential carbonation of concrete over its lifespan, a process where atmospheric CO₂ reacts with the binder to form calcium carbonate in Collins F., (2010). Carbonation is influenced by several factors, including binder composition, CO₂ diffusion rate, compaction, curing practices, and environmental exposure conditions (e.g., temperature, relative humidity, and atmospheric CO₂ concentration). However, this study excludes CO₂ compensation from carbonation, as the exposed surface area of concrete structures is relatively small compared to the total volume. Thus, carbonation is not considered a significant factor in the CO₂-e compensation of the studied materials in Li, *et al.* (2011). Information on the transportation distance of various types of raw materials, the scope of this study will use the Cradle-to-Gate according to ISO 14040:2006 standard. Primary data is the data of raw material transportation distance which will refer to the travel distance. Secondary data is the data obtained from literature review and related research, publicly available documents including databases in Quddus *et al.* (2025). Concrete mix and geopolymer concrete mix proportion of 1 cubic meter that gives concrete compressive strength of 20 MPa at 28 days, greenhouse gas emission coefficient of each raw material production process and greenhouse gas emission coefficient of different transportation processes of different vehicle types are as shown in Table 2. Concrete mixes of this specified strength do not differ significantly in composition, while geopolymer mixes are an example that can be compared.

Table 2. Greenhouse gas emission coefficients for different types of vehicle transport processes (Public Organization: TGO, 2019)

Type of Truck	Gross Vehicle Weight:G VW	Emission Factor	
		Goes (kg CO ₂ -e/(tkm))	Back (kg CO ₂ -e/km)
Semi-truck 18 wheel	32 T	0.0443	0.8684
truck 6 wheel	8.5 T	0.0677	0.4273
truck 4 wheel	7.0 T	0.1411	0.3131
Pickup truck 4 wheel soild box	1.5 T	0.2154	0.2415

Results and Discussion

The estimation of carbon dioxide emissions (CO₂-e) from raw material procurement to the production of ordinary concrete and geopolymer concrete was conducted using the Life Cycle Assessment (LCA) method, specifically the Cradle-to-Gate or Business-to-Business (B2B) in Xiaoshuang *et al.* (2021). approach, as shown in Table 3.

Table 3. Emission Factors Used in Estimating CO₂ Emissions from Various Fuel Types

Energy source	Emission factor _{a,b} EC GWP	Unit
Diesel	2.68	kg CO ₂ -e/L
Electricity	1.35	kg CO ₂ -e/kW h
Liquid Petroleum Gas (LPG)	1.54	kg CO ₂ -e/L
Explosives	0.44	kg CO ₂ -e/kg product

From Table 4, the CO₂-e emissions for the production of 1 cubic meter of ordinary concrete amount to 331.45 kg CO₂-e/m³, comprising 310.98 kg CO₂-e/m³ from raw material production and 20.47 kg CO₂-e/m³ from raw material transportation. For geopolymer concrete, the CO₂-e emissions are 298.78 kg CO₂-e/m³, with 266.37 kg CO₂-e/m³ from raw material production and 32.41 kg CO₂-e/m³ from transportation, as illustrated in Figure 2.

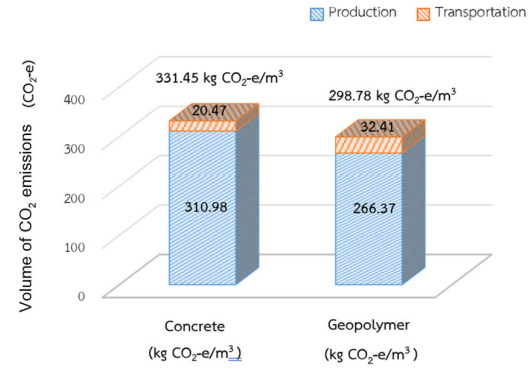
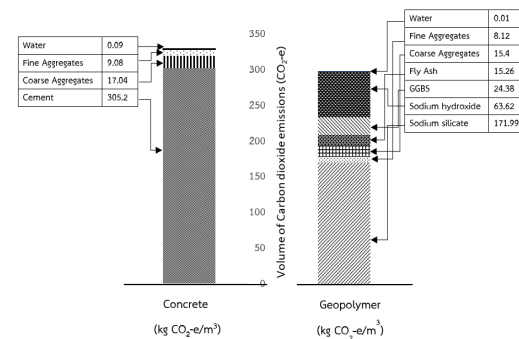
Aggregate Production

Fine and coarse aggregates were assumed to consist of basalt (limestone in Thailand) and locally sourced river sand. Inventory data collected from mines for coarse and fine aggregates were used to estimate the emission factors: 0.0044 kg CO₂-e/kg for coarse aggregates and 0.0037 kg CO₂-e/kg for

fine aggregates. Despite including extraction, crushing, and transportation activities, the emission factors for aggregates remain significantly lower compared to OPC (Ordinary Portland Cement) and alkali activators.

