Environmental Sustainability Assessment of Cement Replacing Materials for Concrete Applications in Selected Southeast Asian Countries

東南アジア諸国におけるコンクリート用セメント代替材料の環境持続可能性評価

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ABSTRACT

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Waste materials such as fly ash and slag as partial substitutes for cement have been widely used to enhance the sustainability of concrete production. However, in many emerging economies, the impact of these cement-replacing materials has not been adequately quantified. The main research objective involves quantifying the economic and environmental impacts of fly ash and slag as cement-replacing material on a wide range of concrete mixtures used in the Philippines and Thailand. Environmental and economic assessments were conducted on 60 concrete mixtures in the Philippines (31 mixtures) and Thailand (29 mixtures). In the Philippines, concrete mixtures from batching plants utilized varying percentages of fly ash (0%, 10%, 15%, and 20%) as cement replacements, with 28-day strength designs ranging from 13.8 to 69.0 MPa. In Thailand, the analysis involved 27 concrete mixtures using different types of fly ash (low and high calcium oxide) and higher fly ash percentages (0%, 25%, and 50%) as cement replacements for compressive strengths of 30 MPa, 35 MPa, and 40 MPa, with specified design ages of 28 and 56 days. Additionally, two Thai mixtures designed for 30 MPa mat foundation with 65% slag and 50% fly ash as cement replacement were examined. Environmental assessment of concrete mixtures was carried out using a cradle-to-gate life cycle assessment in SimaPro 9.3.

High calcium oxide (CaO) fly ash exhibited more substantial environmental savings than low CaO fly ash when utilized as a cement replacement for concrete applications in Thailand, without considering fly ash transportation. The environmental benefits of high CaO fly ash over low CaO fly ash are most pronounced in a 40 MPa concrete mix with 50% fly ash replacing cement at 56 days of age, particularly reducing mineral resource scarcity (10.19%), global warming potential (8.82%), and water consumption (8.22%), excluding transportation. For the endpoint indicators, at 50%

cement replacement, the beneficial impact of fly ash is more substantial, with a reduction in endpoint impacts equal to 42-49.5% for human health, 42-49.2% for the ecosystem, and 35-40.5% for resources in comparison with pure cement concrete. The use of fly ash, regardless of its type, reduced the global warming potential (GWP) of concrete by 22-30.6% and 44-51.4% when fly ash was incorporated by 25% and 50% as replacements for cement, respectively, compared to pure cement concrete. Interestingly, the environmental impact of the concrete mixture does not necessarily decrease with increasing percentages of fly ash as cement replacement when actual fly ash transport is considered. The highest critical distance estimated using terrestrial ecotoxicity (355 km) is 8,120 km shorter than the critical distance computed based on global warming potential (8,475 km), implying that terrestrial ecotoxicity is more crucial (limiting) than global warming potential. In terms of economic benefits, the utilization of 25% and 50% fly ash as a cement replacement significantly reduces the cost of pure cement concrete.

The use of 65% ground granulated blast furnace slag (GGBS) as a cement replacement in Thailand concrete shows significant reductions in global warming potential (60.5%), ozone formation (51.1%), and fossil resource scarcity (49.4%) compared to pure cement concrete. However, additional processing steps involved in the preparation of GGBS resulted in increased impact, particularly on human carcinogenic toxicity. Moreover, long-distance import of GGBS from Tokyo to Bangkok by sea transport has a significant environmental impact. Long-distance sea import is responsible for the largest proportion of terrestrial acidification (92%), ozone formation (90%), and fine particulate matter (88.3%).

Based on the environmental assessment of concrete mixtures in the Philippines, the GWP of concrete using pure ordinary Portland cement (OPC) ranges from 255 to 550 kg CO_2 equivalent. The introduction of fly ash as a partial replacement for cement, at weight percentages of 10%, 15%, and 20%, reduces GWP by 8.5-9.4%, 8.5-12.6%, and 2.4-19.2%, respectively. In the case of low-strength concrete mixtures (e.g., 13.8 MPa) with a design age of 28 days, increasing the fly ash replacement from 10% to 20% results in further reductions in environmental impact across only four impact categories. In contrast, for high-strength concrete (41.37 MPa), the environmental burden is reduced across all 18 midpoint categories. Replacing cement with 20% fly

ash reduces GWP from 427 to 345 kg CO_2, mineral resource scarcity (20%), and water consumption (18.5%). Regarding economic considerations, a 20% fly ash replacement of 41.4 MPa concrete results in an 8% (5.39 USD) cost savings per cubic meter. Our analysis demonstrates that concrete batching plant operators in the Philippines, driven by cost reduction motives, do not reap significant savings when employing more fly ash in lower-strength designs. Learning from the Thai practice, designing the mixtures for a longer specified strength age of 56 days will significantly improve the sustainability of concrete utilizing fly ash as partial cement replacement compared to the 28-day specified age design, including economic benefits.

The findings of this study will assist policymakers, concrete manufacturers, engineers, researchers, and other stakeholders in formulating policy recommendations and developing a comprehensive roadmap that incorporates sustainability in concrete production.

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Above all, I thank God Almighty for all the blessings He has given me and my family. As this chapter concludes, I eagerly anticipate the next steps in my journey. *Maraming maraming salamat sa inyong lahat.*

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LIST OF SYMBOLS/ABBREVIATIONS

Symbols/Abbreviations	Terms
GWP	Global warming potential
SOD	Stratospheric ozone depletion
IR	Ionizing radiation
OZ	Ozone formation, human health
FPM	Fine particulate matter formation
OZT	Ozone formation, terrestrial ecosystems
TA	Terrestrial acidification
FEU	Freshwater eutrophication
MEP	Marine eutrophication
TE	Terrestrial ecotoxicity
FET	Freshwater ecotoxicity
MET	Marine ecotoxicity
HCT	Human carcinogenic toxicity
HNT	Human non-carcinogenic toxicity
LU	Land use
MRS	Mineral resource scarcity
FRS	Fossil resource scarcity
WC	Water consumption
SCM	Supplementary cementitious materials
FAM	Mae Moh fly ash (high CaO)
FAR	BLCP fly ash (low CaO)
LCA	Life cycle assessment
OPC	Ordinary Portland Cement
FA	Fly ash
GGBS	Ground granulated blast furnace slag
dt	transportation distance
SWOT	Strengths, Weaknesses, Opportunities, and Threats
DPSIR	Drivers, Pressures, States, Impacts, and Responses
Mt	million tonnes
kg	kilogram
km	kilometer
m^3	cubic meter
CO_2	carbon dioxide
CaO	calcium oxide

CHAPTER 1
INTRODUCTION

The most commonly used manufactured building material on a global scale is concrete (Arrigoni, Panesar, Duhamel, Opher, Saxe, et al., 2020; Nicoara, Stoica, Vrabec, Rogan, Sturm, et al., 2020; Nwankwo, Bamigboye, Davies, & Michaels, 2020). The rapid rate of global urbanization and population growth for the next decades is expected to bolster the already soaring global demand for this material. With this trend, the importance of a holistic, sustainable development framework in the concrete industry cannot be overemphasized. However, with the increasing urbanization and demand for concrete, environmental effects that are more localized in nature need more attention. Some of the potential consequences include health effects on residents living near production plants, increased CO_2 and gaseous emissions due to the transportation of materials, and increased demand for waste disposal of demolished structures (Marinkovic, 2013; Scrivener, John, & Gartner, 2018).

Concrete is composed of cement, fine aggregates (sand), coarse aggregates (gravel), and water in its simplest form. Depending on the target properties to be improved, admixtures may be added to concrete mixtures. Concrete is used in many infrastructure projects, such as in constructing buildings, pavements, bridges, and even in soil stabilization. One of the reasons why concrete stands out from other building materials is its multipurpose characteristic, such that it can be workable during mixing but strong and durable when it hardens. In addition, the constituents needed to produce concrete are cheaper compared to other construction materials, which makes it ideal for mass production. However, despite the benefits of using concrete, it has some negative impacts as well. Cement, for example, is an essential component in concrete production, and it is among the top contributors to carbon dioxide (CO_2) in the world (Scrivener, John, & Gartner, 2018).

In the 1970s, the production was 0.94 billion tonnes, which steadily increased to 2.284 billion tonnes in 2005 (Nwankwo, Bamigboye, Davies, & Michaels, 2020). In 2018, worldwide cement production was around 4.1 billion tonnes, which significantly increased from the 2017 production of 4.05 billion tonnes. By 2050, it is anticipated that 45 percent of additional cement will be manufactured compared to what is currently produced. Cement manufacturing takes up a lot of energy during processing, with material grinding and cement clinker production accounting for between 20% and 40% of the total production of cement (Taylor, Tam, & Gielen, 2006). Five to eight percent of global carbon dioxide emissions are due to the production of cement (Al-Mansour, Chow, Feo, Penna, & Lau, 2019; Bajpai, Choudhary, Srivastava, Sangwan, & Singh, 2020; Pacewska & Wilińska, 2020). The current state of producing concrete needs to be improved and should no longer be based on twentieth-century conventional Portland cement technology.

Concrete manufacturing has a major effect on the climate, society, and economy. Cement has the most detrimental effects of all the concrete constituents. These impacts are primarily due to the intensive processes involved in cement production. Sustainability can be accomplished by using low-energy materials and encouraging waste reduction and recycling in concrete. Waste materials with specific compatible properties may be used to manufacture concrete (Al-Mansour, Chow, Feo, Penna, & Lau, 2019; Chen & Wang, 2022; Pacewska & Wilińska, 2020). Because of the tremendous magnitude of cement consumption worldwide, even a small percentage reduction in its use will significantly reduce global CO_2 emissions and other impacts. Various cement replacements are sourced from industrial, agricultural, and municipal solid wastes. The industrial by-products that may be utilized in place of using cement in concrete are coal fly ash (Tangtermsirikul, Phethany, Youphalat Kaewmanee, Saengsoy, & Julnipitawong, 2016), silica fume (Luo, Hua, Liu, Sun, Yi, et al., 2022), granulated blast-furnace slag (Costa, Nogueira, Andrade, Carvalho, Elói, et al., 2022), bottom ash (Alderete, Joseph, Van den Heede, Matthys, & De Belie, 2021), and limestone powder (Men, Tangchirapat, Jaturapitakkul, & Ban, 2022). Agricultural ashes from rice husks and palms are also used (Sakir, Raman, Safiuddin, Amrul Kaish, & Mutalib, 2020; Singh, Shehnazdeep, & Bhardwaj, 2020). The most commonly utilized by-product as cement replacement is fly ash due to its magnitude, compatibility with cement, and relatively low cost (Hemalatha, Mapa, George, & Sasmal, 2016). It is a waste product of coal combustion in coal-fired power plants. In 2008, it was estimated that the world produced 777 million tonnes of fly ash (Sakir, Raman, Safiuddin, Amrul

Kaish, & Mutalib, 2020). Fly ash can improve the strength, segregation, and ease of pumping concrete (Arrigoni, Panesar, Duhamel, Opher, Saxe, et al., 2020)

1.1 Problem Statement

In Asia, demand for and production of concrete-making materials is expected to increase (Henry & Kato, 2014). Cement substitutes obtained from materials are widely used to improve the environmental performance of concrete. However, in a number of Asian countries, particularly in Southeast Asia, the sustainability of the actual cement substitutes currently in use has not been thoroughly studied and quantified. Policies governing the use of cement-replacing materials are frequently based solely on concrete's mechanical properties, particularly strength and durability. As a result, sustainability analysis needs to be incorporated into policies to make them more comprehensive and informed. The majority of existing life cycle assessments of concrete utilizing cement substitutes are conducted in Western countries, with very few studies conducted in Southeast Asia. In addition, despite numerous research on the benefits of fly ash, there remains a notable research gap regarding the quantification of the environmental impacts associated with the utilization of different types of fly ash in mass concrete. Previous studies have concentrated on the usage of fly ash in general, and a comparative environmental assessment for different types of fly ash in concrete mixtures has yet to be reported. This study will contribute to the limited research on the sustainability of cement substitute materials, particularly those utilizing fly ash and slag. This study will examine regional variations in concrete products, technological alternatives, modes of transportation, and design mix properties in selected countries and how they contribute to sustainability.

1.2 Significance and motivation

Meeting future concrete demand at a high volume while minimizing environmental impact is a significant challenge. The massive manufacturing and consumption cycles of concrete have a negative environmental impact, rendering the current concrete industry unsustainable. Climate change is one of the most serious environmental threats confronting contemporary society, and the increasing CO_2 concentration in the atmosphere is alarming. As a result, the cement and concrete industry is critical to developing strategies for CO_2 emission reduction. In addition, analyzing and quantifying the aggregate environmental impacts of concrete manufacturing and application in construction projects requires a life cycle approach. This study will help us better understand the environmental impact of using cement to replace materials in concrete for selected Asian countries.

1.3 Objectives of the study

The main objective of this study is to assess the sustainability of using cement-replacing materials, particularly fly ash and slag, for mass concrete applications in the Philippines and Thailand. The following are the specific objectives of this study:

1. Assess the environmental sustainability of fly ash and slag as cement replacement material for mass concrete applications in Thailand.
    a. Conduct a comparative analysis of the environmental and economic implications associated with the utilization of low and high CaO fly ash.
    b. Assess the environmental sustainability performance of locally sourced fly ash and imported slag as substitutes for cement in concrete production.
2. Assess the environmental sustainability of fly ash as a cement replacement material for mass concrete applications in the Philippines.
    a. Examine the environmental and economic impacts of incorporating varying proportions of fly ash as cement replacement materials in mass concrete mixtures designed for low, normal, and high-strength applications, with consideration of prevalent industry practices.
    b. Identify the prevailing challenges and potential opportunities for the sustainable integration of fly ash in the concrete industry.
3. Develop policy recommendations and propose a comprehensive roadmap incorporating sustainability in concrete production to assist various stakeholders such as policymakers, manufacturers, engineers, researchers, and other concrete stakeholders.

1.4 Originality and potential contributions

The majority of published studies on the life-cycle assessment of cement replacing materials for concrete are from Europe, North America, and other developed countries. Few published studies assess the sustainability of various supplementary cementitious materials for Southeast Asian countries, where concrete production is increasing due to numerous construction activities. This research will contribute to developing a framework for assessing the sustainability of cement-replacing materials used in developing countries. No comprehensive report has been published in the literature to date. This will also aid in the quantification of the sustainability of the various types of fly ash available in the countries under study. Many of the studies on the assessment of fly ash concrete analyzed laboratory-prepared concrete mixtures. Our work focuses on actual concrete mixtures from batching plants used in mass concrete applications. Most life cycle assessments compare limited strength and are mainly focused on global warming potential (GWP) for environmental assessment. Our study will fill this gap by fully unraveling the influence of fly ash utilization on actual concrete mixtures at low, normal, and high compressive strengths, including the impact of concrete constituents. Our study aims to quantify the economic and environmental impact of a wide range of concrete mixtures from the concrete industry, emphasizing the use of fly ash and identifying possible options to mitigate those impacts. Finally, this study will also contribute directly to at least four Sustainable Development Goals: SGD9 (Industry, Innovation, and Infrastructure), SDG 11 (Sustainable Cities and Communities), SDG12 (Responsible Consumption and Production), and SDG13 (Climate Action).

The novelty and originality of this research are as follows:

- Our work focuses on actual concrete mixtures from batching plants used in mass concrete applications.
- Most studies only compared limited strength in their life cycle assessments. Our study will address this gap by extensively analyzing the impact of fly ash utilization on the actual concrete mixture on a wide range of compressive strengths from low, normal to high-strength concrete.
- We also investigate the effect of various concrete constituents, as well as the impact of transportation and import.

- Our study will compare the impact of the type of fly ash (low CaO and high CaO), which has not yet been reported in the literature.
- We compare the impact of utilizing fly ash and slag considering import
- Our study is the first life cycle study of mass concrete mixtures used in the Philippine construction industry.
- We have developed a comprehensive DPSIR framework grounded in our environmental, economic, and social assessments of prevailing practices within the industry.

1.5 Scope and limitations

This study will cover a cradle-to-gate life cycle assessment for environmental assessment and material cost analysis of concrete using fly ash and slag as cement replacing materials, with mix designs prepared for mass concrete applications. The concrete mix designs and relevant assumptions will be based on practices by two countries of study: Thailand and The Philippines. The scope of the concrete mixtures and factors investigated are summarized in Table 1.1. Life cycle assessment will be carried out using SimaPro 9.3 software.

Figure 1.1 Map of Southeast Asia showing the countries of study (Ang, Chia, Chua, Devanand, Leong, et al., 2021)

The countries were chosen based on their cement production and coal consumption, which produces fly ash as a byproduct for cement substitutes.

Additionally, the countries boast a burgeoning construction industry with a focus on concrete-based infrastructure development. Thailand has a total production of 36.4 MT while the Philippines has 32 MT, which translates to a per capita of 455kg/capita and 250kg/capita, respectively. Both Thailand and the Philippines were included in the Top 30 countries with high coal consumption in 2016, highlighting their high fly ash yield and the need for a more sustainable utilization of these byproducts. Figure 1.1 shows a map of the country in Southeast Asia where the two countries of study are located.

1.6 Overview of study

This thesis is structured into eight chapters, each dedicated to distinct discussions aligned with the research objectives. Chapter 1 serves as an introductory section, providing a comprehensive overview of the objectives, originality, contributions, significance, research gaps addressed, and limitations inherent in this study.

Chapter 2 presents a thorough review of the existing literature, focusing on the sustainability aspects of concrete and recent studies pertaining to the impact assessment of cement replacement materials, such as fly ash, in mass concrete applications.

In Chapter 3, the methodology employed in this research is elaborated upon, delineating the systematic approach adopted for data collection and analysis.

The subsequent chapters (Chapters 4 to 7) are dedicated to the discussion and analysis of results. Each chapter focuses on specific areas of interest. Concrete mixtures and factors investigated (Chapters 4, 5, and 6) are summarized in Table 1.1. Chapter 4 delves into the environmental and economic assessment of fly ash utilization in Thailand, with particular emphasis on the various types of fly ash (low and high CaO) and their transportation logistics, incorporating critical distance analysis. Chapter 5 compares locally sourced fly ash with another supplementary cementitious material (SCM), imported ground granulated slag, examining the associated impacts of importation and processing. Chapter 6 discusses the findings pertaining to the assessment of environmental and economic impacts of fly ash utilization in low, normal, and high-strength concrete, considering industry practices in the Philippines, are discussed. The results are also compared with those of the case in Thailand. Chapter 7 shifts the focus toward the social aspects of sustainable waste material utilization in the mass concrete industry, identifying pertinent issues based on case studies and key stakeholder interviews and presenting policy recommendations grounded in the Driving Forces-Pressures-State-Impact-Response (DPSIR) framework.

Finally, Chapter 8 serves as the culmination of this study, offering a brief summary and conclusive insights derived from the research findings. This chapter also presents recommendations for potential avenues of future investigation.

Table 1.1 Overview of cases analyzed

Country/ Chapter	Cement Replacing Material	Cases Analyzed	Purpose	Factor Investigated
Thailand *Chapter 4*	Low Cao and High CaO Fly Ash	**27 mixtures;** Concrete mix with 0, 25%, and 50% fly ash replacement from Mae Moh (high CaO) and BLCP (low CaO) power plants 28 days and 56 days specified strength	This aims to compare the sustainability of high-CaO and low-CaO mixtures.	Effect of type of fly ash (low vs high CaO): design age, replacement level Effect of long-distance land transportation
Thailand *Chapter 5*	Fly ash *vs* Slag	**2 mixtures** 30 MPa mat foundation mass concrete with 65% slag and 50% fly ash	This aims to compare fly ash and slag at equivalent strength design	Effect of varying the type of cement replacement (*comparison of similar strength, varying type of replacement*) Effect of import (sea transport)
Philippines *Chapter 6*	Fly ash	**31 mixtures** from ready-mix batching plants in the Philippines Concrete mix with 0, 10, 15, 20% replacements 28 day specified strength design	This aims to compare the sustainability of varying % fly ash substitute	Effect of varying mix proportion of low, normal, and high strength concrete Effect of replacement level (*comparison of similar strength, varying mix proportion*)

CHAPTER 2
REVIEW OF RELATED LITERATURE

Concrete is composed of cement, fine aggregates (sand), coarse aggregates (gravel), and water in its simplest form. Depending on the target properties to be improved, admixtures may be added to concrete mixtures (Corpuz, Rosei Monzon, Orozco, & Germar, 2021). It is workable during mixing but strong and durable when it hardens. In addition, its constituents are cheaper compared to other construction materials, which makes it ideal for mass production. The rapid rate of global urbanization and population growth for the next decades is expected to bolster the already soaring global demand for this material. However, despite the benefits of using concrete, it has some negative impacts as well.

Concrete manufacturing has significant effects on the climate, society, and economy. Cement has the most detrimental effects of all the concrete constituents. Cement, an essential component in concrete production, is among the top contributors of carbon dioxide (CO_2) in the world (Scrivener, John, & Gartner, 2018). Five to eight percent of global carbon dioxide emissions are due to cement production (Al-Mansour, Chow, Feo, Penna, & Lau, 2019; Bajpai, Choudhary, Srivastava, Sangwan, & Singh, 2020; Pacewska & Wilińska, 2020). With these trends, a holistic, sustainable development framework in the concrete industry is essential. Some potential consequences include health effects on residents living near production plants, increased CO_2 and gaseous emissions due to the transportation of materials, and increased demand for waste disposal of demolished structures (Marinkovic, 2013; Scrivener, John, & Gartner, 2018). The current state of producing concrete needs to be improved and should no longer be based on twentieth-century conventional Portland cement technology.

2.1 Impacts of Ordinary Portland cement (OPC) concrete production

The environmental impact associated with concrete is primarily due to the extensive use of natural resources, which results in the continuous emission of about 1 ton of carbon dioxide for every ton of cement produced. Projections indicate a significant escalation in cement production, with estimates suggesting a potential increase to 4 billion tonnes annually (Al-Mansour, Chow, Feo, Penna, & Lau, 2019). This trajectory aligns with recent global production figures, which recorded around 4.1 billion tonnes of cement in 2021 (Nilimaa, 2023), juxtaposed against a global consumption rate of approximately 30 billion tonnes (Monteiro, Miller, & Horvath, 2017). Notably, the surge in cement production is predominantly propelled by emerging and developing nations in the Asian region (Sonebi, Ammar, & Diederich, 2016).

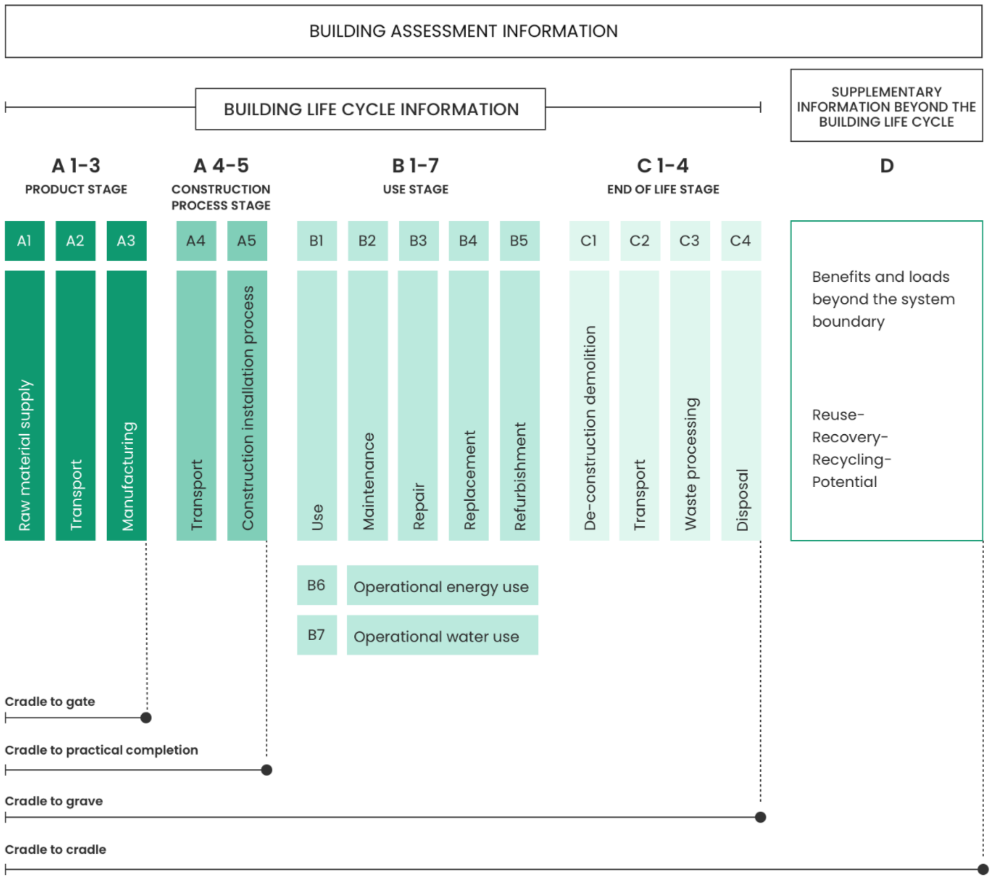

Figure 2.1 Life cycle phases of concrete based on European National (EN) standard (oneclicklca)

The production of Portland cement engenders a spectrum of environmental impacts, spanning resource depletion, global warming, human toxicity, water pollution, acidification, and eutrophication (Habert, 2013). Figure 2.1 illustrates the life cycle of concrete buildings from the acquisition of raw materials from natural reservoirs to their operational lifespan and end-of-life. Predominantly, the environmental burdens associated with concrete are concentrated within the initial phases of this life cycle diagram (A1-3 and A 4-5). Numerous studies on cement and concrete, encompassing studies on concrete raw materials, have delineated various stages of their life cycles, each bearing a significant ecological footprint. An examination of 39,213 ready-mix concrete plants in the United States (Broyles, Gevaudan, & Brown, 2024) has revealed significant variability in the global warming potential (GWP) of concrete mixtures, particularly across different compressive strength design bases. It has been observed that the GWP can peak at levels as considerable as 750 kg CO_2 equivalent per cubic meter, as seen in Figure 2.2.

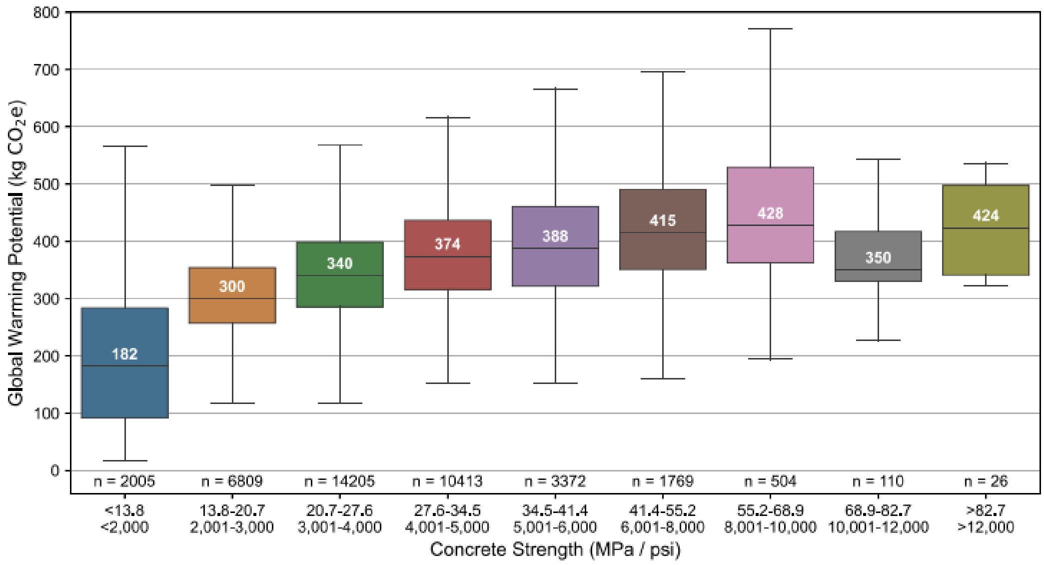

Figure 2.2 Concrete compressive strength and A1-A3 global warming potentials from 39,213 U.S.A. ready-mix concrete EPDs (Broyles, Gevaudan, & Brown, 2024)

2.1.1 Cement production

Cement stands as one of the primary contributors to global carbon dioxide (CO_2) emissions, with projections suggesting a potential surge to four billion tonnes annually by 2030 (Al-Mansour, Chow, Feo, Penna, & Lau, 2019). Global cement production may escalate to 4,682 Mt/yr by 2050, with a predominant consumption pattern observed in developing nations (Tun, Bonnet, & Gheewala, 2021; Y. Wang, Liao, & Liu, 2023). Among the constituents of concrete, cement exerts the most significant adverse impact owing to the intensive processes entailed in its production. As illustrated in Figure 2.3, the cement production cycle begins with quarrying and raw material preparation, followed by clinker production, cement grinding, and distribution. Hence, to enhance the sustainability of concrete, it becomes imperative to employ materials with low energy consumption while promoting waste reduction and recycling in its production.

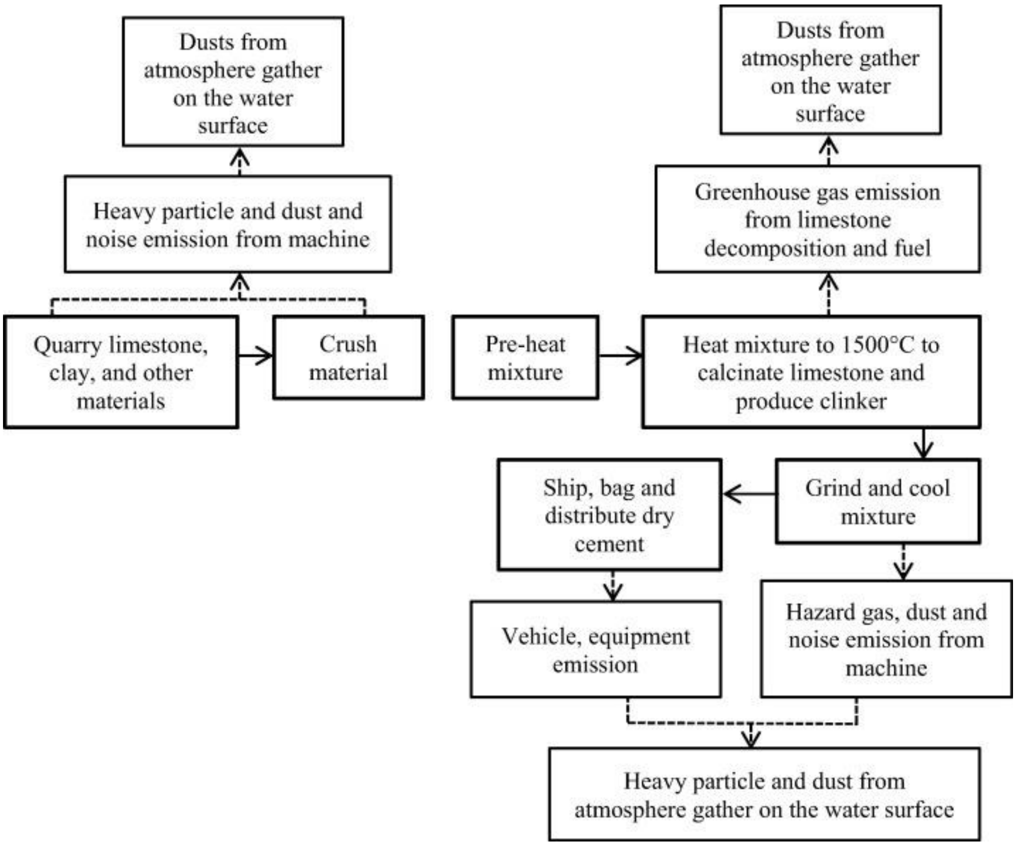

Figure 2.3 Impacts of cement production (Mohamad, Muthusamy, Embong, Kusbiantoro, & Hashim, 2021)

Cement, as the active ingredient in concrete, contributes approximately 6.5% (Qi, Xu, Chen, Guo, & Chen, 2022) to 8% of global greenhouse gas (GHG) emissions (Al-Mansour, Chow, Feo, Penna, & Lau, 2019; Das, Cheela, Mistri, Chakraborty, Dubey, et al., 2022), alongside other notable environmental impacts (De Brito, Hafez, Kurda, & Silvestre, 2022). The environmental impacts of cement manifest impacts on a global, regional, and local scale (Huntzinger & Eatmon, 2009), primarily attributed to emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur oxides (SO_x), and dust. At the local scale of cement production, significant impacts include noise and air quality deterioration from dust emissions (Habert, 2013a) during mining, crushing operations of raw materials, and clinker cooling. Mining activities also lead to natural disturbances, such as landscape and ecosystem alterations (Balboa-Espinoza, Segura-

Salazar, Hunt, Aitken, & Campos, 2023). Regionally, cement production contributes to the acidification of rain and eutrophication in aquatic environments and agricultural soils due to nitrogen oxide (NO_x) and sulfur oxide (SO_x) emissions. Notably, for every metric ton of Portland cement clinker produced, 1.5 to 10 kg of NO_x is released into the atmosphere (Naik, 2008).

The decomposition of limestone in Portland cement production, occurring within the cement kiln, represents a vital process. This chemical reaction denoted as $CaCO_3 \rightarrow CaO + CO_2$, releases 0.5 tons of CO_2 for every ton of CaO produced (Flower & Sanjayan, 2017). On a global scale, CO_2 emissions stem from two major sources. The primary source is the decarbonization of lime, which is responsible for 60–65% of CO_2 emissions and is an essential step in clinker production. The secondary source involves CO_2 generated by the combustion of fossil and alternative fuels during the burning process, accounting for 35–40% of CO_2 emissions (Sonebi, Ammar, & Diederich, 2016). Figure 2.4 illustrates the cement production and capacity across various regions, highlighting extensive cement use in Asian nations.

2.1.2 Aggregates Mining

Aggregates are fundamental components in concrete, encompassing both coarse and fine materials, with artificial aggregates also employed in specific cases. Fine aggregates, predominantly composed of sand, are typically sourced from river quarries, while coarse aggregates are commonly mined from rock formations. The extraction and utilization of these aggregates pose significant environmental challenges. A study by (Ako et al., 2014) underscored the adverse impacts of gravel and sand mining, including landscape destruction, water pollution, and deforestation, leading to notable ecological imbalances globally. Another pertinent aspect of aggregate production is its impact on biodiversity at extraction sites (Sonebi, Ammar, & Diederich, 2016).

When aggregates are processed, carbon dioxide is released through explosives used to blast geological reserves, fuel used by on-site trucks or mixers, primarily for loading and transporting, as well as energy, which contributes to indirect emissions (de Bortoli, 2023). Indirect emissions can account for up to 70% of total emissions. These are the byproducts of electric-driven crushing operations in quarries. Explosives are consumed in trace quantities and produce relatively little pollutants despite their high specific emissions (Şanal, 2018). To mitigate environmental repercussions, attention should be directed towards optimizing the crushing process. Strategic placement of explosives during initial blasting can enhance operational efficiency by breaking rocks into smaller fragments, reducing reliance on electrical crushing equipment (Flower & Sanjayan, 2017).

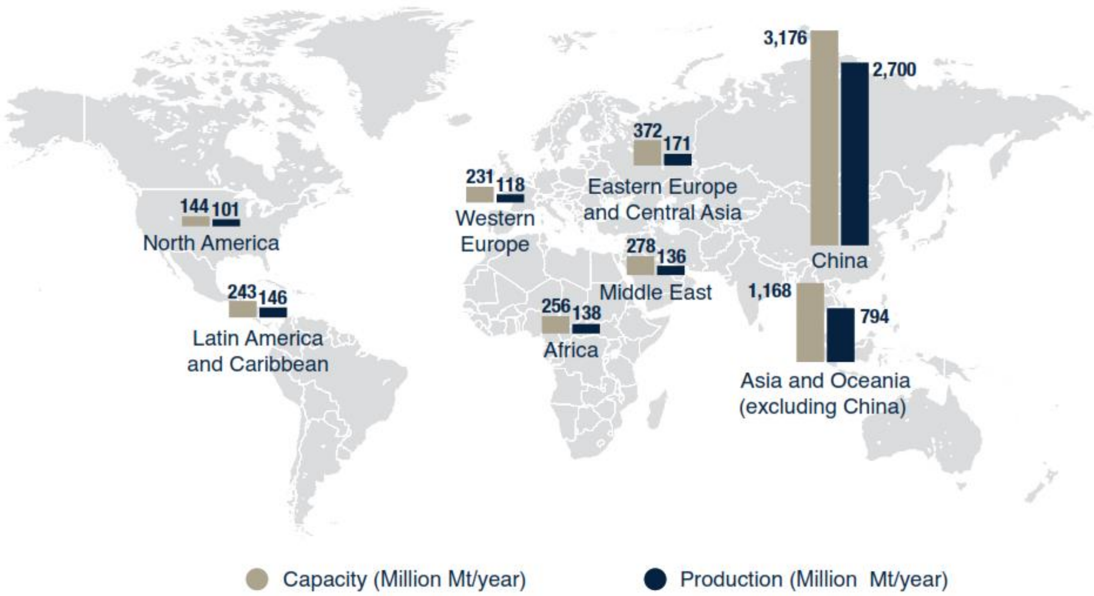

Figure 2. 4 Cement capacity and production in the world (*The impact of COVID-19 in cement industry*, World Bank, 2020)

2.1.3 Water Extraction

Water is a crucial constituent of concrete, and adherence to specific water quality standards is imperative due to the potential adverse effects of heightened concentrations of trace chemicals (American Concrete Institute Committee 130, 2019). Typically drawn from groundwater or surface water sources, the extraction of water for concrete production can pose challenges, particularly when there is excessive demand, leading to potential competition for this vital resource. Furthermore, the indiscriminate disposal of concrete at construction sites poses a risk of water pollution in nearby water bodies. Despite these concerns, research (Şanal, 2018) suggests that water extraction does not significantly contribute to CO_2 emissions per cubic meter of concrete. Moreover, existing literature often overlooks the impact of water use in concrete (Miller, Horvath, & Monteiro, 2018), as its contribution to CO_2 emissions typically remains below 0.5 percent per cubic meter. However, it is important to note that the use of water in concrete production may still contribute to water depletion, an aspect that warrants further consideration and analysis in academic discourse.

2.1.4 Admixtures

Chemical admixtures are commonly employed in concrete to enhance specific properties such as workability and consistency, with the primary sources of admixture emissions stemming from electricity and fuel usage. Among these additives, plasticizers, for instance, are typically incorporated at low concentrations ranging from approximately 0.25 percent to 0.8 percent by weight of the cement utilized, thereby contributing insignificantly to emitted carbon dioxide levels (Bajpai, Choudhary, Srivastava, Sangwan, & Singh, 2020; Şanal, 2018). Table 2.1 shows the approximate global warming potential of various types of admixtures as reported by the American Concrete Institute.

Table 2.1 Potential environmental impacts of chemical admixture based on 30 MPa concrete mixture (American Concrete Institute Committee 130, 2019)

Admixture type	Solids content, percent	Typical dosage, percent of cement	GWP
			kg CO2-Eq
Retarders	10 to 60	0.2 to 2.0	8.78
Set accelerators	10 to 70	1.0 to 3.0	13.37
Air entrainers	5 to 13	0.05 to 1.0	1.77
Hardening accelerators	10 to 70	1.0 to 3.0	22.91
Plasticizers/ high-range water-reducing admixtures	30 to 45	0.2 to 2.0	12.60

Despite their widespread use, limited scholarly attention has been directed towards assessing the environmental impacts of these chemicals in concrete. While Xing et al. (2022) have noted a lack of conclusive evidence regarding the relationship between chemical admixture usage and specific environmental effect indicators, Ji et al. (2022) have reported significant environmental implications associated with plasticizers. Their study quantified a substantial contribution to resource damage, amounting to 44.9%, particularly when plasticizers are employed in typical off-site ultra-high-performance concrete. Notably, plasticizers are commonly derived from petroleum feedstocks, and their manufacturing process is associated with the production of certain chemical components such as SO_x and NO_x.

2.1.5 Concrete mixing at batching plants

Concrete production typically occurs in ready-mix batching plants, where various heavy equipment is utilized to mix concrete constituents. Emissions from these processes are generally minimal. According to Nath et al. (2018), energy consumption for concrete mixing in batching plants can range from 76 to 78 kWh per cubic meter. Sukontasukkul (2009) estimated an energy requirement of approximately 2.15 kWh per cubic meter of fresh concrete for batching plants in Thailand. In mixing plants, the majority of CO_2 emissions stem from the mixing process, which is primarily powered by electricity, accounting for approximately 96% of the total energy used (Flower & Sanjayan, 2017), with a minor contribution from fuel utilized by lifting equipment. Strategies such as situating concrete production plants near major urban centers and on-site concrete production at construction sites, if feasible, can help mitigate the environmental impact of concrete transportation.

2.1.6 Transportation

The transportation aspects inherent in concrete production encompass the conveyance of raw materials from their respective sources to batching plants. These transportation modalities typically entail land-based methods such as truck or train transport, along with maritime transport options. Various studies have documented inventories of energy consumption and CO_2 emissions linked to a unit of concrete output, encompassing carbon emissions attributed to both raw material extraction and concrete transportation to the site. However, existing literature exhibits considerable disparity in findings regarding transportation-related carbon footprint estimates, thus necessitating a comprehensive examination of their implications (Şanal, 2018).

For SCM, the consideration of transportation is imperative in economic and environmental analyses, particularly when SCM availability is constrained in specific regions (Panesar, Kanraj, & Abualrous, 2019). Transportation is recognized as a key contributor to fly ash emissions for these waste materials used for cement replacement concrete. Transportation processes can affect air quality and other environmental factors by releasing sulfur, nitrogen oxides, and other particulates. O'Brien et al. (2009) calculated the critical distance based on greenhouse gas emissions for which fly ash can be delivered by land (11,000km), rail (47,000km), and sea (54,000km) for concrete with a compressive strength of 32 MPa. Panesar et al. (2019) calculated the "breakeven distance" by considering additional factors such as ecotoxicity, human toxicity, resources, and fuels. Jamora et al. (2020) determined a critical distance of 2,841 km when fly ash was used as a replacement for clinker, accounting for the return trip. Historically, land transportation has dominated SCM logistics in many countries, a fact widely acknowledged and incorporated into numerous prior environmental assessments of concrete (Curpen, Teutsch, Kovler, & Spatari, 2023; Delnavaz, Sahraei, Delnavaz, Farokhzad, Amiri, et al., 2022; Panesar, Kanraj, & Abualrous, 2019). Nonetheless, some nations resort to importing concrete materials due to various constraints (Gursel & Ostertag, 2016). Surprisingly, limited research has explored the ramifications of importing SCM for concrete applications. For instance, Hafez et al. (2019) compared imported fly ash from Germany and China with locally recovered fly ash from the UK for blended cement production. The study concluded that when economic allocation was applied, OPC still exhibited a higher impact than imported fly ash. This study also reported a critical sea distance for fly ash transport using a single score indicator of 3,500 km, a considerably lower figure than the 54,000 km reported by O'Brien et al. (2009), who did not consider any allocation scenario. Transportation contributed to nearly 25% of the impact of imported fly ash (López Gayarre, González Pérez, López-Colina Pérez, Serrano López, & López Martínez, 2016). Gursel and Ostertag (2016) investigated the impact of importing cement and aggregates from different countries into Singapore. The study concluded that, in terms of embodied energy and global warming potential, the least environmentally impactful option for importing these materials should be Malaysia, as opposed to Japan, Thailand, or China. No comprehensive environmental assessment has yet been published regarding the impact of import slag for high replacement usage in mass concrete mixtures.

2.2 Sustainability in concrete production

Sustainability, as defined by the World Commission on Environment and Growth (1987), refers to the concept of achieving growth that fulfills present requirements without compromising the ability of future generations to fulfill their own needs. In order to achieve sustainability in concrete manufacturing, it is important to utilize materials that have a long service life while also minimizing or eliminating their carbon imprint in the atmosphere. In construction, sustainability can be incorporated through the following three pillars (Table 2.2):

Table 2.2. Pillars of Sustainable Development in Construction

Element	Strategy
Environment	durable construction minimizes the need for new materials, energy consumption, and waste associated with replacement.
Economic	durable, low-maintenance concrete structures and pavements have superior economic value due to their lower annual cost of ownership.
Social	buildings and pavements that are replaced less often eliminate downtime and disruption associated with maintenance and replacement; worker health and safety across manufacturing and construction processes, advocating for fair labor practices, and mitigating adverse effects on local communities

Considerations encompassing design, construction, maintenance, resilience, and climate adaptation collectively contribute to the holistic sustainability of concrete structures. The optimal performance of concrete is attained through meticulous design and detailing, appropriate mixture proportions, precise production, placement, and curing procedures, as well as timely maintenance and repair interventions (American Concrete Institute Committee 130, 2019). It is imperative to explore novel materials and construction methodologies, coupled with effective inspection and maintenance protocols, to minimize environmental impact, ensure structural integrity, enhance serviceability, and prolong the lifespan of infrastructure and buildings, thereby mitigating the risk of structural failure.

When formulated, processed, and deployed correctly, concrete emerges as a durable and cost-effective construction material. Its utilization in the creation of long-lasting structures facilitates the development of housing and infrastructure that contribute positively to environmental preservation. Sustainability principles can be seamlessly integrated across all stages of concrete's lifecycle, encompassing research and design, material innovation, construction, maintenance and repair, and end-of-life considerations (Tangtermsirikul, 2013), as follows:

a. *Analysis and Design:* Concrete design must prioritize durability and long-term properties while also considering ease of construction and maintenance. Incorporating sustainability provisions into structural codes and standards is essential. Additionally, it is crucial to identify both the functional and structural requirements of concrete and align them with sustainability objectives. Performance-based analysis and design of concrete mix proportions can be integral to achieving sustainability goals.
b. *Materials:* Sustainability in concrete materials can be achieved through the utilization of low-energy consumption materials and by promoting waste utilization and recycling. It is imperative to employ sustainable materials tailored to specific construction types and environmental conditions to ensure prolonged service life. Furthermore, specifying concrete mixtures that incorporate alternative cementitious materials, such as blended cement, and utilizing recycled aggregates whenever feasible are essential practices.
c. *Construction:* Several construction factors significantly impact the long-term sustainability of concrete. These include construction-related energy consumption, effects on the surrounding environment, and economic considerations, including user costs resulting from frost damage. Rapid construction techniques can be employed to reduce construction time. The attainment of a long service life is a fundamental aspect of concrete sustainability, heavily influenced by construction

quality. Sustainable construction techniques are indispensable to optimize structural design, utilize durable or recycled materials, and enhance the efficiency of material production.

d. *Repair, Protection, and Maintenance:* Employing low-cost, low-impact treatments can extend the life of concrete structures and ensure long-term viability. Routine inspections and maintenance are essential for preserving concrete structures and contributing to overall sustainability. Construction efficiency plays a pivotal role in both new construction and preservation efforts, as increased efficiency prolongs concrete life and reduces environmental impact, while treatments decrease energy consumption and greenhouse gas emissions.

e. *Demolition (End-of-Life):* While reusing concrete pavements and employing recycled concrete aggregate are sustainable practices, further improvements can enhance their sustainability and minimize waste streams at the end of concrete's useful life. Techniques such as optimizing the reuse and recycling of concrete materials through testing and characterization can maximize their utility. Additionally, optimizing manufacturing activities for recycled concrete aggregates can further improve sustainability efforts.

2.3 Sustainability in cement production

The global cement industry is actively pursuing decarbonization efforts in alignment with the goals set forth in the Paris Agreement, which aims to limit global warming to below 2 degrees Celsius above pre-industrial levels. Specifically, the European Cement Association has established a target of reducing specific greenhouse gas emissions by approximately 30% by 2030 compared to 1990 levels, with the ultimate aim of achieving carbon neutrality throughout the cement and concrete supply chain by 2050 (IFC, World Bank 2020). These strategies focus on reducing CO_2 emissions across critical sectors, including decarbonization during clinker processing, fuel combustion, transportation, and electricity generation. Recent scholarly literature has extensively explored avenues for enhancing the sustainability of cement production (Poudyal & Adhikari, 2021; Xiang, Pan, Ma, Yang, Lyu, et al., 2024). These include advancements in cement manufacturing technology, the adoption of renewable fuels, the utilization of alternative raw materials for clinker production, the development of eco-friendly cement and clinkers, and the incorporation of supplementary cementitious materials as substitutes for cement or clinker (Imbabi, Carrigan, & McKenna, 2012; Miller, John, Pacca, & Horvath, 2018; Scrivener, John, & Gartner, 2018). Additionally, there is growing interest in carbon capture (Uliasz-Bocheńczyk & Deja, 2024) and storage technologies, although certain principles remain poorly defined and necessitate further comprehensive analysis.

2.4 Cement replacements in mass concrete

The utilization of cement substitutes represents a widespread practice aimed at enhancing the environmental sustainability of concrete production (Fernando, Gunasekara, Law, Nasvi, Setunge, et al., 2021). These substitutes encompass a range of by-products, including coal fly and bottom ashes, ground granulated blast furnace slag, and silica fume, as documented in prior research (Bajpai, Choudhary, Srivastava, Sangwan, & Singh, 2020; Sakir, Raman, Safiuddin, Amrul Kaish, & Mutalib, 2020; Tangtermsirikul, 2013)

One avenue toward achieving tangible sustainability goals lies in the strategic selection of materials. This involves prioritizing locally available products characterized by low embodied energy, recyclability, rapid reusability, durability, and minimal environmental impact. Such an approach fosters the development of environmentally and economically sound concrete structures. By substituting waste materials or other by-products for Portland cement in concrete production, it becomes feasible to create concrete with improved sustainability credentials. Given the significant global scale of cement production, even minor replacements of cement can yield substantial reductions in CO_2 emissions.

A diverse array of cement replacements can be sourced from industrial by-products, agricultural residues, natural sources, and municipal solid wastes. Fine-grained silicate, silica, and aluminosilicate materials, whether of natural or synthetic origin, are commonly employed in cement composites, enabling the formulation of novel, environmentally sustainable cementitious binders with tailored properties. Industrial by-products such as silica fume, coal fly ash, granulated blast-furnace slag, bottom ash, and limestone powder are frequently utilized as substitutes for cement, while agricultural residues from rice husk and palm are also employed in this capacity (Sakir, Raman, Safiuddin, Amrul Kaish, & Mutalib, 2020; Singh, Shehnazdeep, & Bhardwaj, 2020). Natural pozzolans like metakaolin and volcanic ash serve as examples of cement replacements derived from natural sources. Municipal wastes, particularly various types of glass, have also been repurposed as cement replacements (Al-Mansour, Chow, Feo, Penna, & Lau, 2019). Figure 2.5 illustrates some of the most commonly utilized industrial by-products. It is worth noting that certain industrial by-products may serve as replacements for cement alone, while others may substitute for both fine and coarse aggregates. Extensive literature attests to the environmental benefits of cement replacements in terms of emission reduction.

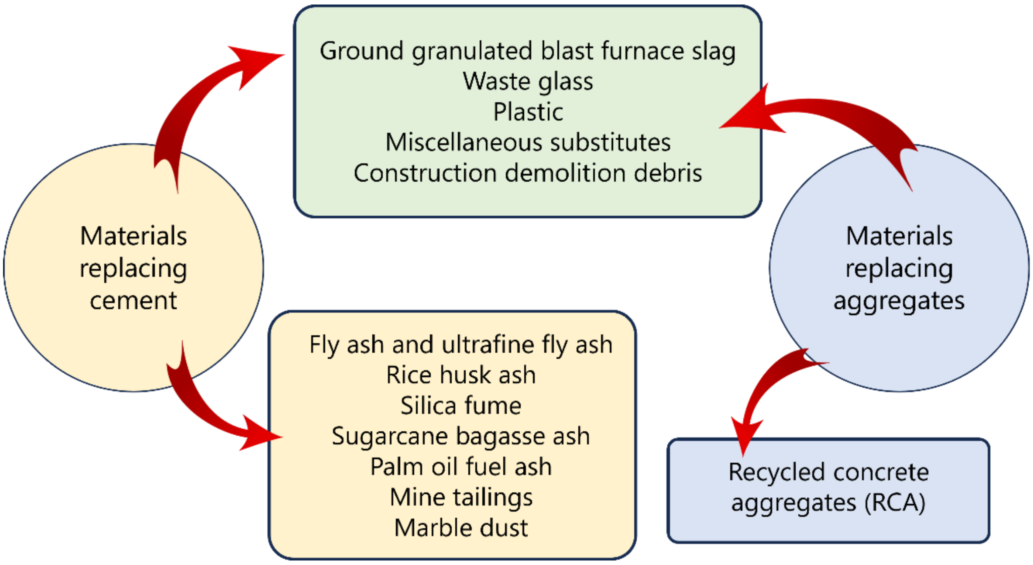

Figure 2.5 Most commonly used industrial by-products as cement substitute

2.4.1 Commonly used cement replacements

Despite the diverse array of properties inherent in various forms of cement substitutes or supplementary cementitious materials, they share a common trait: the ability to undergo chemical reactions that lead to the formation of cementitious binders, thereby replacing those generated through Ordinary Portland cement hydration. SCMs are distinguished by their pozzolanic nature, characterized by the ability to react with aqueous calcium hydroxide (CH) solutions to produce calcium silicate hydrate (C–S–H) (Juenger & Siddique, 2015). When utilized in appropriate proportions, cement-replacing materials have the potential to significantly enhance the long-term durability of concrete.

The incorporation of SCMs into concrete formulations traces its roots back to ancient civilizations such as Greece and Rome, where natural pozzolans like volcanic ash were commonly employed (Nguyen, Chatchawan, Saengsoy, Tangtermsirikul, & Sugiyama, 2019). Figure 2.6 provides a comprehensive overview of the major silica and aluminosilicate groups utilized as cement substitutes. Pacewska & and Wilińska (2020) have classified cement substitutes into two primary categories: pozzolanic materials and hydraulic materials. Pozzolanic materials react with calcium hydroxide and water, while hydraulic materials exhibit self-cementing properties in the presence of water.

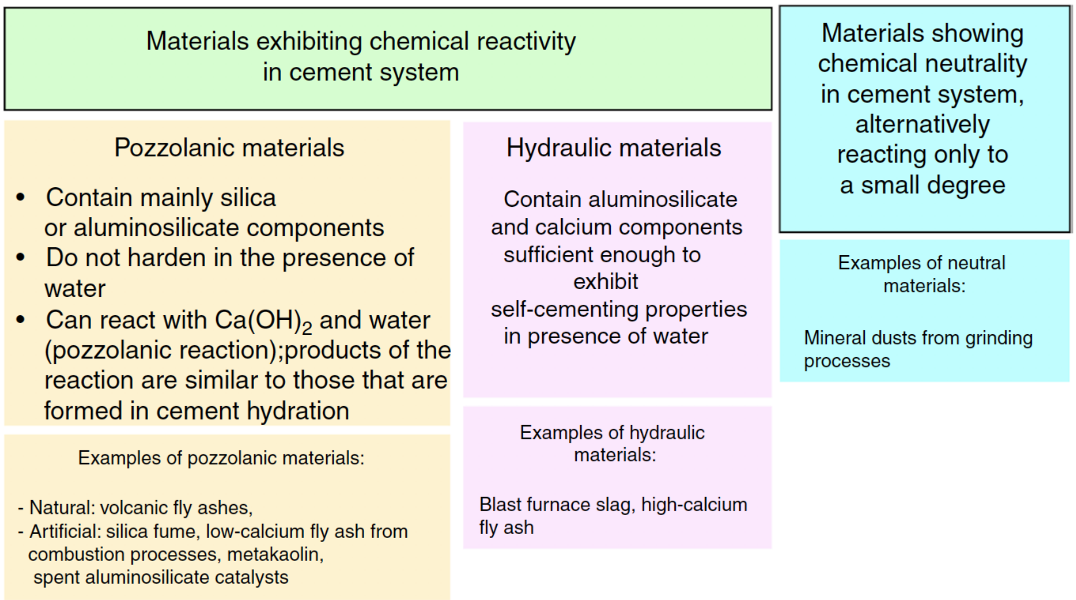

Figure 2.6 The main groups of silica and aluminosilicate SCMs that can be used as cement replacements (Pacewska & Wilińska, 2020)

Fly ash and slag are among the most used wastes as supplementary cementitious materials for partially replacing cement in concrete. Globally, these by-products are generated at a substantial scale, with fly ash production ranging from 900 to 1000 million tonnes and slag production from 140 to 330 million tonnes annually (Giergiczny, 2019; Scrivener, John, & Gartner, 2018). Herath et al. (2020) reported that the production of fly ash varies significantly across different countries and regions. In

Australia, the annual production of fly ash is approximately 14 Mt, while in India, it stands at a substantial 169.25 Mt/yr. China leads the chart with a remarkable 580 Mt, and the United States produces approximately 43.5 Mt of fly ash annually. However, despite the substantial production, the current average utilization of fly ash remains relatively low, accounting for only about 53.5% of the total ash produced (Heidrich, Feuerborn, & Weir, 2013). On the other hand, O'Connor et al. (2021) reported that Europe generates 18.4 Mt of steel slag annually at 85.6% usage, while the United States produces 10 Mt with 85.4% utilization. Japan, a leader in steel slag recycling, produced 14.1 Mt in 2016 with 98.4% utilization. China, the world's top steelmaker, disposes 70.5% of its slag rather than being repurposed. This points to a significant untapped potential for the increased utilization of fly ash and slag in various applications.

2.4.1.1 Fly ash

Due to its magnitude, compatibility with cement, and relatively low cost, fly ash (FA) is the most widely produced and used supplementary cementitious material on a global scale (Hemalatha, Mapa, George, & Sasmal, 2016). In recent decades, several studies have been conducted to quantify the environmental and mechanical performance benefits of fly ash substitution for different concrete applications, such as mortar (Menéndez, Álvaro, Hernández, & Parra, 2014; Miyamoto, Naruse, Hayashi, Minagawa, & Hisada, 2022), self-compacting concrete (Celik, Meral, Petek Gursel, Mehta, Horvath, et al., 2015), and geopolymer (Kumar, Perumal, & Ramamurthy, 2022; Mishra, Nanda, Patro, Das, & Mustakim, 2022). Other studies explored using fly ash with other waste materials, such as sugarcane bagasse ash (Arenas-Piedrahita, Montes-García, Mendoza-Rangel, López Calvo, Valdez-Tamez, et al., 2016), palm oil fuel ash (Men, Tangchirapat, Jaturapitakkul, & Ban, 2022), copper tailings (Külekçi, 2022), and blast furnace slag, among others.

It is a coal combustion by-product, accounting for at least 85% of the ash generated in coal-fired power plants (Heidrich, Feuerborn, & Weir, 2013). Coal ash is a waste product of coal combustion in coal-fired power plants. When pulverized coal is burned in power plants, molten minerals are released that cool to form fine ash. These microscopic particles, referred to as fly ash, remain suspended in the exhaust gas and are often disposed of as waste. Fly ash constitutes 80% of the total residue stemming from the combustion of pulverized coal in coal-fired power plants (Bajpai, Choudhary, Srivastava, Sangwan, & Singh, 2020; Hemalatha, Mapa, George, & Sasmal, 2016). It is extremely fine and bright and is extracted electrostatically or mechanically. (Bajpai, Choudhary, Srivastava, Sangwan, & Singh, 2020; Hemalatha, Mapa, George, & Sasmal, 2016). The remaining twenty percent is heavier and has a sand-like texture. This settles into grates under the boilers and is referred to as bottom ash (Sakir, Raman, Safiuddin, Amrul Kaish, & Mutalib, 2020; Singh, Shehnazdeep, & Bhardwaj, 2020). However, the global average usage of fly ash is just 53.5% of the total output (Herath, Gunasekara, Law, & Setunge, 2020). In 2008, it was estimated that the world produced 777 million tonnes of fly ash (Sakir, Raman, Safiuddin, Amrul Kaish, & Mutalib, 2020). Fly ash can potentially improve the compressive strength and segregation of concrete (Arrigoni, Panesar, Duhamel, Opher, Saxe, et al., 2020) as well as its many durability properties (Dabarera, Saengsoy, Kaewmanee, Nakazaki, Lerdsupavaree, et al., 2019; Tangtermsirikul, Phethany, Youphalat Kaewmanee, Saengsoy, & Julnipitawong, 2016). The use of fly ash as a cement replacement will minimize landfill disposal.

The composition of fly ash varies according to the coal grade from which it is made. In general, fly ash is composed primarily of SiO_2, Al_2O_3, Fe_2O_3, and CaO, with minor amounts of other components. Sakir et al. (2020) collected the chemical compositions of fly ash and other widely used cement substitutes (from different studies) and summarized them in Table 2.3 (Nwankwo, Bamigboye, Davies, & Michaels, 2020). As a by-product of coal combustion, fly ash is considered a recyclable material. It is a finely divided residue commonly used as a pozzolan. In the presence of water, fly ash includes siliceous and aluminous materials that react with CaOH to form a cement paste. Due to its composition of silt-sized particles that are generally spherical in shape and range in size from 10 to 100 microns, fly ash is typically finer than Portland cement and lime. These tiny glass spheres help to increase the fluidity and workability of new concrete. Fly ash's fineness has a significant effect on its pozzolanic reactivity (Nicoara, Stoica, Vrabec, Rogan, Sturm, et al., 2020).

Table 2.3. Chemical composition of various cement replacements as summarized and compiled by (Sakir, Raman, Safiuddin, Amrul Kaish, & Mutalib, 2020)

Chemical Composition (wt.%)	FA [1]	BA [1]	SF [1]	GGBS [1]	LP [1]
SiO_2	36–65	44–59	85–99	28–41	0–8
CaO	1–19	1–17	0–4	37–50	45–55
Al_2O_3	17–29	5–32	0–6	5–14	0–3
Fe_2O_3	4–31	2–9	0–3	0–1	0–2
MgO	0–7	1–3	0–5	4–10	0–7
SO_3	0–3	0–2	0–2	0–3	0–1
Na_2O	0–2	0–1	0–2	0–3	0–1
K_2O	0–3	1–8	0–2	0–2	0–1
P_2O_5	0–2	0–1	0–1	–	–
TiO_2	0–2	0–3	–	0–1	–
LOI	0–5	1–13	0–6	1–2	36–45
Sp. gravity	2.26	2.64	2.24	2.88	2.72

The benefits of utilizing fly ash for concrete applications are threefold: savings in CO_2 emissions, reduction in the disposal of fly ash to the environment, and improvement of concrete qualities. Fly ash has been used to replace up to 60% of cement (Banupriya, John, Suresh, Divya, & Vinitha, 2016). Fly ash enhances the strength at later ages, segregation, and pumping ability of concrete (Arrigoni, Panesar, Duhamel, Opher, Saxe, et al., 2020). The remarkable pozzolanic reactivity of fly ash primarily hinges on its fineness (Kakasor Ismael Jaf, Abdulrahman, Abdulrahman, Salih Mohammed, Kurda, et al., 2023), and its positive impact becomes particularly discernible during extended hydration periods, typically exceeding 28 days (Giergiczny, 2019; Nicoara, Stoica, Vrabec, Rogan, Sturm, et al., 2020). The use of fly ash as a substitute for cement has been widely documented to improve the environmental performance of concrete, as well as other properties such as workability, expansive property (Nguyen, Saengsoy, & Tangtermsirikul, 2018), permeability (Shi, Xu, Shi, & Zhou, 2008), and other durability attributes (Fernando, Gunasekara, Law, Nasvi, Setunge, et al., 2023). Additionally, fly ash is an excellent material for mass concrete and a variety of other applications. As a result, for nearly sixty years, fly ash has been successfully used as a mineral admixture in Portland cement concrete. It contributes significantly to net energy savings, greenhouse gas emissions, and other adverse air pollution reductions. By substituting fly ash for cement, the amount of products from coal combustion activity, which will eventually be disposed of in landfills, can be reduced, leading to the conservation of natural resources.

2.4.1.2 Ground granulated blast furnace slag

Ground granulated blast-furnace slag (GGBS) is a by-product of steel and/or iron production. The most dominant compositions in GGBS are CaO and SiO_2, followed by MgO and Al_2O_3 (Pal, Mukherjee, & Pathak, 2003). GGBS allows a relatively high cement replacement level without compromising concrete strength (J. Ahmad et al., 2022) due to its self-cementing properties (Sakir, Raman, Safiuddin, Amrul Kaish, & Mutalib, 2020). Additionally, it improves concrete workability (Manjunatha, Seth, KVGD, & A, 2022) and durability (Kanavaris, Soutsos, & Chen, 2023). Slag can improve concrete's resistance to chloride attack (Pradhan, Chang Boon Poh, & Qian, 2022), an important long-term durability attribute of concrete. Although fly ash and slag are considered avoided wastes (Panesar, Kanraj, & Abualrous, 2019; Pushkar, 2017), certain processing and preparation of these materials may necessitate additional energy and emissions, which must also be quantified (Pradhan, Chang Boon Poh, & Qian, 2022). As a result, the environmental impact of SCM substitution cannot be linearly proportional to the substitution level. A comprehensive analysis is imperative to understand the overall environmental performance of SCM utilization in diverse concrete applications.

Globally, the annual production of ground-granulated blast furnace slag ranges from approximately 300 to 360 million tonnes. GGBS primarily consists of CaO and SiO2 minerals, with notable proportions of MgO and Al_2O_3. Its inherent self-cementing properties enable high replacement percentages of cement without compromising the compressive strength of the resulting concrete product (Sakir et al., 2020). The incorporation of GGBS as a replacement for cement offers several advantages for sustainable concrete practices, including improved concrete performance, reduced waste material, and decreased carbon footprint. With its high cementitious content, GGBS can typically substitute up to 50% of Portland cement, thereby significantly reducing the overall carbon footprint of concrete structures. Furthermore, GGBS has been employed to mitigate cracking tendencies and reduce embodied CO_2 in concrete structures (Samad, 2017). However, it is important to note that some concrete structures constructed with slag cement may experience premature failure due to restrained shrinkage.

2.4.2 Effects of cement replacements on strength and durability of mass concrete

Strength is a fundamental mechanical property of concrete, primarily characterized by its high compressive strength and relatively low flexural strength. The incorporation of various cement replacements in concrete can significantly influence both compressive and flexural strength, driven by the diverse chemical reactions between these replacements and other concrete constituents. For instance, the pozzolanic reaction in concrete containing fly ash typically occurs later in the curing process due to the alkalinity of the pore solution, resulting in a slower rate of strength development. However, substantial strength improvement is commonly observed between 28 and 90 days (Imbabi, Carrigan, & McKenna, 2012). Nevertheless, replacements exceeding 20% in concrete can impair the hydration system, leading to slower strength development and adversely affecting concrete strength (Hemalatha, Mapa, George, & Sasmal, 2016). Regulatory specifications often limit fly ash replacement in concrete to 40% (Rashad, 2015) to mitigate such delayed strength development. In the study of Al-Mansour et al. (2019), as summarized in Table 4, this delayed strength development is observed.

Research by Singh et al. (2020) demonstrated that while the addition of ground coal bottom ash may initially decrease compressive strength, it becomes more comparable to control concretes at longer curing times, such as 28 days. The fusion of coal bottom ash with cement has been found beneficial for optimizing compressive strength, particularly with low levels of modification. Similarly, flexural strength enhancement was observed, albeit at lower levels of modification.

The hydration process of ground granulated blast-furnace slag with ordinary Portland cement (OPC) relies on the cement's alkali content and hydroxyl ions (Pal, Mukherjee, & Pathak, 2003). The pozzolanic reaction of GGBS is relatively slow compared to pure OPC, with early strength primarily attributed to OPC clinker hydration. Enhancing the early strength of high GGBS replacement concrete poses a challenge, which is addressed by particle size reduction to increase material reactivity (He, Ma, Su, Lan, Zheng, et al., 2018).

Table 2.4. Effect of major cement replacing materials on the durability properties of mortar (Sakir et al, 2020)

	Carbonation Resistance	Acid Resistance	ASR Resistance	Sulphate Resistance	Chloride Resistance	Freezing and Thawing Resistance
SCM	Effect	Effect	Effect	Effect	Effect	Effect
FA	–	–	▲	▲	▲	▲
SF	▲ ▼	▲	▲	▲	▲	▲
GGBS	–	–	–	▲	▲	–
WGP	▼	–	▲	▲	▲	–
LP	▼	–	–	No effect ▼	–	–
MK	▼	▲	▲	▲	▲ ▼	▲
POFA	–	–	–	▲	–	–
RHA	–	▲	–	▲	▲	–
BA	▼	–	▲ ▼	▲	–	▼
VA	–	–	▲	–	▲	–

Note: "▲" indicates an increase and "▼" indicates a decrease in the behavior.

FA – fly ash, SF – silica fume, GGBS – ground granulated blast furnace slag, WGP – waste glass powder, LP – limestone powder, MK – metakaolin, POFA – pal oil fuel ash, RHA – rice husk ash, BA – bottom ash, VA – volcanic ash

Concrete durability refers to its ability to resist degradation from external forces like corrosion, abrasion, and chemical attack, as well as internal factors (Adesanya & Raheem, 2010). Enhanced concrete longevity is economically beneficial, reducing maintenance costs and extending structure lifespan. However, concrete durability is compromised in aggressive environments like marine settings due to the potential leaching of cement hydration products, such as CH and C-S-H, driven by high chloride and sulfate ion concentrations (G. Li, Zhang, Song, Liu, & Zhang, 2018). Incorporating pozzolans in concrete promotes the formation of additional calcium-silicate-hydrate, enhancing pore structure impermeability and, consequently, concrete durability (Nwankwo, Bamigboye, Davies, & Michaels, 2020). Table 2.4 shows a summary by Sakir et al. (2020) of the effects of various cement replacements on the durability performance properties of mortar.

2.4.3 Environmental, economic, and social impacts of cement replacements

Cement substitutes derived from diverse waste materials are generally acknowledged to offer greater environmental benefits compared to cement produced from raw materials. Their utilization not only diverts waste from landfills but also enhances the sustainability of concrete production.

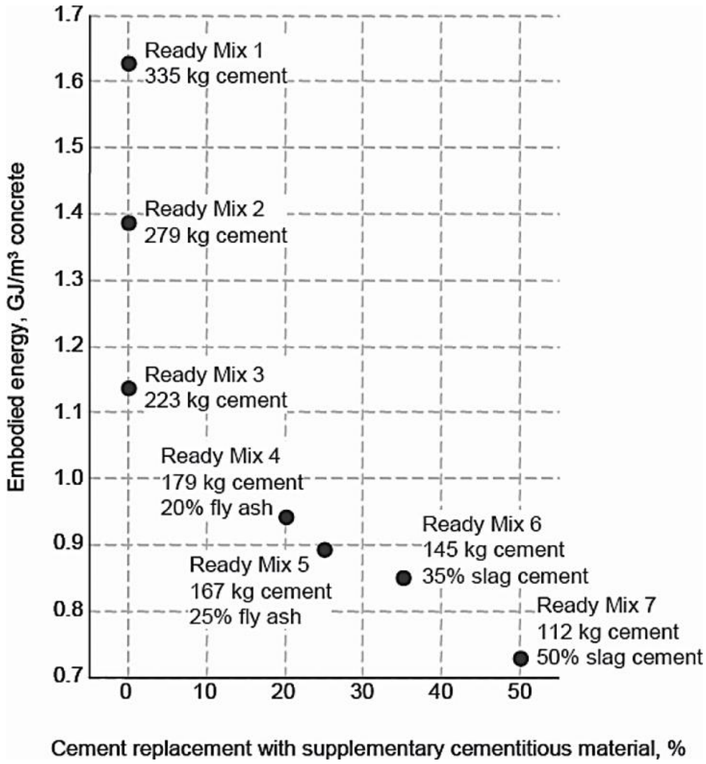

Figure 2.7 Embodied energy (ACI 130R-19) of concrete with various replacements

Extensive life cycle analyses consistently demonstrate that cement substitutes typically result in lower carbon dioxide emissions compared to the production of Ordinary Portland cement. The relationship between cement replacements and CO_2 emissions is presented in Figure 2.7. Notably, a higher percentage of cement replacement correlates with lower emissions, underscoring the environmental advantages of employing such substitutes.

2.4.3.1 Environmental impact

Fly ash, being a by-product with low embodied energy, is widely recognized as an environmentally favorable material. Its direct substitution for cement presents several environmental advantages. Firstly, incorporating fly ash into concrete applications facilitates the recycling of this by-product, reducing the need for additional cement production. Consequently, this substitution diminishes greenhouse gas emissions and conserves resources essential for cement manufacturing. Moreover, the utilization of fly ash significantly contributes to net energy savings, reductions in greenhouse gas emissions, and mitigation of other harmful air pollutants. By displacing cement with fly ash, the volume of coal combustion products disposed of in landfills is notably decreased, further conserving natural resources.

The substitution of coal fly ash for cement also mitigates health risks for the general population. The primary concern regarding fly ash disposal revolves around its potential release of toxic heavy metals, which pose risks to both the environment and human health. Improper disposal methods, such as open landfills or wet ponds, can lead to groundwater contamination and environmental hazards. However, when fly ash is incorporated into concrete mixtures, these heavy metals are typically immobilized, minimizing the risk of leaching. Extensive academic literature supports this finding, demonstrating that the addition of fly ash to concrete mixtures greatly reduces the probability of leaching (Müllauer, Beddoe, & Heinz, 2015; Panesar, Kanraj, & Abualrous, 2019; Saha & Sarker, 2017).

2.4.3.2 Economic impact

The cost and energy intensity of concrete are primarily attributed to cement, making it the most significant factor in concrete production. Introducing fly ash as a partial substitute for cement yields economic benefits by reducing the unit cost of concrete. This reduction in cost stems from various factors, including diminished disposal expenses for fly ash, the release of land previously allocated for disposal, potential financial gains from alternative land use, and savings resulting from the replacement of scarce or expensive natural resources in cement production.

A notable economic advantage of incorporating fly ash lies in the potential cost savings achieved by reducing the reliance on cement in concrete manufacturing. As a waste by-product requiring no additional manufacturing costs, fly ash offers concrete producers a means to reduce production costs substantially by reducing the cement content. The utilization of fly ash can often replace up to 20%-30% of the cement in concrete mixes, with some applications even allowing for substitution rates of up to 50% (Thangaraj, 2012). Moreover, fly ash has emerged as a vital component in high-performance concrete formulations, renowned for their extended service life compared to conventional concrete. By enhancing the durability and toughness of concrete, fly ash contributes to lower maintenance costs and prolonged service life for concrete structures (Rashad, 2015).

2.4.3.3 Social impact

At present, social assessment associated with concrete production remains scant. Various literature has explored the multifaceted social dimensions of sustainability within concrete production, with considerations extending beyond environmental concerns. Material durability is sometimes intertwined with social sustainability, highlighting the importance of evaluating aspects such as the quality of materials, human health and safety, security, and serviceability (Opon & Henry, 2019). Initiatives striving for sustainable concrete production must, therefore, meticulously assess social impacts alongside environmental and economic factors. This involves ensuring worker health and safety across manufacturing and construction processes, advocating for fair labor practices, and mitigating adverse effects on local communities (Backes & Traverso, 2024; Kanagaraj, N, Alengaram, Raj R, B, et al., 2022). Moreover, comprehensive sustainability assessments should encompass social equity and community engagement by involving and consulting with local communities in decision-making processes while also respecting indigenous rights and cultural heritage and ensuring equitable access to resources and benefits associated with concrete production and construction projects (Kanagaraj, N, Alengaram, Raj R, B, et al., 2022). Engaging various stakeholders, including local communities, value chain actors, society, and workers, is crucial for fostering social sustainability within concrete production endeavors (Martínez-Muñoz, Martí, & Yepes, 2022).

The use of fly ash in concrete offers various social benefits, particularly concerning concrete workability and durability. Fly ash enhances the workability of fresh concrete, leading to improved handling during both laboratory testing and field applications (Arrigoni, Panesar, Duhamel, Opher, Saxe, et al., 2020). Technicians working with fresh concrete experience greater ease in handling, attributed to the lower temperatures and extended setting times characteristic of fly ash concrete compared to conventional Portland cement blends. Furthermore, fly ash concrete exhibits improved pumpability and requires less effort to fill concrete forms, simplifying the placement process (Krithika & Ramesh Kumar, 2019). These attributes contribute to higher levels of satisfaction among concrete technicians and workers involved in concrete construction projects.

Moreover, the long-term strength development of fly ash concrete, particularly in pavement applications, results in reduced wear and tear on roadways subjected to heavy traffic from trucks and automobiles. The enhanced durability of fly ash concrete translates to less frequent replacement of buildings and pavements, thereby minimizing downtime and disruptions associated with maintenance and replacement activities. Consequently, communities benefit from the prolonged service life of concrete infrastructure, leading to improved safety, reduced inconvenience, and lower costs associated with infrastructure maintenance and repair. Nevertheless, the intricate dynamics of stakeholders in construction projects present challenges to conducting effective social sustainability assessments, underscoring the need for standardized frameworks and methodologies to guide such evaluations.

2.5 Cement replacing materials in selected Southeast Asian countries

Asia stands as the world's foremost consumer of coal, representing 66 percent of global coal consumption. Coal ash, a residual product of coal combustion in coal-fired power plants, is produced in substantial quantities in Southeast Asia (Figure 2.8). Typically, coal-fired power plants burn coal containing an average ash content of about 10%. This ash comprises approximately 80% fly ash and 20% bottom ash, along with other solid residues resulting from coal combustion (US FHWA Report, 2015).

The mineral composition of fly ash exhibits variation depending on the type or rank of coal burned. Silica content typically ranges between 40% and 60%, while alumina content falls within the range of 20% to 30%. The iron content varies considerably, with significant quantities of alkalis also present. The presence of substantial amounts of CaO confers its pozzolanic characteristic upon fly ash (Hewlette, 1998). Table 2.5 demonstrates that the CaO content differs across regions, with the

Philippines and Vietnam exhibiting low CaO content, while Thailand generally registers high CaO content.

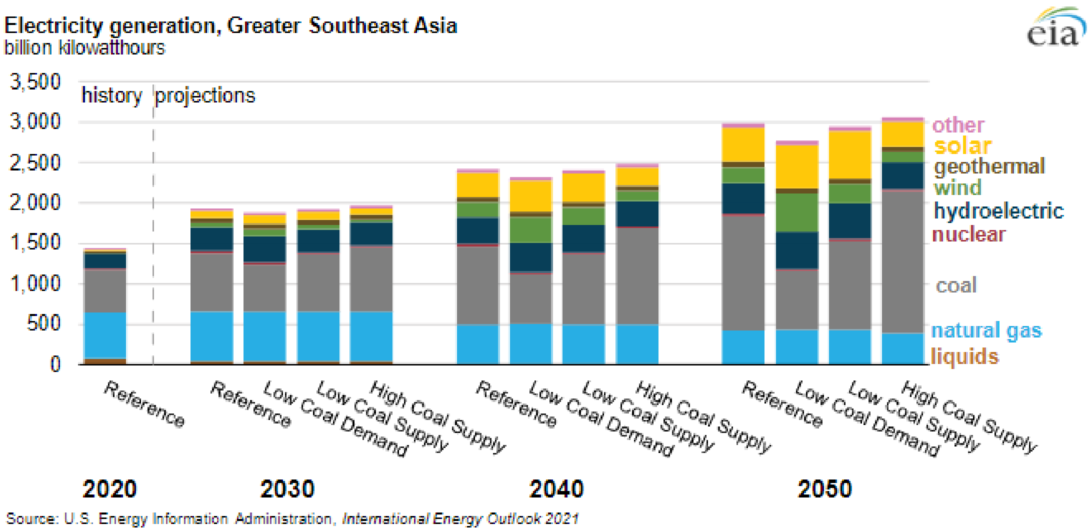

Figure 2.8 Coal Consumption in Southeast Asia (Source: eia)

Comparative analysis, as depicted in Table 8, reveals that high CaO fly ashes offer advantages such as faster setting times, increased early strength, and improved resistance to carbonation. Conversely, low CaO fly ashes offer benefits, including reduced heat generation, decreased alkali-silica reaction (ASR) expansion, and enhanced resistance to sodium sulfate and acidic environments (Tangtermsirikul, Phethany, Youphalat Kaewmanee, Saengsoy, & Julnipitawong, 2016). These varying characteristics in fly ash necessitate adjustments in concrete mixture design to accommodate specific project requirements.

Table 2.5 Properties of fly ashes in some ASEAN countries (sources: Thailand and Vietnam: Tangtermsirikul, et al.; Philippines: Pozzolanic Philippines)

Composition/Properties	Thailand	Vietnam	Philippines
SiO_2 (%)	20 - 65	21-58 (majority 50-58)	45-55
CaO (%)	**1-35 (majority 10-25)**	**1.2-15 (majority 1.2-2)**	**10.6***
Al_2O_3 (%)	5 - 40	12-26 (majority 20-26)	15-25
Fe_2O_3 (%)	1 - 15	5-12 (majority 5-9)	5-10
SO_3 (%)	0^+-10 (majority 1.5-4.0)	0.06-10.5 (majority 0.5-2.5)	<5
MgO (%)	0^+ - 5	0.3-2.0 (majority 0.3-1.5)	1-4
(Na_2O+0.658K_2O)	0.5 - 2.5 (majority >1.5)	(2.5-3.5)	
Free lime	1 – 5	<0.008-2.0 (majority <0.02)	
Amorphous content	70-85	48-91 (majority 78-91)	
Specific gravity (g/cm^3)	1.7 - 2.4	2.1-2.6	
Blaine fineness (cm^2/g)	1800 – 4000 (majority <3000)	1800-4000 (majority 1800-2500)	
% Retained on sieve #325	20 - 65	15-30	
Loss on ignition (%)	**0.1 – 5 (about 80%<1.0)**	**5-30 (majority 6-15)**	**<5**
Water requirement (% of control)	93-106 (majority <100%)	94-115	98-105
Strength activity index at 28 days (% of control)	65-100 (majority >75%)	78-95 (majority 78-85)	>75 (87.6 recent data)

2.5.1 Philippines

The construction sector in the Philippines is experiencing rapid expansion, as evidenced by its significant contribution to the nation's capital investments. According to data from the Department of Trade and Industry, the construction industry accounted for 69.6% of the country's overall capital investments or gross capital formation in the second quarter of 2021 (Philippine Statistics Authority, 2021). Within this sector, cement production plays a pivotal role, with the Philippines boasting 16 active integrated cement plants, collectively possessing a capacity of 33.6 million metric tonnes per year, as reported by the Global Cement Directory 2020 (Global Cement, 2020). Moreover, the country hosts three operational grinding plants with a combined capacity of 2.2 million metric tonnes per year, bringing the total cement production capacity to 35.8 million metric tonnes annually. Additionally, there are two decommissioned or mothballed integrated plants, two under construction, and three proposed grinding plants, indicating sustained growth and development in this industry (Global Cement, 2020). Over the years, cement production in the Philippines has exhibited a significant upward trend. For instance, data indicates an increase from 13.067 million metric tonnes in 2003 to 24.050 million metric tonnes in 2015 (Global Cement, 2020).

In tandem with industrial expansion, the Philippines has witnessed a surge in coal-fired power generation, constituting a substantial portion of the country's energy mix. Approximately 38% of the Philippines' electricity is generated by coal-fired power stations, contributing significantly to the nation's carbon footprint. The installed capacity of coal-fired power plants surged from 4867 MW in 2010 to 8838 MW in 2018, reflecting the escalating energy demand (Philippine Department of Energy, 2018). Given this trajectory, projections suggest that coal ash output could potentially rise to 11.48 million metric tonnes by 2035, up from 2.78 million metric tonnes in 2018.

In 2018, the Philippine Department of Energy reported a total coal consumption of 30.8 million metric tonnes, with 84.6% utilized by coal-fired power plants, resulting in the generation of 3.1 million metric tonnes of coal ash (Philippine Department of Energy, 2018). Notably, the disposal of coal ash presents environmental challenges, particularly concerning surface and groundwater contamination due to its metal and mineral content. Despite concerns, leaching tests conducted on coal ash have revealed no significant metal leaching (Gallardo, Susan; Dungca, 2012).

However, the management of coal ash remains a pressing issue, with existing coal-fired power plants struggling to handle their ash by-products, necessitating additional ash ponds and landfills. For instance, power plants in the Visayas cities of Naga and Toledo encounter difficulties disposing of their coal ash, generated at a rate of 120 metric tonnes per day (Gallardo, Susan; Dungca, 2012). Given these challenges, sustainable strategies for coal ash disposal and management are imperative to mitigate environmental risks associated with its accumulation.

2.5.2 Thailand

In Thailand, fly ash is predominantly sourced from two major power plants, namely Mae Moh and BLCP, with Mae Moh fly ash (Figure 2.9) constituting nearly 80% of the country's total fly ash production (Wanna, Saengsoy, Toochinda, & Tangtermsirikul, 2020). However, recent years have witnessed a surge in demand for fly ash, surpassing its supply capacity, thereby leading to escalated prices and increased CO_2 emissions associated with transportation.

Figure 2. 9 Map showing the proximity of fly ash sources from Bangkok, Thailand

The combined annual production of fly ash from Mae Moh and BLCP power plants amounts to approximately 3 million tonnes. Thailand's coal sources vary, encompassing both domestic and imported coal types, with lignite being the most prevalent. In contrast, neighboring Southeast Asian countries utilize coal types such as sub-bituminous, bituminous, and anthracite. Consequently, Thai fly ashes, predominantly sourced from Mae Moh, exhibit characteristics including low SiO_2 content, high CaO content, elevated SO_3 content, considerable alkali content, and sporadically, high free lime content. Additionally, Thai fly ashes typically feature low specific gravity, fine Blaine particle size, and minimal loss on ignition. The water demand for Thai fly ashes ranges between 93 and 103 percent, with high CaO fly ashes from Mae Moh necessitating less than 100% water, while low CaO fly ashes from sources near Bangkok often require more water due to their less spherical particle morphology.

In terms of concrete application, the strength activity index of Thai fly ashes typically falls within the range of 65 to 100 percent after 28 days, with a majority surpassing the threshold of 75 percent, rendering them suitable for use in concrete mixtures (Tangtermsirikul, Phethany, Youphalat Kaewmanee, Saengsoy, & Julnipitawong, 2016). These findings underscore the nuanced characteristics and utilization potential of fly ash in Thailand's construction and industrial sectors, emphasizing the importance of understanding fly ash properties for effective material selection and engineering applications.

Table 2.6 Performances of low CaO fly ash (FAR) when compared with high CaO fly ash (FAM) (Tangtermsirikul et al. 2016)

	Better	Similar	Worse
Properties of Fly Ash Concrete			
Initial slump			●
Slump loss		●	
Early compressive strength			●
Long-term compressive strength	●		
Semi-adiabatic temperature rise of concrete	●		
Durability Properties of Fly Ash Concrete			
Alkali-aggregate reaction	●		
Autogenous shrinkage			●
Total shrinkage			●
Carbonation			●
Chloride resistance (rapid chloride permeability test, chloride binding capacity, depassivation time, corrosion degree)		●	
Sodium sulfate resistance	●		

Despite numerous research on the benefits of fly ash, there remains a notable research gap regarding the quantification of the environmental impacts associated with the utilization of different types of fly ash in mass concrete. Previous studies have concentrated on the usage of fly ash in general, and a comparative environmental assessment for different types of fly ash in concrete mixtures has yet to be reported. The impact of fly ash varies with the type of fly ash used (Tangtermsirikul & Kaewkhluab, 2002). Moreover, the design of concrete mixtures is subject to variation based on the type of fly ash utilized (Table 2.6). For example, low CaO fly ash is frequently used to improve concrete resistance to alkali-silica reactions (Saha, 2018) and sulfate attacks (Kasaniya, Thomas, & Moffatt, 2021), providing a distinct advantage in aggressive environmental conditions. It also provides better acid resistance (Pather, Ekolu, & Quainoo, 2021) to concrete. High CaO fly ash is also commonly used in concrete manufacturing due to its higher reactivity and capacity to improve early compressive strength than low CaO fly ash. Due to its abundance, low CaO fly ash is often used, such as in Japan (Tangtermsirikul, 2005), Vietnam, and the Philippines. In Thailand, fly ash is typically sourced from Mae Moh (high CaO) and BLCP (low CaO) power plants. Mae Moh fly ash is more popular, accounting for almost 80% of total Thai fly ash production. Yet, in recent years, demand for fly ash has outstripped supply, resulting in higher prices and transportation-related CO_2 emissions (Wanna, Saengsoy, Toochinda, & Tangtermsirikul, 2020).

2.6 Quantifying impacts of cement replacements in mass concrete

2.6.1 Life cycle assessment

To quantify the impacts of cement and concrete production, life cycle assessment (LCA) of concrete or cement replacements has been carried out in several literatures for assessment of impact (Colangelo, Forcina, Farina, & Petrillo, 2018; Panesar, Kanraj, & Abualrous, 2019; Salas, Ramirez, Rodríguez, Petroche, Boero, et al., 2016). It stands as a versatile and adaptable method employed to ascertain the environmental impacts of a product. Given its versatility, there exists no universal approach for conducting LCA assessments, as the responsibility lies with the organization undertaking the analysis to devise a realistic implementation tailored to their specific needs and applications while adhering to the International Standard (ISO 14040). Essentially, LCA serves as a pivotal tool for evaluating the environmental footprints of processes and commodities throughout their lifecycle. As outlined by the ISO standards 14040 and 14044 (ISO, 2006a), the process of Life Cycle Analysis encompasses four primary stages, delineated as (1) goal definition and scope, (2) life cycle inventory (LCI) development, (3) environmental impact assessment (EIA), and (4) result interpretation as shown in Figure 2.10.

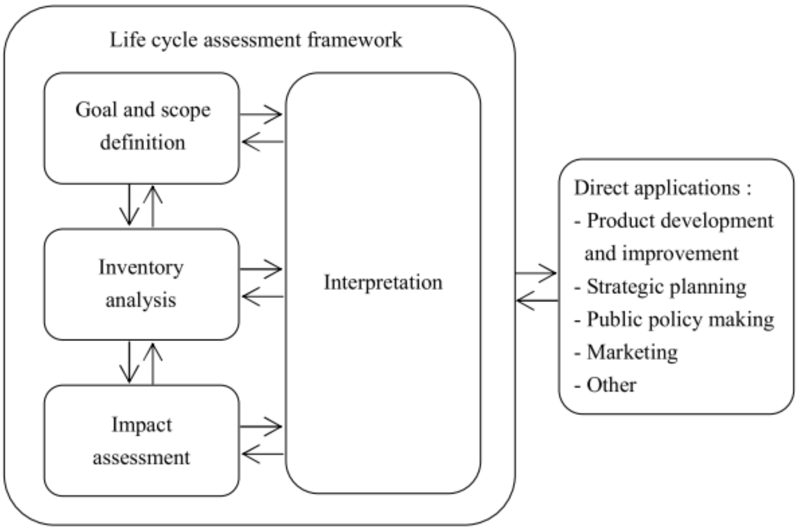

Figure 2.10 Life cycle assessment based on ISO 14040 (Kawai, Sugiyama, Kobayashi, & Sano, 2005)

Table 2.7 delineates the key activities essential for conducting a life cycle assessment pertinent to the manufacturing of concrete.

Table 2.7. LCA Components for Concrete LCA

LCA Component	Description for Concrete LCA
Goal Scope and Definition	Definition of scope and functional unit. Compilation of various inputs and outputs in the concrete production process, which includes all materials and processes.
Impact Assessment	Determining and evaluating the magnitude and environmental burdens in the concrete life cycle.
Interpretation	Impacts are analyzed, and the best options for sustainability are highlighted with other relevant observations.

The predominant focus of life cycle studies documented in the literature pertains to cradle-to-gate assessments. This form of boundary analysis commences with the extraction of raw materials (sourcing) and culminates with the delivery of cement packaging from the factory. As depicted in Figure 2.11, the life cycle of concrete development emphasizes cradle-to-gate considerations (Panesar et al., 2019). Notably, Panesar et al. (2019) scrutinized the transportation of fly ash via truck as part of the aforementioned life cycle assessment and identified three environmental impact categories exerting the most significant influence on the evaluation: human toxicity, ecotoxicity, and energy and fossil fuels, in descending order of impact magnitude.

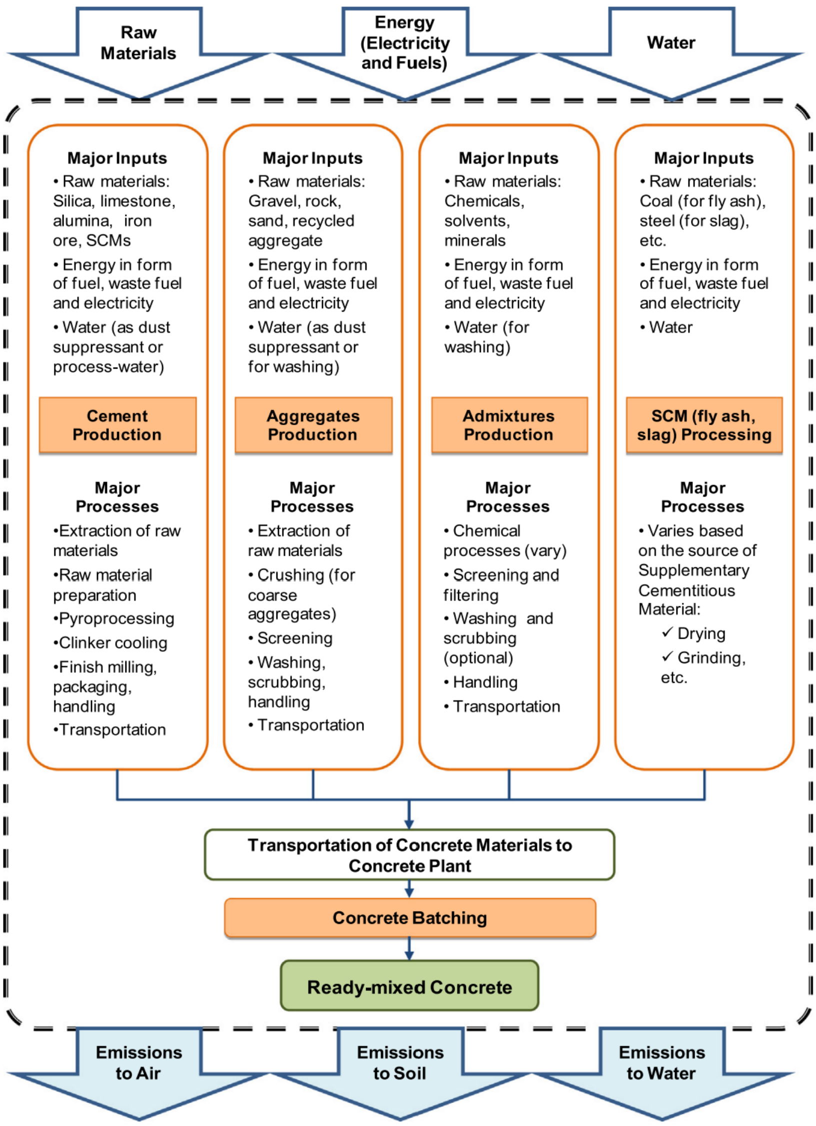

Figure 2.11 General system boundary and emissions associated with cradle-to-gate concrete production (Petek Gursel, Masanet, Horvath, & Stadel, 2014)

2.6.2 Impact assessment methods

Life cycle impact assessments are typically conducted at the midpoint and endpoint levels. Notably, previous research in the field of impact assessment of concrete has predominantly focused on midpoint impacts (Celik, Meral, Petek Gursel, Mehta, Horvath, et al., 2015; Habibi, Tavakoli, Esmaeili, & Golzary, 2022; Radwan, Onn, Mo, Yap, Chin, et al., 2022). The selection between midpoint and endpoint methods for impact assessment depends on considerations of relevance and reliability (Bare, Hofstetter, Pennington, & de Haes, 2000). In this study, preference is given to the endpoint method due to its greater relevance, as it allows for the comparison of the different options investigated. Endpoint impact assessment has been used in the assessment of concrete gravity dams (Mostafaei, Keshavarz, Rostampour, Mostofinejad, & Wu, 2023) and concrete with recycled aggregates (Xing, Tam, Le, Hao, & Wang, 2023). The endpoint method facilitates the generation of comparable single overall environmental score and damage-focused indicators, which can easily be understood by decision-makers (Vieira, Calmon, & Coelho, 2016). Endpoints are often components that the public believes should be protected (Bare & Gloria, 2008).