Table 4. Summary of CO₂-e Emissions from Raw Material Procurement to the Production of Ordinary and Geopolymer Concrete

Product	GHG emission (CO ₂ -eq) (kg CO ₂ -e)		Total kg CO ₂ -e/m ³
	Production	Transportation	
Concrete	310.98	20.47	331.45
Geopolymer Concrete	266.37	32.41	298.78

**Figure 2. Total carbon dioxide equivalent (CO₂-e) emissions from raw material acquisition to the production of conventional concrete and geopolymer concrete for 1 cubic meter****Figure 3. (a) Scope of CO₂ emissions for producing 1 cubic meter of conventional concrete. (b) Scope of CO₂ emissions for producing 1 cubic meter of geopolymer concrete**

From the estimation of carbon dioxide emissions ($\text{CO}_2\text{-e}$), the difference between fine aggregates in conventional concrete and geopolymer concrete is $0.96 \text{ kg CO}_2\text{-e/m}^3$ as shown in Figure 3, which is found to be slightly lower or not significantly different, has been further explained.

Comparison Between Ordinary Concrete and Geopolymer Concrete

From Figure 2, summarizes the carbon dioxide equivalent ($\text{CO}_2\text{-e}$) emissions from various activities, ranging from raw material acquisition to the production and construction of 1 cubic meter of concrete. Portland cement contributes the most significant $\text{CO}_2\text{-e}$ emissions. The assessment indicates that the $\text{CO}_2\text{-e}$ emissions for producing 1 cubic meter of conventional concrete are $331.45 \text{ kg CO}_2\text{-e/m}^3$, comprising $310.98 \text{ kg CO}_2\text{-e/m}^3$ from raw material production and $20.47 \text{ kg CO}_2\text{-e/m}^3$ from raw material transportation. In contrast, the $\text{CO}_2\text{-e}$ emissions for producing 1 cubic meter of geopolymer concrete amount to $298.78 \text{ kg CO}_2\text{-e/m}^3$, with $266.37 \text{ kg CO}_2\text{-e/m}^3$ arising from raw material production and $32.41 \text{ kg CO}_2\text{-e/m}^3$ from raw material transportation. For conventional concrete, the proportion of $\text{CO}_2\text{-e}$ emissions attributed to Portland cement accounts for 92.12% of the total emissions, equivalent to $305.24 \text{ kg CO}_2\text{-e/m}^3$. Comparatively, the geopolymer binder system, consisting of fly ash, sodium silicate, and sodium hydroxide, contributes $250.87 \text{ kg CO}_2\text{-e/m}^3$.

Despite the high energy consumption required for producing alkaline activators (e.g., sodium silicate and sodium hydroxide), the total $\text{CO}_2\text{-e}$ emissions for the mixtures used in this study are approximately $331.45 \text{ kg CO}_2\text{-e/m}^3$ for conventional concrete and $298.78 \text{ kg CO}_2\text{-e/m}^3$ for geopolymer concrete, resulting in a 10% reduction in emissions.

Conclusions

This study assessed the total carbon dioxide equivalent ($\text{CO}_2\text{-e}$) emissions from all activities required to source raw materials, produce concrete, and construct 1 cubic meter of concrete. It compared $\text{CO}_2\text{-e}$ emissions from geopolymer concrete and 100% OPC concrete. The $\text{CO}_2\text{-e}$ emissions of geopolymer concrete were found to be approximately 10% lower than that of OPC concrete. The primary factors leading to higher than expected CO_2 emissions for geopolymer concrete included the transportation of raw materials for producing alkaline activators, high energy consumption during activator production, and the

need for high-temperature curing to achieve adequate strength in geopolymer concrete. While geopolymer concrete demonstrates lower overall $\text{CO}_2\text{-e}$ emissions, the significant environmental impact associated with the production of sodium silicate must be acknowledged as a limiting factor for large-scale implementation. This aspect should be elaborated further to provide a balanced perspective on the feasibility and sustainability of geopolymer concrete. Also, there is another problem: making it a strong alkaline is corrosive, and the mixing process is not yet familiar. The workers and the concrete mixer have been accustomed to concrete for a long time.

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