2.6.3 Studies on life cycle assessment of concrete

The process of life cycle assessment has been used to determine the sustainability of various construction materials (Abeysundra, Babel, Gheewala, & Sharp, 2007). Table 2.8 shows some of these studies. Life cycle assessment has conventionally been employed to holistically evaluate the environmental aspects of cement and concrete (Ahmad, Alsulamy, Raza, Salmi, Abid, et al., 2023; X. J. Li & Zheng, 2020; Tighnavard Balasbaneh, Sher, Yeoh, & Koushfar, 2022), including the use of SCM. Life cycle assessment has been widely used throughout the preceding decade to evaluate the greenhouse gas emissions related to the use of fly ash in concrete (Patrisia, Law, Gunasekara, & Wardhono, 2022; Pradhan, Chang Boon Poh, & Qian, 2022; Seto, Churchill, & Panesar, 2017), as well as other impacts (Milani & Kripka, 2019). Several studies have quantified the benefits of fly ash as a cement substitute in various types of concrete, including precast concrete (Fernando, Gunasekara, Law, Nasvi, Setunge, et al., 2021), pervious concrete (Chen & Wang, 2022), high-strength concrete (Orozco, Babel, Tangtermsirikul, & Sugiyama, 2023), geopolymer (Bajpai, Choudhary, Srivastava, Sangwan, & Singh, 2020), 3D printed concrete (Chaiyotha, Kantawong, Payakanitia, Pinitsoontorn, & Chindaprasirt, 2023), self-healing concrete

(Y. Liu, Zhuge, Fan, Duan, & Wang, 2022), and marine concrete (S. Liu, Lu, Li, Pan, Jiang, et al., 2022).

Tait and Cheung (2016) conducted a life cycle assessment on three concrete mixtures, including ordinary Portland cement concrete and mixtures with 35% fly ash and 70% slag replacement, and concluded that mixtures with a greater proportion of replacement materials have superior environmental performance. According to Mohammadi and South (2017), the global warming potential derived from LCA for 14 concrete benchmark products in Australia ranges from 209 to 521 kg CO_2 equivalent. Regarding service life, carbon footprint, and embodied energy, Nath et al. (2018) provide research on concretes containing 30% and 40% fly ash by weight of the binder. Gursel and Ostertag (2019) stated that replacing 40% or 100% of the sand in high-strength concrete with copper slag reduced the global warming potential by 12% and 30%, respectively. Pradhan (2022) showed that concrete with 30% fly ash and 50% slag had a lower environmental impact when service life was considered. Current findings by Patrisia et al. (2022) reported a reduction of 5.25 to 35 % in the global warming potential of alkali-activated slag concrete under marine exposure but a greater negative impact of fly-ash geopolymer concrete compared to Portland cement concrete. Vieira et al. (2018) performed an environmental assessment of fly ash and slag utilization in self-compacting concrete (SCC), considering strength and service life, and concluded that using slag is preferable. In addition, Celik et al. (2015) showed that 55% fly ash replacement by weight of cement creates highly workable SCC mixtures with low global warming potential for concrete manufacture. In comparison with concrete made with pure OPC, Chen et al. (2019) discovered that applying fly ash on pervious concrete displayed the highest overall performance in balancing several criteria, including cost, material properties, greenhouse house gas reduction, and energy. Using LCA, Hafez et al. (2020) concluded that transporting fly ash from China to the United Kingdom negates the environmental advantages of its replacement of cement. The study of Radwan et al. (2022) demonstrates that 50% and 70% OPC substitution will lower the impact by an average of 44% and 61%, regardless of the blending scheme of fly ash and/or slag

In the Singapore context, Pradhan et al. (2022) investigated the environmental impact of partial substitution of cement in concrete by limestone calcined clay, 30% fly ash (30FA), and 50% GGBS (50GGBS) for 55 MPa concrete. The study reported global warming potential (GWP) reductions of 34% (30FA) and 44% (50GGBS) when compared to OPC concrete. Manjunatha et al. (2022) investigated several substitutions of GGBS up to 30% against nine impact categories. The results of this study show that GGBS concrete improved workability and reduced GWP potential but contributes to almost 90% of mineral resource scarcity. Aslani et al. (2023) reported that CO_2 emissions of fly ash (47FA) concrete are 37% greater than 50GGBS in the Canadian setting. In a comprehensive literature review, Yılmaz and Seyis (2021) recognized that one of the gaps in comparing SCM in concrete studies is the overemphasis on the effects of global warming for environmental assessment. While GWP is undoubtedly a critical concern, comprehending the concrete's environmental footprint is equally crucial for informed material selection and holistic decision-making.

Table 2.8 Life cycle assessment of cement and concrete studies from various literature

Author, Year, Country	**Product/ Process; Functional Unit**	**Software, Inventory Database**	**Test Cases**	**Scope**	LCA Performed
Tait & Cheung, (2016) **United Kingdom**	Concrete, 1 cubic meter 2016	SimaPro, Recipe Midpoint, ecoinvent	100% OPC, 35% FA, 70% GGBS	Cradle -to- gate	Process-based LCA
Mohammadi & South, (2017) **Australia**	Concrete, 1 cubic meter 2017	GaBi, ReCiPe Midpoint	Concrete products in the market of Australia Fly Ash: 40-80, GGBS: 35-80	Cradle -to- gate	Process based
Tun, Bonnet, & Gheewala, (2020) **Myanmar**	Cement, 1 tonne cement	SimaPro, Recipe Midpoint	Cement factories	Cradle -to- gate	Process-based

Gursel & Ostertag, (2019) **Singapore**	Concrete, Copper slag as sand replacement; 1 cubic meter	GreenConcrete LCA Tool, ReciPe Midpoint	Copper slag with 10-30% replacement as fine aggregates	Cradle-to-gate	Process based
Panesar, Kanraj, & Abualrous, (2019), **Canada**	Concrete, 1 cubic meter	GaBi 8.1	25, 35, 50 replacement of FA, effect of fly ash transportation Modeled service life using Life 365	Cradle-to-grave	Process-based with LCC for fly ash
Hossain, Poon, Lo, & Cheng, (2017) **Hongkong**	Cement	SimaPro, IMPACT 2002 Midpoint assessment	Use of glass powder, biofuel from locally sourced wood	Cradle-to-gate	Process-based LCA
Nath, Sarker, & Biswas, (2018) **Europe**	Marine Concrete, impact of fly ash	SimaPro	30, 40% replacement Service life calculated per concrete cover depth 10 to 100	Cradle-to-grave	Process-based LCA
Celik, Meral, Petek Gursel, Mehta, Horvath, et al., (2015) **USA and Turkey**	Self-consolidating concrete	GreenConcrete LCA	Mixture with fly ash and pulverized limestone, 55% replacement	Cradle to gate	Economic-input output

CHAPTER 3
METHODOLOGY

3.1 Methodological framework

Two major components are included in the general framework (Figure 3.1) used in this study: (1) a stakeholder interview to understand the motivation/barrier for using waste material in the concrete construction industry, and (2) an impact assessment of the current use of waste materials, specifically fly ash and slag, in mass concrete applications using life cycle midpoint and endpoint assessment. By understanding the barriers and quantitatively assessing the sustainability dimension of the current practice, a comprehensive formulation of a framework for more sustainable utilization of fly ash is developed. In addition, an analysis of the institutional, economic, social, and technological barriers related to the utilization of waste materials in actual practice is carefully documented and analyzed.

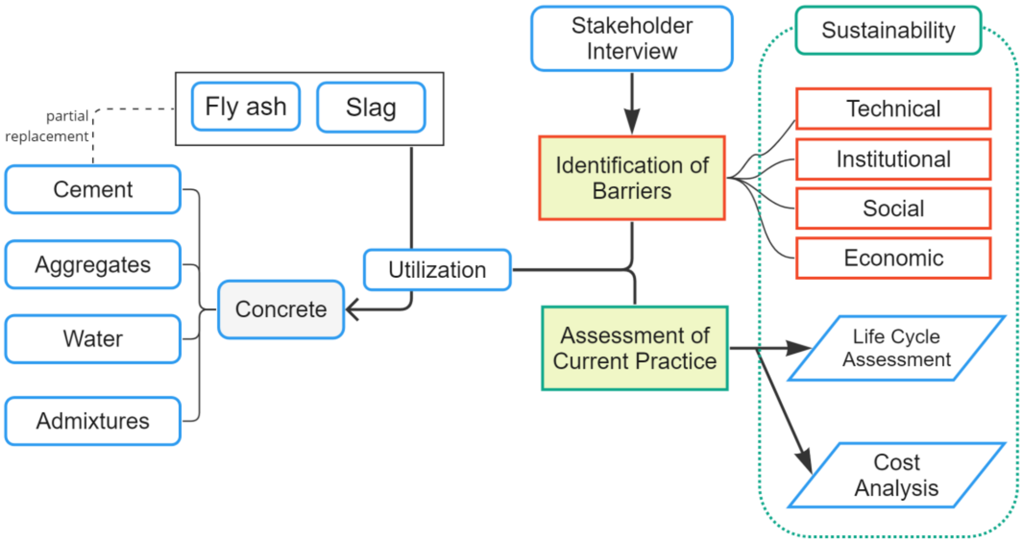

Figure 3.1 The methodological framework of the study

3.2 Mass concrete mixtures

Environmental and economic assessments for 60 mass concrete mixtures in the Philippines and Thailand were performed to accomplish the research objectives. In the case of the Philippines, thirty-one (31) mixtures obtained from concrete batching plants utilize different percentages of fly ash (0%, 10%, 15%, and 20%) as cement replacements, with 28-day strength designs ranging from 13.8 to 69.0 MPa. For the Thai context, twenty-seven (27) concrete mixtures were analyzed with higher fly ash percentages (0%, 25%, and 50%) as cement replacements for compressive strengths of 30 MPa, 35 MPa, and 40 MPa at specified design ages of 28 and 56 days. Two additional Thai cases were analyzed to compare the impacts of utilizing 50% fly ash and 65% slag as cement replacements for a 30 MPa mass concrete mixture.

3.2.1 Concrete mix designs in the Philippines

Thirty-one (31) concrete mix designs were gathered from actual data from two representative batching plants in the Philippines. Table 3.1 shows the mix designs provided by the batching plants using ordinary Portland cement only (0FA) and those with 10% (10FA), 15% (15FA), and 20% (20FA) fly ash replacements by weight of the cement. These replacement levels fall within the Philippine concrete industry's commonly used fly ash replacement. The concrete mixtures analyzed in this study are actual concrete mixtures used by the ready-mixed concrete batching plants, with varying 28-day compressive strength. The design mixtures in the Philippines are typically reported in pounds per square inch (psi). These design strengths were converted to SI units of MPa. The compressive strengths range from 2,000 – 10,000 psi (13.8-69.0 MPa). This range of strength design reflects the diverse concrete mixtures manufactured in the Philippines. According to interviews with batching plant owners and concrete experts, most concrete mixes produced in the country are designed at 27.6-34.5 MPa.

Concrete can be categorized into the following groups based on its 28-day compressive strength: low strength for concrete with a compressive strength below 20 MPa, normal strength for concrete with a compressive strength between 20 MPa and 40 MPa, and high strength for concrete with a compressive strength above 40 MPa. In the Philippines, 3,000 psi (20.7 MPa) or less is considered low strength, while 6,000 psi (41.4 MPa) or higher is considered high strength for mass concrete applications. House slabs, ground slabs, residential beams and columns, rigid pavements, suspended slabs, bridge decks, shear walls, and concrete walls all benefit from these design mixes (Table 3.2). Typically, high-strength concrete is used in high-rise buildings and other unique structures. All the studied batching plants are located in the capital region of the Philippines.

Table 3.1 Concrete mixtures for mass concrete in the Philippines with varying strength design and fly ash as cement replacement

Mix #	28-day Compressive Strength, psi (MPa)	Cement, kg	Fly Ash, kg	Water, kg	Gravel, kg	Sand, kg	Admixture, kg	% Fly Ash	water to binder (w/b)
1	2000 (13.8)	260	0	130	950	995	3.12	0%	0.50
2	3000 (20.7)	280	0	150	1020	880	3.60	0%	0.54
3	3500 (24.1)	310	0	165	945	920	3.66	0%	0.53
4	4000 (27.6)	360	0	150	985	845	4.00	0%	0.42
5	5000 (34.5)	360	0	145	985	900	4.60	0%	0.40
6	6000 (41.4)	460	0	150	975	810	5.04	0%	0.33
7	7000 (48.3)	500	0	145	975	805	6.00	0%	0.29
8	8000 (55.2)	520	0	120	990	790	6.76	0%	0.23
9	10000 (69.0)	600	0	140	1015	650	7.80	0%	0.23
10	2000 (13.8)	234	26	130	950	995	3.12	10%	0.50
11	3000 (20.7)	252	28	150	1020	880	3.60	10%	0.54
12	3500 (24.1)	279	31	155	990	950	3.72	10%	0.50
13	4000 (27.6)	324	36	145	965	895	4.68	10%	0.40
14	5000 (34.5)	324	36	145	985	900	4.60	10%	0.40
15	6000 (41.4)	414	46	155	970	800	5.52	10%	0.34
16	7000 (48.3)	450	50	130	855	895	6.50	10%	0.26
17	8000 (55.2)	468	52	120	990	790	6.76	10%	0.23
18	10000 (69.0)	540	60	140	1015	650	7.80	10%	0.23
19	3000 (20.7)	272	48	165	945	925	3.52	15%	0.52
20	3500 (24.1)	281	49	165	945	920	3.66	15%	0.50
21	4000 (27.6)	298	53	165	975	875	3.90	15%	0.47
22	5000 (34.5)	323	57	140	985	885	4.90	15%	0.37
23	6000 (41.4)	357	63	150	975	810	5.04	15%	0.36
24	7000 (48.3)	400	70	145	975	805	6.00	15%	0.31
25	10000 (69.0)	519	91	145	1050	625	7.93	15%	0.24
26	2000 (13.8)	256	64	165	1078	830	2.56	20%	0.52
27	3000 (20.7)	272	68	165	1078	814	2.72	20%	0.49
28	3500 (24.1)	288	72	165	1078	798	2.88	20%	0.46
29	4000 (27.6)	304	76	165	1078	782	3.04	20%	0.43
30	5000 (34.5)	352	88	165	1078	735	3.52	20%	0.38
31	6000 (41.4)	368	92	165	1078	719	3.68	20%	0.36

The concrete mixtures investigated in this study incorporate varying percentages of fly ash as partial replacements for cement, specifically 0%, 10%, 15%, and 20%. These replacement levels align with the typical practices observed in the Philippine concrete construction industry. The fly ash utilized is sourced from coal-fired power plants in the Philippines and is mixed into the concrete as a mineral admixture at the concrete production plants. It is important to note that the fly ash is obtained from third-party suppliers. The specific type of fly ash employed in the batching plants is classified as Class F fly ash according to ASTM C618. The chemical composition of this fly ash includes a CaO content of 10.6%, SiO_2 content of 53.1%, Al_2O_3 content of 17.5%, and Fe_2O_3 content of 5.48%. The loss on ignition (LOI), as determined through testing conducted in accordance with ASTM C311, is recorded as 2.7. The provided chemical composition details were obtained directly from the fly ash supplier.

Table 3.2 Number of concrete mixtures analyzed from the Philippines and their applications.

Fly Ash Replacement	**0%**	**10%**	**15%**	**20%**	**Typical applications**
Low strength (13.8-20.7 MPa)	2	2	1	2	Elements of a typical residential structure, low-traffic pavement
Normal strength (24.3-34.5 MPa)	3	3	3	3	House slabs (ground slabs), columns and beams for residential applications, rigid pavements, bridge decks, suspended slabs, walls (including shear walls), and most mid-rise structures (up to 15 stories)
High Strength (41.4-69.0 MPa)	4	4	3	1	Most high-rise structures (up to 20 stories), elevated transport infrastructures, special infrastructures with high load

3.2.2 Concrete mix designs in Thailand

Two different types of fly ash were used for different concrete mixtures intended for mass concrete applications: (1) high CaO (FAM) fly ash from the Mae

Moh coal-fired power plant in Lampang Province and (2) low CaO (FAR) fly ash from the BLCP power plant in Rayong Province.

Table 3.3 Inventory of concrete mixtures and transportation distances (Thailand)

Mix No.	Design Strength	Age	Fly Ash	Type	Binder	Cement	Fly Ash	Water	Sand	Gravel	w/b
Unit	*MPa*	*days*	*%*		*kg*	*kg*	*kg*	*kg*	*kg*	*kg*	
1	30	28	0	OPC	390	390	0	195	739	1038	0.50
2	30	28	25	FAM	390	293	97	184	739	1038	0.47
3	30	28	50	FAM	390	195	195	149	764	1074	0.38
4	30	28	25	FAR	396	297	99	182	739	1038	0.46
5	30	28	50	FAR	404	202	202	143	764	1074	0.35
6	30	56	25	FAM	350	262	88	174	764	1074	0.50
7	30	56	50	FAM	350	175	175	147	783	1100	0.42
8	30	56	25	FAR	355	266	89	172	764	1074	0.49
9	30	56	50	FAR	364	182	182	142	783	1100	0.39
10	35	28	0	OPC	415	415	0	187	739	1038	0.45
11	35	28	25	FAM	415	311	104	175	739	1038	0.42
12	35	28	50	FAM	415	208	208	140	763	1072	0.34
13	35	28	25	FAR	419	314	105	174	739	1038	0.42
14	35	28	50	FAR	440	219	219	132	763	1072	0.30
15	35	56	25	FAM	375	281	94	174	755	1061	0.46
16	35	56	50	FAM	375	188	188	138	783	1100	0.37
17	35	56	25	FAR	380	286	95	172	755	1061	0.45
18	35	56	50	FAR	400	200	200	133	777	1092	0.33
19	40	28	0	OPC	440	440	0	180	739	1038	0.41
20	40	28	25	FAM	440	329	110	167	739	1038	0.38
21	40	28	50	FAM	440	219	219	132	763	1072	0.30
22	40	28	25	FAR	445	334	111	165	739	1038	0.37
23	40	28	50	FAR	472	236	236	142	739	1038	0.30
24	40	56	25	FAM	400	300	100	165	755	1061	0.41
25	40	56	50	FAM	400	200	200	128	783	1100	0.32
26	40	56	25	FAR	407	305	102	163	755	1061	0.40
27	40	56	50	FAR	446	223	223	134	758	1065	0.30
Transportation Distances (km)			600 (FAM) 190 (FAR)			120		-	60	120	

These power plants are located at distances of 600 km (Mae Moh) and 190 km (BLCP) from the capital city, Bangkok, which serves as a primary hub for concrete construction production. Both fly ashes comply with the requirements of Thai Industrial Standard (TIS 2135-2545). Based on this standard, FAR is classified as Class 2a (low CaO), and FAM is classified as Class 2b (high CaO) fly ash. These fly ashes were used in 24 (out of 27 in total) concrete mixtures of varying cement replacement (Table 3.3), designed compressive strength, and age to attain the designed strength (notified hereinafter as simply the design age). The chemical properties of the two sources of fly ash are shown in Table 3.4.

Table 3.4 Chemical properties of low CaO (FAR) and high CaO (FAM) fly ash from Thailand (Wanna et al., 2020)

Fly ash	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Free Lime	Loss on Ignition
FAM	40.9	22.4	13.64	13.63	2.93	0.89	2.39	1.93	0.22	0.46
FAR	61.91	20.35	5.20	2.32	1.35	0.79	1.36	0.28	0.19	5.68

3.2.3 Concrete mixture for fly ash and slag comparison

For the purposes of comparing the performance of utilizing different types of SCM, two Thailand concrete mixes containing 50% fly ash (50FA) and 65% ground granulated blast furnace slag (65GGBS) with an equivalent compressive strength of 30 MPa at 56 days were analyzed for environmental performance. Table 3.5 shows the composition of the 30MPa mass concrete mixture using GGBS and FA as partial cement replacements.

Table 3.5 Concrete mix designs with pure OPC, GGBS, and FA for 30 MPa concrete (Thailand)

Mix	Total binder (kg/m^3)	w/b	Cement (kg/m^3)	Fly ash (kg/m^3)	Slag (kg/m^3)	Water (kg/m^3)`	Sand (kg/m^3)	Gravel (kg/m^3)
OPC	390	0.5	390	-	-	195	739	1038
50FA	324	0.46	162	162	-	149	835	1076
65GGBS	323	0.60	113	-	210	194	799	1029

These concrete mixtures were compared to a control mixture of pure Ordinary Portland cement (OPC) designed for 30 MPa compressive strength at a specified age of 28 days. Pure-cement concrete is typically designed for 28 days since it does not exhibit further strength development beyond this point, unlike cement with supplementary cementitious material replacement. The concrete mix design represents an actual mixture used for a thick mat foundation obtained from a previous study (Dabarera et al., 2019). The initial slumps are approximately 7.5 cm and 4 cm for 50FA and 65GGBS, respectively. The chemical compositions of the binders are shown in Table 3.6.

Table 3.6 Chemical compositions of OPC, GGBS, and FA (Thailand)

Binder	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
OPC	22.0	5.40	3.0	63.4	2.7	2.0
GGBS	33.5	14.35	0.26	43.3	5.1	2.1
Fly ash	36.1	19.4	15.1	17.4	3.0	0.8

3.3 Environmental assessment: life cycle assessment

This study employs the International Organization for Standardization (ISO) 14040 standard for LCA, which has been used in earlier investigations (Habert, 2013b; Panesar, Kanraj, & Abualrous, 2019). It is a well-established tool for the environmental assessment of different concrete mixtures (Vieira, Ponsioen, Goedkoop, & Huijbregts, 2016). The SimaPro 9.3 LCA program and the ecoinvent 3.8 database were used to evaluate the concrete mixtures. SimaPro has been extensively utilized in the LCA of concrete and cement (Hossain, Poon, Lo, & Cheng, 2017; Tun, Bonnet, & Gheewala, 2020). On the other hand, ecoinvent has recently been regarded as one of the finest construction materials databases (Olagunju & Olanrewaju, 2020). The life cycle study was conducted with local conditions in the Philippines. To assess the influence of fly ash on various concrete mix designs, a cradle-to-gate life cycle assessment of various concrete mixtures was made, similar to many previous studies (Panesar, Kanraj, & Abualrous, 2019; Tait & Cheung, 2016).

3.3.1 Scope, functional unit, and assumptions

The functional unit selected for this study is one cubic meter of concrete, a widely adopted measure in numerous Life cycle assessment investigations concerning concrete (Gursel & Ostertag, 2019; Panesar, Kanraj, & Abualrous, 2019). The system boundary depicted in Figure 3.2 includes all the processing inputs required for concrete manufacturing. The scope of this study extends from cradle to gate, encompassing all major manufacturing processes for concrete constituents and associated life-cycle phases. The concrete mix designs selected are for use in mass concrete. The system boundary includes the extraction and production of raw materials (cement, fine aggregate or sand, coarse aggregate or gravel), transportation, and mixing in batching plants. The emissions attributed to transportation are considered in relation to fly ash and GGBS.

Fly ash as a partial cement substitute is obtained from coal-fired power plants and mixed at concrete production plants. This study did not consider the impacts associated with the electricity production from coal-fired power plants where fly ash is sourced. This assumption was also used in Tait and Cheung's (2016) LCA study. However, we considered transportation and preparation (i.e., transfer to silo, quality control) as significant sources of emissions associated with fly ash. In the Philippines and Thailand, a third-party supplier delivers fly ash to concrete producers. Raw materials are transported by trucks (lorry) of class size between 16 to 32 tonnes, operated by diesel. Additional analysis was conducted to determine the impact of importing slag via maritime shipping. The study did not consider the emissions in furnace pig iron production, which is similar to the assumptions followed by Aslani et al. (2023) for GGBS. Only treatment and management steps, such as slag granulation, drying, and grinding for GGBS from power plants to delivery facilities, were considered. These assumptions were consistent with the assumption that fly ash and GGBS have "waste" status (Pushkar, 2017).

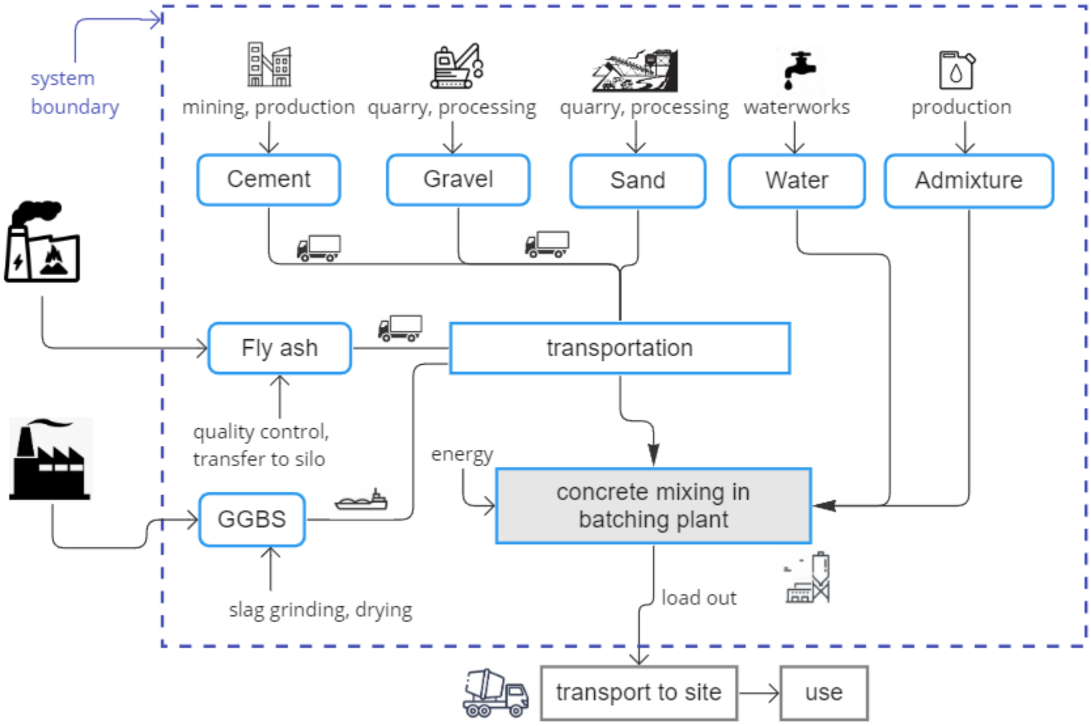

Figure 3.2 System boundary used for environmental assessment of mass concrete

The end-of-life strategy for concrete is beyond the scope of this investigation. Given that the concrete mixtures under examination were designed to meet similar strength requirements and functional specifications, factors related to the construction, service, and demolition stages were deemed to have no direct influence on the findings of this study.

3.3.2 Life cycle inventory of concrete constituents: Philippines

Ordinary Portland cement, gravel, sand, and water are the primary components of concrete. A life cycle inventory of concrete ingredients needs to be acquired to conduct a comprehensive life cycle assessment of various concrete mixtures containing cement substitutes. The summary of data sources and relevant assumptions are listed in Table 3.7.

Table 3.7 Data sources and assumptions (Philippines)

Input	**Remarks**
Concrete mixture	listed in Table 1, obtained from batching plant operators
Electricity source	"electricity, medium voltage {PH}" in ecoinvent *PH = Philippines
Electricity for concrete mixing at batching plant	2.15 kWh per m^3 of fresh concrete (Sukontasukkul, 2009)
Cement	based on ASTM C150 (Portland cement) production process used in the Philippines. "cement, Portland" available in ecoinvent with inputs modified to reflect data from Holcim Philippines (Holcim Philippines, 2018) for cement production: 90% "clinker" ; 5% "gypsum, mineral", 5% "limestone, crushed"
Gravel	"gravel, crushed" available in ecoinvent
Sand	"sand" in ecoinvent with input modified to reflect sand production in the Philippines based on interview: • 20% Sand {RoW}| gravel and quarry operation • 80% Sand {RoW}| sand quarry operation, extraction from river bed
Admixture	"chemical, organic" in ecoinvent
Water	"tap water" in ecoinvent
Fly ash	preparation emission (minimal drying, grinding, transfer to silo, etc.) was estimated to be 0.43 GJ/t (Kawai, Sugiyama, Kobayashi, & Sano, 2005) for input energy and 0.0015 t-CO_2/tonne (Wanna, Saengsoy, Toochinda, & Tangtermsirikul, 2020)
Transportation distances (cement, gravel, sand, fly ash)	listed Table 2, estimated using GIS from batching plant to material sources
Transport mode	"Transport, freight, lorry 16-32 metric tonne, euro3" in ecoinvent

Local data for cement production were obtained from a comprehensive environmental impact assessment report of a major cement factory in the Philippines (Holcim Philippines, 2018). The grinding process consists of 90% clinker, 5% gypsum, and 5% mineral filler. The information used to describe Portland cement production is based on the American Society for Testing and Materials' technical standard (ASTM

C150) for Portland cement. The Philippines' local cement standard adopts the ASTM Standard. The dataset utilized for sand transformation describes a blend of riverbed and quarry sand. According to interviews with operators of ready-mix batching plants, roughly 80% of the aggregates come from riverbeds, and 20% are from quarries. For gravel, the dataset represents the operation of open-pit mechanized mining. Drilling, blasting, separating, and collecting are done on the mining site. The utilized chemical additives are superplasticizers. Worldwide data was utilized for admixture because most Philippine admixtures are imported from overseas. Type G polycarboxylate admixtures conforming to ASTM C494 are the most frequently used admixtures in the country. For the emission caused by this plasticizer, GLO or global average data were used in ecoinvent. The electricity utilized is medium voltage in the Philippine electrical market.

The transportation of cement-replacement materials in the context of life cycle assessment is a critical component of this study. In this investigation, all the examined components are transported via truck, with weights ranging from 16 to 32 tonnes. To estimate the transportation data, the latitude of the concrete batching plant’s suppliers (i.e., material sources) is utilized, and the land route is calculated using a geographical information system (Arc GIS). The data obtained represents the average distances between the sources and the batching plants situated within the metropolitan area. The mode of transport used in the ecoinvent database is specified as “transport freight lorry 16-32 metric tonnes euro 3,” and the geographical data for the rest of the world (RoW) is employed. The gravel source was 36 kilometers from the batching plant. On the other hand, the sand or fine aggregates were obtained from a river quarry approximately 100 kilometers from the concrete batching plants. No transportation is associated with the water used in concrete production as it is directly distributed to the concrete batching plants either by central waterworks or pumped from groundwater. The distances from the source to the batching plant (one-way) are listed in Table 3.8. This study does not account for the effects of return trips involving empty trucks. The batching plants considered are located in the capital region of the Philippines.

Table 3.8 Average one-way transportation distances for concrete materials from sources to batching plant (Philippines)

Material	**Distance from source to batching plant**
Cement	150 km
Fly Ash	121 km
Gravel	36 km
Sand	100 km
Water	0

3.3.3 Life cycle inventory of concrete constituents: Thailand

The conditions considering practices in Thailand were used in this study. The concrete compositions utilized are outlined in Table 3.3. The study conducted by Sukontasukkul (2009) and Wanna et al. (2020) included information on the manufacture of cement, aggregates, and fly ash processing. The description of Portland cement manufacture was based on the technical standard for Portland cement, known as ASTM C150, established by the American Society for Testing and Materials (ASTM). The cement manufactured in Thailand has been determined to meet the ASTM and Thai Industrial Standards (TIS 15) requirements. The dataset utilized for sand transformation was derived from the research conducted by Sukontasukkul (2009), which indicates that riverbeds serve as the principal source of fine aggregates in Thailand. For gravel, the dataset encompasses open-pit mechanized mining activities, encompassing drilling, blasting, separation, and collection conducted at mining sites. According to Sukontasukkul's (2009) data, the electricity usage for ready-mixed batching plants in Bangkok is projected to be 2.15 kW/m^3. Medium electricity mix was selected in the inventory data as in the study of Manjunatha et al. (2021). In Thailand, fly ash is transported to concrete producers by an external provider through trucks powered by diesel engines. These trucks have a capacity that varies between 16 and 32 tonnes, with inventory available in ecoinvent. Since the slag is mainly imported from other countries, the inventory used was the global average or rest-of-the-world

(RoW). The inventory used in ecoinvent is "Ground granulated blast furnace slag {RoW}." This dataset represents the treatment of molten blast furnace slag, producing an output of ground-granulated blast furnace slag. This inventory for the production of GGBS encompasses the following process steps (i) quenching/granulation, (ii) dewatering and/or drying, (iii) crushing, (iv) grinding, and (v) storage in pile and silo. The transportation used to import slag is "Transport, freight, sea, ferry {GLO}."

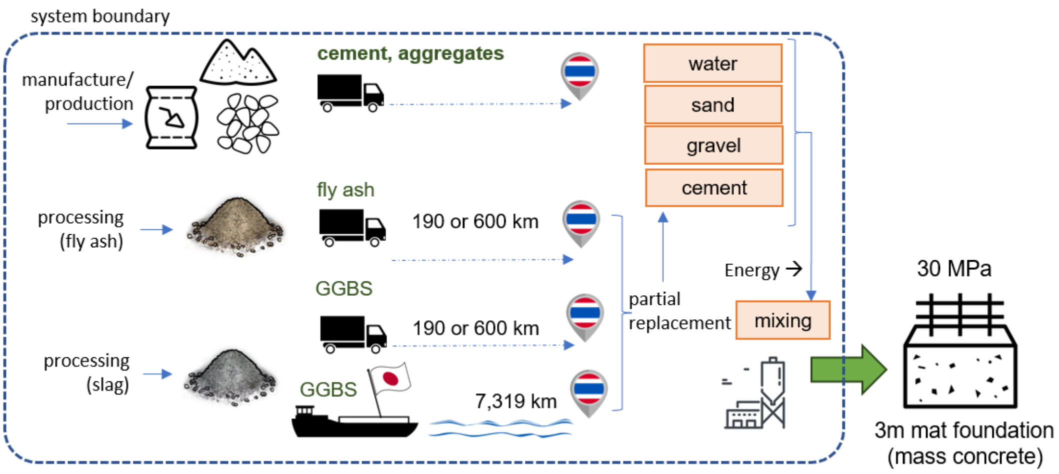

Figure 3.3 System boundary conditions showing the processes and transportation considered for cradle-to-gate life cycle assessment of 30MPa mass concrete (mat foundation) with fly ash and GGBS as cement replacements in Thailand.

In this investigation, transportation distances of 120 km were considered for both cement and gravel, while a distance of 60 km was considered for sand. Additionally, 600 km and 190 km transportation were used for fly ash and GGBS. These represent the distances from the capital Bangkok, a significant hub for concrete production, to the sources of fly ash: Mae Moh (600 km) and BLCP (190 km) power plants. Water transportation is not considered, as water is immediately supplied to concrete batching facilities via central waterworks or groundwater extraction. The measurement of transportation is commonly denoted in tonne-kilometers (tkm), which quantifies the movement of one metric tonne of goods over a distance of one kilometer. The slag is transported from the Port of Tokyo (Japan) by sea at a distance of 7,319 km (or 3,952 nm) to the Port of Bangkok (Thailand), as shown in Figure 3.3. This is because about 68% of imported slag in 2021 used in Thailand's construction industry was obtained from Japan (TrendEconomy, 2023).

3.3.4 Midpoint and endpoint impact assessment

The comprehensive analysis of environmental impacts associated with concrete mixtures was conducted using ReCiPe midpoint (18 impact categories) and endpoint (3 impact categories). The impact analysis was conducted using the latest, state-of-the-art 2016 version of ReCiPe. Due to its broad application in numerous scientific models, the consensus model, also known as the Hierarchist model of ReCiPe, is utilized in this study. This approach is based on widely recognized timeframe and other factors (Gursel & Ostertag, 2019). The midpoint and endpoint impact analyses are the two most common assessment techniques used to determine the influence of concrete mixtures. Midpoint impacts are considered more precise and contain a greater volume of scientific data (Bare & Gloria, 2008). Endpoint impacts encompass adverse effects on human health, the ecosystem, and the availability of resources. The relationship between midpoint and endpoint impacts is shown in Figure 3.4.

Due to the increased level of uncertainty in regional impact assessment data, the ReCiPe guidelines recommended a midpoint-oriented approach, which was used in this study. Midpoint impacts are considered more precise and contain a greater volume of scientific data (Bare & Gloria, 2008). The impacts based on the ReCiPe2016 Midpoint (Hierarchist) Method include 18 categories (Huijbregts, Steinmann, Elshout, Stam, Verones, et al., 2017). The abbreviations and units used in succeeding discussions are also defined in Table 3.9.

Table 3.9 Impact categories considered in life cycle assessment with corresponding abbreviations and units

Impact category	**Abbreviation**	**Unit**
Global warming potential	GWP	kg CO_2 eq
Stratospheric ozone depletion	SOD	kg CFC11 eq
Ionizing radiation	IR	kBq Co-60 eq
Ozone formation, Human health	OZ	kg NO_x eq
Fine particulate matter formation	FPM	kg $PM_{2.5}$ eq
Ozone formation, Terrestrial ecosystems	OZT	kg NO_x eq
Terrestrial acidification	TA	kg SO_2 eq
Freshwater eutrophication	FEU	kg P eq
Marine eutrophication	MEP	kg N eq
Terrestrial ecotoxicity	TE	kg 1,4-DCB
Freshwater ecotoxicity	FET	kg 1,4-DCB
Marine ecotoxicity	MET	kg 1,4-DCB
Human carcinogenic toxicity	HCT	kg 1,4-DCB
Human non-carcinogenic toxicity	HNT	kg 1,4-DCB
Land use	LU	m^2a crop eq
Mineral resource scarcity	MRS	kg Cu eq
Fossil resource scarcity	FRS	kg oil eq
Water consumption	WC	m^3

The endpoint technique has advantages since it produces simple outcomes by evaluating damages to human health, the ecosystem, and resources. For the human health category, ReCiPe employs disability-adjusted life years (DALY), which represent a life lost in years or damaged due to environmental impacts. The ecosystem damage category is assessed by species/year; this represents species lost in a year because of emissions to the environment, water body, etc. The resource damage category is based on economic loss due to a marginal rise in costs because of resource scarcity. The cost associated with this resource damage is expressed in equivalent 2013 U.S. dollars (D. Olagunju & A. Olanrewaju, 2021). Midpoint and endpoint approaches are complementary. However, the endpoint characterization provides better information on the environmental relevance of the environmental flows. Moreover, the contribution of concrete is greater at the endpoint level than at the midpoint (Dong & Ng, 2014).

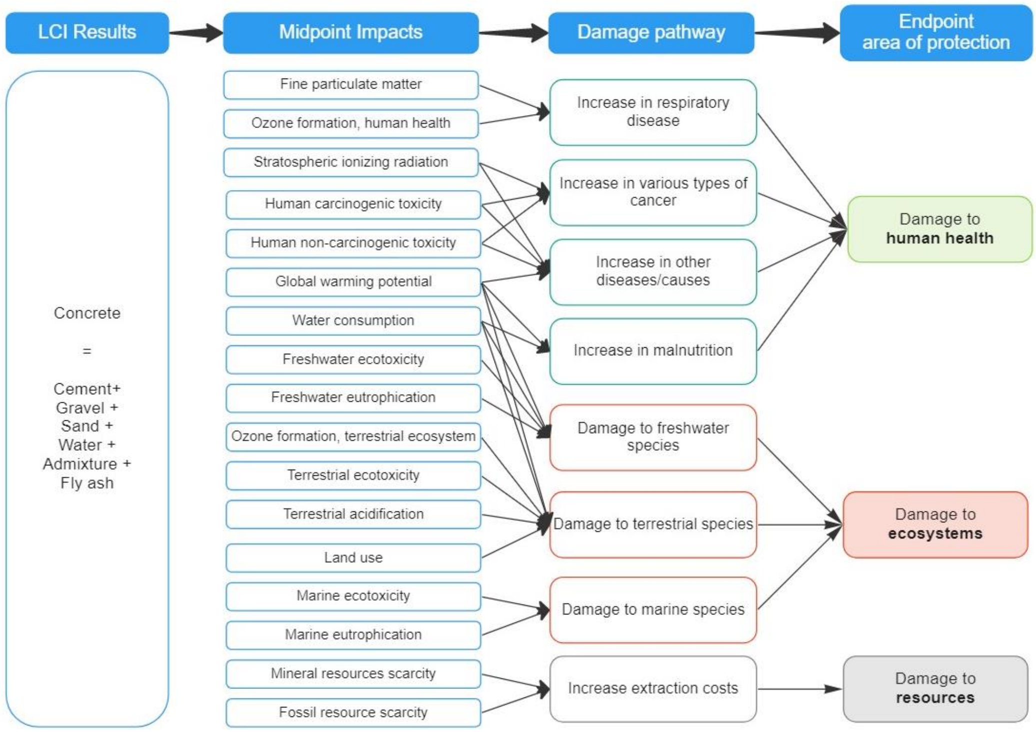

Figure 3.4 Overview of the impact categories that are covered in the ReCiPe 2016 method and their relation to the areas of protection (Huijbregts et al., 2017).

3.3.5 Statistical analysis

The paired t-test was employed to assess the significance of differences in the impacts (damages) among concrete mixtures. This statistical analysis method allows for the determination of whether the mean difference between two sets of observations is statistically significant. In the context of this study, the t-test is employed to examine whether the substitution of cement with fly ash has a substantial impact on reducing the associated endpoint impact across concrete mixtures. Endpoint impacts of concrete mixtures with similar compressive strength designs but different fly ash content are considered data pairs. The interpretation of the test results is based on a 95% level of confidence or a 5% level of significance. Under this threshold, a difference between the impacts is deemed significant if the *p*-value is less than 0.05.

In addition, correlation analysis is conducted to discern the influence of specific concrete components on the endpoint damage indicators related to human health, ecosystems, and resources. Correlation analysis is a bivariate examination that evaluates the strength and direction of the association between two variables.

Spearman's correlation coefficient (ρ) is utilized in this study to explore the monotonic relationship between continuous or ordinal variables. The correlation coefficient can range from +1 to -1, with its value indicating the strength of the association. A coefficient closer to +1 indicates a stronger positive correlation between the variables. Spearman correlation provides valuable insights into the impact of concrete components on endpoint indicators, especially when prior knowledge of the relationship is limited. This method of analysis has also been used in a previous study on the life cycle assessment of concrete (Tripathy & Acharya, 2023). The statistical software Minitab 21 was used to perform all statistical analyses.

3.3.6 Scenario and critical distance analyses

A critical transportation distance analysis was conducted to assess the threshold at which the inclusion of fly ash in concrete mixtures would no longer yield overall environmental benefits. To isolate the influence of fly ash type, a scenario was investigated where the transportation distance of fly ash was assumed to be zero. Through sensitivity analysis, the transportation distance of fly ash was varied from zero to 9,000 km, and the corresponding effects on relevant environmental impacts were investigated. This study utilized scenario-based and sensitivity analysis approaches to determine the critical transportation distance, offering a comprehensive examination of the factors impacting the environmental effects of incorporating different types of fly ash in concrete mixtures. Additionally, to deepen understanding regarding the impact of long-distance fly ash transportation on mass concrete mixtures, a detailed substance and process analysis of all midpoint impact categories was conducted for a 40MPa 50FAM concrete mixture with a specified age of 56 days, chosen as a representative sample. This concrete mix was selected due to its representation of the design mixture with the highest reduction in global warming potential compared to pure cement. By analyzing the high fly ash replacement sourced from the longest distance in this concrete mix, we aimed to gain a more thorough understanding of the impact of fly ash transportation.

The study employed a scenario to comprehensively analyze the factors that influence the environmental impact of fly ash and slag in concrete mixtures. To understand the impact of the type of SCM only, a scenario was considered in which the transportation of SCM was zero. Both sea and land modes were considered to determine the impact of transportation on slag. The transportation for slag varied between 190 and 600 km by land, the same distance as the fly ash sources. These distances are representative of the proximity of power plants from which a significant portion of fly ash is procured in the Bangkok region. To maintain consistency in our comparative analysis, these distances of power plants also serve as the distance from the source of GGBS for this analysis. Similar to the analysis conducted for fly ash concrete, a substance and process contribution analysis was performed to unravel the underlying substances and processes contributing to long-distance sea transportation of slag for use in mass concrete.

To compare the incremental impact of transporting slag using maritime shipping as compared to land travel, the following Equation was used:

$$R_t = \frac{\text{impact per km (sea)}}{impact\ per\ km\ (land)} \tag{3.1}$$

where R_t = relative impact of transportation modes

3.3.7 Comparative analysis: Thailand and Philippines

The environmental impact of concrete mixtures used in the Philippines and Thailand was compared using scenario analysis. Thailand was chosen because of its history of employing high fly ash replacement levels in mass concrete mixtures. This comparison will also provide a regional comparative perspective on the practices of two Southeast Asian countries. A concrete mixture with a similar strength design (35 MPa, normal strength, Table 3.10) was selected for this comparison.

Table 5 depicts the concrete mixture used for mass concrete in Thailand. The fly ash used as cement replacement in the design is a high CaO fly ash (FAM) obtained from the Mae Moh coal-fired powerplant. In this study, we look at the effects of increased fly ash substitution as well as longer specified strength age (56 days). LCA was conducted considering conditions summarized in Section 3.3.3, providing cement, aggregate, and fly ash inventory data in Thailand. Thai cement meets ASTM C150 and TIS 15 requirements for ordinary Portland cement. Sand transformation data was based on the study of Sukontasukkul (2009), which found that riverbeds are the main source of fine aggregates, whereas gravel data was from open-pit mechanized mining. Ready-mixed batching facilities use 2.15 kW/m^3 of electricity. For comparative analysis, the transportation considered for fly ash for both countries is 121 km. This study examines 120 km of cement and gravel transport and 60 km of sand transport.

Table 3.10 Thailand concrete mix design for mat foundation concrete (35 MPa)

Design Strength	Days	Fly Ash	Binder	Cement	Fly Ash	Water	Sand	Gravel	w/b
		%	kg	kg	kg	kg	kg	kg	
35 MPa	56	25	375	281	94	174	755	1061	0.46
35 MPa	56	50	375	188	188	138	783	1100	0.37

3.4 Economic analysis

3.4.1 Cost analysis of mass concrete mixtures in the Philippines

An economic analysis was carried out to estimate the effect of fly ash on concrete mixtures' initial cost. The material costs were determined using price quotes provided by suppliers to concrete batching plants. All costs were calculated using 2022 pricing. The concrete batching plant observed that the prices of materials are normally sold in bulk to them by the suppliers. As a result, the values are slightly lower than market pricing. Table 3.11 summarizes the cost.

Table 3.11 Unit prices of concrete materials (Philippines)

Material	Price (PhP) per tonne	Price (USD) per tonne
Cement	5,440.00	99.78
Gravel	360.71	6.62
Sand	716.48	13.14
Admixture	4,5130.00	827.75
Fly Ash	3,200.00	58.69
Water	107.01	1.96

It is worth noting that the cost of fly ash is primarily associated with transportation and logistical expenses incurred in delivering the fly ash to concrete batching plants. Prices were collected in Philippine Pesos (PhP) and converted to USD using the Central Bank of the Philippines' exchange rate as of January 26, 2023 (1 USD = 54.52 PhP).

3.4.2 Cost analysis of mass concrete mixtures in Thailand

An economic evaluation was carried out to assess the initial cost implications of incorporating fly ash in concrete mixtures. The prices of cement, gravel, and sand were obtained from a laboratory supplier, while the cost of fly ash was obtained from a previously published study (Wanna, Saengsoy, Toochinda, & Tangtermsirikul, 2020). The cost of water was based on published data from the Public Waterworks Authority of Thailand. The resulting costs were summarized and presented in Table 3.12. All prices were obtained in Thai Baht (THB) and were converted to US Dollars (USD) using the exchange rate provided by the Bank of Thailand as of March 23, 2023 (1 USD = 34.22 THB).

Table 3.12 Inventory of prices for the unit cost of concrete components (Thailand)

Material	Price (THB) per tonne	Price (USD) per tonne
Cement	2,395	69.98
Gravel	292	8.53
Sand	230	6.72
Fly Ash	1,600 (FAM) 639 (FAR)	46.76 18.67
Water	32	0.94

3.5 Challenges and opportunities towards sustainable waste utilization

Interviews with key stakeholders were conducted to understand the motivation and barriers to using cement replacing material in the Philippine concrete construction industry, specifically, but not limited to, fly ash. The motivations and barriers to waste utilization in concrete construction were qualitatively identified using the interview structure developed by Henry and Kato (Henry & Kato, 2014) with minor adjustments. In-depth, semi-structured interviews were conducted with a diverse group of key stakeholders with decades of expertise in the concrete building industry. The semi-structured interview adhered to a general structure but allowed for an in-depth discussion of individual issues. The interview covers a wide range of issues, including specific industry conditions in the Philippines, current waste material use, and the possibilities and constraints of large-scale waste material use (institutional, economic, social, and technological). The specific questions posed to the stakeholders are listed in Table 3.13.

Table 3.13 Interview questions to stakeholders/experts from the Philippines

1. Could you provide insights into the current condition of concrete in the Philippines based on your expertise and experience?
2. In the concrete production industry, are waste materials currently being utilized? • What is the rate of utilization of waste materials? • Which specific waste materials are commonly used, and is there a predominant choice? • Where are these waste materials typically sourced from? • In your opinion, what are the benefits of incorporating waste materials in concrete production?
3. Are there any notable challenges associated with the utilization of waste materials in mass concrete production?
4. From your perspective, what strategies or approaches can be employed to overcome the challenges related to the utilization of waste materials in concrete production?
5. Are you familiar with any laws or regulations in the Philippines that promote the utilization of waste materials in concrete production? If so, could you provide further details about these regulations and their impact?

A combination of individual online and offline interviews and focus group discussions were conducted. Given the nature of our research objectives and the flexibility afforded by semi-structured interviews, conducting these interviews both online and offline would yield similar results. Ten interviews were conducted in all. The interviewees have a minimum of 10 years of experience coming from various industries within the concrete construction industry. The interviews were conducted following relevant ethical guidelines and regulations in the Philippines, and all subjects gave their informed consent. Table 3.14 highlights the stakeholders who were interviewed and their corresponding backgrounds. The respondents were chosen because they had specific experience in concrete development, use, and management, which allowed them to identify the issues in the national context. The analysis of the interview data was conducted using the SWOT (Strengths, Weaknesses, Opportunities, Threats) and PEST (Political, Economic, Social, and Technological) techniques, which enabled us to organize the findings into structured points (social and institutional, economic, technical).

Table 3.14 Background of expert stakeholders interviewed (Philippines)

Stakeholders in the Philippines	Number	Years of Experience
Concrete consultant	2	40+
Contractor	3	20-30
Concrete Testing Manager	1	30+
Academe	2	10+
Batching Plant Owner	2	10+

CHAPTER 4
ENVIRONMENTAL AND ECONOMIC IMPACTS OF FLY ASH UTILIZATION IN THAILAND MASS CONCRETE: EFFECT OF FLY ASH TYPE AND TRANSPORTATION

This Chapter discusses the environmental and economic impacts of fly ash utilization as a partial cement replacement for mass concrete mixtures in Thailand. Specifically, this covers significant findings on the environmental and economic impacts of utilizing low CaO and high CaO fly ash for application in mass concrete at various strength designs and fly ash replacements, the impact of fly ash transportation on the environmental performance of mass concrete mixtures, the critical distance at which different types of fly ash can be sourced without exceeding the impact of pure cement concrete.

4.1 Effect of fly ash type on midpoint impacts without fly ash transportation

To isolate the influence of fly ash type, a scenario was examined in which the transportation distance of fly ash was eliminated (df = 0 km) in concrete mixtures incorporating fly ash. The findings revealed a significant reduction in global warming potential, with low CaO fly ash demonstrating reductions ranging from 22% to 49% and high CaO fly ash showing reductions ranging from 23% to 51% when compared to pure cement concrete (Figure 4.1). These values exceed the 17% reduction reported by Van den Heede et al. (2017) and are comparable to the 42% reduction reported by Mocharla et al. (2022) for a 50% replacement of cement with fly ash in concrete.

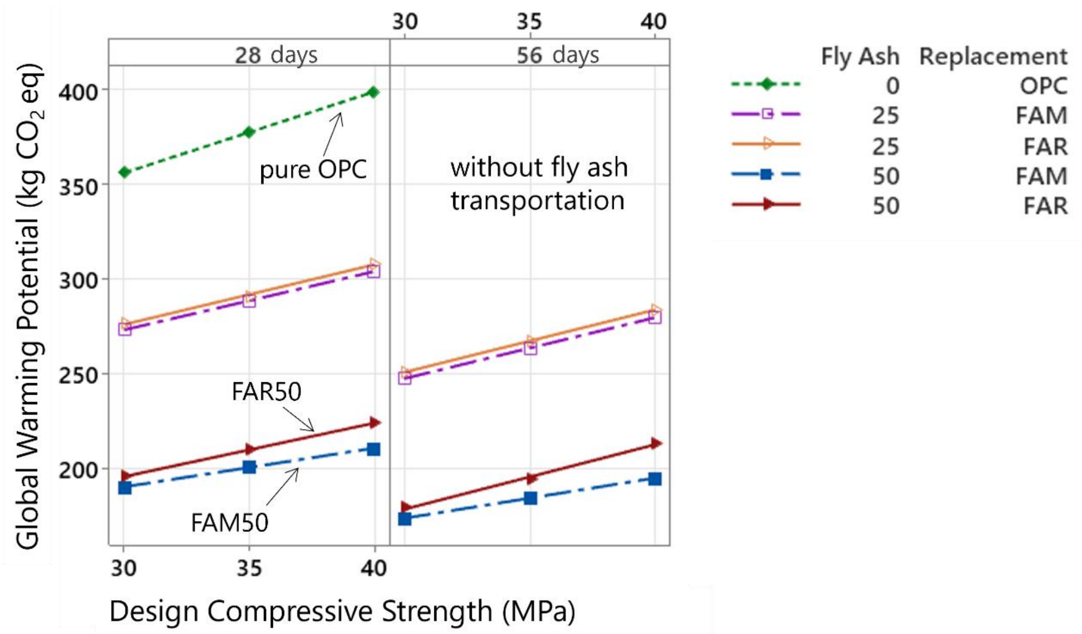

Figure 4.1. Comparison of global warming potential (GWP) for different concrete mixtures in Thailand with varying fly ash replacements without fly ash transport

Concrete mixtures utilizing high CaO fly ash (FAM) exhibited a lower global warming potential than those with low CaO fly ash (FAR). The impact of fly ash type was more noticeable at a higher replacement level of 50% (Figure 4.1). When FAM is compared to FAR, the difference in GWP reduction (from the cement-only mix) for a 25% fly ash replacement was only 1-1.6%. However, for a 50% replacement, this difference between FAM and FAR ranged from 3-6.5% and 3-9.7% for 28 days and 56 days of design age, respectively. The net CO_2 reduction benefit of FAM over FAR was particularly noticeable in concrete mixtures designed for higher strength, such as the 40 MPa concrete at 56 days, where the GWP for high CaO fly ash was 195 kg CO_2 eq (FAM50) compared to 214 kg CO_2 eq for low CaO fly ash (FAR50). This can be attributed to the strength of the development of low CaO fly ash compared to high CaO fly ash. Concrete mixtures incorporating low CaO fly ash exhibit slower strength development, necessitating a higher cement content to achieve equivalent strength levels as those achieved with high CaO fly ash. The high CaO fly ash reacts faster, maximizing binder use. It was reported that fly ash with higher CaO gives better strength development at an early age than fly ash with lower CaO content (Tangtermsirikul & Kaewkhluab, 2002). The self-cementitious capacity of high CaO fly ash results in early strength development and, with correct proportioning, in economy and quality. As shown in Figure 4.2, FAM concrete mixtures use less binder (cement + fly ash) than FAR fly ash mixtures. The utilization of high CaO fly ash in concrete allows for a reduction in the amount of cement used, leading to decreased carbon emissions compared to low CaO fly ash. In order to achieve a comparable strength after 56 days with a 50% fly ash replacement by weight of cement, concrete incorporating low CaO fly ash necessitates a lower water-to-binder (w/b) ratio compared to concrete incorporating high CaO fly ash.

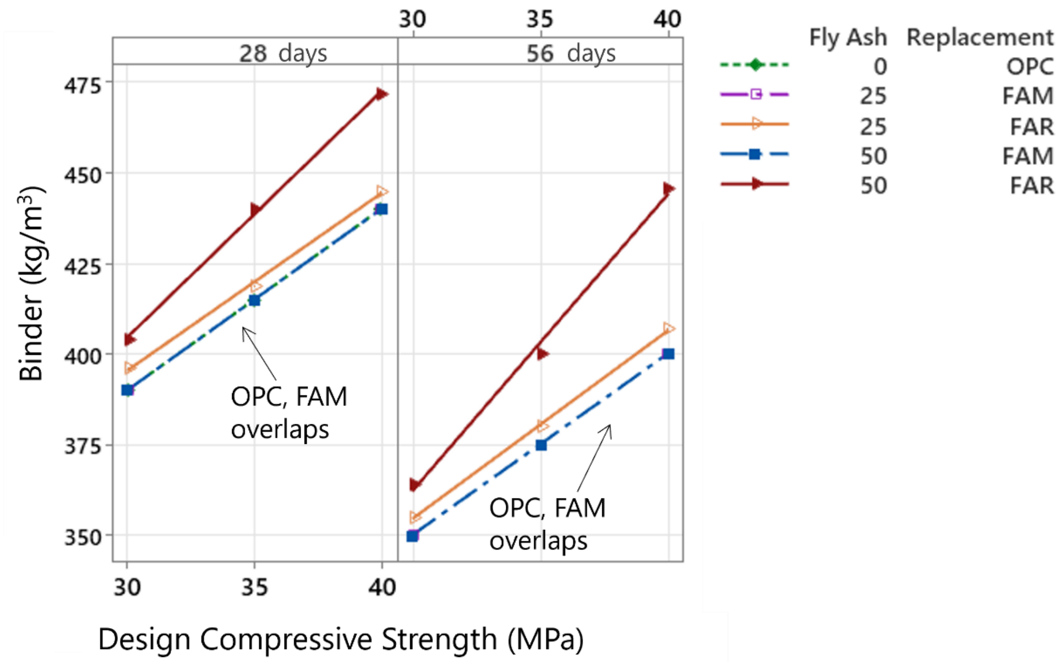

Figure 4.2. Binder content of various concrete mixtures in Thailand

The environmental impact of different fly ash types on various midpoint categories is presented in Figure 4.3. The results indicate that a higher level of fly ash replacement in concrete mixtures leads to a greater reduction in environmental burden for several impact categories. At a 25% replacement level (Figures 4.3a, 4.3b, 4.3c), the difference in impact between high CaO and low CaO fly ash is negligible but becomes more pronounced at a 50% replacement level (Figures 4.3d, 4.3e, 4.3f), especially for high-strength concrete mixtures. The reduction in environmental burden is most significant for the midpoint categories of MRS (10.19%), GWP (8.82%), and WC (8.22%) for high CaO fly ash compared to low CaO fly ash, as shown in Figure

4.3f. Impact categories such as HCT, TA, FPM, FRS, MEP, OZ, and OZT show a 6-7% difference, whereas IR and LU exhibit no difference between the two types of fly ash (nearly 0%).

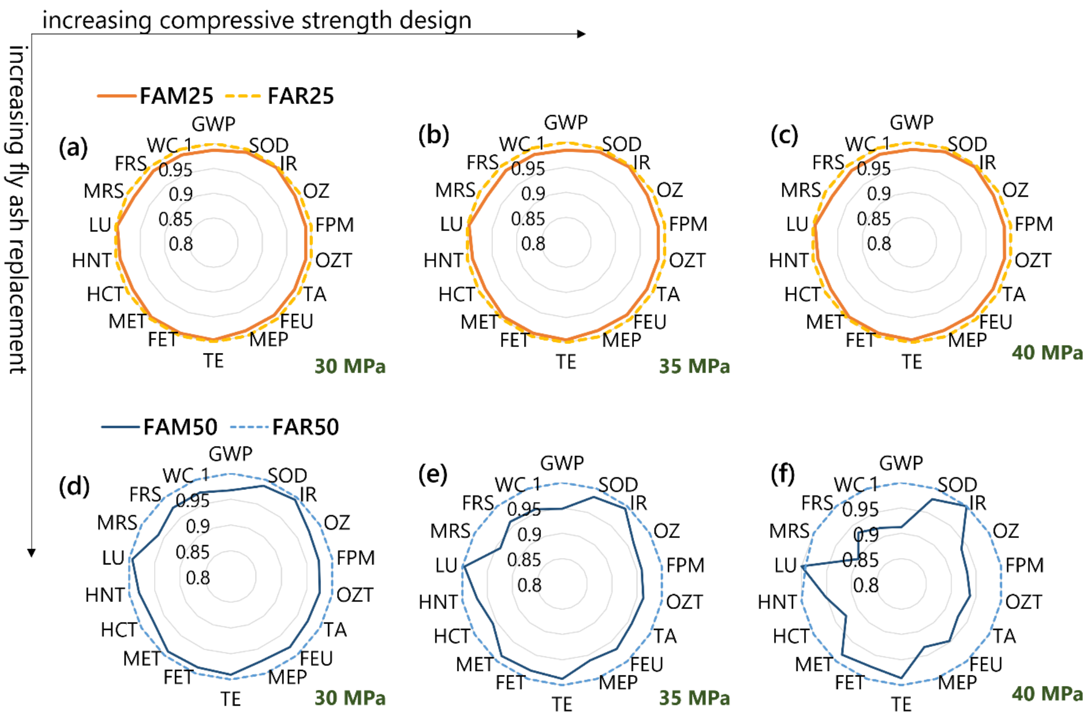

Figure 4.3. Comparison of midpoint impacts for 25% cement replacement using low CaO (FAR) and high CaO (FAM) fly ash in concrete mixtures of (a) 30 MPa, (b) 35 MPa, and (c) 40 MPa, as well as for 50% replacement in (d) 30 MPa, (e) 35 MPa, and (f) 40 MPa concrete mixtures, without fly ash transportation (Thailand)

4.2 Midpoint impact analysis considering fly ash transportation

The global warming potential of various concrete mix designs, including pure cement (OPC) and those with 25% and 50% fly ash replacements of different types (FAM and FAR), considering actual fly ash transportation distances, is shown in Figure 4.4. The results demonstrate that increased design strength is associated with a higher global warming potential, as higher cement content leads to greater strength and, thus, a more significant climate change impact. Cement's impact on the environment has been extensively discussed in the literature (Bumanis, Korjakins, & Bajare, 2022; Das, Cheela, Mistri, Chakraborty, Dubey, et al., 2022; De Brito, Hafez, Kurda, & Silvestre, 2022).

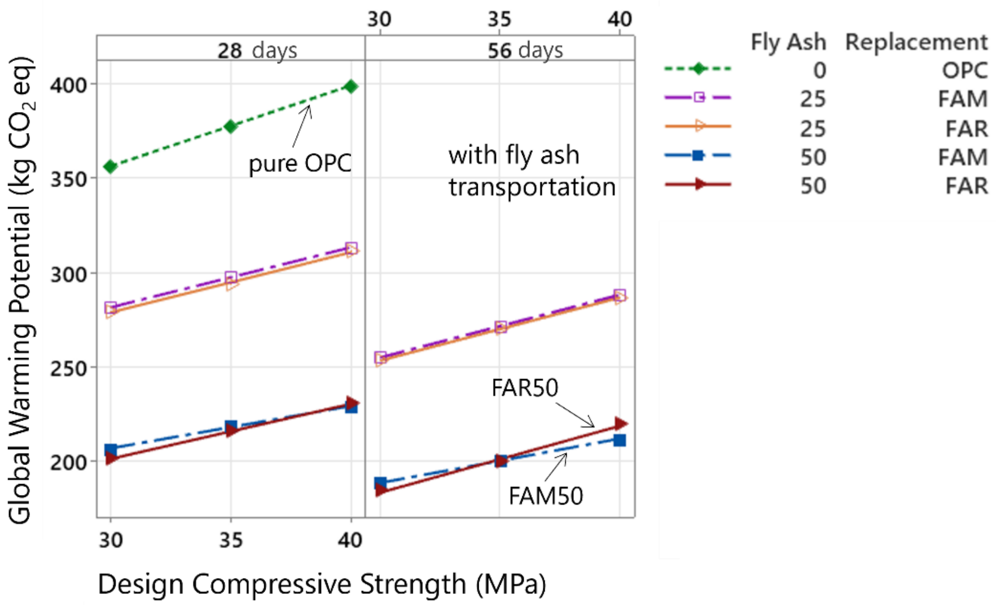

Figure 4.4 Comparison of global warming potential (GWP) for different Thai concrete mixtures with varying fly ash replacements, considering fly ash transport

The global warming potential of concrete is reduced by 22-30.6% and 44-51.4% when fly ash, regardless of the type and considering actual transportation, is used by 25% and 50% in comparison to pure cement concrete (Figure 4.4). Statistical analysis using paired *t*-test with a 95% confidence level showed that replacing cement with fly ash, whether FAM or FAR, significantly reduced GWP compared to pure cement concrete (p<0.05). This result is significantly higher than the 6% reduction for 25% fly ash replacement in pavement concrete reported by Habibi et al. (2022). This finding emphasizes the potential for concrete industry sustainability actions, particularly in countries with large-scale concrete production. Moreover, designing the concrete mixture to achieve the required strength at 56 days, as opposed to 28 days, can further contribute to reducing the global warming potential. For instance, in the case of 30 MPa concrete in Figure 4.4, the CO_2 reduction benefits exhibited a 5-7% improvement when considering a design age of 56 days instead of 28 days. This improvement can be attributed to the pozzolanic activity of fly ash, which leads to an increase in strength at later ages in fly ash concrete (Nassar & Room, 2023). Thus, incorporating a longer design age becomes crucial for maximizing sustainability in concrete production, particularly for mass concrete utilizing fly ash.

The environmental impact of concrete mixtures with 56-day design strengths of 30 MPa (Figure 4.5a), 35 MPa (Figure 4.5b), and 40 MPa (Figure 4.5c), incorporating different types of fly ash (FAM and FAR) and replacement percentages (0%, 25%, and 50%), is assessed and normalized against the environmental impact of the cement-only mixture (OPC concrete) across 18 midpoint categories.

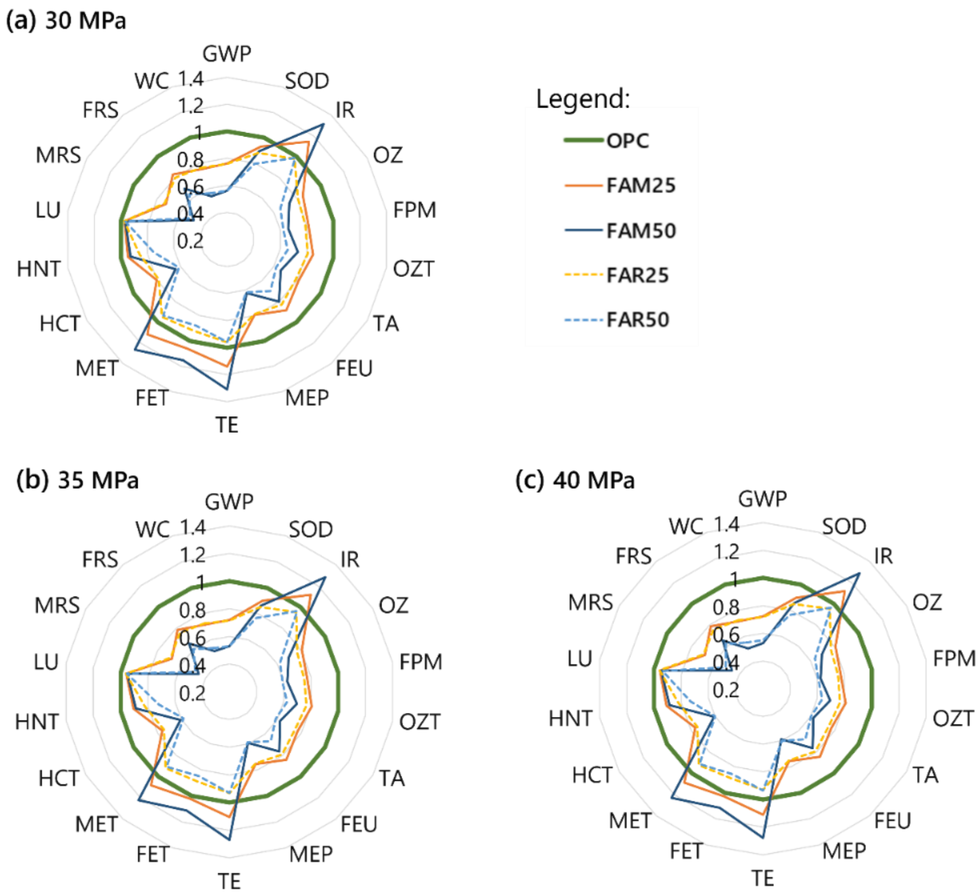

Figure 4.5 Midpoint impact characterization for 56-day design concrete with actual fly ash transportation in Thailand for (a) 30 MPa, (b) 35 MPa, and (c) 40 MPa concrete

All concrete mixtures have a positive environmental burden. Pure cement concrete has the highest environmental impact in 14 midpoint categories (GWP, SOD, OZ, FPM, OZT, TA, FEU, MEP, HCT, HNT, LU, MRS, FRS, WC). For BLCP fly ash (FAR, low CaO), an increase in the percentage of fly ash replacement (from 25% to 50%) led to a further reduction in the environmental burden of these impact categories.

This is due, in part, to a reduction in the amount of cement used. MRS, GWP, HCT, TA, and FPM show the greatest reduction. The normalization results in Figure 4.6 for 35 MPa concrete show that TE, GWP, and FRS are the three most significant indicators, followed by OZT, OZ, and HCT. Normalization reduces complex units to fractions of average citizen scores for each effect category.

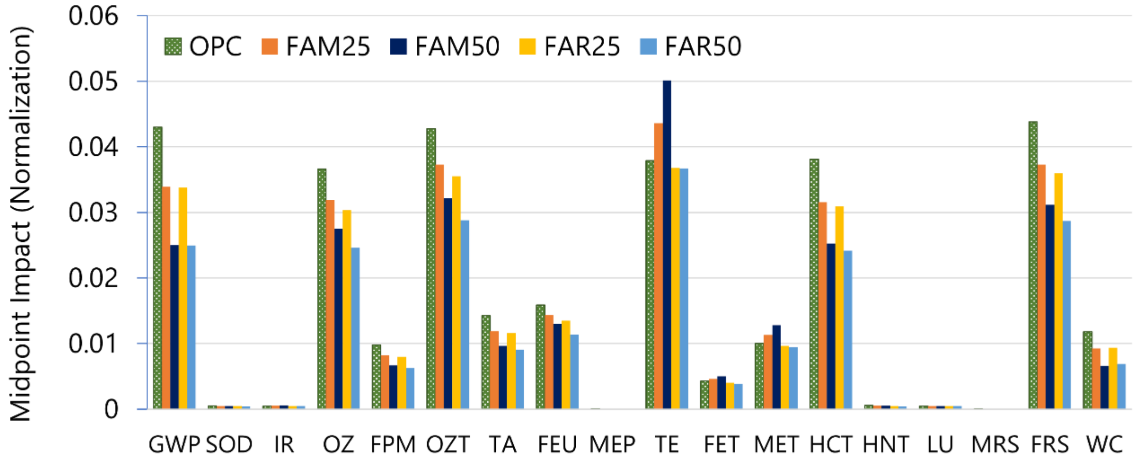

Figure 4.6 Midpoint impact normalization for 35 MPa Thailand mass concrete with varying fly ash as cement replacement

When examining the effects of fly ash type and replacement level, the patterns observed for global warming potential (Figure 4.4) do not hold true for terrestrial ecotoxicity and fossil resource scarcity (Figure 4.7). The results for other midpoint impacts are shown in Appendix A. Considering fly ash transport, concrete mixtures containing FAM fly ash exhibit greater terrestrial ecotoxicity than pure cement and FAR concrete mixtures. In terms of fossil resource scarcity (FRS), both FAM and FAR mixtures exhibit a lower impact than OPC mixtures. However, the difference between the impacts of FAR and FAM is more pronounced for fossil resource scarcity than for global warming potential. Specifically, FAM concrete shows a significantly higher ($p<0.05$) FRS impact than FAR concrete at 25% and 50% cement replacements for 30 MPa, 35 MPa, and 40 MPa concrete.

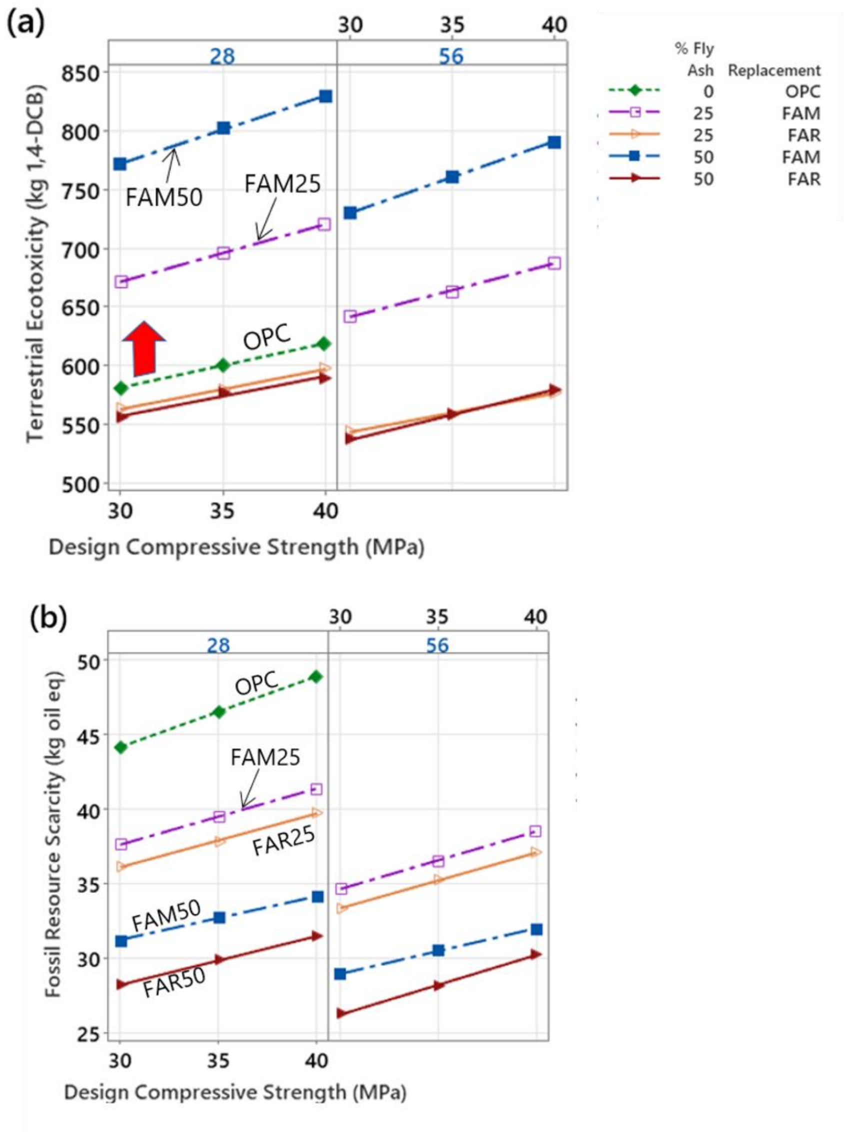

Figure 4.7 Significant impacts of concrete mixtures with different fly ash types and replacement in Thailand considering actual fly ash transportation: (a) terrestrial ecotoxicity and (b) fossil resource scarcity.

Interestingly, the environmental impact of the mass concrete mixture does not necessarily decrease with increasing percentages of fly ash as cement replacement when actual fly ash transport is considered. When 25% and 50% high CaO (FAM) fly ash was used in 30 MPa (Figure 4.5a), 35 MPa (Figure 4.5b), and 40 MPa (Figure 4.5c) concrete, the environmental load for TE, FET, MET, and IR was higher than in cement-only mixture. For instance, in 40 MPa concrete (Figure 4.5c), FAM25 showed 11.1%, 2.7%, 8.6%, and 12.1% higher impacts in TE, FET, MET, and IR, respectively, while FAM50 exhibited 27.8%, 11.5%, 22.9%, and 29.0%, higher impacts compared to cement-only concrete. This implies that a higher cement replacement level may not always result in a lower midpoint impact in a cradle-to-gate analysis, consistent with the findings of Panesar et al. (2019). Notably, FAM is sourced at a significantly greater distance than FAR (600 km vs. 190 km), emphasizing the importance of considering transportation impacts when assessing the environmental performance of fly ash and other supplementary cementitious materials (SCMs) in general.

Although using SCMs in concrete is prevalent, SCM supplies may be limited in some places (Shobeiri, Bennett, Xie, & Visintin, 2023). In addition, the phasing out of coal-fired units will reduce the supply of locally available fly ash. The cost and environmental impact of transporting fly ash may become significant if transported at a significant distance. In the Philippines, where coal-fired power plants remain a mainstream electricity supply, fly ash is located between 2 km and 1,200 km (Jamora, Gudia, Go, Giduquio, & Loretero, 2020), away from ready-mixed batching plants. Transportation's impact has been studied most in terms of GWP. However, GWP is not the only impact of transportation. Transportation processes can affect air quality and other environmental factors by releasing sulfur, nitrogen oxides, and other particulates. Still, these impacts have received little attention in the literature.

In terms of global warming potential, clinker production emerges as the most significant contributor, constituting approximately 74% of the total impact (Figure 4.8a), whereas fly ash transport accounts for 8%. Notably, other significant impacts predominantly associated with clinker production include ozone formation affecting human health (41%), formation of fine particulate matter (41%), ozone formation affecting terrestrial ecosystems (41%), terrestrial acidification (44%), and human carcinogenic toxicity (43%). A detailed substance and process analysis of all midpoint impact categories is summarized in Appendix B, considering a 40MPa FAM50 concrete with a specified age of 56 days.

Contribution analysis considering 40MPa FAM50 (56 days concrete) shows that truck transportation of fly ash has a higher impact contribution than cement for TE, FET, MET, and IR at 50% fly ash replacement (Figure 4.8). Transportation accounts for approximately 43% (TE), 39% (FET), 42% (MET), and 39% (IR) of the environmental impacts for FAM50, and 21% (TE), 18% (FET), 20% (MET), and 19%

(IR) for FAR50. TE, FET, MET, and IR are less frequently discussed in concrete literature than CO_2 emissions (Feng et al., 2023).

Ecotoxicity occurs when organic substances and chemicals are released into the air, water, and land (Thushari & Babel, 2022). Process contribution analysis shows that terrestrial ecotoxicity is predominantly caused by brake wear emissions, constituting around 84%, with a minor contribution from clinker production (9%) (Figure 4.8b). Brake wear particulate matter is a significant contributor to non-exhaust particle emissions, accounting for 21% of the total traffic-related PM_{10} emissions. A fraction of about 35–55% of brake wear becomes airborne, while the remaining fraction deposits either on the vehicle or at road sites (Zum Hagen, Mathissen, Grabiec, Hennicke, Rettig, et al., 2019). Furthermore, the type of fuel utilized in vehicles impacts the extent of air pollution (Delnavaz, Sahraei, Delnavaz, Farokhzad, Amiri, et al., 2022).

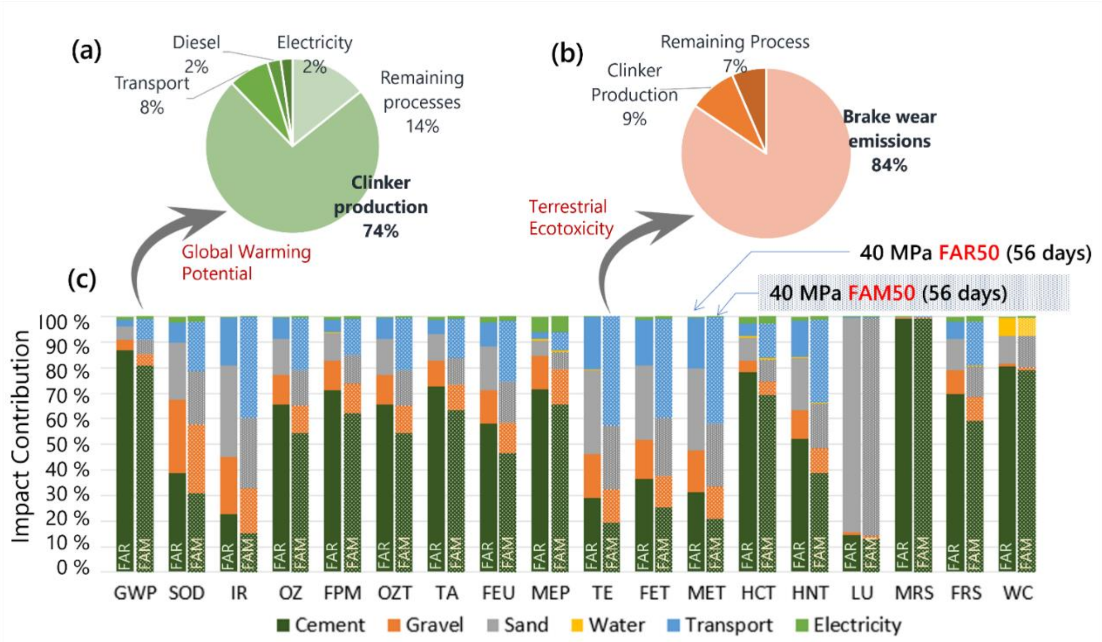

Figure 4.8 Contribution analysis for significant impacts considering actual fly ash transportation: (a) global warming potential and (b) terrestrial ecotoxicity; (c) contribution of various concrete components to midpoint impact categories for low CaO (FAR) and high CaO (FAM) fly ash (Thailand)

A substance contribution analysis (40 MPa 50FAM 56 days concrete, Appendix B) indicates that terrestrial ecotoxicity predominantly stems from upstream emissions of copper (64%), antimony (24%), and zinc (5%), with air emissions of copper and antimony primarily linked to fly ash transportation (44-46%). Antimony, found in brake pads as Sb_2S_3, undergoes oxidation to Sb_2O_3 during braking, a compound categorized as potentially carcinogenic (Bukowiecki, Lienemann, Hill, Figi, Richard, et al., 2009). Recent observations of antimony enrichment in airborne particles in various countries highlight its harmful effects (Iijima, Sato, Yano, Kato, Kozawa, et al., 2008). Copper, widely used in brake pads alongside brass, Cu-oxides, and Cu-sulfides, is a significant source of copper pollution in urban areas (Straffelini, Ciudin, Ciotti, & Gialanella, 2015). Novel copper-free brake pad formulations are thus being introduced to address these issues.

Other toxicity indicators greatly affected by fly ash transportation, such as marine ecotoxicity and freshwater ecotoxicity, are primarily driven by brake wear and tyre emissions. Freshwater ecotoxicity is predominantly attributed to the release of zinc into aquatic environments, comprising approximately 64% of the overall impact. This discharge is principally linked to land transportation of fly ash, constituting 44% of the total zinc emissions. Specifically, in the case of a 40MPA 50FAM concrete mixture at the age of 56 days, tire wear emissions contribute significantly, accounting for approximately 56% of the overall environmental burden. Notably, zinc finds utility in vehicle tire manufacturing as zinc oxide (ZnO), serving as an activator in the rubber vulcanization process (Degaffe & Turner, 2011). Conversely, marine ecotoxicity exhibits a similar trend, primarily attributed to brake wear emissions, which constitute approximately 62% of the total impact, mirroring patterns observed in terrestrial ecotoxicity as previously discussed. Ionizing radiation is an indicator that ultimately impacts human health, typically related to an increase in cancer and hereditary diseases due to radiation exposure (Frischknecht, Braunschweig, Hofstetter, & Suter, 2000; Huijbregts, Steinmann, Elshout, Stam, Verones, et al., 2017).

Another pertinent aspect, particularly within the current context of Thailand and concrete production, is the issue of fine particulate matter (FPM). This study highlights FPM as a significant environmental concern, as evidenced by normalization analysis (Figure 4.6). The formation of fine particulate matter is primarily associated with clinker production, accounting for 41% of the total impact, followed by material transportation (9%) and diesel consumption in cement and aggregate factories (9%). An upstream substance analysis reveals that emissions of nitrogen oxides, particulates

(<2.5um), and sulfur oxides are the primary contributors to FPM, representing 36%, 34%, and 28% of the total impact, respectively, in the production of 40MPA 50FAM concrete at 56 days.

Process contribution analysis further reveals that the utilization of diesel in the production of gravel and sand markedly influences significant impacts, notably contributing to phenomena such as ozone formation and freshwater eutrophication.

4.3 Endpoint impact analysis

In terms of endpoint indicators, the use of fly ash has been found to significantly reduce damage to human health (Figure 4.9a), ecosystems (Figure 4.9b), and resources (Figure 4.9c) when compared to concrete that utilizes pure cement. The reduction is more significant when the replacement of cement with fly ash is higher, such as at 50% fly ash replacement. When 25% fly ash is used as cement replacement, the damage to human health, ecosystem, and resources is reduced by 22-29.4%, 21-29.2%, and 17-23.8%, respectively, compared to the cement-only mixture.

In comparison to OPC concrete, the beneficial impact of fly ash is more substantial at 50% cement replacement, with reductions in endpoint impacts of 42-49.5% for human health, 42-49.2% for the ecosystem, and 35-40.5% for resources. The type of fly ash used significantly impacts the reduction of endpoint indicators. Compared to FAR50 fly ash, FAM50 fly ash reduces damage to human health, ecosystems, and resources by 8.7%, 8.8%, and 5.1%, respectively, in a 40 MPa concrete mixture at 56 days design age.

When considering the actual transportation of fly ash, the endpoint indicators for FAM concrete show slightly higher values than FAR concrete at both 25% and 50% replacement levels for human health (Figure 4.9d) and the ecosystem (Figure 4.9e). However, this difference lacks statistical significance at a 95% confidence level. The observed impact on human health can be attributed to two damage pathways: increased disease incidence and various types of cancer resulting from ionizing radiation exposure (Huijbregts, Steinmann, Elshout, Stam, Verones, et al., 2017). Additionally, transportation-related ecotoxicity indicators contribute to damage to freshwater species (FET), damage to marine species (MET), and damage to terrestrial species (TE), collectively impacting the ecosystem. Furthermore, MRS and FRS contribute to increased extraction costs and consequent resource damage (Figure 4.9f).

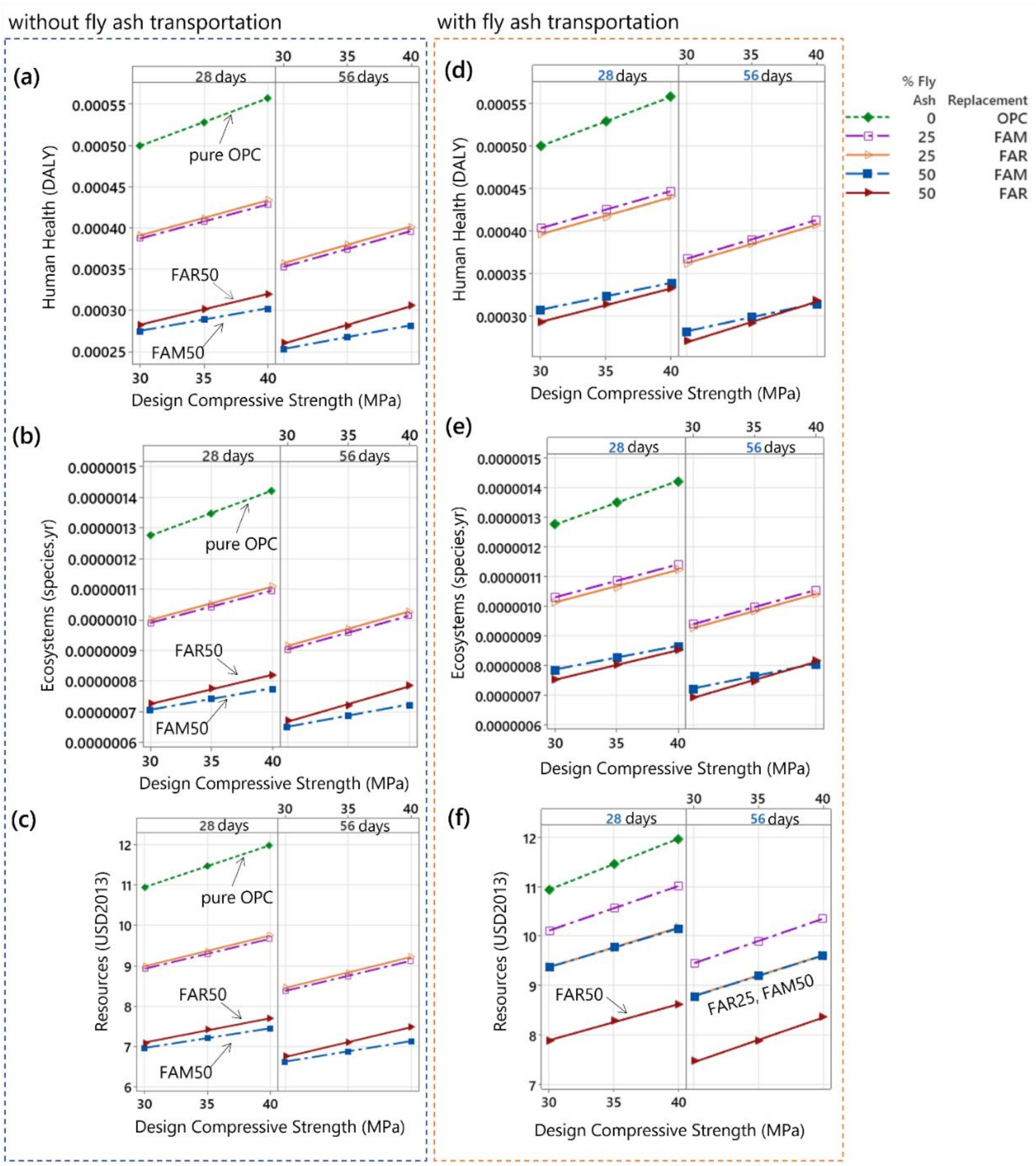

Figure 4.9 Comparison of endpoint impact damages of Thailand mass concrete for (a) human health, (b) ecosystems, and (c) resources when fly ash transport is not considered, and (d) human health, (e) ecosystems, and (f) resources when actual fly ash transport is considered.

Fossil resource scarcity primarily stems from operations in hard coal mining and preparation (23%) utilized in cement production, followed by onshore petroleum and gas production (23%). Thailand's conventional electricity generation continues to rely heavily on natural gas and coal (Tanthanawiwat, Gheewala, Nilsalab, Schoch, & Silalertruksa, 2024), thus significantly exacerbating this impact. Substance analysis of upstream processes in ecoinvent identifies crude oil, hard coal, and natural gas, contributing 40%, 35%, and 23%, respectively, to this impact. Through process analysis, it is discerned that mineral resource scarcity is primarily exacerbated by clay pit operations, contributing approximately 72% of the impact within the context of cement production. Using fly ash in concrete mixtures can significantly reduce the environmental damage associated with human health, ecosystems, and resources compared to pure cement concrete. However, to fully assess the environmental impacts of fly ash-containing concrete, the transportation of fly ash must also be considered. Furthermore, selecting fly ash type plays a crucial role in reducing environmental damage.

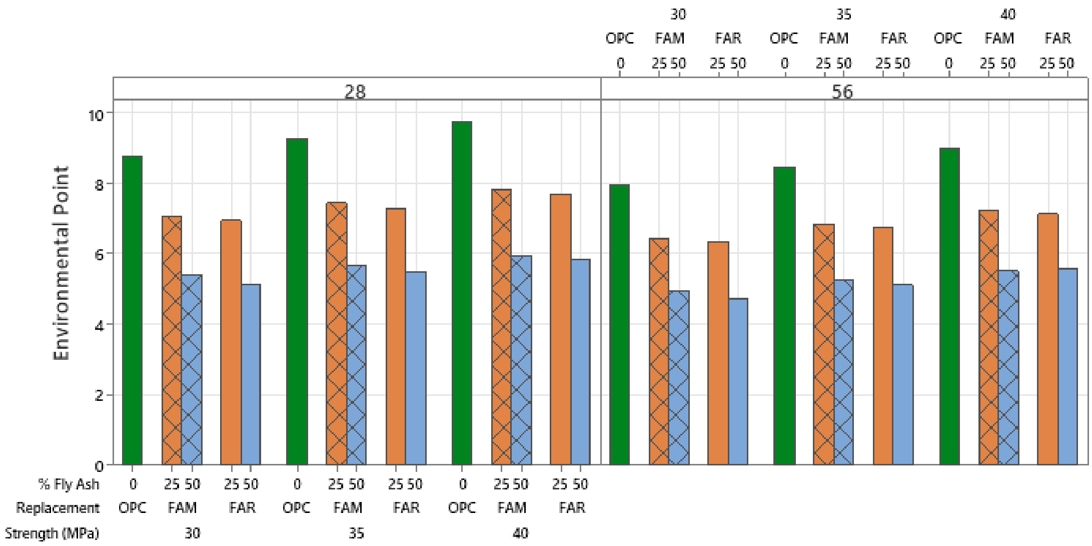

Figure 4.10 Single score environmental point of various Thailand concrete mixtures with different types of fly ash

The single score environmental point, which incorporates all the impacts of different mass concrete mixtures, is illustrated in Figure 4.10. Empirical evidence demonstrates that, for any given design strength, the environmental impact of pure-cement concrete is significantly greater than that of mixtures using 25% and 50% fly ash as substitutes for cement.

4.4 Impact of fly ash type on critical transportation distance

The results of our critical distance analysis considering fly ash type (low CaO and high CaO), replacement percentage (25% and 50%), and fly ash transportation distance are shown in Figures 4.11 and 4.12.

As previously discussed, the transportation of fly ash impacts ionizing radiation and ecotoxicity indicators (TE, MET, and FET). Based on normalization (Figure 4.6), TE is the most significant of these indicators. Therefore, in conjunction with GWP, we employed TE to identify the critical transportation distance for fly ash. The critical distance represents the maximum distance at which fly ash can be transported from its source to the batching plant without causing a higher environmental impact than concrete made with pure cement. This critical distance is determined by the point of intersection between the environmental impacts (GWP or TE) of ordinary Portland cement (OPC) concrete and fly ash concrete in Figure 4.11 and Figure 4.12. Our findings indicate a linear increase in GWP and TE as the fly ash transportation distance increases. This trend is consistent with the findings of previous studies (Das, Cheela, Mistri, Chakraborty, Dubey, et al., 2022; Panesar, Kanraj, & Abualrous, 2019). Since ground transportation is predominantly utilized in Thailand, our discussion focuses on this mode of transport. The transportation distances for other concrete constituents, such as cement, gravel, and sand, were kept constant using the data provided in Table 2. Given the substantial impact of fly ash type on 40 MPa concrete, this specific strength level was selected for comparative calculations of the critical transportation distance.

When considering GWP, FAM50 exhibits the lowest impact at a transit distance of 0 km, followed by FAR50 (Figure 4.11). Concrete mix with FAR50 starts to have a greater GWP impact than FAM25 and FAR25 at 3,700 km and 4,000 km, respectively. FAR50 has the shortest critical distance of around 5,910 km (5,903 km in Figure 4.11) when compared to FAM25 (8,475 km), FAR25 (8,011 km), and FAM50 (7,252 km). This indicates that high CaO fly ash (FAM) can be sourced from a greater distance while maintaining lower CO_2 emissions compared to low CaO fly ash (FAR) at a similar percentage of cement replacement. The critical distances from this study fall close to or within the range reported from previous studies considering one-way fly ash transport: 6,486 km (Jamora, Gudia, Go, Giduquio, & Loretero, 2020) and 11,000 (O'Brien, Ménaché, & O'Moore, 2009) using an articulated truck. However, it should be noted that the type of fly ash and different replacement percentages were not taken into account in either research.

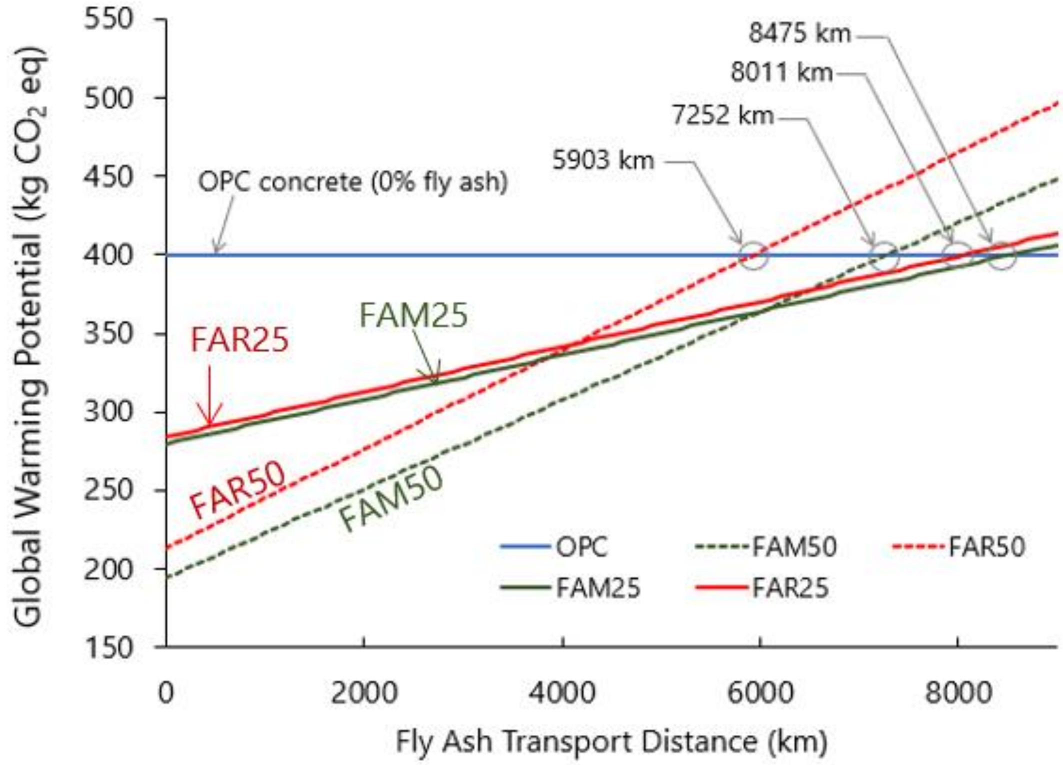

Figure 4.11 Impact of fly ash transport on global warming potential, along with the critical distance identified for 40 MPa Thailand concrete containing high CaO fly ash (FAM) and low CaO fly ash (FAR) at different percentages of cement replacement.

All the critical distances determined by this study based on GWP are much greater than Thailand's longest distances, which are approximately 1,650 km north to south and 800 km east to west. For comparison, Thailand's land border is only 4,863 km long. This implies that the GWP of concrete containing at least 25% fly ash (either low CaO or high CaO) as cement replacement will always be lower than that of cement-only concrete mixture, regardless of the source in Thailand. This finding is consistent with the study by Komkova and Habert (2023), where it was highlighted that concrete materials can be transported over long distances without significantly compromising total CO_2 emissions. However, this may also imply that when different sources are considered, GWP may not provide the sole critical decision-making input for environmental sustainability consideration.

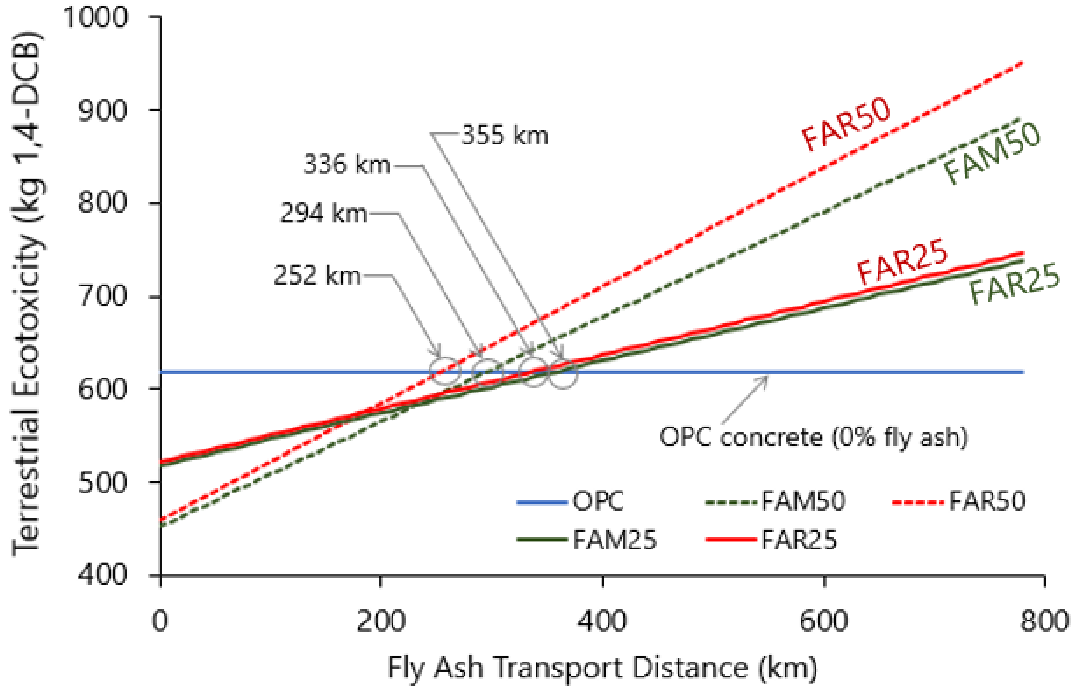

Figure 4.12 Impact of fly ash transport on terrestrial ecotoxicity, along with the critical distance identified for 40 MPa Thailand concrete containing high CaO fly ash (FAM) and low CaO fly ash (FAR) at different percentages of cement replacement.

In terms of terrestrial ecotoxicity, FAR50 demonstrates a higher impact compared to FAM25 and FAR25 at fly ash transport distances of 160 km and 180 km, respectively (Figure 4.12). FAM25 has the longest critical distance of about 360 km (355 km in Figure 4.12), followed by FAR25 (336 km) and FAM50 (294 km), while FAR50 has the shortest critical distance of around 260 km (252 km in Figure 4.12). Concrete with high CaO fly ash (FAM) has a longer critical distance than concrete with low CaO fly ash (FAR). Notably, the longest critical distance estimated using terrestrial ecotoxicity (355 km for FAM25) is 8,120 km shorter than the critical distance determined based on global warming potential (8,475 km), indicating the potential significance of terrestrial ecotoxicity as a limiting factor (impact). All critical distances based on terrestrial ecotoxicity exceed the current source distance of FAR fly ash (190 km), explaining why terrestrial ecotoxicity and other related impacts (e.g., freshwater ecotoxicity and marine ecotoxicity) are lower for concrete mixtures incorporating FAR fly ash compared to ordinary Portland cement (OPC) concrete.

The relatively low critical distance values obtained when TE is employed as an indicator elucidate the negative benefit of fly ash from Mae Moh (600 km) compared to FAR fly ash from the BLCP power plant in terms of ecotoxicity indicators. A survey of 8 studies from different countries conducted by Hafez et al. (2019) revealed a range of fly ash sources spanning from 10 km to 945 km from concrete batching plants, indicating the diversity of potential fly ash sources. The upper bound of this study significantly exceeds the critical distance calculated using terrestrial ecotoxicity. The determination of critical distance is of practical importance, particularly when considering the most suitable fly ash source for sustainability. It should be noted that although the calculated critical distances in this study are based on the utilization of fly ash from Mae Moh and BLCP, we anticipate that the trend for other countries will be similar when comparing low and high CaO fly ash. It's important to emphasize that this critical distance analysis does not incorporate uncertainty analysis. However, it is anticipated that the observed trend will remain consistent. Furthermore, transportation significantly affects cost. For example, the cost of FAM fly ash is 2.5 times higher in cost than FAR (Wanna, Saengsoy, Toochinda, & Tangtermsirikul, 2020) owing to long-distance transportation.

4.5 Economic analysis

Figure 4.13 illustrates the cost of concrete mixtures per cubic meter, which is computed by multiplying the material amount (kg/m^3) by the unit cost (USD/kg). The cost of concrete mixtures varies from 37.33 USD to 60.28 USD, and it increases proportionally with the strength due to the high cement content, which accounts for over half of the overall cost in most cases. Cement contributes to 72-77% of total expenses in pure OPC concrete, 44-57% in concrete with 50% fly ash replacement, and 60-69% in concrete with 25% fly ash replacement.

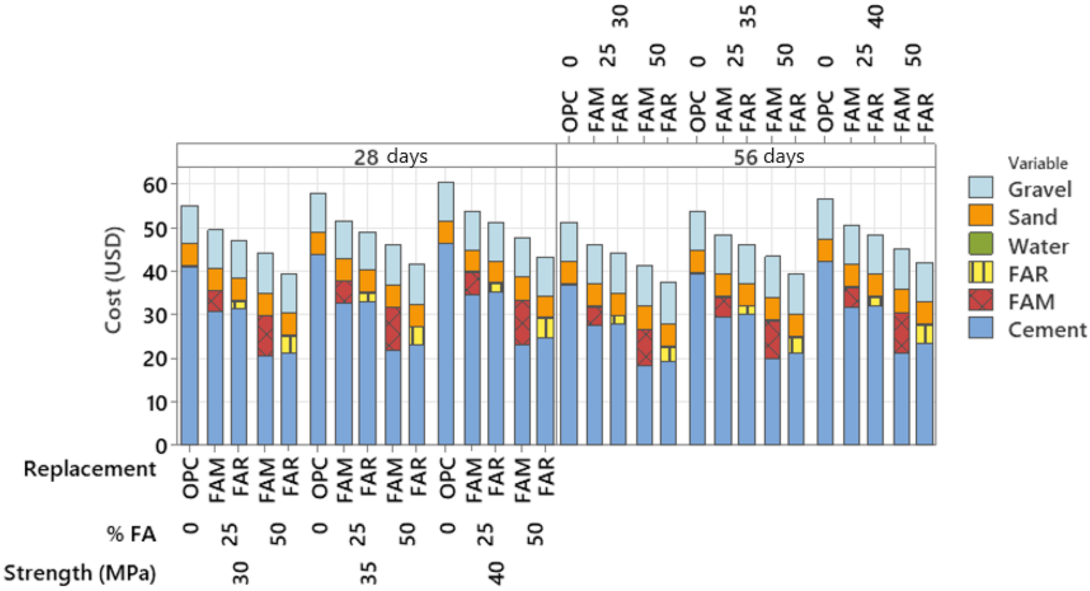

Figure 4.13 Total material cost in USD of various concrete mixtures from Thailand with different fly ash replacements.

The use of fly ash significantly reduces the total cost of the concrete mixture, emphasizing its economic value. The FAR fly ash provides greater economic benefits, resulting in 14-15% cost savings for 25% replacement and 27-28% for 50% replacement. In comparison, the high CaO fly ash from the Mae Moh coal-fired power plant saves 10-11% (FAM25) and 19-21% (FAM50). The primary driver of the cost savings is the relatively low cost per kilogram of fly ash. However, the cost of fly ash is influenced by factors such as drying, silo transfer, storage, and transportation. Furthermore, the high demand for fly ash in Thailand raises its cost compared to other countries in Southeast Asia. FAM fly ash is more expensive than FAR fly ash because it is sourced from a greater distance (410 km). As shown in the figure, when high CaO fly ash is used, the absolute cost required for cement is less than FAR. However, the total cost of the concrete mixture is still higher when FAM is used due to the higher unit cost of FAM fly ash relative to FAR. FAM contributes 9-10% of the overall cost for a 25% replacement, while FAR contributes only 4%. For a 50% replacement, FAM contributes 20-21%, and FAR contributes 9-10%.

Furthermore, a higher percentage of fly ash replacement results in a higher aggregate cost contribution. Sand contributes 9-14%, while gravel accounts for 15-25%

of the entire cost. Generally, aggregates contribute 26-39% of the total cost when fly ash is used, compared to 23-28% when pure cement is used in concrete mixtures. This highlights the significance of aggregates in lowering the cost of concrete mixtures when a high FA alternative for cement is used. Additionally, sustainable aggregate techniques should be explored and investigated.

Water has the smallest cost contribution, at 0.3-0.4%. Nevertheless, it should be noted that this water expense is solely attributable to the consumption of the mixture. Water can also be utilized for cleaning, washing, dust control, and other purposes in a batching plant. The use of recycled water can save costs and reduce overall water consumption in the concrete industry.

4.6 Implications for enhancing concrete environmental sustainability

This study has demonstrated the environmental advantages of high CaO fly ash, sourced from the Mae Moh power plant, over low CaO fly ash, sourced from the BLCP power plant, when utilized as a cement replacement for mass concrete applications. Table 3 presents a comparative summary of the environmental impact associated with the use of low and high CaO fly ash. This information can be beneficial to stakeholders such as policymakers, engineers, and researchers aiming to improve the sustainability of mass concrete production. However, it is imperative to note that sustainability should not be evaluated solely based on global warming potential or CO_2 reduction.

Utilizing low or high CaO fly ash in concrete production has its advantages and disadvantages (Table 2.6), which ought to be evaluated based on factors such as the intended purpose, environmental considerations, and engineering constraints. For instance, in situations where early compressive strength is a priority, high CaO fly ash may represent a more suitable alternative, whereas low CaO fly ash could prove advantageous in environments characterized by aggressive conditions. To further enhance both sustainability and performance, certain limitations associated with the use of fly ash can be addressed through the incorporation of ultrafine materials as binders, such as ultrafine (Agrawal & Savoikar, 2022) or nano fly ash (Mohana & Leela Bharathi, 2022). The utilization of ultrafine fly ash has been found to prevent the reaction of harmful ions in concrete (Jones, McCarthy, & Booth, 2006) while concurrently enhancing mechanical properties and durability (J. Wang & Dong, 2023).

Table 4.1 Comparative summary of environmental impacts of high CaO (FAM50) and low CaO (FAR50) without and with fly ash transportation for 40 MPa Thailand mass concrete mixture.

Indicator	**Without fly transport** (effect of fly ash type)		**With actual fly ash transport**	
	FAR	**FAM**	**FAR** (190 km)	**FAM** (600 km)
Midpoint Impacts				
Global warming potential*	△	▼	△	▼
Stratospheric ozone depletion	△	▼	▼	△
Ionizing radiation	■	■	▼	△+
Ozone formation (human health)*	△	▼	▼	△
Fine particulate matter formation	△	▼	▼	△
Ozone formation (terrestrial ecosystems)*	△	▼	▼	△
Terrestrial acidification	△	▼	▼	△
Freshwater eutrophication	△	▼	▼	△
Marine eutrophication	△	▼	△	▼
Terrestrial ecotoxicity*	△	▼	▼	△+
Freshwater ecotoxicity	△	▼	▼	△+
Marine ecotoxicity	△	▼	▼	△+
Human carcinogenic toxicity*	△	▼	■	■
Human non-carcinogenic toxicity	△	▼	▼	△
Land use	■	■	■	■
Mineral resource scarcity	△	▼	△	▼
Fossil resource scarcity*	△	▼	▼	△
Water consumption	△	▼	△	▼
Endpoint Impacts				
Human Health	△	▼	■	■
Ecosystem	△	▼	■	■
Resources	△	▼	▼	△

*significant impact based on normalization
▼ = lower impact; △ = higher impact; ■ = similar or comparable (less than 1% difference)
+ = higher impact than pure cement concrete

This study will enhance sustainable concrete production by providing valuable insights into the use of different types of fly ash as a cement replacement material for mass concrete applications. Study results will assist in the reduction of impacts associated with concrete by utilizing fly ash, which would otherwise be disposed of in landfills. The determination of critical distance may assist the construction industry in considering the most suitable source of fly ash for cement replacement. The findings will aid in formulating policies that support sustainable development in the mass concrete industry. In the future, a comprehensive cradle-to-grave LCA coupled with durability modeling will provide more insight into the environmental performance of mass concrete with different types of fly ash. Investigating alternative transportation modes for various cement-replacing waste materials, such as rail or water transport, could also help identify ways to reduce these impacts. Future studies may also investigate the environmental performance of fly ash from diverse sources, such as municipal waste incineration. Finally, investigating the impact of incorporating other waste, such as recycled aggregates, in conjunction with different types of fly ash in mass concrete could yield valuable insights for enhanced sustainability.

4.7 Summary

Fly ash type and transportation distance affect the environmental performance of mass concrete mixtures. Independent of fly ash transportation, high CaO fly ash concrete exhibits better environmental benefits compared to low CaO fly ash concrete. Using high CaO fly ash, the reduction in environmental load is greatest for mineral resource scarcity (10.19%), global warming potential (8.82%), and water consumption (8.22%) compared to low CaO fly ash for high strength and high fly ash replacement without fly ash transport. Increasing the design age from 28 to 56 days enhances the environmental benefits of fly ash concrete. Long-distance transportation of fly ash negatively impacts ionizing radiation and ecotoxicity indicators. However, 50% fly ash replacement with transportation reduces global warming potential by 44-51.4%, compared to pure cement concrete. When considering significant fly ash transportation distances, a higher percentage of cement replacement does not always result in reduced environmental impacts.

CHAPTER 5
IMPACT ASSESSMENT OF SLAG AND COMPARISON WITH FLY ASH AS CEMENT REPLACEMENT FOR MASS CONCRETE IN THAILAND: IMPACTS OF MARITIME IMPORT

This Chapter compares the environmental performance of utilizing fly ash with another type of cement replacement material, ground granulated blast furnace slag (GGBS), for mass concrete applications in Thailand. A comprehensive comparison of the environmental performance (midpoint and endpoint impacts) of using different types of supplementary cementitious material (SCM), such as fly ash and slag, as partial cement replacement for mass concrete applications using life cycle assessment, considering SCM preparation and transport, quantification of the environmental impacts of importing slag by maritime shipping, and comparison of the impacts of land and sea transport for obtaining slag. These multifaceted investigations collectively contribute to a deeper understanding of the environmental aspects of SCM utilization in concrete production, aiding in informed decision-making processes and pursuing more sustainable construction practices.

5.1 Comparative environmental impacts of fly ash and GGBS in mass concrete mixtures without SCM transportation

To comprehensively assess the environmental performance of concrete incorporating SCMs, we first conducted an analysis that effectively eliminates the influence of SCM transportation. This analysis focused on comparing the environmental impact of a 30 MPa concrete mix utilizing 50% fly ash (50FA) and 65% ground granulated blast furnace slag (65GGBS) as partial cement replacements against a reference mixture comprised solely of Ordinary Portland Cement (OPC). The results (Figure 5.1) indicate a substantial reduction in the associated global warming potential (GWP) per cubic meter of concrete when either fly ash (164 kg CO_2 eq, 54% reduction) or GGBS (141 kg CO_2 eq, 61% reduction) were employed as partial cement replacements in concrete mixtures compared to OPC mixture (357 kg CO_2 eq). The substantial reduction is primarily attributed to the decrease in cement usage when utilizing fly ash and GGBS as cement replacements. This corroborates the findings from several prior research studies that emphasize the contribution of cement to the overall greenhouse gas emissions of concrete mixtures (Hossein, AzariJafari, & Khoshnazar, 2022; Nakic, 2018; Tinoco, de Mendonça, Fernandez, Caldas, Reales, et al., 2022).

The utilization of fly ash leads to reductions in all 18 midpoint impact categories when compared to the cement-only mixture (Figure 5.1, Appendix C). Notably, substantial reductions exceeding 50% were observed in the impact categories of mineral resource scarcity (58.1%), water consumption (51.1%), and global warming potential (54.2%). Huang et al. (2018) noted that building materials greatly contribute to MRS and GWP impacts, categories where fly ash is most beneficial based on the findings of this study. The land use impact has exhibited the least improvement, with a mere 4% reduction observed. Prior chapter discussion has observed that the primary factor influencing land use is aggregates rather than cement. In this investigation, the aggregate content of 50FA and 65GGBS concrete is marginally greater than that of cement-only concrete.

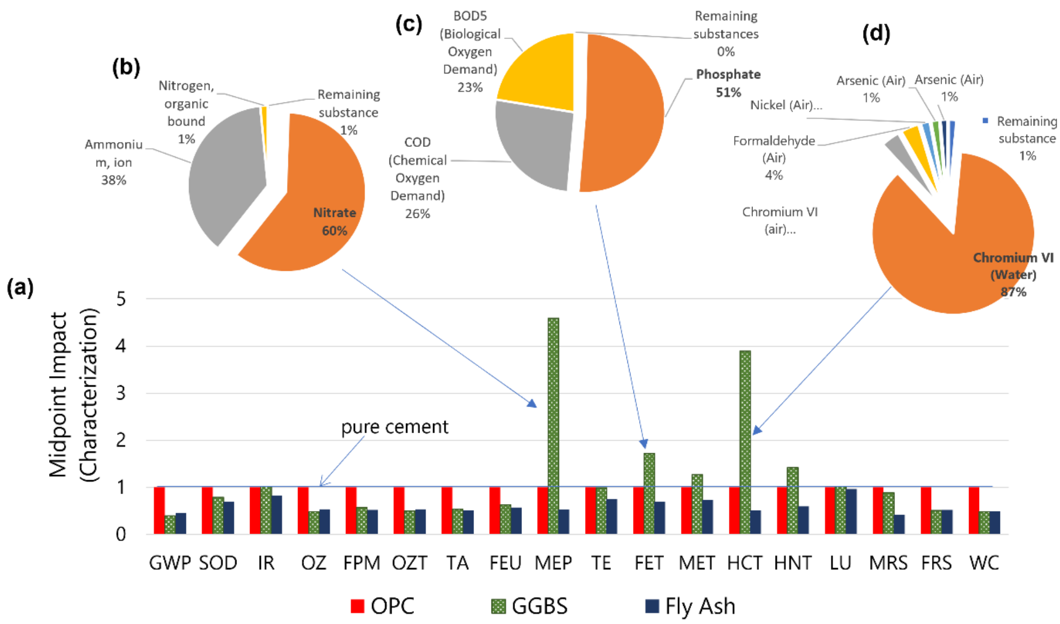

Figure 5.1 (a) Comparative midpoint impacts of Thailand concrete mixture with 65% GGBS and 50% fly ash as cement replacement normalized with respect to pure-cement (OPC) concrete mixture. Substance contribution analysis for (b) marine eutrophication, (c) freshwater ecotoxicity, and (d) human carcinogenic toxicity for 65GGBS concrete.

When compared with pure-cement concrete (Figure 5.1a), the use of 65GGBS showcased its greatest benefits (reduction) in impact categories associated with global warming potential (60.5%), ozone formation (51.1%), and fossil resource scarcity (49.4%). The high degree of cement replacement achievable with GGBS makes it a preferred choice where CO_2 reduction is of paramount importance in environmental assessments. The lower GWP of GGBS causes this reduction compared to that of OPC. Processing of GGBS from solid steel slag consumes about six times less energy than cement production, according to previous findings (Ali, Ouni, & Kurda, 2022). In a comparative analysis with other SCM, 65GGBS outperformed 50FA concrete in five impact categories, including GWP, OZ, OZT, FRS, and WC. However, it is noteworthy that 65GGBS concrete exhibited worse environmental performance compared to the cement-only mix in seven midpoint categories (IR, MEP, FET, MET, HCT, HNT, LU). These findings demonstrate that high cement replacement does not always imply improved environmental performance. Therefore, it is critical to assess the type of SCM used to replace concrete cement. In the Canadian context (25 MPa, 50GGBS), Aslani et al. (2023) also found that GGBS concrete has higher impacts in some midpoint categories (TE, FET, MET, HCT, HNT, MRS) despite having a significant reduction in GWP (41.10%). This underscores the multifaceted nature of SCM-based concrete mixtures. While they exhibit substantial reductions in global warming potential and other impactful categories, specific environmental burdens such as marine eutrophication and human carcinogenic toxicity warrant careful consideration, especially regarding the choice of SCM and its production processes.

For 65GGBS concrete, the most pronounced environmental burdens observed in this study were associated with marine eutrophication and human carcinogenic toxicity, registering at 0.00095 kg N eq and 1.57 kg 1,4-dichlorobenzene (1,4-DCB) per m^3 concrete, respectively. These values represent approximately 4.59 and 3.89 times higher impacts compared to the cement-only mixture. Ecotoxicity arises as a consequence of the introduction of organic and chemicals into the atmosphere, hydrosphere, and lithosphere (Thushari & Babel, 2022). The elevated burden of marine eutrophication in GGBS concrete mixtures can primarily be attributed to GGBS processing, which contributes to more than 90% of the impact (Figure 5.2). This impact category is primarily influenced by emissions affecting water environments, such as nitrate and phosphate discharge, which causes eutrophication. A substance contribution analysis further elucidated that these impacts are primarily driven by emissions affecting water quality, notably nitrate (Figure 5.1b), phosphate (Figure 5.1c), and chromium VI (Figure 5.1d). Slag contains Cr in various concentrations (Piatak, Parsons, & Seal, 2015). However, Maghool et al. (2017) noted that the concentrations of Cr in slag after processing may already be classified as non-hazardous or non-dangerous.

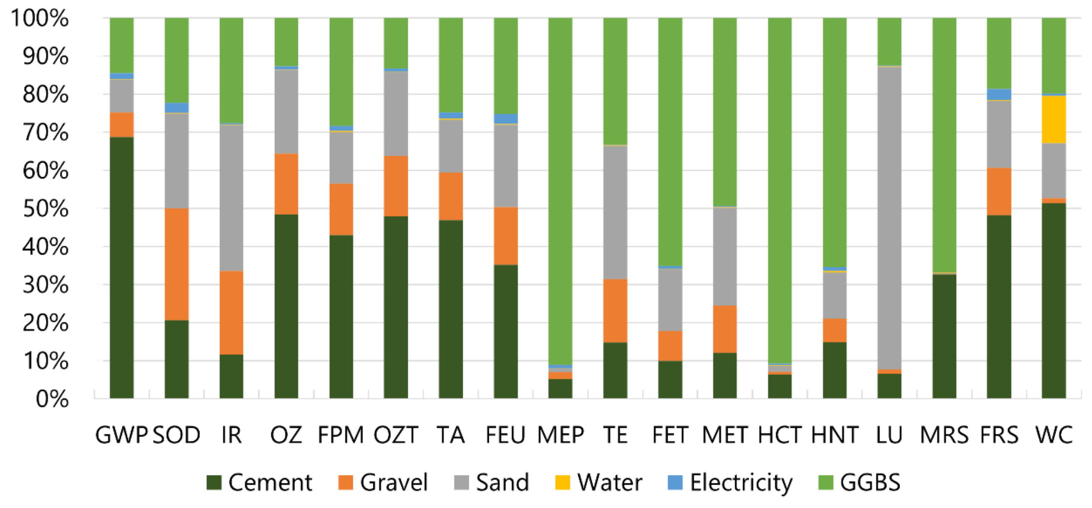

Figure 5.2 Contribution analysis for 30 MPa 65GGBS Thailand concrete mixture (without transportation)

The analysis also revealed a significant contribution concerning FET, MET, HNT, and MRS from GGBS production, accounting for over 50% of the impact in the mixture. The results of this study show similar findings to that of the study by Manjunatha et al. (2022) (50 MPa, 30GGBS), reporting a significant impact of GGBS on freshwater ecotoxicity, human carcinogenic toxicity, and mineral resource scarcity in comparison to the pure-cement mixture.

5.2 Midpoint impacts considering various modes of SCM transportation

Even when considering transportation, our findings confirm a long-held consensus in literature: cement usage is the primary determinant of global warming potential (GWP) in concrete (Figure 5.3). In line with this idea, our findings show that, even after accounting for long transportation distances, pure cement mixtures have the highest GWP when compared to all scenarios, including cement alternatives. Importantly, this result highlights the significant CO_2 emissions savings achievable by using GGBS in place of conventional Portland cement (OPC) concrete, even when delivered over great distances.

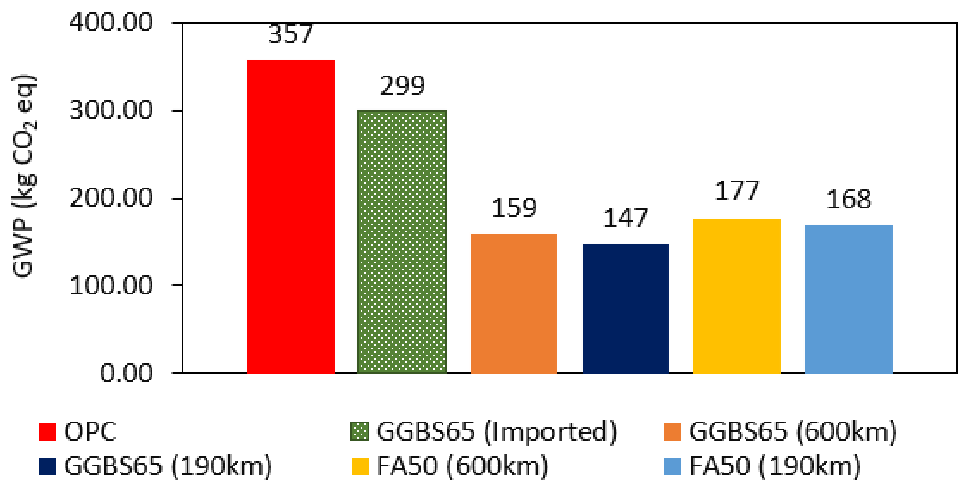

Figure 5.3 Global warming potential for pure-cement, 65GGBS, and 50FA Thailand concrete mixtures considering transportation of SCM.

Across all land transportation distances, it is evident that incorporating SCMs leads to a substantial reduction in carbon dioxide (CO_2) emissions (Figure 5.3) compared to pure cement concrete. 65GGBS concrete transported over 190 km exhibits the highest reduction, reaching 59%. For a similar strength of 30 MPa, the reduction obtained in this study is close to that of the CO_2 reduction obtained in the study of Kim et al. (2018), obtaining a reduction of 68% at 70% GGBS replacement of cement. It outperforms fly ash concrete in terms of GWP reduction primarily due to its higher cement replacement ability. These findings on GWP reduction are also consistent with previous studies that compare GGBS and FA at similar strength with different cement replacement levels (Aslani, Hachem-Vermette, & Zahedi, 2023; Pradhan, Chang Boon Poh, & Qian, 2022). Compared to fly ash concrete, GGBS performs much better in terms of global warming potential (11-13%) and ozone formation (9-11%) at both road distances considered.

5.2.1 Midpoint environmental impacts considering land transportation (local source)

The impacts are significantly increased when long-distance land or maritime transport is considered. Figure 5.4 provides a detailed assessment of the environmental performance of concrete mixtures containing 65% GGBS and 50% fly ash while considering actual transportation. Our investigation includes both land transit through the truck and maritime transportation of SCM, with distances ranging from 190 km to 600 km (for land) and 7,319 km (for maritime, equal to 3,952 nautical miles).

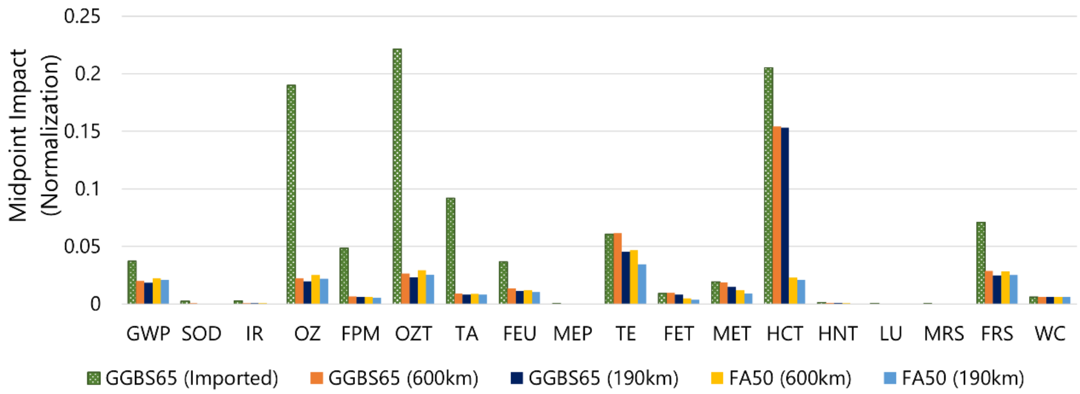

Figure 5.4 Comparative midpoint impacts (a) normalization of Thailand pure cement concrete (OPC) and concrete mixtures containing slag and fly ash transported at various distances and modes

Fly ash provides significant environmental benefits across numerous categories, including SOD, IR, FEU, MEP, TE, FET, MET, HCT, HNT, and MRS, with differences surpassing 10% when compared to GGBS concrete (Figure 5.4). Water consumption for both SCMs remains roughly constant regardless of transportation distance. Adding fly ash and GGBS improves the workability of concrete (Giergiczny, 2019). All the environmental impacts resulting from the use of fly ash are lower than those associated with pure-cement concrete at a transportation distance of 190 km (Figure 5.5).

Conversely, for the same distance, considering slag, the impacts are higher in categories such as IR, MEP, TE, FET, MET, HCT, HNT, and LU. This demonstrates that, when considering short-distance SCM transport, fly ash delivers improved overall environmental performance. However, it is important to note that the reduction in GWP, in relation to pure cement, decreases slightly (by 3%) as the transportation distance of the SCM increases from 190 km to 600 km. Transportation of SCM has been widely seen as an important factor that affects the environmental performance of SCM (O'Brien et al., 2009). The current option (diesel trucks) for transporting materials can be improved by considering the use of different types of vehicles in the future. For instance, the comparative assessment conducted by Balboa-Espinoza et al. (2023) revealed that the environmental performance of diesel vehicles was inferior to their electric counterparts, specifically in relation to indicators such as global warming potential, stratospheric ozone depletion, and terrestrial acidification. This discrepancy can primarily be attributed to the combustion of fuel in diesel vehicle operations. Railroad transportation can also significantly reduce the CO_2 emissions associated with conventional articulated trucks (O'Brien, Ménaché, & O'Moore, 2009).

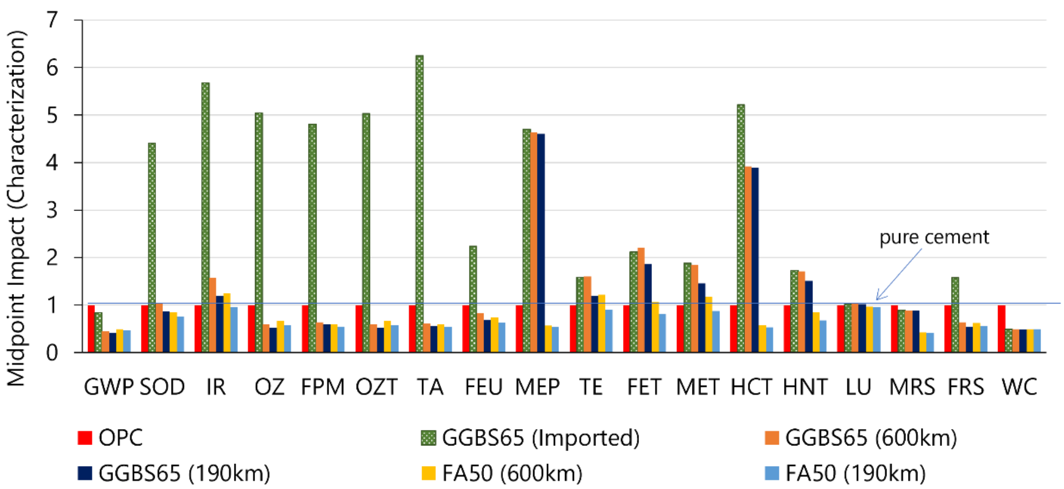

Figure 5.5 Comparative midpoint impacts (characterization) of 30 MPa Thailand pure cement concrete (OPC) and concrete mixtures utilizing 65% GGBS and 50% fly ash as cement replacement transported at various modes and distances

5.2.2 Impacts of importing GGBS by maritime shipping

One of the prominent advantages of utilizing ground granulated blast furnace slag in concrete is its substantial reduction in global warming potential (GWP). Even when considering long-distance sea transportation (import), our study reveals that incorporating 65% GGBS leads to a remarkable 16% reduction in the GWP of concrete. In the study of Hafez et al. (2020), it was also noted that if the UK imports fly ash using sea transport from China (9,000 km) or Germany (1,400 km), it will still have CO_2 benefits compared to OPC based on life cycle assessment for GWP with economic allocation. Beyond GWP, the use of imported GGBS also yields notable benefits regarding mineral resource scarcity and water consumption, with impact reductions of 11% and 51%, respectively. Importantly, the advantage of 65GGBS in reducing water consumption remains largely consistent even when transportation is accounted for. Cement is a water-intensive process, and reducing its use provides a large savings for water, which is now becoming a global problem.

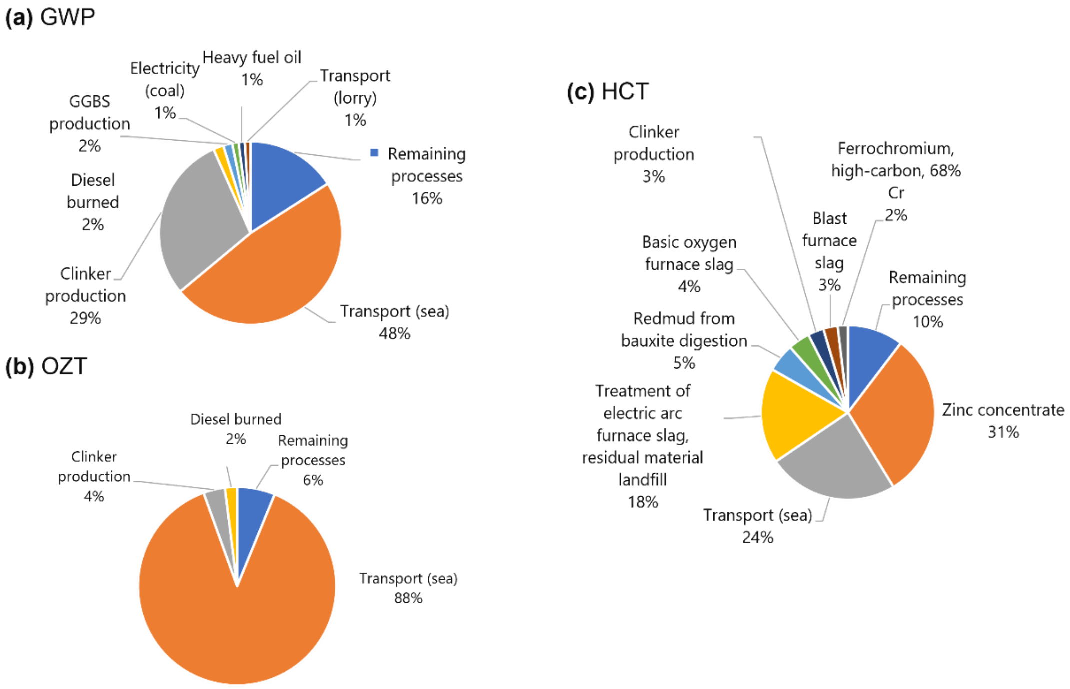

Figure 5.6 Contributing processes for (a) global warming potential, (b) ozone formation, and (c) human carcinogenic toxicity of 30 MPa concrete with 65% imported GGBS in Thailand

A comprehensive comparison also demonstrates that, when compared to 50FA concrete transported 600 km by land, imported 65GGBS concrete has a greater impact on the environment in all categories except water consumption (Figures 5.4, 5.5). Imported 65GGBS has a greater impact than pure cement mixtures in 15 impact categories, with impacts exceedingly twice those of OPC for SOD, IR, OZ, FPM, OZT, TA, FEU, MEP, FET, and HCT. This observable increase in impact highlights the repercussions of importing GGBS from abroad. The unfavorable contribution of maritime transport is depicted in Figure 5.6. In terms of transportation, normalization analysis reveals that the most significant impacts are GWP, OZ, FPM, OZT, TA, FEU, TE, HCT, and FRS (Figure 5.4). Sea transport significantly contributes to some of these impacts (Figures 5.6a, 5.6b, 5.6c).

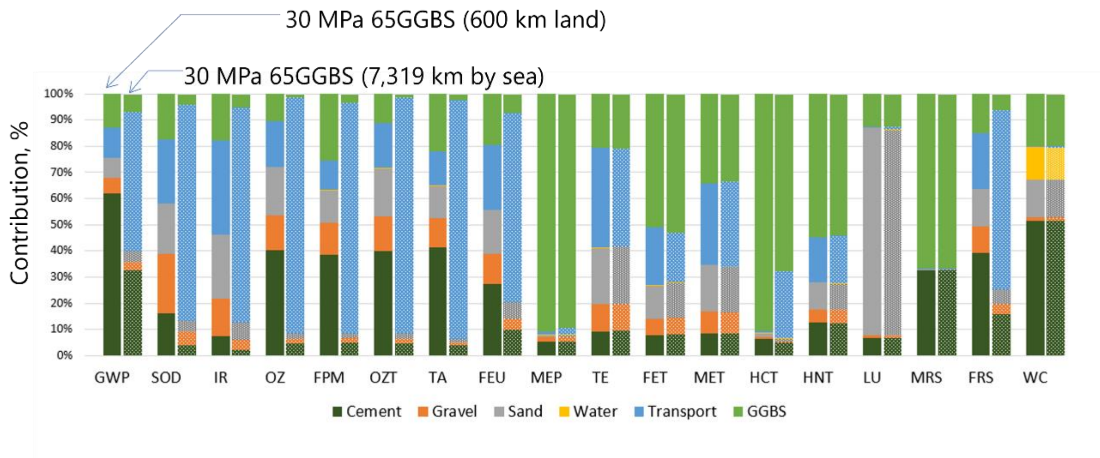

Figure 5.7 Comparative contribution analysis of concrete constituents for 30MPa Thailand concrete with 65% GGBS cement replacement for long-distance land (600 km) and sea (7,319 km) transport

A contribution analysis was conducted to delineate the respective contributions of individual constituents within GGBS concrete. In Figure 5.7, we present a comparative assessment of the impact attributable to each constituent, including cement, sand, gravel, water, and GGBS, considering both land (600 km) and sea (7,319 km) transportation of GGBS. The environmental burden associated with incorporating 65GGBS as a cement replacement is attributable to slag processing. GGBS is produced by rapidly quenching the hot blast furnace slag with water, followed by grinding (Dai, Wang, Xie, Xue, Duan, et al., 2019). This allows it to develop binding properties suitable for its application as a cement substitute. Grinding requires additional energy and consequential emissions (Pradhan, Chang Boon Poh, & Qian, 2022). As depicted in Figure 5.7, 65GGBS processing emerges as a prominent contributor in some impacts, accounting for a substantial portion of marine eutrophication at 90-91%, human carcinogenic toxicity ranging from 68-91%, and mineral resource scarcity at 67%.

The long-distance maritime transportation of 65GGBS (import) significantly impacts SOD, IR, OZ, FPM, OZT, TA, and FEU, with an impact contribution between 73% to 92% of the overall impact. Sea transportation is responsible for the largest proportion of terrestrial acidification (92%), ozone formation (90%), and fine particulate matter (88.3%). Ytreberg et al. (2021) emphasized that engine emissions from ships affect air quality and climate change in relation to GWP; the contribution of imports through shipping accounts for 53.3% of the overall impact. The route of transportation for slag is evidently a crucial aspect that influences its effects on mass concrete mixtures.

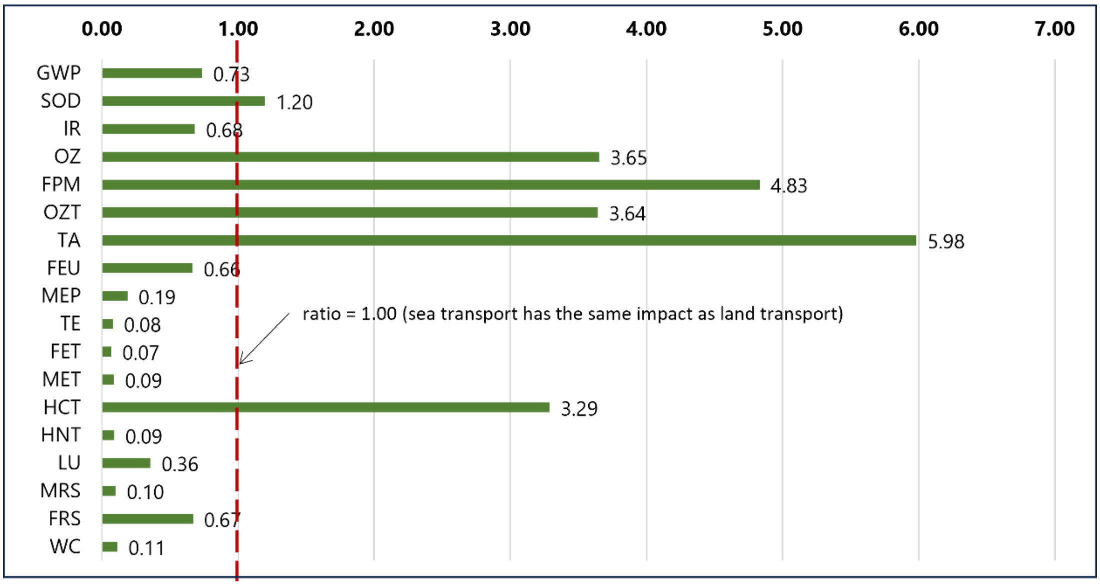

Figure 5.8 Ratio of the impact of sea transport to land transport per km slag transported (30 MPa Thailand mass concrete)

Figure 5.8 depicts the impact of transportation modes between sea transport and land transport per kilometer of slag transported calculated using Equation (3.1). Notably, sea transport of slag outperforms land transport in 12 impact categories. Sea transport emits

27% less CO_2 per kilometer than land transport of slag. It also proves highly advantageous over land transport in areas related to ecotoxicity (TE, FET, MET), human non-carcinogenic toxicity, and mineral resource scarcity, displaying relative differences exceeding 90% for each of these midpoint categories. Ecotoxicity has been known as one of the negative impacts of land transport by diesel-fueled trucks (Panesar, Kanraj, & Abualrous, 2019) due to brake wear emissions that cause PM_{10}. On the other hand, shipping exerts a pronounced negative impact on ozone formation, fine particulate matter, terrestrial acidification, and human carcinogenic toxicity. In these categories, the impact of sea transport is 2.29 to 4.98 times greater than land transport. When sea transport is employed instead of land transport, the two most significant impacts are in the areas of acidification (TA) and particulate matter (FPM), with values equivalent to 4.98 times and 3.83 times, respectively, that of land-based transportation. Shipping generates multiple waste streams that are responsible for the emissions of hundreds of contaminants into the marine environment. It has been recognized as an anthropogenic contributor to SO_x, NO_x, and ammonia, which can result in acidification (Hassellöv, Turner, Lauer, & Corbett, 2013). Fine particulate matter in 65GGBS concrete is predominantly contributed by sulfur dioxide (54%) and nitrogen oxide (34%), with over 90% of these emissions originating from sea transport. These findings underscore the significance of these impacts, which have received comparatively limited attention within the concrete literature but warrant further investigation.

5.3 Endpoint impact analysis

The endpoint analysis findings indicate that mass concrete mixtures' influence on human health surpasses their impact on ecosystems and resources. The key factors contributing to human health damage (Figure 5.9a) in the case of cement-only mixtures and those containing supplementary cementitious materials (SCM) as replacements when transported via land transit are global warming (56-66%) and the formation of fine particulate matter (32-39%). In the case of sea-imported GGBS, it has been observed that fine particulate matter contributes to roughly 73% of the adverse effects on human health. While previous studies have extensively examined the contribution of concrete to carbon dioxide (CO_2) emissions, additional research is needed to explore the potential impact of fine particulate matter on human health deterioration. Research findings indicate that fine particle matter has been identified as a primary cause of increased mortality rates and has a substantial role in the overall levels of air pollution.

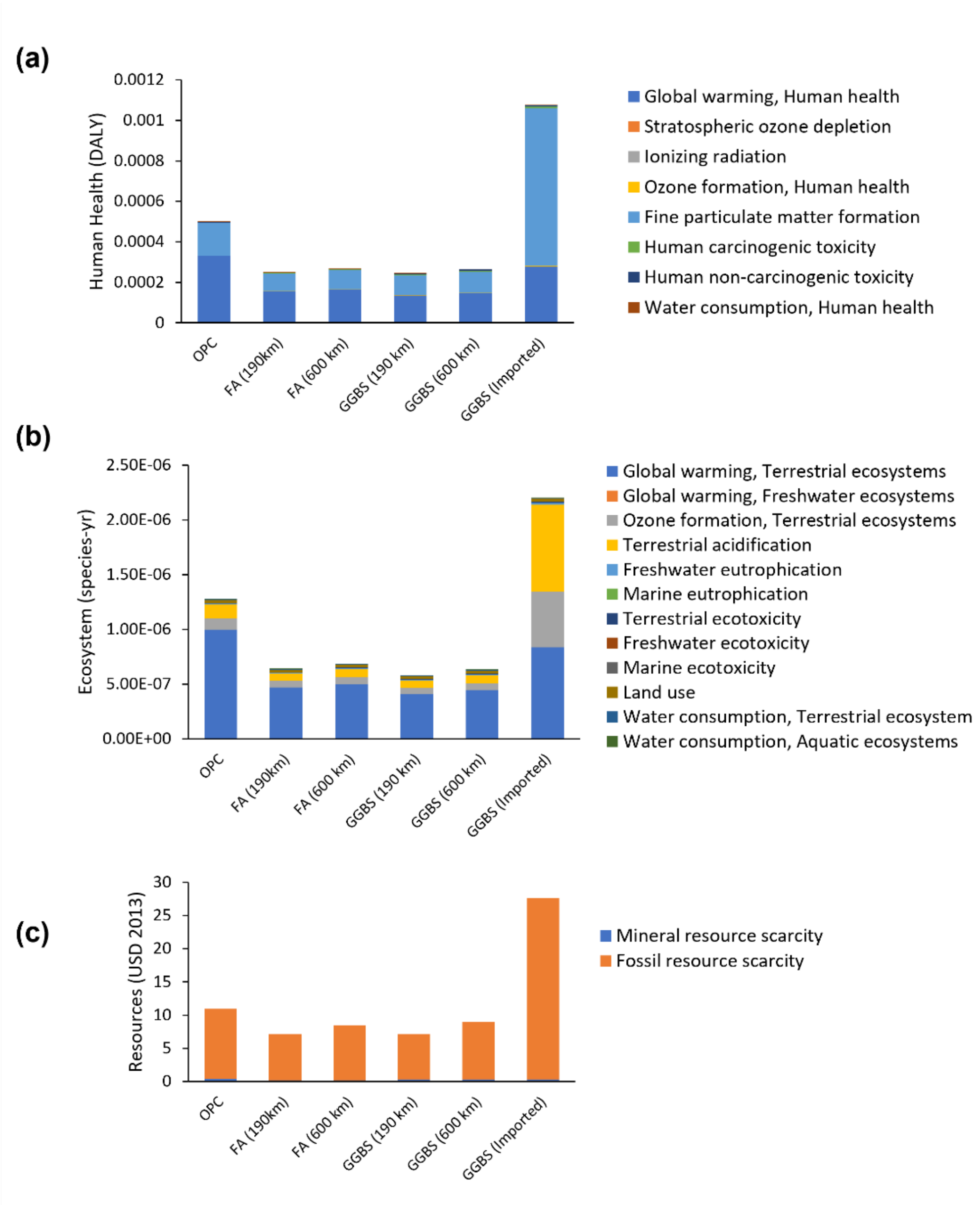

Figure 5.9 Endpoint impact results for (a) human health, (b) ecosystems, and (c) resources for 30 MPa Thailand concrete with 65% GGBS and 50% fly ash as cement replacement transported at various modes and distances

The impact of substituting cement with fly ash on ecosystem deterioration (Figure 5.9b) exhibits a comparable trend to its influence on human health. Global warming has emerged as the predominant catalyst for environmental degradation, responsible for around 70-78% of the ecological harm attributed to climate change. In the case of concrete mixtures incorporating imported ground granulated blast furnace slag, it has been observed that terrestrial acidification and ozone formation are responsible for more than 50% of the overall ecosystem damage. Terrestrial acidification poses a significant global challenge to plant diversity. The transportation of goods in the marine environment is the primary contributor to terrestrial acidification, resulting in possible adverse effects and associated damages. This phenomenon is principally attributed to the emission of human-generated air pollutants, namely nitrogen oxides (NO_x), ammonia (NH_3), and sulfur dioxide (SO_2), which are predominantly released during the process of cement production (Supriya, Chaudhury, Sharma, Thapliyal, & Singh, 2023) as well as during shipping (Gursel & Ostertag, 2016; Ytreberg, Åström, & Fridell, 2021a). An analysis of upstream processes involved in the production of 65GGBS concrete reveals that terrestrial acidification primarily results from airborne emissions of sulfur dioxide (62%) and nitrogen dioxide (37%), with 93% and 92%, respectively, contributed by sea transport of GGBS. These oxide emissions have the potential to remain suspended in the atmosphere and be transported to nearby land masses, leading to acidification in terrestrial ecosystems. Previous studies have indicated that shipping activities impact terrestrial ecosystems through eutrophication and acidification, as well as pose risks to human health due to the release of air pollutants (Ytreberg, Åström, & Fridell, 2021b). Similarly, ozone formation is attributed to nitrogen oxides in the atmosphere. The ecological damage caused by ecotoxicity in freshwater, land usage, and water consumption is estimated to constitute a mere 1% of the total impact.

The degradation of resources (Figure 5.9c) exhibits a comparable trend to that observed in relation to human health and ecosystems, with imported GGBS having the most significant impact. The utilization of fly ash and GGBS as substitutes for cement, except for imported GGBS, results in a notable reduction in resource damage as compared to a mixture with only cement. The scarcity of fossil fuels accounts for 99% of the total impact on resources for all concrete mixtures. Fossil depletion is mainly caused by a large demand for coal, petroleum, electricity, and natural gas in the manufacturing of aggregates and cement (Huang, Zhao, Fishman, Chen, Heeren, et al., 2018).

5.4 Practical applications

This study has shown that the type of SCM and its corresponding mode of transportation are essential aspects of the environmental impact of concrete. To aid decision-makers in selecting the most appropriate SCM, we compare the impacts in Figure 5.10 for using 50FA and 65GGBS based on the most significant impacts from normalization and endpoint analysis. The elevated environmental impact of importing slag (Figure 5.11, Table 5.1) emphasizes the significance of sourcing SCMs from nearby regions. One possible mitigation method for reducing transportation-related environmental impacts is to reduce the importation of materials from faraway nations in favor of locally accessible SCMs. While GWP has typically served as the primary benchmark for measuring SCM environmental performance, our findings highlight the need to consider other environmental measures.

Controlling cracking is critical in the context of mass concrete. The high degree of cement hydration during mass concrete pouring can quickly result in concrete cracking, endangering mechanical qualities, durability, safety, and serviceability (X. Li, Yu, Chen, Deng, & Yu, 2023). Furthermore, the exothermic hydration reactions accompanying cement hydration can cause dramatic heat gradients within enormous concrete structures, with negative environmental consequences (Ghasabeh & Göktepe, 2023). A prior study (Dabarera, Saengsoy, Kaewmanee, Nakazaki, Lerdsupavaree, et al., 2019) found that fly ash concrete outperforms GGBS concrete in terms of limiting thermal cracking propensity. Our study's combined findings provide decision-makers with a more informed approach to selecting the best SCM, considering the numerous scenarios involving slag or fly ash.

Table 5.1 Comparative summary of environmental impacts of 65GGBS and 50FA without and with SCM transportation for 30 MPa Thailand mass concrete mixture.

Indicator	Without SCM Transport (effect of SCM type)		With SCM Transport	
	65GGBS	**50FA**	65GGBS (imported)	50FA (600km)
Midpoint Impacts				
Global warming potential	▼	△	△	▼
Stratospheric ozone depletion	△	▼	△+	▼
Ionizing radiation	△	▼	△+	▼
Ozone formation (human health)	▼	△	△+	▼
Fine particulate matter formation	△	▼	△+	▼
Ozone formation (terrestrial ecosystems)	▼	△	△+	▼
Terrestrial acidification	△	▼	△+	▼
Freshwater eutrophication	△	▼	△+	▼
Marine eutrophication	△+	▼	△+	▼
Terrestrial ecotoxicity	△	▼	△+	▼
Freshwater ecotoxicity	△+	▼	△+	▼
Marine ecotoxicity	△	▼	△+	▼
Human carcinogenic toxicity	△+	▼	△+	▼
Human non-carcinogenic toxicity	△+	▼	△+	▼
Land use	△	▼	△+	▼
Marine resource scarcity	△	▼	△	▼
Fossil resource scarcity	▩	▩	△+	▼
Water consumption	▩	▩	▩	▩
Endpoint Impacts				
Human Health	▩	▩	△+	▼
Ecosystem	▼	△	△+	▼
Resources	▩	▩	△+	▼

▼ = lower impact; △ = higher impact; ▩ = similar or comparable (less than 5% difference)
\+ = higher impact than pure cement concrete

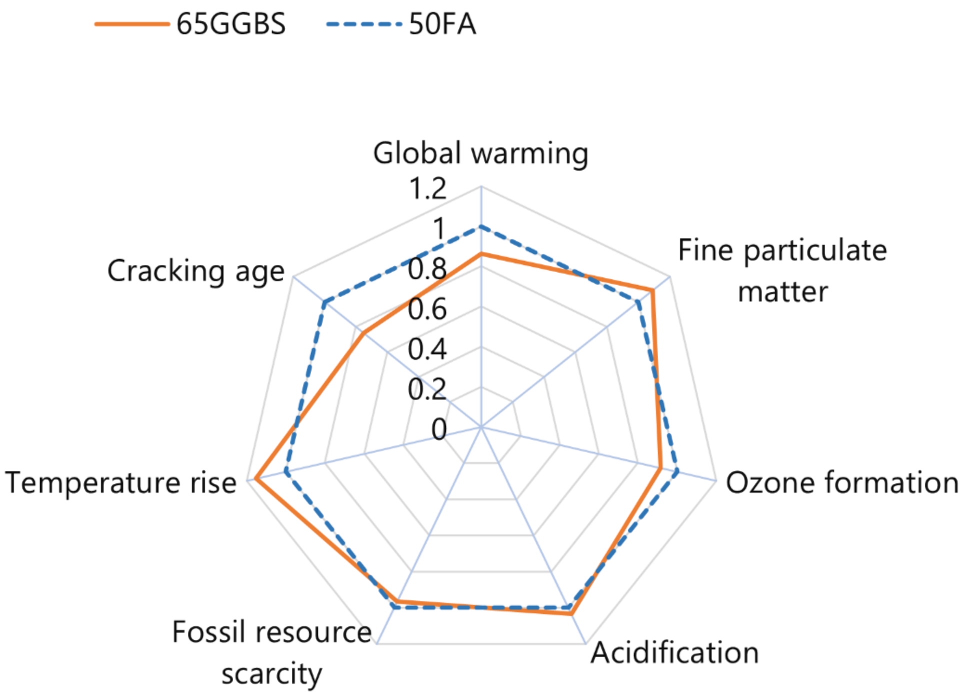

Figure 5.10 Comparison of the impacts of 65GGBS on the most significant impacts, including temperature and cracking performance relative to 50FA for 30 MPa Thailand mass concrete

To encourage the broader use of waste materials such as fly ash and slag, there is a need to integrate their utilization into established regulatory frameworks. Notably, Thailand has emerged as a successful example in the application of fly ash in mass concrete. This success can be attributed to the absence of constraints within their current standards and practices, which do not impose any restrictions on the maximum quantity of fly ash that can be incorporated into mass concrete applications. Specifically, the Thailand Industrial Standard, known as TIS 2135, provides clear guidelines for the utilization of fly ash in concrete, categorizing it based on quality class (classes 1, 2, and 3) and CaO content (Tangtermsirikul, Saengsoy, Kaewmanee, Julnipitawong, & Samranwanich, 2023). This supportive regulatory environment has fostered the effective utilization of fly ash in mass concrete projects.

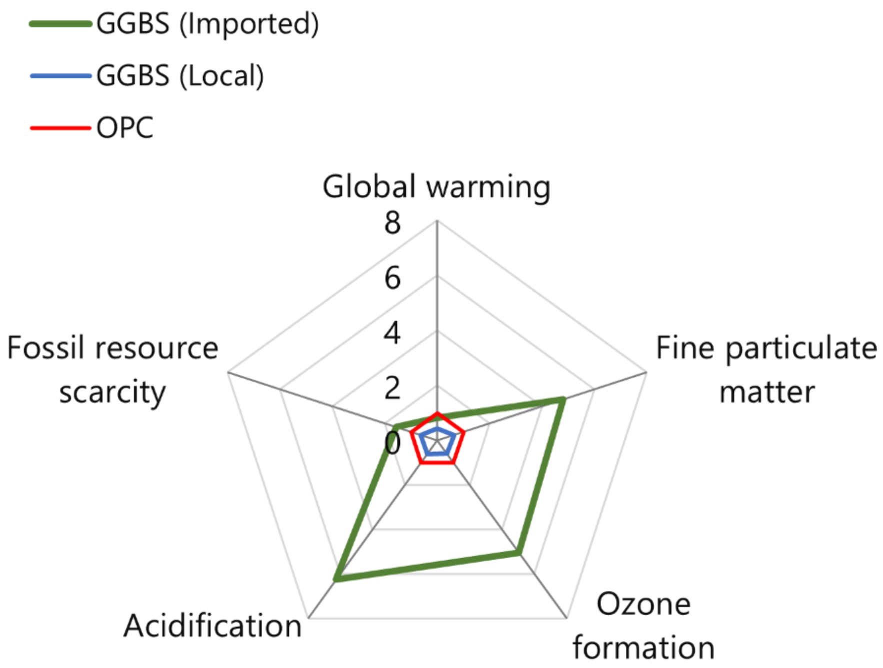

Figure 5.11 Comparison of the effects of locally sourced and imported slag relative to pure cement concrete for 30 MPa Thailand mass concrete

5.5 Summary

This Chapter comprehensively assesses the environmental performance of mass concrete mixtures incorporating GGBS (65%) and fly ash (50%) as cement replacement. Our investigation comprehensively discusses the intricate interplay between the choice of supplementary cementitious material, transportation distance, and environmental impact. In the absence of SCM transportation considerations, our results demonstrate a substantial reduction in global warming potential with the utilization of either fly ash (54% reduction) or GGBS (61% reduction) as partial cement replacements compared to Ordinary Portland cement concrete. GGBS processing contributes significantly to marine eutrophication and human carcinogenic toxicity, magnifying these impacts approximately 4.59 and 3.89 times, respectively, compared to the cement-only mixture. The long-distance import of GGBS substantially influences the environmental performance of GGBS concrete, surpassing that of pure cement mixtures in 15 impact categories. Specifically, impacts exceed twice those of OPC for

SOD, IR, OZ, FPM, OZT, TA, FEU, MEP, FET, and HCT. Endpoint indicators underscore GGBS's better environmental performance when transportation is omitted or when sourced locally. For damages to human health and ecosystems, 65% GGBS exhibits a marginal advantage over 50% fly ash concrete. The utilization of fly ash and GGBS, except for imported GGBS, led to a notable reduction in resource damage compared to the cement-only mixture. The results of this study will enhance the understanding of SCM selection's multifaceted implications on concrete's environmental performance. It underscores the significance of considering SCM type, transportation logistics, and their intricate interplay, providing valuable insights for sustainable concrete production. To further enhance sustainability, future studies may investigate the impact of regional variations and emerging innovations in transportation, as well as end-of-life disposal of mass concrete utilizing fly ash and slag.

CHAPTER 6
ENVIRONMENTAL AND ECONOMIC IMPACTS OF FLY ASH UTILIZATION IN PHILIPPINES MASS CONCRETE: EFFECT ON LOW, NORMAL, AND HIGH STRENGTH MIXTURES

This Chapter discusses the findings that quantify the economic and environmental impact of a wide range of concrete mixtures from the Philippine concrete industry, emphasizing the use of fly ash and identifying possible options to mitigate those impacts. This covers the midpoint and endpoint impacts associated with low-strength, normal-strength, and high-strength mass concrete mix design, the impact of using fly ash in these different types of concrete mixtures, the contribution of each concrete constituent, and the effects of specified age to achieve the design.

6.1 Midpoint impacts of varying pure-cement concrete mix designs

Figure 6.1 shows the environmental impact of concrete made with pure OPC for 18 midpoint categories. The values for each impact category are graphically presented as normalized values with respect to the concrete mixture having the maximum value. All the concrete mix designs resulted in a positive environmental burden. It can be observed that, in general, as the design strength increases, the associated environmental impact increases for almost all impact categories except for land use. One central point of interest is that the GWP increases proportionally to the cement content of the mixture. This finding on GWP confirms the trend with previous studies (Kurda, Silvestre, & de Brito, 2018; Pradhan, Chang Boon Poh, & Qian, 2022). Kurda, Silvestre, & de Brito (2018) explained that this is mainly because of the heating process involved during cement production: $CaCO_3$ + heat → CaO + CO_2.

As for the impact on land use, it can be observed that the lower-strength design puts a higher environmental burden on this category. This can be explained by the fact that higher-strength designs use more cement and lower-strength designs use more aggregates, significantly impacting land use indicators. For example, 13.8 MPa concrete uses 1,945 $kg/m^{3,}$ while 69.0 MPa concrete uses 1,665 kg/m^3 of combined fine (sand) and coarse (gravel) aggregates. This indicates that aggregate quantity largely influences land use impact.

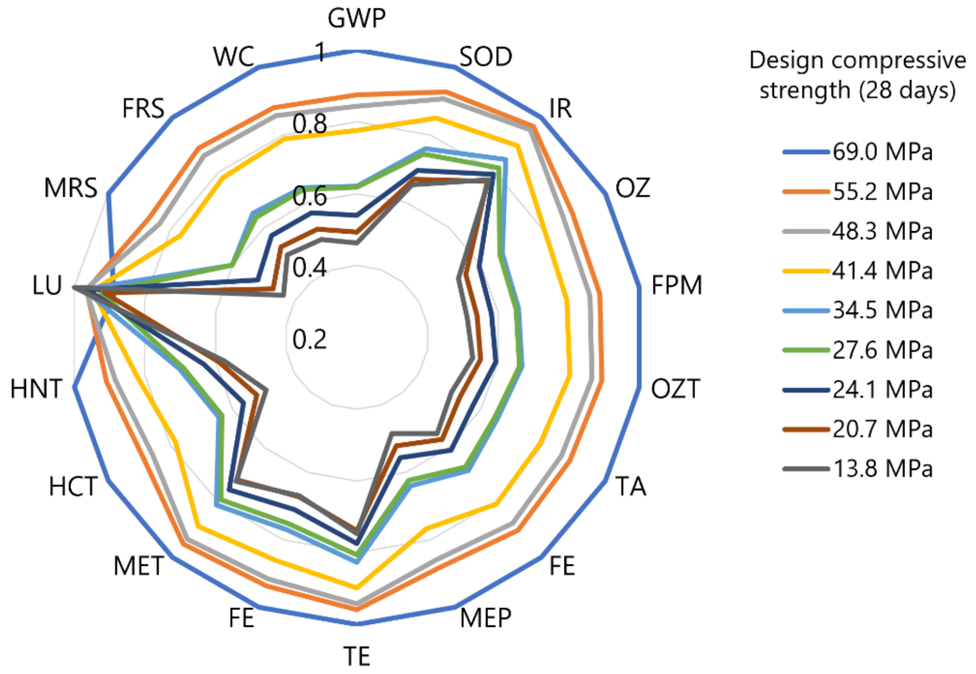

Figure 6.1 Environmental impacts of pure cement concrete from the Philippines with various compressive strength design

6.2 Impact of fly ash utilization in mass concrete mixtures

Figure 6.2 shows that higher design strength resulted in higher global warming potential, as indicated in the positive slopes for all concrete mixes. The higher kg CO_2 eq value is driven by the higher strength achieved by higher cement content in the concrete mix, which leads to a higher global warming potential and higher climate change impact. This trend is similar to the study of concrete products in Australia (Mohammadi & South, 2017).

This study's range of values obtained was around 255-550 kg CO_2 eq for concrete with pure OPC. The GWP values for all concrete mixtures are listed in Appendix D. When cement used was replaced by 10%, 15%, and 20% of fly ash by weight, the GWP values were reduced by the following ranges: 8.5-9.4%, 8.5-20.7%, and 2.4-19.2%, respectively. Greenhouse warming caused by CO_2 has a global effect. The higher replacement value lowers the environmental burden on this indicator. It should be noted that at lower strength designs, the difference between the global warming potentials of the various mixes is smaller compared to higher strength mix designs.

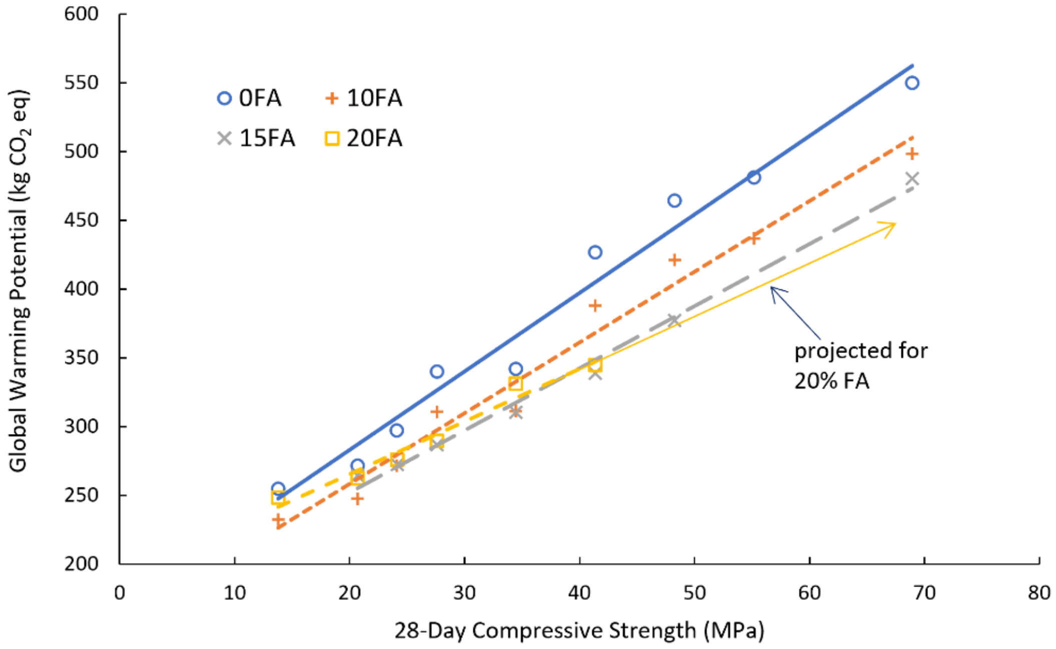

Figure 6.2 Global warming potential of Philippines mass concrete mixtures with 0% (0FA), 10% (10FA), 15% (15FA), and 20% (20FA) fly ash as cement replacement at various strength designs

For a similar 28-day strength design of around 40 MPa, the result of this study with 20% fly ash replacement shows a close GWP value (344 kg CO_2-eq) with that reported by Mohammadi & South (2017) for benchmark concrete products in Australia (335 kg CO_2-eq), which replaces cement by 23% (15 % by fly ash and 8% by slag). However, as noted by Hafez et al. (2020), caution should be taken when comparing the results of two studies due to the variability of methods and conditions. Thus, a comparative analysis of concrete mixes with the same condition will provide better insight. The paired *t*-test was performed to compare the GWP values of the following replacements: (a) 0% with 10%, 15%, and 20%, (b) 10% with 15% and 20%, and (c) 15% with 20% fly ash replacements. The corresponding p-values for each pair of comparisons are summarized in Table 6.1.

Results of paired *t*-test at a 5% level of significance showed that with the utilization of 10% and 15% fly ash, a significant difference in GWP was observed from concrete made from pure OPC. Considering strengths above 27.6 MPa (normal to high strength), a significant difference at a 5% significance level was observed with the reduction of GWP when pure OPC is replaced with 10, 15, and 20% fly ash. This 28-day strength is important as it is one of the most produced strengths for mass concrete in the Philippines. Additionally, a significant difference between 10% and 15% was observed in this strength range. This indicates that fly ash replacement significantly reduces the global warming potential in higher-strength concrete mix designs. This provides an opportunity for future fly ash utilization for sustainable high-strength infrastructures.

Table 6.1 Results of paired t-test (p-values) for comparison of global warming potentials for Philippines mass concrete mixtures

Strength Considered	**13.8 – 69.0 MPa**				**27.6 MPa and above (normal to high-strength concrete)**			
Fly ash, %	**0**	**10**	**15**	**20**	**0**	**10**	**15**	**20**
0	-				-			
10	0.000*	-			0.000*	-		
15	0.005*	0.116	-		0.004*	0.038*	-	
20	0.059**	0.888	0.179	-	0.0146*	0.507	0.211	-
**significant at 5% significance level; **significant at 10% significance level*								

In Figure 6.3a, a comparison of the environmental impact of using different fly ash replacements for cement in concrete was investigated. The actual values of environmental impacts for these concrete mixtures are listed in Appendix D. The mix design for 27.6 MPa, the most common in the Philippines, was considered a representative sample. Results show that concrete made from pure OPC has a higher environmental impact in all indicators. Normalization converts complicated units into fractions of an average citizen's scores per impact category. Based on the normalized results (Figure 6.3b), global warming, ozone formation, terrestrial ecotoxicity, human carcinogenic toxicity, and fossil resource scarcity are the most significant indicators.

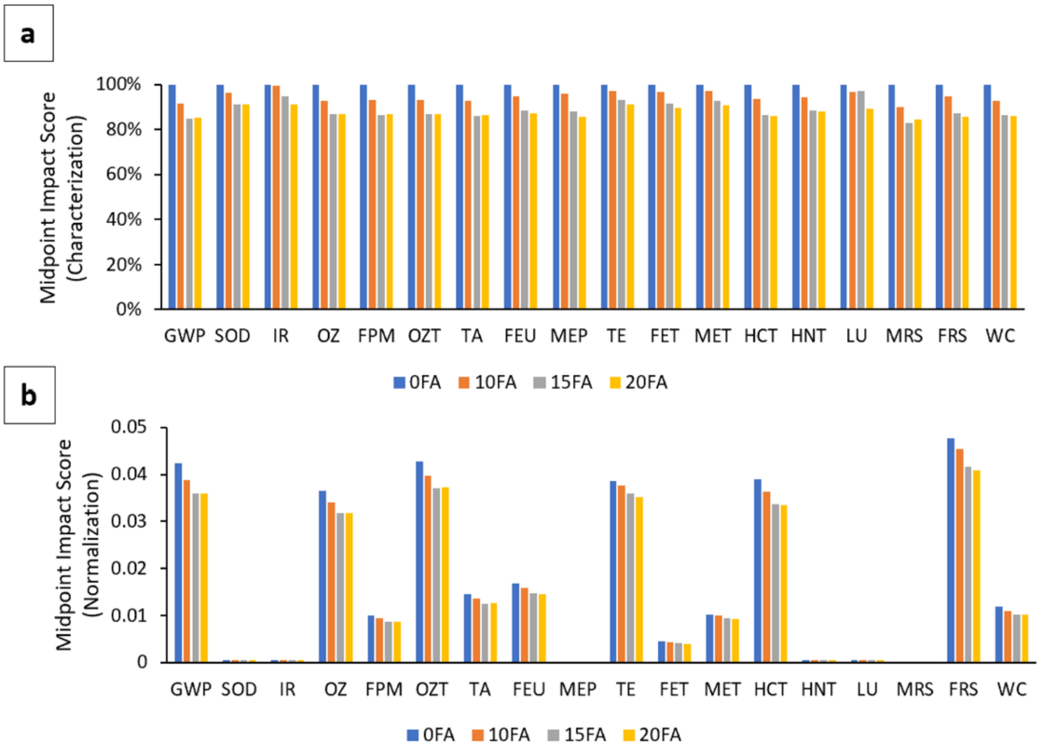

Figure 6.3 Midpoint impact (a) characterization and (b) normalization results for 27.6 MPa Philippines concrete with varying percentages of fly ash as cement replacements

The favorable effect of high fly ash substitution in high-strength mix designs is seen in all other impacts. Figure 6.4 shows the impact of all the design strengths. The significant indicators such as ozone formation (0.58-1.14 kg NO_x eq), terrestrial ecotoxicity (542-727.78 kg 1,4-DC B), human carcinogenic toxicity (0.37-0.72 kg 1,4-DC B), and fossil resource scarcity (36.83-73.65 kg oil eq) at various strength and fly ash replacement follows the same trend as the global warming potential. The impact is more visible in higher compressive strength designs. For all these indicators, the concrete mix design with zero fly ash replacement yields the highest value of environmental burden.

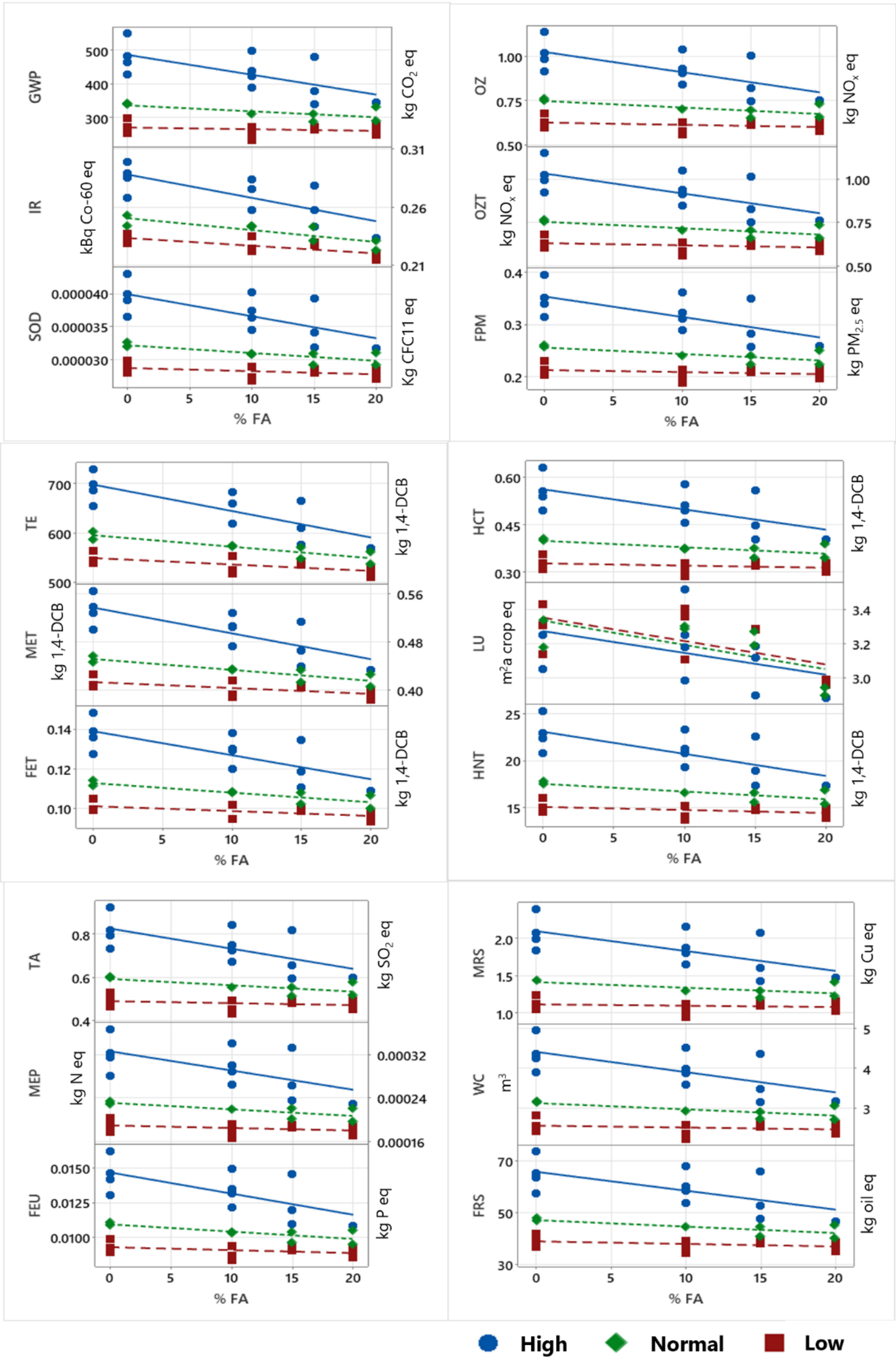

Figure 6.4 Midpoint impacts of low, normal, and high strength mass concrete mixtures from the Philippines with varying fly ash as cement replacement

Figure 6.5 highlights the impact of using fly ash for low-strength (13.8 MPa, Figure 6.5a), normal-strength (27.6 MPa, Figure 6.5b), and high-strength (41.4 MPa, Figure 6.5c) concrete.

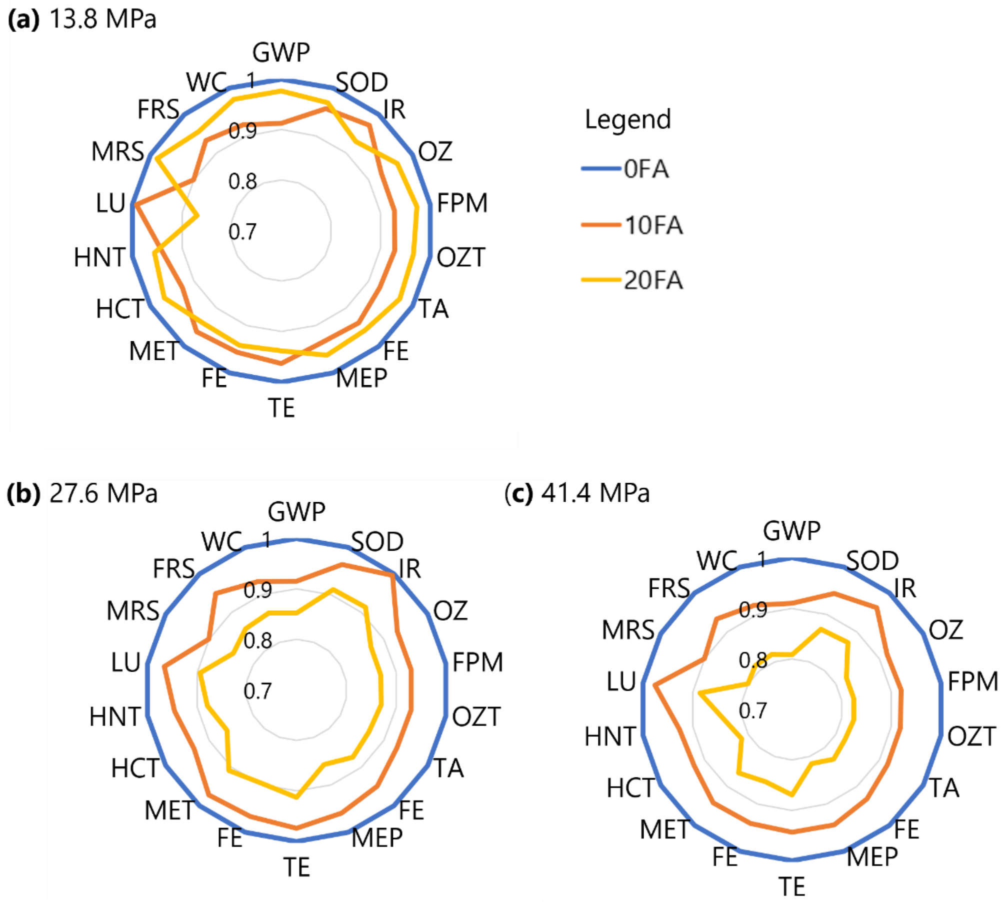

Figure 6.5 Environmental impacts of (a) low (13.8 MPa), (b) normal (27.6 MPa), and (c) high strength (41.4 MPa) concrete with 10% (10FA) and 20% (20FA) fly ash as cement replacement relative to pure-cement concrete (0FA) from the Philippines

At low strength (Figure 6.5a), the 20% fly ash replacement mix shows worse environmental performance than the 10% mixture. This can be explained by the fact that in the Philippines, more cement is used for concrete mixtures with higher fly ash replacements to achieve the same 28-day compressive strength. This indicates that there is still an opportunity for improvement in the practice of concrete mix designs in the industry by specifying the long-term strength, i.e., 56 or 91 days rather than 28 days as the design strengths. The beneficial effect of fly ash is most noticeable at longer ages, i.e., greater than 28 days, due to the slow rate of pozzolanic reaction. Concrete containing fly ash develops strength more slowly, but substantial improvement in strength is typically observed between 28 and 90 days (Imbabi, Carrigan, & McKenna, 2012). Generally, more than 20% replacement in concrete impairs the hydration system, resulting in a slower rate of strength development; this has a detrimental effect on the strength of concrete (Hemalatha, Mapa, George, & Sasmal, 2016). Thus, concrete strength is more beneficial to be specified at a longer age to achieve the environmental benefit of fly ash at high replacement. This is a reasonable practice, especially for mass concrete.

It can be observed from the three radial graphs (Figure 6.5) that the beneficial effect of fly ash at higher replacement is much more realized at higher strength design. A larger inner radial graph means a greater reduction in the environmental impact relative to concrete with pure OPC. High fly ash replacement may not be very beneficial at a lower strength. In fact, for 13.8 MPa concrete (Figure 6.5a), increasing fly ash replacement from 10% to 20% shows a further reduction of environmental impact to only four impact categories. In contrast, for 41.4 MPa concrete (Figure 6.5c), the environmental burden is reduced in all 18 categories when 10FA is compared to 20FA concrete. The GWP was reduced from 427 kg CO_2 eq to 345 kg CO_2 eq when OPC was replaced with 20% fly ash. MRS was reduced by 19.9%. Other indicators, such as OZ, FPM, OZT, TA, FE, MEP, HNT, HCT, FRS, and WC, were reduced to a range of 16-18%. The remaining indicators, such as SOD, IR, TE, FE, MET, and LU, were reduced to a range of 11-14%. This indicates that the environmental impact strongly decreases when cement is replaced with fly ash. The ranges of percentage reduction for all impact categories with 10% fly ash substitution are 0.85%-9.89% (13.8 MPa), 0.45%-9.88% (27.6 MPa), and 2.36-9.91% (41.4 MPa). At 20% replacement with fly ash, the impact reduction ranges are 1.56-13.13% (13.8 MPa), 7.49%-15.46% (27.6 MPa), and 11.51-19.91% (41.4 MPa). For 41.4 MPa concrete with 20% fly ash replacement, the most significant reduction of impact due to the fly ash utilization is observed for global warming potential, mineral resources scarcity, and water consumption, with 19.2%, 19.9%, and 18.4%, respectively. The reduction in GWP and MRS is due to the significant reduction in cement. For MRS, reduced cement usage will translate to less mineral consumption for cement production. For WC, the reduction is explained by the fact that the use of fly ash reduces the water demand for concrete. Hence, the use of fly ash should enable the production of concrete with a lower water content compared to OPC concrete with the same workability (Thomas, 2007). The lowest reduction is observed in the land use impact, with only an 11.5% reduction.

6.3 Endpoint impact analysis

The effects of using different fly ash replacements on human health for different concrete mix designs are illustrated in Figure 6.6 and Appendix E. When utilizing 10%, 15%, and 20% fly ash, the reduction is 7.9-8.7%, 2.6-19.9%, and 2.6-18.7%, respectively, when compared to pure-cement concrete. The paired *t*-test comparison (Appendix E) with pure OPC concrete indicates a significant difference (reduction in human health damage) at 95% confidence for 10% and 15% ($p<0.05$) fly ash replacement. By substituting 20% fly ash for cement, the impact on human health falls dramatically at a 10% level of significance. This indicates that the use of fly ash will significantly lessen the negative effects of concrete production on human health. The extent of human health damage caused by global warming (65.12%) and fine particulate matter generation (33.44%) for 27.6 MPa concrete, one of the most widely used concrete mixes in the Philippines, is shown in Figure 6.7a. Overall, these two categories account for more than 98% of all human health damage. Global warming is a major environmental concern, and the role of concrete in CO_2 production has been widely discussed in scientific literature (Nilimaa, 2023). However, the influence of fine particulate matter should be examined as well. This is because studies have shown that tiny particles cause more life years to be lost. According to the findings of this investigation, fine particulate matter accounts for 33.44% of the total contribution by a 27.6 MPa concrete. Dust contributes considerably to PM_{10} and $PM_{2.5}$, particularly as a result of cement manufacture, ready-mix facilities, and limestone mining (Hottle, Hawkins, Chiquelin, Lange, Young, et al., 2022). Fine particulate matter is a critical health issue that needs to be addressed because it is a major source of the country’s air pollution levels. Current concentrations of $PM_{2.5}$ in urban regions of the Philippines exceed the guidelines of the World Health Organization (WHO), according to published studies (Alas, Müller, Birmili, Kecorius, Cambaliza, et al., 2018; Tantengco & Guinto, 2022).

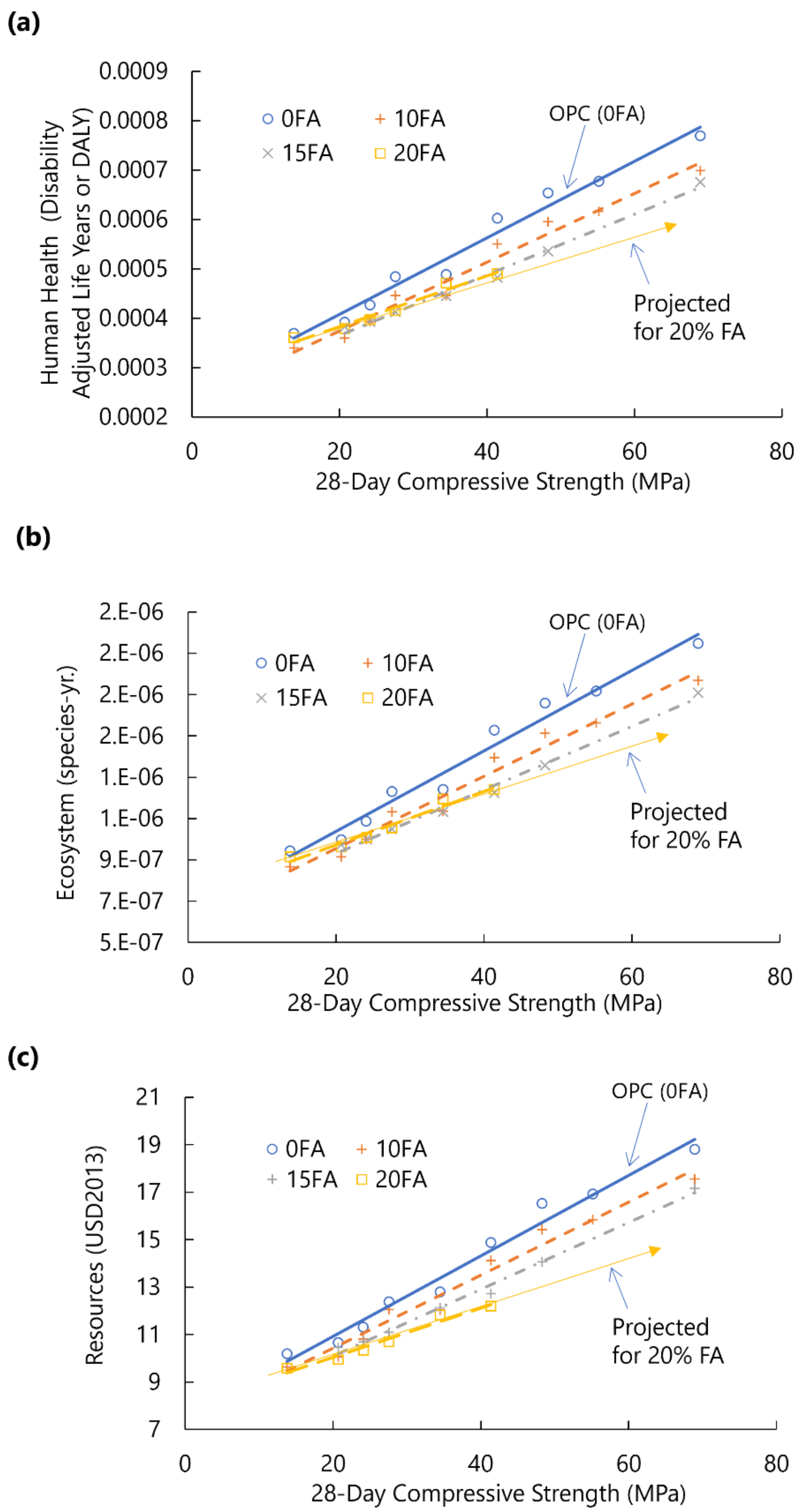

Figure 6.6 Endpoint impacts on (a) human health, (b) ecosystem, and (c) resources of 31 Philippine concrete mixtures with 0%, 10%, 15%, and 20% fly ash as cement replacement.

Air pollution continues to have a devastating impact on the health of Filipinos. Traffic enforcers in Metro Manila, for instance, are 124 times more likely to develop chronic obstructive pulmonary disease if continuously exposed to high $PM_{2.5}$ concentrations (Tantengco & Guinto, 2022). Reduced cement use by replacing fly ash in manufacturing concrete batching plants will significantly minimize the generation of fine particulate matter by reducing the fly ash disposed of in landfills, as well as the emissions generated during cement production.

The influence of utilizing fly ash as a replacement for cement on ecosystem damage (Figure 6.6c) follows a similar pattern (Appendix E) to the results obtained from human health (Figure 6.6a). Considering a 27.6 MPa concrete, global warming is the primary cause of environmental damage (77%) and consequently to human health due to climate change (Figure 6.7a). Terrestrial acidification (10.28%), ozone formation (7.97%), and land use (2.29%) are the other major drivers of ecological destruction, as shown in Figure 6.7b. Other factors, such as eutrophication, ecotoxicity, and water use, have little impact on ecosystem damage. Terrestrial acidification is a global hazard to plant diversity, mainly produced by NO_x, NH_3, and SO_2, which are anthropogenic atmospheric pollutants (Dentener, Stevenson, Ellingsen, Van Noije, Schultz, et al., 2006). This causes acidification of rivers/streams and soil. All these harmful gases are released during the production of cement. In the Philippines, sustainability initiatives are yet to be incorporated into cement production. Acidification causes the mobilization of heavy metals and soil leaching, which has an adverse effect on terrestrial and aquatic ecosystems (Macasieb, Orozco, & Resurreccion, 2021), as well as plants, by disturbing the food chain. The main factors influencing acidification are NO_x and SO_2 in air and H_2S and H_2SO_4 in water systems (T. H. Kim & Chae, 2016). The combustion of diesel fuels mainly generates ozone during the different stages of concrete's life cycle. Other midpoint impacts account for less than 3% of total ecological damage. The impact of using fly ash at various 28-day compressive strengths on the ecosystem is similar to that of the impact on human health.

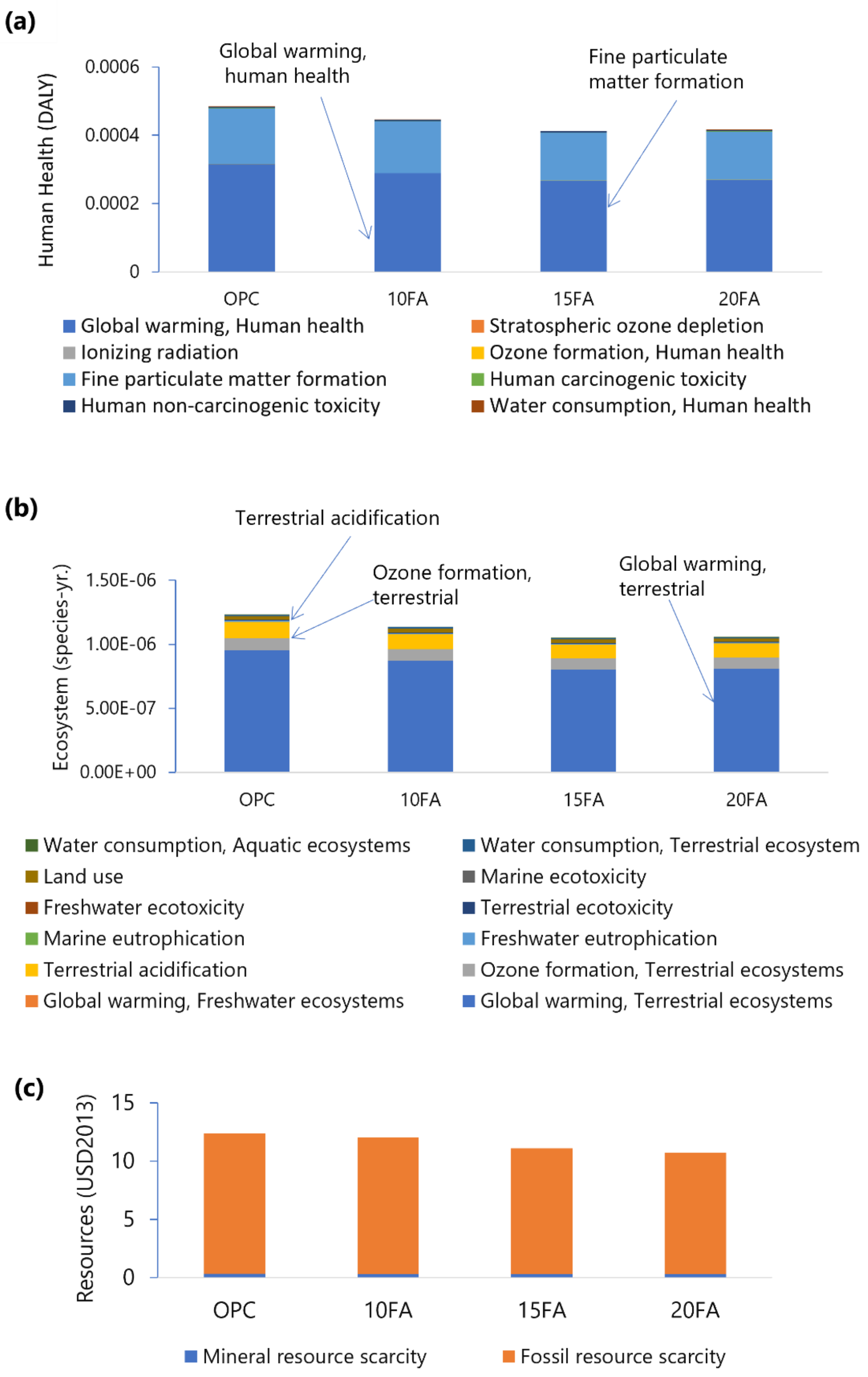

Figure 6.7 Significant midpoint impact indicators contributing to endpoint impacts of (a) human health, (b) ecosystem, and (c) resource damage for 27.6 MPa concrete from the Philippines

The environmental advantage of employing fly ash is particularly obvious in the domain of resource damage reduction (Figure 6.6c, Appendix E). Compared to pure OPC concrete mixtures, statistical analysis using paired *t*-tests (Appendix E) demonstrates a significant reduction in damage to resources values when cement is substituted by fly ash at 10, 15, and 20 percent by weight replacements ($p<0.05$). The figure also shows that when the concrete mix design with 20% fly ash replacement is projected at a higher compressive strength, a more significant reduction in environmental burden can be obtained. When fly ash replacement is increased from 15% to 20%, the reduction in resource degradation is substantial at the 95% confidence level ($p<0.05$). Almost all the harm to resources in a representative 27.6 MPa concrete is caused by fossil fuel scarcity, accounting for 99% of the overall impact (Figure 6.7c). At 35 MPa compressive strength, the damage to resources (USD 12.8) for pure cement concrete shows a close result to the USD 15.8 quantified damage in the study of Chottemada, Kar, & Kara De Maeijer (2023) for concrete in the Indian context.

The effects of employing fly ash in the three endpoint categories are shown in Figure 6.8. It shows the percentage reduction in each of the three endpoint categories (damage to human health, ecosystem, and resources) for low-strength (13.8 MPa), normal strength (27.6 MPa), and high-strength (41.4 MPa) concrete mix designs with 10% and 20% fly ash replacements, respectively. In the figure, the greater the reduction, the better the environmental benefit of using fly ash.

For high fly ash replacement (20FA) at normal (27.6 MPa) and high-strength (41.4 MPa) concrete, there is a greater reduction in damages for all endpoint groups. However, at a lower strength (13.8 MPa) concrete mix (Figure 6.8), the 10% fly ash replacement mix outperforms the 20% fly ash mixture in terms of environmental performance (percentage reduction in endpoint damages). This can be explained by the fact that, in order to achieve the same 28-day compressive strength in the Philippines, concrete mixtures with higher fly ash replacements use more cement. Thus, the benefit of high fly ash replacement is not fully realized for low-strength concrete mix designs. This suggests that there is still room for improvement in the industry’s concrete mix designs by specifying long-term strength, i.e., 56 or 91 days rather than 28 days as the design strength. Furthermore, because of the slow rate of pozzolanic reaction, the beneficial impact of fly ash is most visible at later ages, i.e., longer than 28 days

(Imbabi, Carrigan, & McKenna, 2012). By comparison, for a 40 MPa concrete with 25% fly ash replacement of mass concrete mixture in Thailand, the damage to human health, ecosystem, and resources has been reduced by 29.4%, 28.2%, and 23.8%, respectively, when 56 days design strength is considered.

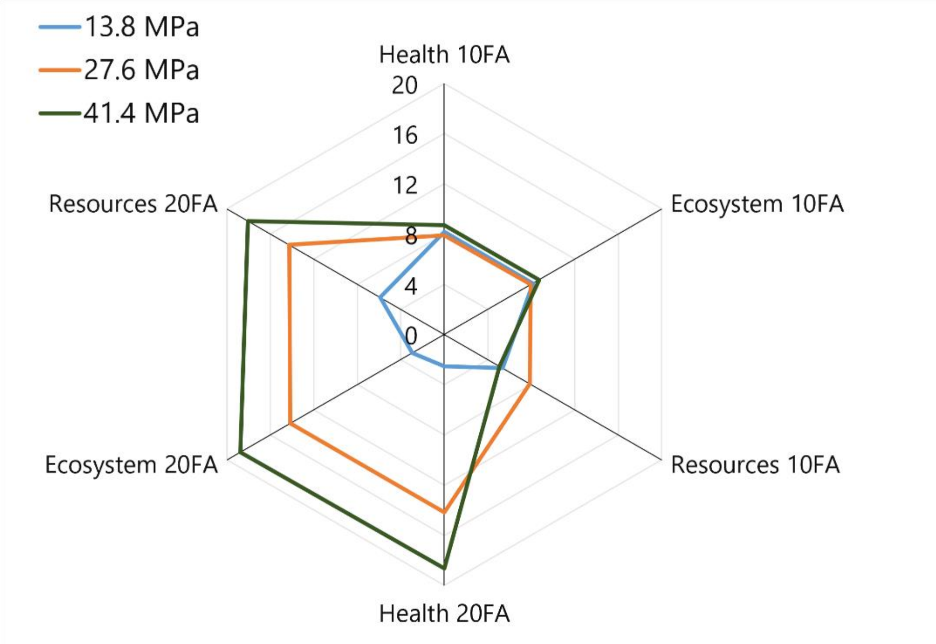

Figure 6.8 Percentage in reduction of the endpoint impacts of low (13.8 MPa), normal (27.6 MPa), and high (41.4 MPa) strength concrete with 10% and 20% fly ash replacements relative to pure cement (OPC) concrete from the Philippines

A single score is assigned to incorporate the entire environmental burden encompassing impacts on human health, ecosystem, and resources. This score is calculated in SimaPro and integrates various aspects of life cycle assessment results, including characterization, normalization, damage assessment, and weighting. The resulting single score, known as the environmental point or "Pt," allows for the relative differences between the 31 concrete mixes to be effectively compared. The higher the environmental point, the higher the impact of the corresponding concrete mixture. By utilizing this dimensionless unit, the overall environmental impact can be readily comprehended, thus facilitating effective communication with decision-makers.

Results (Figure 6.9) show that fly ash delivers more environmental benefits at higher 28-day compressive strength mix designs with higher cement replacement than at lower compressive strength mix designs.

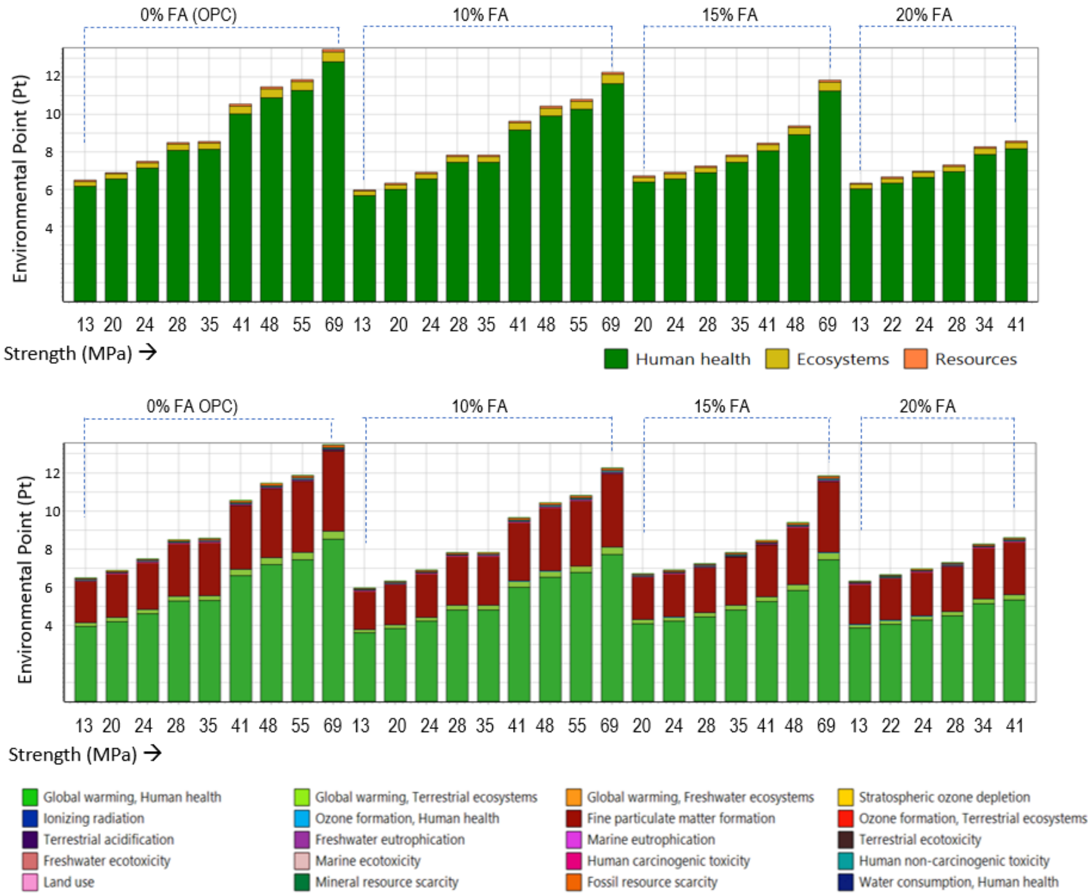

Figure 6.9 Contribution of midpoint and endpoint damage indicators to the overall environmental impact of Philippine concrete mixtures with various strengths and fly ash content

The environmental impact of concrete containing pure cement has been reduced by the following ranges when utilizing 10 to 20 percent fly ash as a replacement to cement in concrete: 2.16-18.65%, 2.55-18.65%, and 2.96-18.77% for Human Health, Ecosystem, and Resources, respectively. The greatest percentage decrease is obtained when 20% fly ash is used in high-strength concrete (41.4 MPa), whereas the smallest percentage reduction is obtained when a similar replacement is used in low-strength concrete (13.8 MPa). The more the amount of fly ash, the smaller the environmental effect, with pure cement concrete constantly producing the greatest environmental load. The results also demonstrate that health damage is the main contributing factor for all concrete mix designs. More than 90% of the environmental load is related to human health problems. This suggests that concrete production has a greater health impact than the environment and resources.

6.4 Contribution analysis

Figure 6.10 compares the impact of various concrete constituents for different concrete strengths. These include cement, sand, gravel, water, and admixture impacts. Here, we consider a low strength of 13.8 MPa and a high strength of 69.0 MPa concrete mix design. It is observed that the impact of sand on land use is more significant in lower-strength designs. On the other hand, chemical admixture significantly impacts marine eutrophication and fossil resource scarcity. Because admixture usage is also higher when the strength design is higher, the corresponding environmental impact is also higher. In general, cement has the most significant environmental impact.

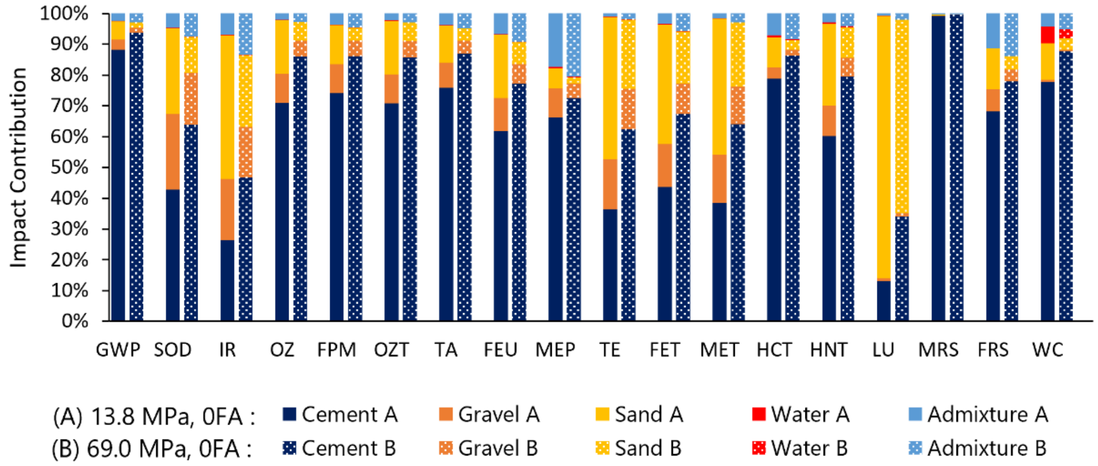

Figure 6.10 Contribution analysis for environmental impacts of concrete constituents for (A) low strength, 13.8MPa and (B) high strength, 69.0 MPa concrete (Philippines)

It is observed that the cement has the highest global warming potential (Figure 6.10), representing almost 90% of the total impact compared to other constituents. Additionally, cement contributes to almost 100% of the impact on mineral resource scarcity. These impacts are mainly because of the intensive processes involved in the mining and production of cement. The use of fly ash, which reduces the amount of cement in the concrete mixture, reduces this environmental impact significantly, especially for high-strength mass concrete (Fig 6c). The use of fly ash also resulted in reduced impact on land use. A contribution analysis for endpoint impacts shows that cement contributes the most to all the damage indicators. For example, for 13.8 MPa (Figure 6.11a) and 41.4 MPa (Figure 6.11b) concrete mixtures, this contribution is substantially more for human health (82.94%, 89.41%) and ecosystem (82.07%, 89.16%) damage than for resources (53.54%, 64.51%). A Spearman correlation analysis (Appendix E) reveals a very strong relationship between cement content and ecosystem damage (ρ=0.996) and human health (ρ=0.996).

At the lowest strength design (13.8 MPa), aggregates (sand and gravel) have a higher combined relative impact than cement on six impact categories: stratospheric ozone depletion, ionizing radiation, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, and land use. When concrete strength is increased, the impact of cement for 17 categories also increases, except for land use. Sand has the highest land use impact. Aggregates in concrete are composed of coarse and fine aggregates. Major sources of fine aggregates (sand) are quarrying activities in the river, while coarse aggregates are typically sourced through the mining of rocks. These aggregates have their fair share of environmental damage. A study by Ako et al. (2014) identified landscape destruction, water pollution, and deforestation as a consequence of gravel and sand mining. Global quarrying practices for coarse aggregates have significantly altered the ecological balance. In a 13.8 MPa concrete mixture with 20% fly ash as a replacement for cement, for example, the land use impact is primarily attributed to sand quarry operations, accounting for 81% of the total impact, followed by a minor contribution from hard coal mining and preparation (5%). Substance analysis indicates that the principal driver for this impact is the occupation of mineral extraction sites, comprising 86% of the overall impact.

For endpoint impacts, as shown in Figure 6.11a, the contribution of aggregates for low-strength (13.8 MPa) concrete mix are 14.07%, 15.21%, and 31.18% for human health, ecosystem, and resources, respectively. This is higher than in 41.4MPa (Figure 6.11b) concrete, with contributions of aggregates 7.91% for human health, 8.39% for the ecosystem, and 22.47% for resources. The lower contribution of aggregates for higher-strength concrete is also explained by the fact that they require larger paste content (lower aggregate content) compared with lower-strength concrete mixtures. In this study, the aggregates are mining products sourced from a significant distance. One of the Philippines' challenges is maintaining a sustainable and steady supply of aggregates. It is reported from stakeholder interviews that many batching plant operators are concerned with the future supply of aggregates in the country. This calls for sustainable practices such as the utilization of recycled aggregates. Again, the viability of recycled aggregates for applications to concrete has been reported in various studies (Tejas & Pasla, 2023; Xing, Tam, Le, Hao, & Wang, 2022), but actual use in the industry has not been realized. With the country experiencing a surge in development, the industry must fully commit to its efficiency goals to ensure the optimal use of the country's quarry resources.

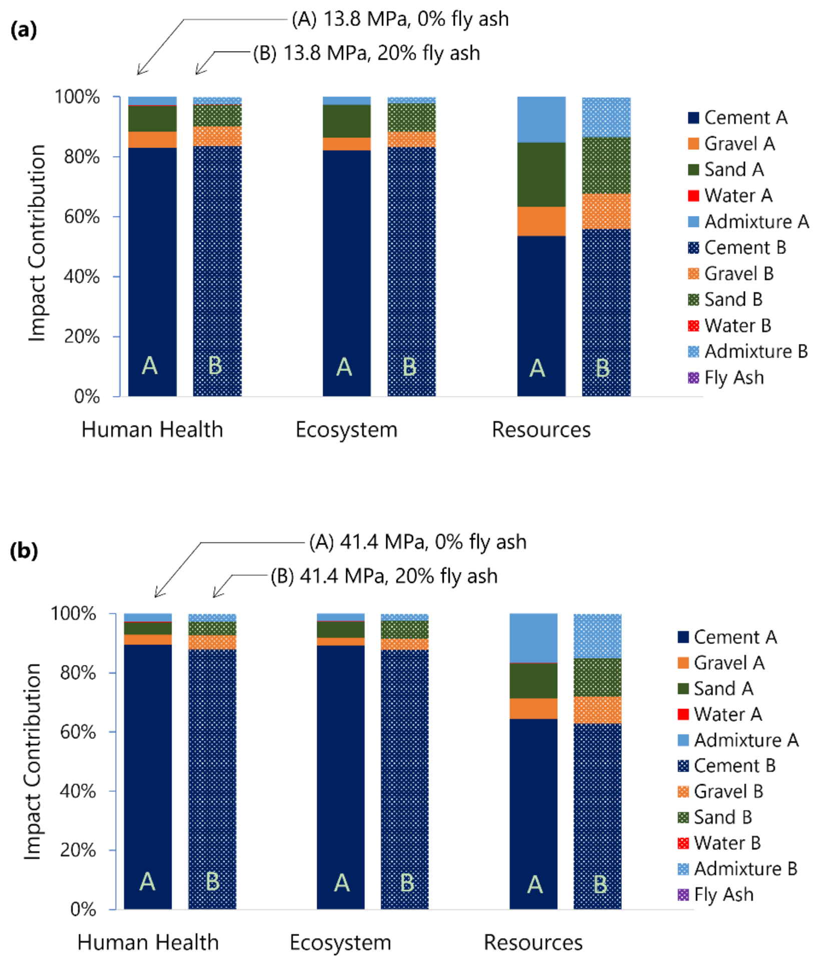

Figure 6.11 Contribution of concrete constituents to endpoint impacts of (a) low strength (13.8 MPa) and (b) high strength (41.4 MPa) concrete mixtures with 0% and 20% fly ash as cement replacements (Philippines)

The use of superplasticizers and water-retarding admixtures, which are common in the Philippines, also shows a significant impact, especially on marine eutrophication and fossil resource scarcity. Admixture is typically used to enhance specific concrete qualities in the fresh and hardened state (Corpuz, Rosei Monzon, Orozco, & Germar, 2021). This can include but is not limited to workability and consistency. The primary sources of admixture emissions are electricity and fuel. These admixtures are typically introduced at very low concentrations by the weight of the cement used. For all the mixtures considered, the average admixture utilized was 1.27 ± 0.17% by weight of the binder. However, even the low dosage of admixture contributes significantly to some of the midpoint impacts (IR, MEP, HCT, FRS), as shown in Figure 6.10, as well as damage to resources. The impact associated with resources accounts for 16.79% of 41.4 MPa concrete (Figure 6.11b). A strong correlation was found using the Spearman correlation (Appendix E) for all the damaged resources and the use of admixture (ρ=1.00). This demonstrates that enhancing plasticizer production (or decreasing consumption) is another viable option for sustainable concrete manufacture. Few researchers have examined the environmental effects of incorporating chemicals into concrete. Xing, Tam, Le, Butera, Hao, et al. (2022) stated that there is insufficient evidence to conclude the relationship between chemical admixture use and each environmental effect indicator. Conversely, Ji et al. (2022) reported a substantial impact of plasticizers. Their research quantified that the contribution of plasticizers to resource damage is 44.9% when employed in typical off-site ultra-high-performance concrete. Plasticizers are often made from petroleum feedstocks, which, throughout the manufacturing process, result in the production of certain chemical components, including SO_x and NO_x. These acidic gases, when emitted, will settle on land or water and modify the pH value, causing damage to the ecosystem (Jamarani, Erythropel, Nicell, Leask, & Marić, 2018). Excessive usage of chemical admixture may be detrimental to marine life in the long run and is a cause for concern given the Philippines' vast water body as an archipelagic country.

Using water in concrete does not significantly contribute to CO_2 emission but contributes approximately 5% to water scarcity. Water sources usually are groundwater or surface water. Excessive production of concrete may significantly lead to potential competition in water extraction from this source. In addition, indiscriminate disposal of concrete in construction sites may also lead to water pollution in nearby water bodies.

6.5 Economic Analysis

The total cost per cubic meter of each concrete mix is calculated by multiplying the material amount (kg/m^3) by the unit cost (USD/kg). Figure 6.12 depicts the cost per cubic meter of concrete mixtures in US dollars. Material costs rise in tandem with strength, owing mainly to the high cement content, which accounts for more than half of the entire cost (59.07% on average). It can be seen that the concrete mixtures produced with pure OPC have the highest material cost compared to when fly ash is utilized at 10%, 15%, and 20% replacements for high-strength concrete mixtures.

When compared to a cement-only mixture, a 20% fly ash replacement of 41.4 MPa concrete results in an 8% (5.39 USD) cost savings per cubic meter. The results reveal that the economic benefit of using fly ash is greater for high-strength concrete mixtures than for low-strength concrete mixtures. For a 13.8 MPa concrete mixture, for example, replacing OPC with 10% fly ash saves only 1.07 USD. Remarkably, the substitution of OPC with 20% fly ash in a low-strength (13.08 MPa) concrete mixture incurs an additional cost of 1.64 USD. This suggests that there is no significant additional economic benefit to increasing the fly ash substitution from 10% to 20% using the current design practice of the surveyed batching plants. Data demonstrates that concrete batching plant operators in the Philippines, whose primary motive for employing fly ash is cost reductions, do not benefit from greater savings when using more fly ash for lower-strength designs. The fundamental reason for this is that reaching the same 28-day strength with the 20% fly ash mix design would necessitate more binder and, hence, more cement. The potential cost savings for concrete mixtures with 10%, 15%, and 20% fly ash replacement of cement range from 0.70% to 3.01%, 0.03% to 9.75%, and 3.68% to 7.99%, respectively, compared to conventional pure cement concrete mixtures.

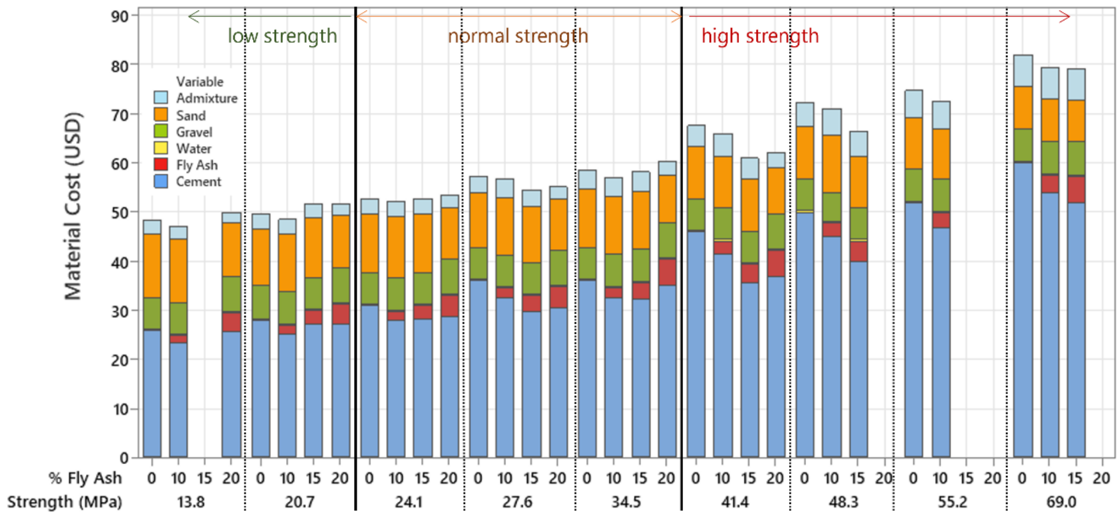

Figure 6.12 Material cost per cubic meter of low, normal, and high-strength Philippine concrete mixtures with varying fly ash as cement replacement

The average admixture used in all the mixes studied was 1.27 ± 0.17% by weight of the cement. Even a small amount of admixture addition significantly impacts cost due to its high unit price. The contribution of admixture amounts to 6.25% of the overall cost on average. On average, gravel and sand contribute 11.2% and 18.9% of the total cost per cubic meter, respectively. The cost of water per cubic meter of concrete remains negligible at 0.50%, whereas fly ash contributes to an average of 5.66% of the total cost.

6.6 Comparison with mass concrete in Thailand

The Philippines' pure-cement concrete exhibits a slightly lower global warming potential (GWP) of 342 kg CO_2 eq than the Thai mixture at 344 kg CO_2 eq, primarily due to its reduced cement usage. However, adding chemical admixtures offsets this lower cement content, which results in heightened impacts in other midpoint categories, mainly marine eutrophication and fossil resource scarcity. Compared to the Philippines mixture (Figure 6.13), the pure cement mix from Thailand demonstrates lower environmental impacts across 16 categories. Contribution analysis reveals that clinkerization accounts for nearly 80% of the GWP.

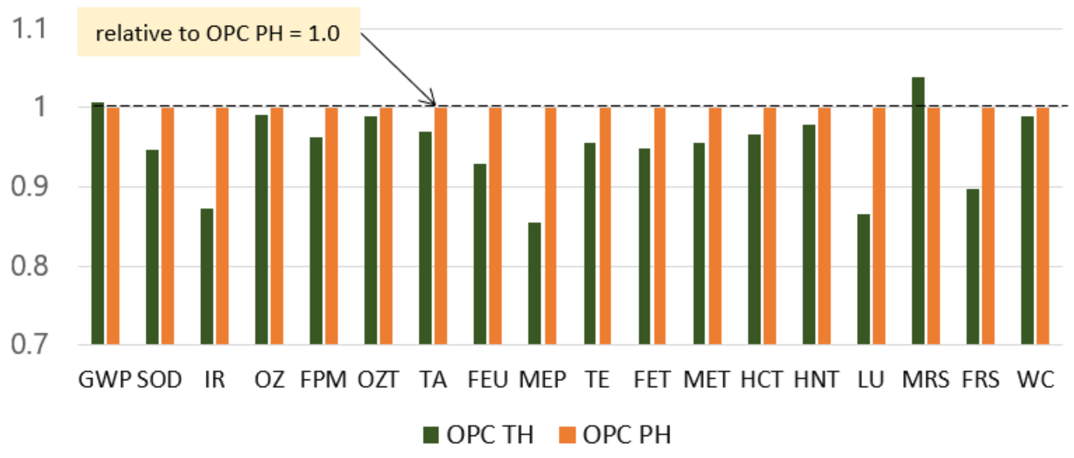

Figure 6.13 Comparative midpoint impacts of pure-cement 35 MPa mass concrete mixtures from Thailand and the Philippines

As indicated in Figure 6.14, The incorporation of fly ash consistently reduces all environmental impacts compared to pure cement mixtures. Thailand concrete mixtures utilizing fly ash have lower midpoint impacts than the Philippine mixture (20FA) in the range of 11-28% (FAM25) and 21-46% (FAM50). In Thailand, fly ash at 25% and 50% replacement levels reduces concrete's GWP by 22-23% and 43-46%, respectively. In the Philippines, a 20% fly ash replacement yields around 8% reduction (315 kg CO_2 eq) due to the increased cement content necessary to achieve the same 28-day compressive strength. According to Figure 6.14b, the most significant parameters are GWP, OZ, OZT, TE, HCT, and FRS. They all have a normalization score greater than 0.02. Figure 6.15 depicts the respective values for these midpoint indicators. This graph shows the significant beneficial impact of 50% fly ash (Thailand) use on all indicators.

As mentioned previously, one of the primary concerns with the mass concrete practice in the Philippines is that the concrete mixtures are designed to achieve the specified strength at 28 days, even when utilizing fly ash. Figure 6.15 shows that the environmental benefit of using fly ash is more evident when the age is 56 days rather than 28 days. Higher levels of fly ash substitution will also result in greater environmental advantages. When OPC concrete (Philippines) was compared to concrete with 50% fly ash (Thailand), a considerable reduction in environmental effect was seen for the 50% fly ash mixture. When comparing ordinary Portland cement

(OPC) concrete to concrete with 50% fly ash, the most substantial reductions occur in mineral resource scarcity (MRS, 49.6%), GWP (46.4%), and water consumption (WC, 44.2%). Reduced cement usage significantly contributes to the GWP and MRS reductions, as it translates to lower mineral consumption in cement production. For WC, the reduction stems from fly ash's ability to decrease the water demand in concrete (Burgos-Montes, Alonso, & Puertas, 2013), allowing for a lower water content compared to OPC concrete with similar workability. Other indicators such as IR, TE, FET, MET, and LU improved significantly compared to pure cement concrete but only slightly when compared to 25% fly ash replacement, as seen in Figure 6.14a.

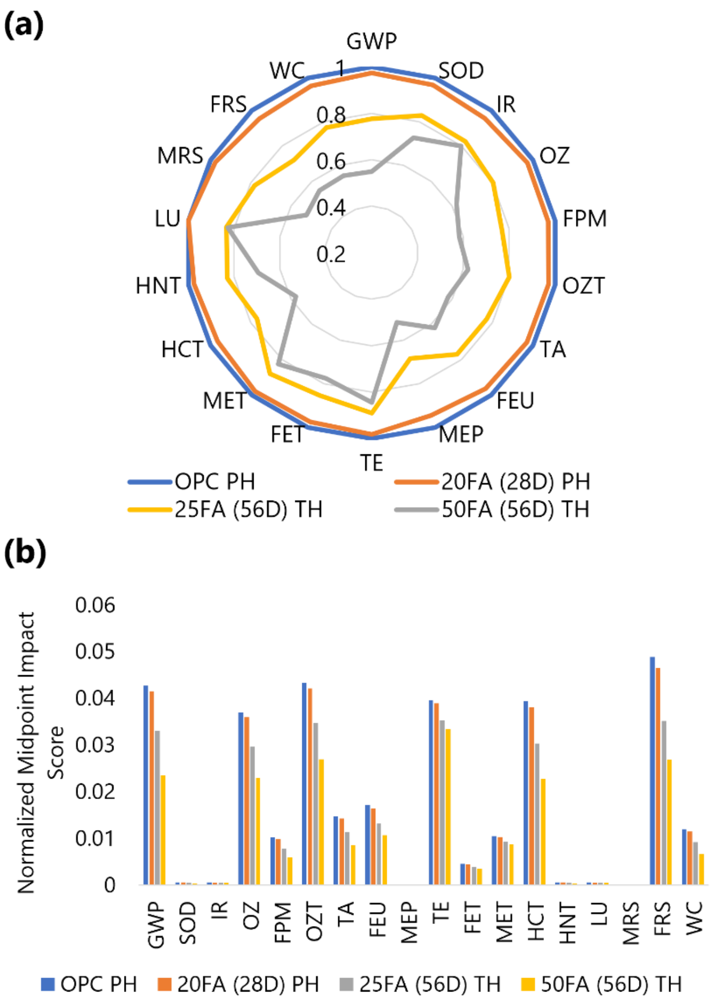

Figure 6.14 Comparative environmental impacts of Philippines and Thailand concrete mixtures for 35 MPa concrete: (a) characterization (b) normalization

The contribution of significant processes and utilities on GWP and TE, two significant environmental impacts, are shown in Figure 6.16. GWP is predominantly affected by clinkerization (nearly 80%), according to a contribution analysis shown in Figure 6.16a. This study verified prior findings that lowering cement significantly influences reducing the GWP associated with concrete mixtures. However, ecotoxicity indices such as TE are more affected by brake wear emissions than by the clinker manufacturing process (Figure 6.16b).

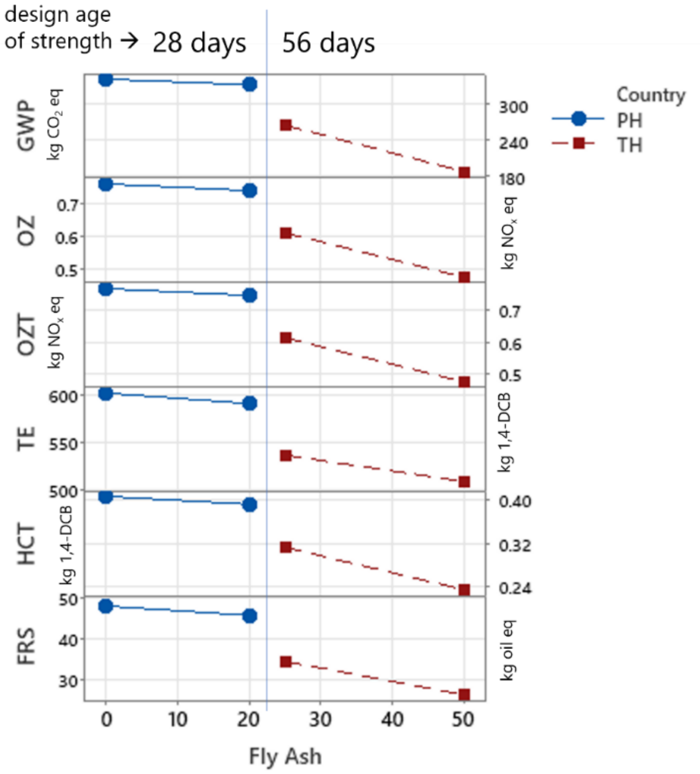

Figure 6.15 Comparison of environmental performance for 35 MPa mass concrete mixture in Philippines and Thailand for significant midpoint impacts

The terrestrial ecotoxicity of concrete with 50% fly ash replacement (Thailand) is 79%, which is contributed by brake wear emission and only 13% due to clinkerization, as shown in Figure 6.16b. The brake wear emission contribution observed for concrete mix with 50% Thai fly ash is higher than in pure OPC concrete (Philippines) due to the transportation of fly ash. This shows that transportation influences this ecotoxicity indicator more than cement consumption. In comparison to CO_2 emissions, greenhouse gas emissions, and global warming potential, the environmental effect categories of ecotoxicity, such as TE, FET, and MET, are less frequently explored in concrete literature. Ecotoxicity is the release of organic substances and chemicals into the air, water, and land, which impacts the surrounding ecosystem. Another factor to consider is the transportation of supplementary cementitious materials. If fly ash is limited nearby, its usage in concrete may be restricted further due to transportation costs and environmental impact.

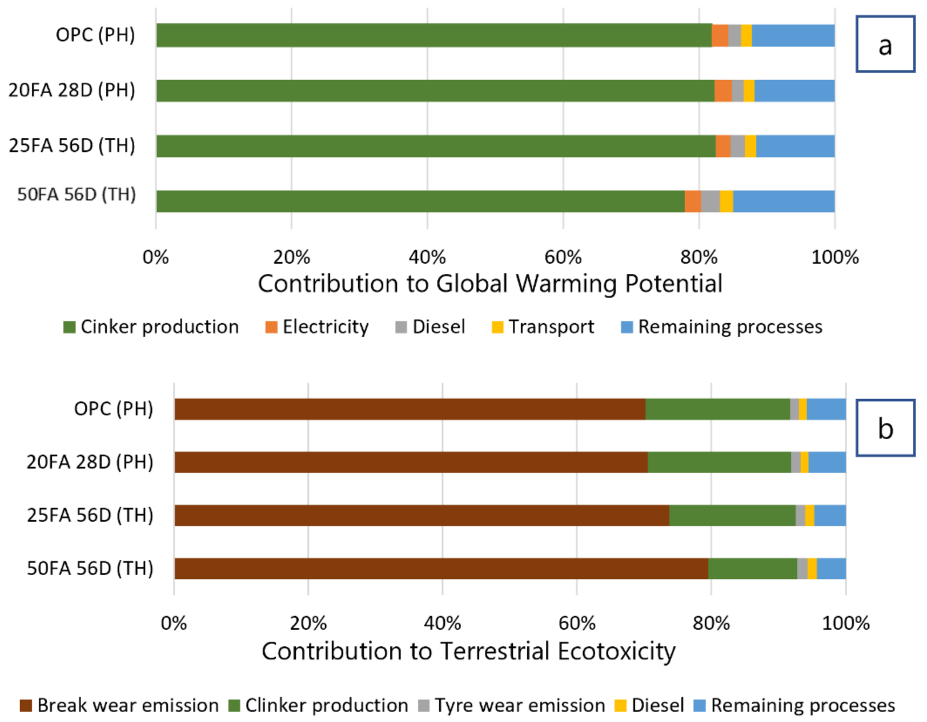

Figure 6.16 Processes and utilities contributing to (a) global warming potential and (b) terrestrial ecotoxicity for 35 MPa mass concrete mixture from Philippines and Thailand with 28 and 56 days specified design age

6.7 Summary

Higher substitution of cement with fly ash has shown a positive effect on the design of high-strength concrete, resulting in a substantial reduction of the environmental impact across all 18 midpoint and three endpoint categories. Conversely, concrete with lower strength designs exhibits a greater impact on land utilization compared to concrete with higher strength. Global warming and fine particulate matter generation are the most significant contributors to human health damage. Terrestrial acidification, ozone formation, and land use are the other major drivers of damage related to the ecosystem. An analysis of the environmental impact of concrete constituents reveals that cement has the greatest impact in all cases. High fly ash replacement was found to be less beneficial for lower-strength mixtures with a 28-day specified age design. The greater quantity of aggregates incorporated into the concrete mixture leads to increased land use impact, while increased admixture results in an increased impact on marine eutrophication and fossil resource scarcity. Designing the mixtures for a longer specified strength age of 56 days significantly improved the sustainability of mass concrete utilizing fly ash as partial cement replacement compared to the 28-day specified age design. The economic benefit of using fly ash is greater for high-strength concrete mixtures than for low-strength concrete mixtures. Transportation has a substantial impact on the ecotoxicity indicator. The use of admixture in mass concrete production has a significant impact on resource damage.

CHAPTER 7
CHALLENGES AND OPPORTUNITIES FOR SUSTAINABLE UTILIZATION OF WASTE MATERIALS IN PHILIPPINE CONCRETE CONSTRUCTION INDUSTRY

This Chapter delves into the social dimensions, challenges, and opportunities surrounding the sustainable utilization of fly ash as a partial cement replacement for mass concrete in the Philippines. A comparative examination of fly ash utilization practices for mass concrete production in both the Philippines and Thailand has been conducted to pinpoint areas for improvement. Leveraging strengths, identifying weaknesses, exploring opportunities, and assessing threats (SWOT analysis) along with the Drivers, Pressures, States, Impacts, and Responses (DPSIR) framework, this chapter aims to formulate robust policy recommendations. These recommendations are based on the findings of environmental and economic analyses presented in the preceding Chapters.

7.1 Social, institutional, economic, and technical aspects: interview results

An in-depth, semi-structured interview with the various experts provided insight into the current institutional, economic, social, and technical aspects that impede the broader adoption of waste materials in concrete construction. The major points are summarized as follows:

a. *Social and Institutional*. The experts indicated that there is a widespread belief in the construction industry that using waste material results in a lower-quality concrete product (compared to pure cement concrete), which has a negative impact on the performance of concrete structures. Furthermore, the current regulatory framework does not actively promote the use of these waste materials in concrete production. This is seen as a significant barrier to its widespread use. In addition, industrial by-products and wastes are commonly associated with toxicity and health risks. Sustainability is also not well-appreciated in the industry due to a lack of awareness among concrete producers, contractors, and consumers about the benefits of sustainable concrete production and the impacts of unsustainable practices.

b. *Economic.* One key economic impediment is an overemphasis on the initial cost of concrete construction, with the long-term benefits of waste material utilization being underappreciated. The interviewees mentioned that, to the best of their knowledge, many batching plant operators are concerned about the increased costs of integrating new technology, methods, and/or materials for large-scale concrete applications. Another major issue for certain waste by-products (i.e., slag, rice husk ash) is the country's unstable local supply. Importing these materials (i.e., slag) will incur additional costs. Only fly ash from coal-fired power stations is now accessible in a constant supply. The country's high proportion of coal-fired power plants is one of the critical reasons for the widespread use of fly ash. Geographical issues are also important economically, as some waste goods must be transported by water due to the country's archipelagic character. However, due to their durability benefits for the marine environment, the Philippines' expansive coastlines present an outstanding potential for fly ash in marine concrete.

c. *Technical.* Another hindrance is a lack of technical knowledge in managing innovative ingredients for concrete mixtures. Many concrete technicians are uncertified since certification is not yet required by regulations. More research is needed to develop effective quality control methods for ensuring the consistent and reliable use of fly ash in mass concrete production. Currently, Philippine codes and practices place a high importance on concrete strength performance. As a result, technological resources for durability testing are limited. Concrete must be exceptionally durable due to the country's extended wet season and high humidity. Certain by-products, such as fly ash, slag, and rice husk ash, may help in this respect. Furthermore, one expert interviewee observed a lack of strong linkage between the university and the industry. While the Philippine universities have done multiple studies on various waste materials, most of these have been conducted in academic laboratories and have not been scaled up for industrial application.

7.2 SWOT analysis and DPSIR framework

A Strengths, Weaknesses, Opportunities, and Threats or SWOT analysis (Figure 7.1) was conducted based on the results of key stakeholder interviews and case studies (Appendix F). The SWOT analysis is used to formulate recommendations for promoting the use of waste material in concrete construction in the Philippines. At the moment, there is a lot of room for improvement in the current practice. Laws and regulations must be strengthened to ensure that sustainability is incorporated in concrete production. Proactively promoting waste materials in concrete construction industries is necessary. One way to motivate businesses to practice sustainability, particularly for government-funded projects, is to provide them with the necessary incentives.

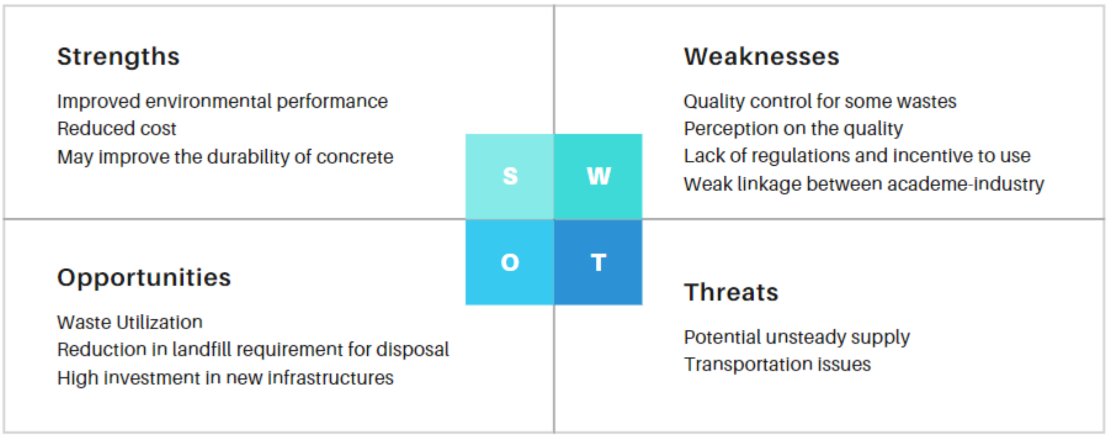

Figure 7.1 SWOT Analysis of the utilization of waste materials in concrete in the Philippines

Consequently, there arises a necessity to integrate sustainability analysis into policies to enhance their comprehensiveness and informed decision-making. To address this need, a proposed framework (Figure 7.2) is introduced, designed to incorporate the multifaceted environmental, economic, and social dimensions inherent in sustainable fly ash utilization using the DPSIR framework. This framework facilitates the formulation of policy recommendations by encompassing the complex interplay of factors associated with fly ash utilization.

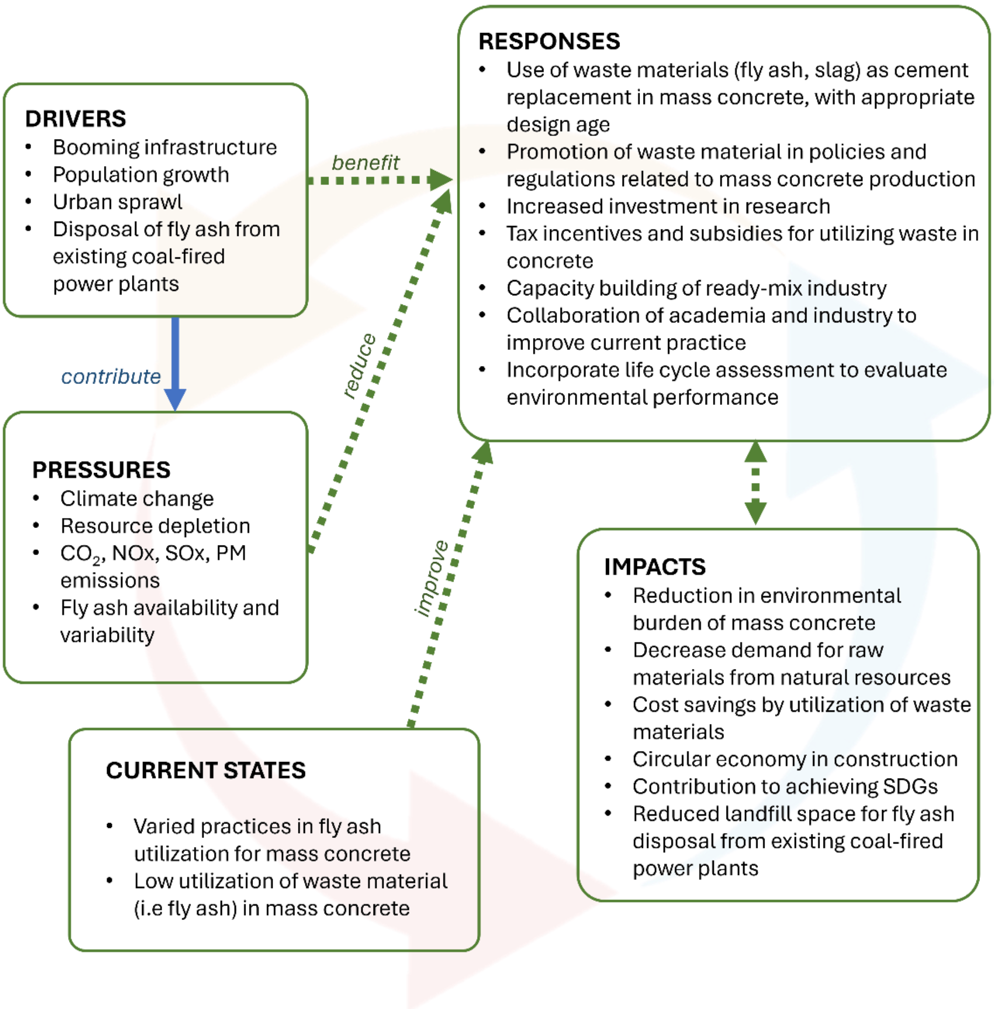

Figure 7.2 DPSIR framework for sustainable fly ash utilization in mass concrete for the Philippines

7.3 Improving the current practice: comparison between Philippine and Thailand

Significant barriers to using fly ash as a cement substitute in mass concrete include institutional, economic, social, and technical dimensions. The Philippines can learn from Thailand's success with high fly ash use. A general comparison is shown in Table 7.1.

The higher percentage of fly ash used as a cement replacement in Thailand (25-50%) compared to the Philippines (10-20%) suggests a stronger emphasis on fly ash utilization in Thai mass concrete production. This higher utilization rate in Thailand indicates a greater awareness of the benefits of fly ash and more established practices for incorporating it into concrete mixes. The presence of local standards and a manual of practice promoting fly ash utilization in Thailand, in contrast to the reliance on US standards in the Philippines, indicates a more structured and supportive regulatory framework for fly ash utilization in Thailand. This regulatory environment may contribute to higher confidence in fly ash quality, consistency, and performance among stakeholders in Thailand, facilitating its broader adoption in mass concrete applications.

Table 7.1 Comparison of Philippines and Thailand fly ash practices and conditions

Aspect	**Philippines**	**Thailand**
% fly ash used as cement replacement	10-20%	25-50%
Source of fly ash	Coal-fired power plants, varied sources all over the country	Mostly from Mae Moh and BLCP coal-fired power plants
Design strength for fly ash concrete	28 days	56 days
Global warming potential reduction of fly ash concrete compared to pure cement	<20%	> 40%
Type of fly ash commonly used	Class F (ASTM, US standard)	low and high CaO (Thai Standard)
Utilization of fly ash in the concrete industry	limited	widespread
Regulation or standard specification	adopts US standards, no local standard of practice	promoted through manual of practice, local standards available
Mode of transport of fly ash	Land, water	Land

At present, no specific Philippine law or regulation directly requires the use of waste materials for concrete construction. Many of the existing codes and regulations have yet to incorporate sustainability, such as in the National Building Code of the Philippines (NBCP) for vertical construction and in the guidelines for public infrastructure projects issued by the Department of Public Works and Highways (DPWH). However, it is critical to emphasize that no rule bans waste materials from being used in private or public infrastructure projects. Concrete mix design regulations are performance-based. In the Philippines, concrete is proportioned according to the American Concrete Institute's Code 211.1 or Standard Practice for Selecting Proportions for Normal-Density and High-Density-Concrete.

Philippine regulations permit the use of fly ash, slag, limestone powder, and other pozzolans. Figure 7.3 depicts the present waste stream of these materials in the Philippines. If left unused, these materials will typically end up in landfills and take up space. For rice husk ash, open burning practice in rural areas is also rampant. In the Philippines, waste materials are disposed of in accordance with Republic Act (RA) 9003, the Ecological Solid Waste and Management Act, and Republic Act 6969, or the Toxic Substances and Hazardous and Nuclear Wastes Control Act. RA 9003 governs general municipal solid wastes, while RA 6969 was enacted to regulate, control, and oversee activities involving poisonous substances and hazardous waste. The Department of Trade and Industry (DTI) is a critical component of the cement industry's economic regulation. Violations of these regulations due to non-compliance with quality requirements may result in the closure of factories. New standards for the required certification of Portland Cement and Blended Hydraulic Cement with Pozzolan are contained in the Department Administrative Order (DAO) of DTI. Numerous Philippine National Standards (PNS) on cement and concrete are based on American Society for Testing and Materials (ASTM) specifications (ASTM). The Philippine Clean Air Act of 1999 regulates the cement industry's emissions, and its rules and regulations are administered by the Department of Environment and Natural Resources (DENR).

The difference in design strength for fly ash concrete between the two countries (28 days in the Philippines vs. 56 days in Thailand) may reflect variations in construction practices, performance requirements, and durability considerations. The longer design strength duration in Thailand suggests a focus on achieving higher levels of strength and durability in concrete structures, which may be influenced by local building codes, standards, and project specifications. In the Philippines, admixture is used to compensate for the delayed strength development of fly ash concrete. This often affects both the cost and environmental performance of concrete mixtures, such as global warming potential, among others. The substantial reduction in global warming potential achieved by using fly ash concrete compared to pure cement in Thailand (>40%) indicates a strong environmental incentive for fly ash utilization in Thai mass concrete production. This significant reduction suggests that the environmental benefits of fly ash utilization may be more pronounced in Thailand than in the Philippines.

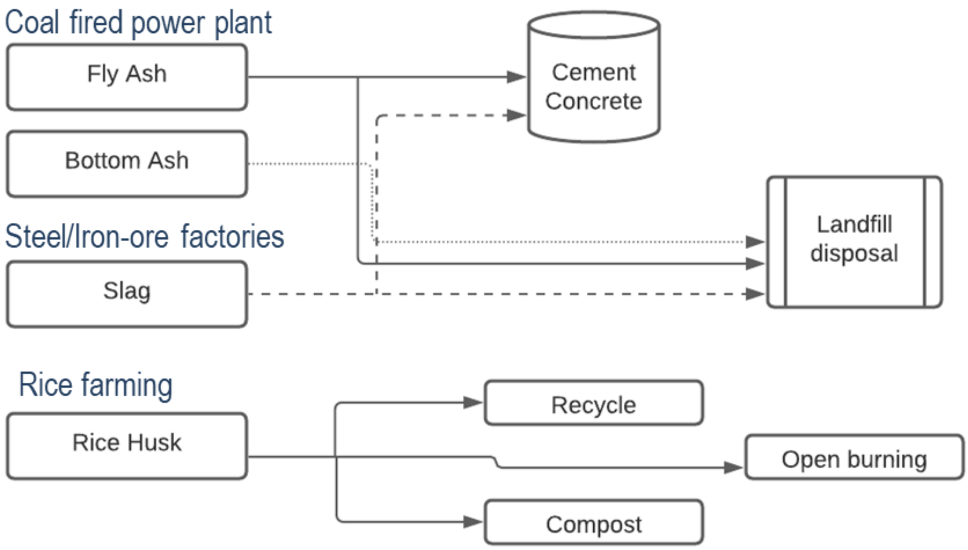

Figure 7.3 Waste materials in the Philippines with potential as cement replacements in mass concrete

The centralized sourcing of fly ash from specific coal-fired power plants in Thailand, such as Mae Moh and BLCP, may contribute to more consistent quality and availability of fly ash compared to the Philippines, where fly ash is obtained from various power plants across the country. This centralized sourcing in Thailand could lead to more reliable supply chains and potentially lower transportation costs. The difference in the mode of transport of fly ash between the two countries (land and water in the Philippines vs. primarily land in Thailand) may reflect variations in infrastructure, geography, and logistical considerations. The reliance on land transport in Thailand may be more cost-effective or logistically feasible due to factors such as proximity to power plants, road networks, and transportation infrastructure. Results from this study suggest that when long distance is considered, factors such as ecotoxicity and global warming may be greatly affected.

Overall, the comparative analysis highlights several key differences and similarities in fly ash utilization practices between the Philippines and Thailand, with implications for industry stakeholders, policymakers, and researchers interested in promoting sustainable concrete production practices.

7.4 Opportunities for sustainable fly ash utilization in the Philippines

Sustainable practices should be explored not only for cement replacement but also for other concrete materials, such as aggregates and chemical admixtures. The following are identified opportunities for sustainable fly ash utilization in the Philippines based on the results of environmental and economic impact assessment and key stakeholder interviews:

a. High fly ash replacement demonstrates greater benefits at higher concrete strength levels, providing an opportunity for improvement in the Philippine concrete industry.
b. Specifying concrete strength at later ages can maximize the environmental benefits of fly ash at high replacement, particularly in the context of mass concrete.
c. Further research is needed to optimize the use of fly ash in concrete production, including determining ideal mix proportions and processing techniques. Enhanced collaboration between academia and industry is essential to improve current practices.
d. Strengthening laws and regulations is necessary to integrate sustainability into concrete production, with active promotion of waste materials within the industry. A supportive environment that fosters sustainability in construction, encompassing legal and economic aspects, should be established.

e. Policies governing the use of cement-replacing materials should consider sustainability analysis to provide comprehensive and informed guidelines. Current regulations and standards for concrete production in the Philippines may require further development to ensure sustainability, necessitating more comprehensive and stringent policies.

7.5 Policy recommendations for the Philippines

The following are policy recommendations to promote the transition to more environmentally friendly and socially responsible concrete production:

a. Emissions regulations and environmental performance evaluation:

- Set emissions regulations and limitations for concrete production facilities, including requirements for particulate matter, nitrogen oxides (NO_x), sulfur dioxide (SO_2), and carbon dioxide (CO_2) emissions.
- Mandate environmental performance evaluation through life cycle assessment to provide a more comprehensive assessment of environmental impact beyond just global warming potential. Assessment could focus on other significant impacts (in addition to global warming potential) identified in this study, including ozone formation, fine particulate matter, terrestrial acidification, freshwater eutrophication, toxicity, fossil resource scarcity, and water consumption.

b. Promotion of supplementary cementitious materials (SCM):

- To maximize environmental advantages, prescribe minimum percentages of supplementary cementitious materials (SCMs), such as fly ash, with a maximum limit determined by performance. For example, consider a minimum of 15% fly ash as cement replacement for mass concrete within the next five years. This can be increased to 25% in the future when appropriate guidelines and codes of practice are developed, similar to Thailand's experience.
- Specifically for fly ash, a longer design strength (e.g., 56 days from the current 28 days) for mass concrete applications is recommended to maximize environmental advantages.

- Critical distance analysis should be included in assessing the source of raw materials. Global warming potential and ecotoxicity can be used as environmental indicators to determine critical distance.

c. **Financial incentives for sustainable concrete production:**

- Provide financial incentives for using waste materials as cement replacements for mass concrete. These incentives could be in the form of tax breaks or tax credits to ready-mix batching plants or concrete construction companies. Prioritize the use of local waste materials to support regional sustainability efforts.

d. **Integrate sustainable practices in government infrastructure projects:**

- Government infrastructure projects can mainstream the use of waste materials in concrete production by requiring government contractors to either minimum usage of waste as cement replacement or maximum embodied carbon. Specifically, a minimum of 15% fly ash as cement replacement may be required for normal-strength mass concrete and 20% fly ash for high-strength mass concrete infrastructures.

e. **Support for research and collaboration:**

- Support and provide funding for collaborative research activities across academia, industry, and government agencies to address critical difficulties in sustainable concrete production, such as optimizing the concrete mix design, lowering embodied energy, and improving durability and performance.

f. **Training and education:**

- Create training programs, workshops, and certification programs for concrete industry professionals, engineers, architects, and construction workers to increase understanding of sustainable concrete production.

7.6 Summary

Significant barriers to using fly ash as a cement substitute in mass concrete include institutional, economic, social, and technical dimensions. These barriers are primarily driven by the industry's assumption that incorporating waste materials, such as fly ash, compromises concrete quality and the lack of recognition for the long-term benefits of waste material utilization in the Philippines. Furthermore, the weak connection between academia and industry hinders the implementation of state-of-the-art findings in large-scale industrial applications. It is essential to enhance laws and regulations that incentivize the use of waste materials to promote sustainable concrete production. Future research may explore the sustainability of other waste materials for mass concrete applications.

CHAPTER 8
CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary and conclusion

Environmental and economic assessments for 58 mass concrete mixtures reveal significant reductions in global warming potential and other environmental burdens with partial fly ash substitution of cement, particularly in higher compressive strength designs. Higher substitution of cement with fly ash has shown a positive effect, resulting in a substantial reduction of the environmental impact across all 18 midpoint and three endpoint categories.

Fly ash type and transportation distance affect the environmental performance of mass concrete based on an analysis of Thailand mixtures. Independent of fly ash transportation, high CaO fly ash concrete exhibits better environmental benefits compared to low CaO fly ash concrete. Using high CaO fly ash, the reduction in environmental load is greatest for mineral resource scarcity, global warming potential, and water consumption compared to low CaO fly ash for high strength and high fly ash replacement without fly ash transport. Global warming and fine particulate matter generation are the most significant contributors to human health damage caused by concrete production. Terrestrial acidification, ozone formation, and land use are the other major drivers of damage related to the ecosystem. Transportation has a substantial impact on the ecotoxicity indicator.

The use of 65% ground granulated blast furnace slag (GGBS) as a cement replacement in Thailand's mass concrete shows significant reductions in global warming potential, ozone formation, and fossil resource scarcity compared to pure cement concrete. However, GGBS processing contributes significantly to marine eutrophication and human carcinogenic toxicity. The long-distance import of GGBS substantially influences the environmental performance of GGBS concrete, surpassing that of pure cement mixtures in 15 impact categories. Endpoint indicators underscore GGBS's better environmental performance when transportation is omitted or when sourced locally.

High fly ash replacement was found to be less beneficial for lower-strength mixtures with a 28-day specified age design, as evident in the assessment of Philippine concrete mixtures. Concrete with lower strength designs exhibits a greater impact on land utilization compared to concrete with higher strength. The use of chemical admixture results in an increased impact on marine eutrophication and fossil resource scarcity. Designing the mixtures for a longer specified strength age of 56 days significantly improved the sustainability of mass concrete utilizing fly ash as partial cement replacement compared to the 28-day specified age design, including economic benefits.

Challenges to waste material adoption in the concrete industry were identified, including institutional, economic, social, and technical barriers. To address these challenges and promote sustainability, policy recommendations, and a comprehensive roadmap are proposed, emphasizing longer design ages and improved regulations to incentivize waste material utilization. This study contributes valuable insights for policymakers, manufacturers, engineers, and researchers to advance sustainable concrete production practices.

8.2 Recommendations and future research prospects

Future studies should focus on a thorough investigation of improving sustainability in mass concrete that incorporates waste materials. This could entail conducting additional research into refining the composition of concrete mixtures to optimize environmental benefits while retaining structural integrity. The following are some recommendations for further research which build on the findings of this study:

a. End-of-life management measures may be incorporated into life cycle assessment, focusing on concrete disposal and recycling possibilities. A cradle-to-grave analysis will allow for a full examination of the whole lifecycle of these components in concrete, including the use of waste as cement replacement materials. The durability and service life of concrete may be added to the present model for this research.
b. Regional variations in transportation infrastructure, as well as developing innovations in transportation modes, merit more examination due to their major impact on environmental consequences based on the findings of this study.

These possibilities involve using electric vehicles, comparing rail and truck transportation, and differences in fuel kinds, among others. Understanding how transportation logistics affect the overall sustainability of concrete manufacturing will allow for the creation of more efficient supply chains and transportation procedures. Critical transportation for various strength designs and midpoint or endpoint indicators may also be performed considering return trips of empty vehicles.

c. Scenario analysis employing various energy mixes for extracting and processing concrete raw materials could shed light on the impact of energy sources on the overall sustainability of concrete manufacturing, assisting in identifying pathways for lowering carbon emissions and reliance on fossil fuels.

d. Conducting uncertainty analysis with Monte Carlo simulation techniques can provide useful insights into the robustness of sustainability assessments and assist stakeholders in making decisions across a variety of conditions and scenarios.

e. Undertake an expansive social assessment encompassing dimensions of equity, inclusion, justice, and employment, among other pertinent factors, within concrete production, particularly focusing on waste utilization as a replacement for cement.

f. Integrate comprehensive lifecycle cost analysis and detailed economic feasibility studies into sustainability assessments to capture the long-term economic benefits of using fly ash in concrete. This should account for the extended service life, potential savings in waste management, as well as detailed cost-benefit analyses considering factors such as availability, transportation, processing costs, and market demand. Assessments should include potential cost savings from reduced cement usage and possible financial incentives for waste material utilization.

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APPENDICES

APPENDIX A

SCATTERPLOT OF MIDPOINT IMPACTS OF MASS CONCRETE FROM THAILAND WITH LOW AND HIGH CAO FLY ASH

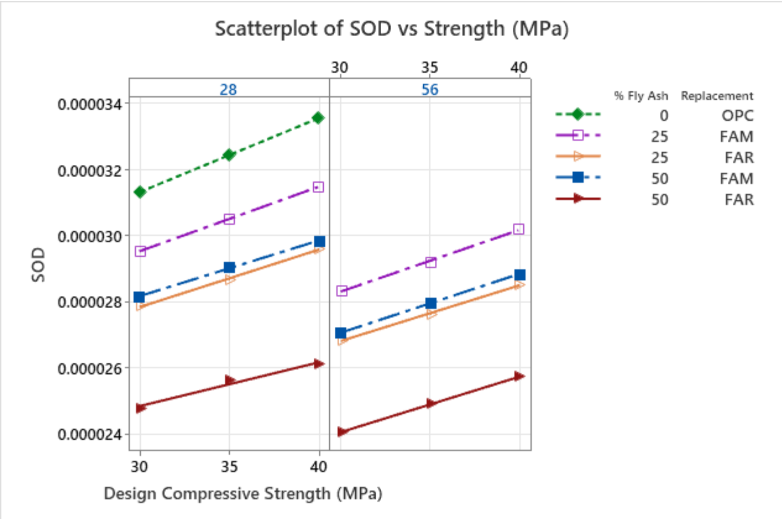

Figure A.1 Scatterplot of SOD vs compressive strength

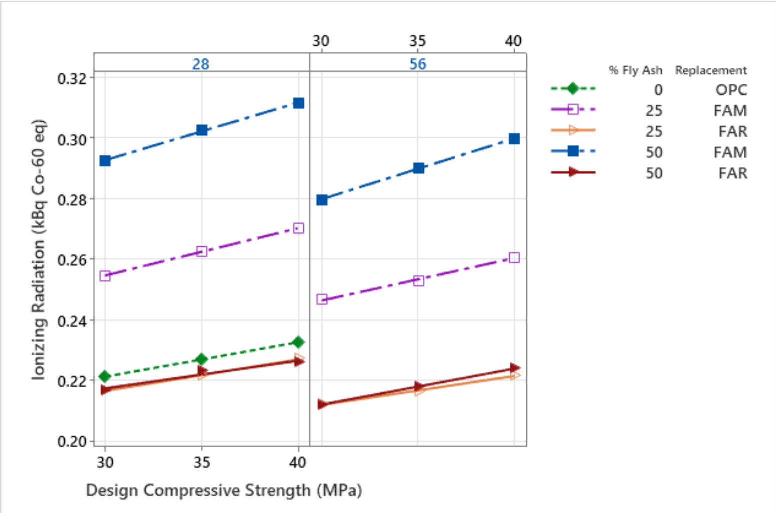

Figure A.2 Scatterplot of IR vs compressive strength

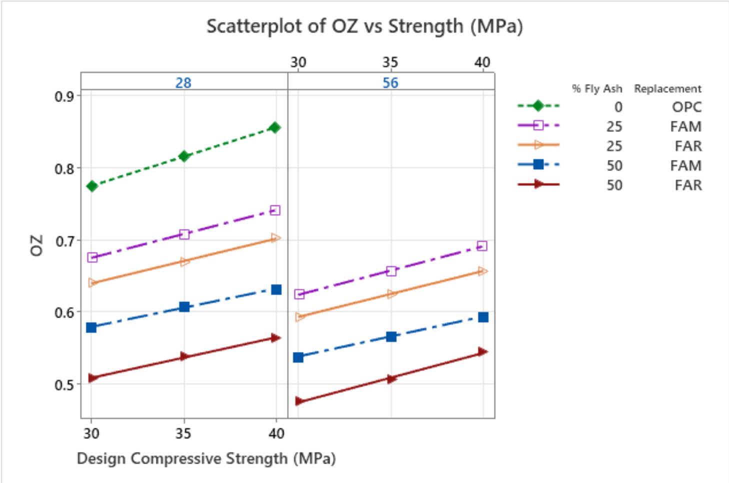

Figure A.3 Scatterplot of OZ vs compressive strength

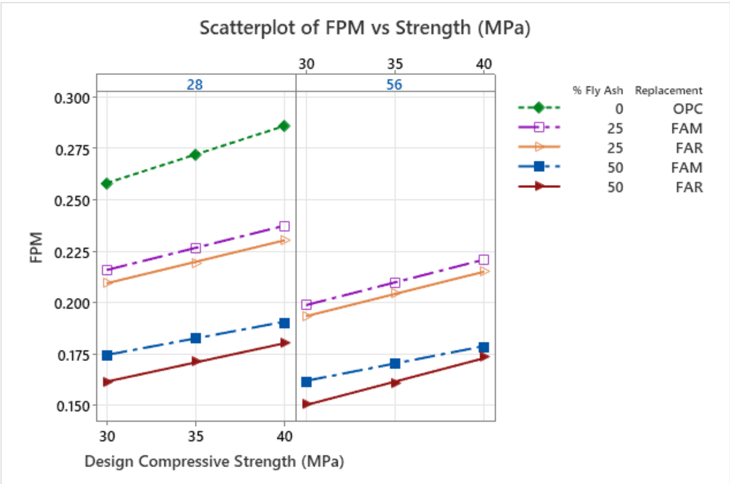

Figure A.4 Scatterplot of FPM vs compressive strength

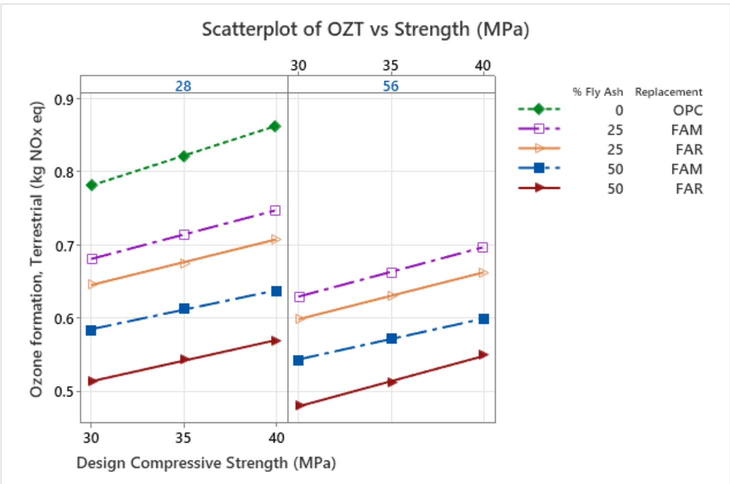

Figure A.5 Scatterplot of OZT vs compressive strength

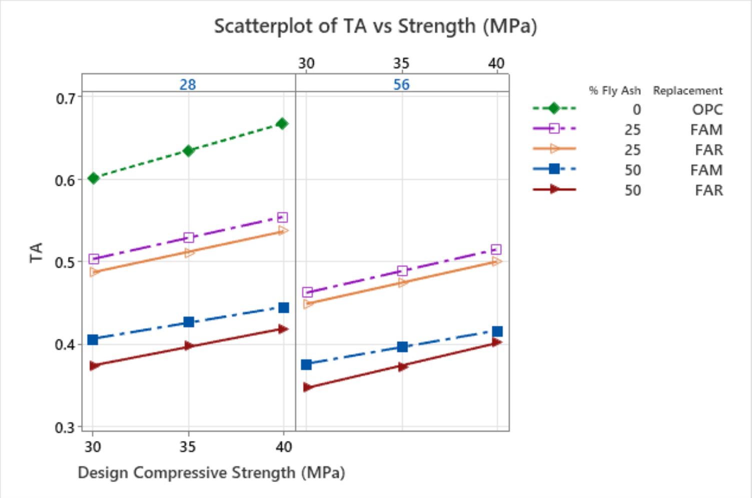

Figure A.6 Scatterplot of TA vs compressive strength

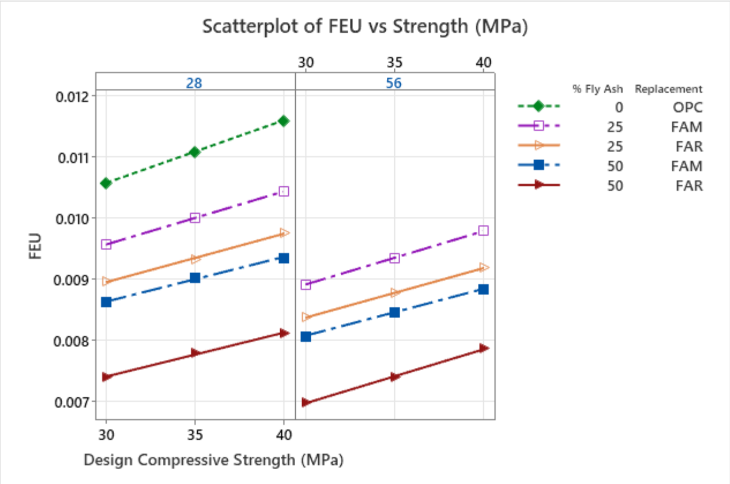

Figure A.7 Scatterplot of FEU vs compressive strength

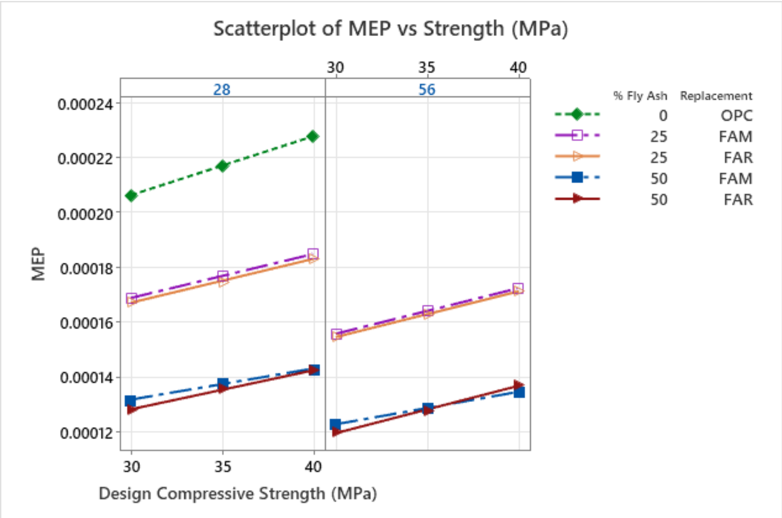

Figure A.8 Scatterplot of MEP vs compressive strength

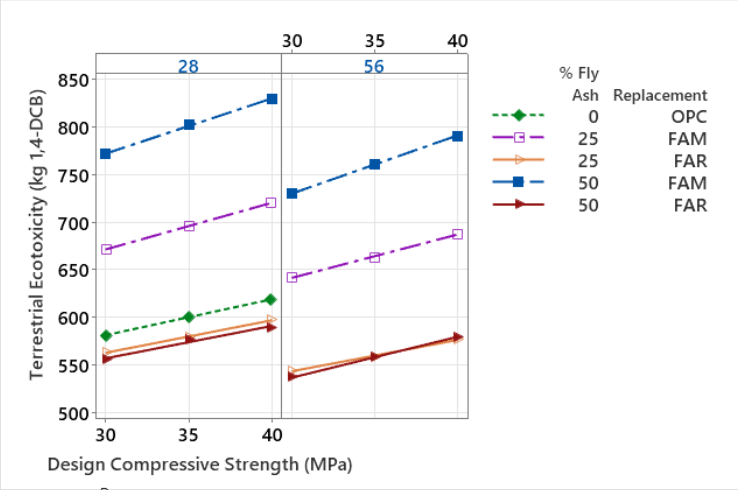

Figure A.9 Scatterplot of TE vs compressive strength

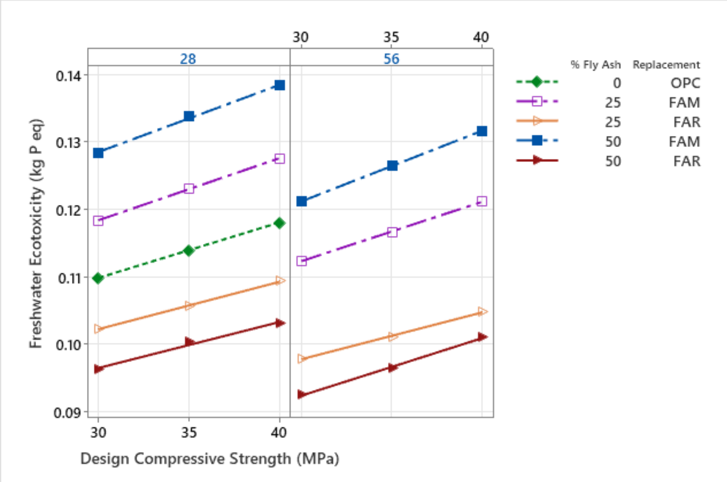

Figure A.10 Scatterplot of FET vs compressive strength

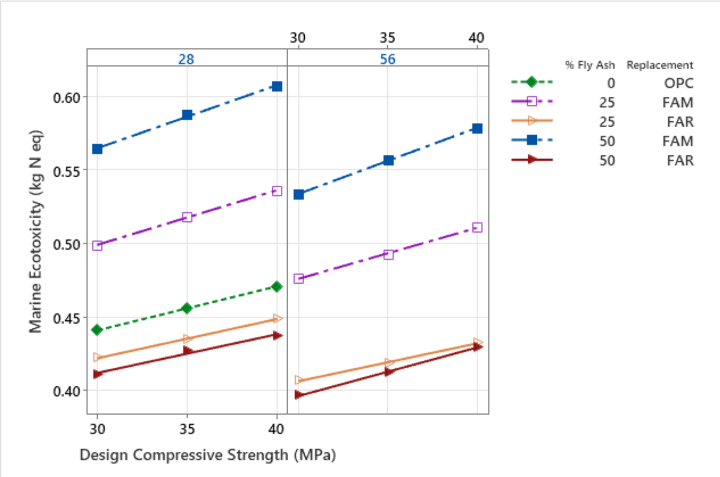

Figure A.11 Scatterplot of MET vs compressive strength

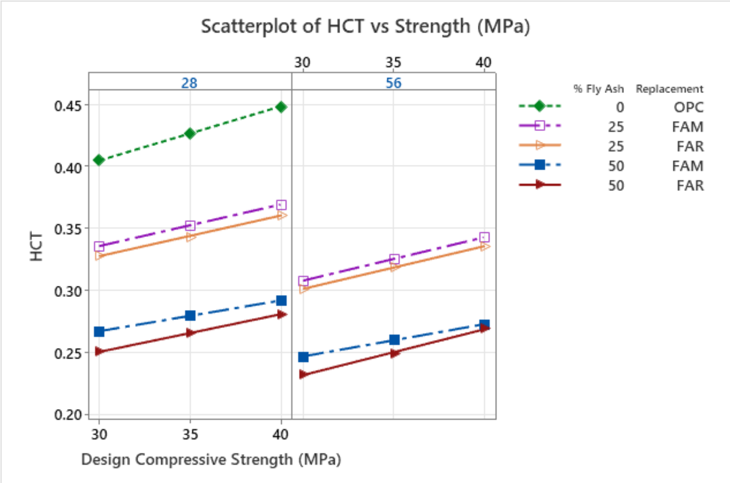

Figure A.12 Scatterplot of HCT vs compressive strength

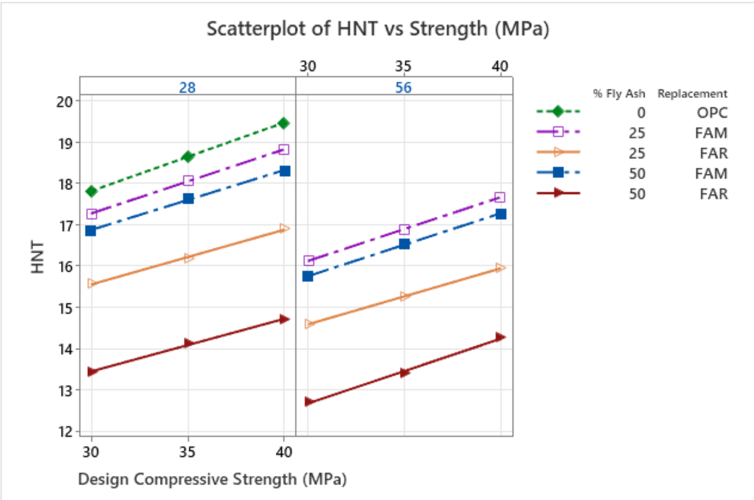

Figure A.13 Scatterplot of HNT vs compressive strength

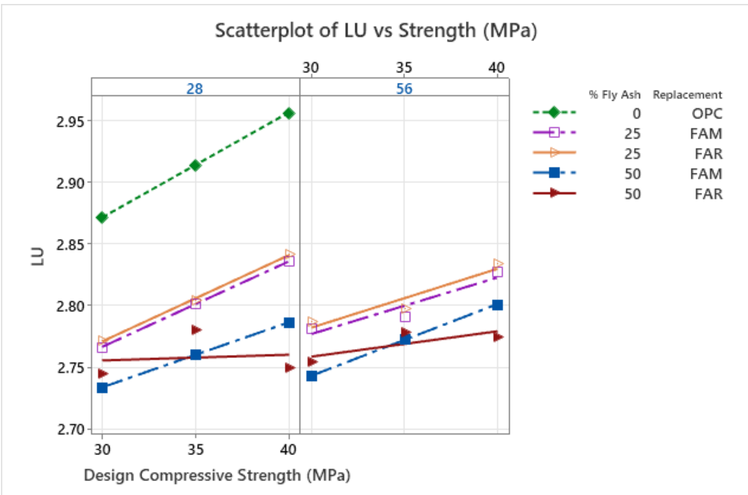

Figure A.14 Scatterplot of LU vs compressive strength

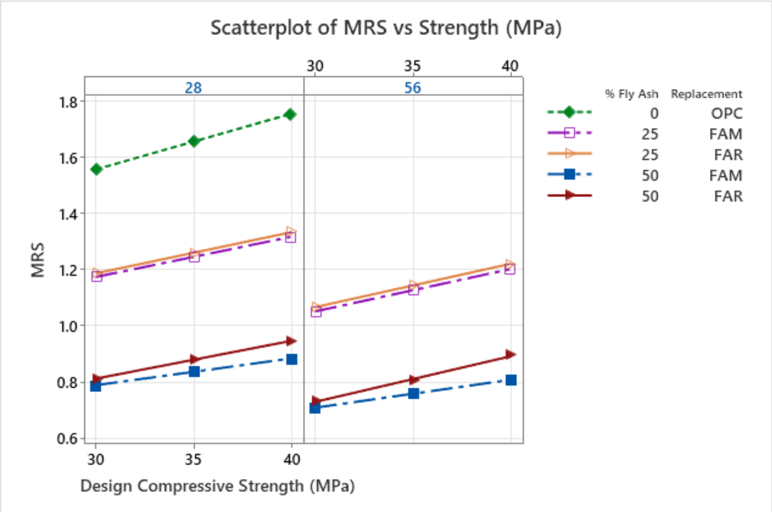

Figure A.15 Scatterplot of MRS vs compressive strength

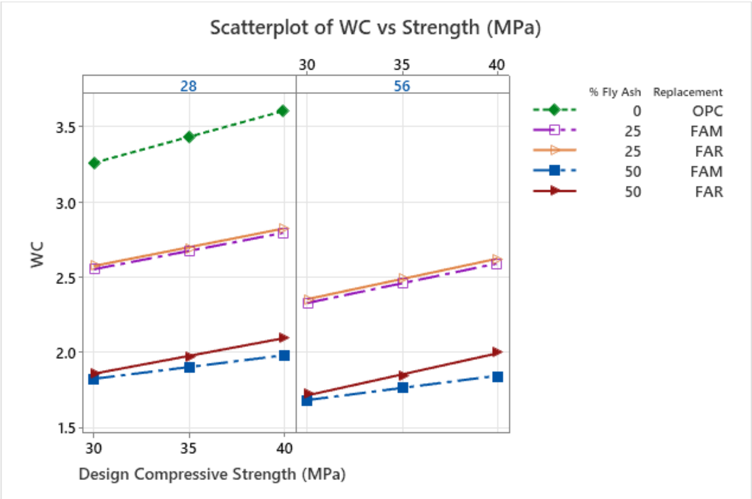

Figure A.16 Scatterplot of WC vs compressive strength

APPENDIX B

PROCESS AND SUBSTANCE CONTRIBUTIONS FOR 40MPA FAM50 (56 DAYS) MASS CONCRETE MIXTURE IN THAILAND

I. Process contribution analysis

Notes:
"Electricity" = electricity used in mixing at concrete batching plants
"Transpo" = transportation of fly ash

Table B.1 Process contributions for global warming

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	80.70%	4.58%	5.62%	0.04%	7.99%	1.07%
Remaining processes	38.35%	22.59%	26.66%	0.22%	6.54%	5.64%
clinker production	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Transport, freight	0.24%	3.59%	7.03%	0.00%	89.14%	0.00%

Table B.2 Process contributions for Stratospheric ozone depletion

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	31.00%	26.66%	20.69%	0.13%	19.32%	2.20%
Remaining processes	38.53%	22.31%	18.50%	0.20%	16.77%	3.69%
Petroleum and gas production, on-shore	12.64%	17.53%	27.75%	0.02%	41.97%	0.08%
Petroleum production, onshore	12.64%	17.53%	27.75%	0.02%	41.97%	0.08%
Diesel, burned in building machine	13.20%	42.70%	44.04%	0.00%	0.03%	0.03%
Nitric acid production	40.33%	56.10%	1.20%	0.03%	2.23%	0.09%

Table B.3 Process contributions for Ionizing radiation

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	15.25%	17.29%	27.68%	0.09%	39.42%	0.27%
Remaining processes	51.43%	11.37%	24.58%	1.13%	8.09%	3.40%

Low level radioactive waste; treatment of, plasma torch incineration	13.24%	17.62%	27.85%	0.03%	41.16%	0.10%

Table B.4 Process contributions for Ozone formation, Human health

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	54.22%	10.78%	13.68%	0.04%	20.76%	0.52%
Remaining processes	46.55%	17.97%	24.06%	0.21%	8.51%	2.71%
clinker production	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Transport, freight, lorry	10.24%	6.08%	11.96%	0.00%	71.72%	0.00%
Diesel, burned in building machine	13.20%	42.70%	44.04%	0.00%	0.03%	0.03%

Table B.5 Process contributions for Fine particulate matter formation

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	61.97%	11.83%	10.84%	0.17%	14.13%	1.06%
Remaining processes	39.76%	13.64%	21.91%	0.25%	20.60%	3.85%
Clinker production	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Transport, freight, lorry	0.24%	3.59%	7.03%	0.00%	89.14%	0.00%
Diesel, burned in building machine	13.20%	42.70%	44.04%	0.00%	0.03%	0.03%
Electricity production, lignite	69.52%	28.91%	0.82%	0.74%	0.01%	0.01%
Electricity production, hard coal	69.44%	28.87%	0.90%	0.74%	0.04%	0.01%

Table B.6 Process contributions for Ozone formation, Terrestrial ecosystems

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	54.14%	10.81%	13.72%	0.04%	20.76%	0.52%
Remaining processes	46.60%	17.82%	23.89%	0.20%	8.79%	2.69%
Clinker production	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Transport, freight, lorry	10.24%	6.08%	11.95%	0.00%	71.73%	0.00%

Diesel, burned in building machine	13.20%	42.70%	44.04%	0.00%	0.03%	0.03%

Table B.7 Process contributions for Marine ecotoxicity

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	20.78%	12.77%	24.38%	0.11%	41.65%	0.32%
Remaining processes	49.01%	11.20%	15.30%	0.90%	20.82%	2.77%
Brake wear emissions, lorry	10.28%	14.05%	27.66%	0.01%	48.01%	0.00%
Tyre wear emissions, lorry ; treatment of	10.28%	14.05%	27.66%	0.01%	48.01%	0.00%
clinker production	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table B.8 Process contributions of materials for Terrestrial acidification

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	63.11%	10.23%	10.28%	0.15%	15.03%	1.21%
Remaining processes	41.58%	14.96%	21.33%	0.30%	17.73%	4.11%
Clinker production	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Transport, freight, lorry 16-32 metric ton	0.24%	3.59%	7.03%	0.00%	89.14%	0.00%
Electricity production, hard coal	69.44%	28.87%	0.90%	0.74%	0.04%	0.01%
Diesel, burned in building machine	13.20%	42.70%	44.04%	0.00%	0.03%	0.03%

Table B.9 Process contributions for Freshwater eutrophication

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	46.47%	12.07%	15.85%	0.09%	23.59%	1.93%
Remaining processes	29.73%	15.00%	21.82%	0.21%	32.08%	1.15%
Petroleum production, onshore	12.64%	17.53%	27.75%	0.02%	41.97%	0.08%
Spoil from hard coal mining, treatment of, in surface landfill	94.00%	3.02%	0.96%	0.08%	1.11%	0.82%

Spoil from lignite mining, treatment of, in surface landfill	51.08%	19.90%	2.39%	0.56%	0.32%	25.76%

Table B.10 Process contributions for Land use

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	12.78%	1.36%	85.20%	0.15%	0.27%	0.24%
Remaining processes	85.17%	9.07%	1.32%	0.99%	1.81%	1.63%
Sand quarry operation, extraction from river bed	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%

Table B.11 Process contributions for Marine eutrophication

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	65.43%	13.80%	6.55%	0.73%	7.28%	6.21%
Remaining processes	54.76%	19.57%	9.87%	1.16%	12.16%	2.50%
Spoil from hard coal mining, treatment of, in surface landfill	94.00%	3.02%	0.96%	0.08%	1.11%	0.82%
Natural gas, unprocessed, at extraction, production	93.16%	0.33%	0.25%	0.02%	0.17%	6.08%
Wastewater, average| treatment of, capacity 1E9l/year	43.63%	29.20%	13.73%	0.84%	4.40%	8.19%
SOx retained, in hard coal flue gas desulfurisation | desulfurisation of hard coal flue gas	29.87%	12.27%	1.64%	0.36%	0.28%	55.58%

Table B.12 Process contributions for Mineral resource scarcity

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	98.89%	0.31%	0.36%	0.14%	0.30%	0.01%
Remaining processes	82.02%	5.27%	4.94%	2.41%	5.21%	0.14%
Clay pit operation	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Iron ore, crude ore, 46% Fe; iron ore mine operation, 46% Fe	99.66%	0.01%	0.32%	0.00%	0.00%	0.00%

Table B.13 Process contributions for Human carcinogenic toxicity

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	69.32%	4.89%	8.86%	0.80%	13.41%	2.73%
Remaining processes	43.84%	14.56%	16.50%	2.56%	13.63%	8.91%
clinker production	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Electric arc furnace slag, treatment of electric arc furnace slag, residual material landfill	79.48%	0.52%	19.71%	0.10%	0.10%	0.10%
Transport, freight, lorry	0.24%	3.59%	7.03%	0.00%	89.14%	0.00%

Table B.14 Process contributions for Human non-carcinogenic toxicity

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	38.72%	9.60%	17.48%	0.37%	32.39%	1.45%
Remaining processes	45.34%	12.64%	16.59%	2.13%	14.84%	8.45%
Clinker production	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Brake wear emissions, lorry	10.28%	14.05%	27.66%	0.01%	48.01%	0.00%
Tyre wear emissions, lorry	10.28%	14.05%	27.66%	0.01%	48.01%	0.00%
Transport, freight, lorry	0.24%	3.59%	7.03%	0.00%	89.14%	0.00%

Table B.15 Process contributions for Fossil resource scarcity

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	59.29%	9.18%	11.98%	0.07%	17.45%	2.03%
Remaining processes	59.57%	11.35%	10.78%	0.18%	14.51%	3.61%
hard coal mine operation and hard coal preparation	99.98%	0.01%	0.01%	0.00%	0.00%	0.00%
Petroleum and gas production, on-shore	12.64%	17.53%	27.75%	0.02%	41.97%	0.08%
production, onshore	12.64%	17.53%	27.75%	0.02%	41.97%	0.08%
Natural gas production	93.17%	0.32%	0.25%	0.02%	0.17%	6.08%

Natural gas, unprocessed, at extraction	93.16%	0.33%	0.25%	0.02%	0.17%	6.08%
production, onshore	12.64%	17.53%	27.75%	0.02%	41.97%	0.08%

Table B.16 Process contributions for Water consumption

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Remaining processes	52.31%	15.35%	5.28%	16.46%	3.41%	7.19%
Electricity production	99.99%	0.00%	0.01%	0.00%	0.00%	0.00%
Tap water production, conventional treatment	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Gravel and quarry operation	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%

Table B.17 Process contribution for Terrestrial ecotoxicity

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	19.15%	12.98%	24.94%	0.10%	42.75%	0.07%
Remaining processes	21.30%	17.33%	24.54%	1.53%	34.28%	1.02%
Brake wear emissions, lorr	10.28%	14.05%	27.66%	0.01%	48.01%	0.00%
Clinker production	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table B.18 Process contributions for Freshwater ecotoxicity

Process	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all processes	25.19%	12.16%	22.86%	0.13%	38.74%	0.93%
Remaining processes	54.89%	8.46%	13.30%	0.89%	20.38%	2.08%
Tyre wear emissions, lorry	10.28%	14.05%	27.66%	0.01%	48.01%	0.00%
Brake wear emissions, lorry	10.28%	14.05%	27.66%	0.01%	48.01%	0.00%
Natural gas, unprocessed, at extraction| production	93.16%	0.33%	0.25%	0.02%	0.17%	6.08%
Water discharge from petroleum/natural gas extraction, onshore; treatment of	12.73%	17.55%	27.75%	0.02%	41.88%	0.08%

II. Substance contribution analysis

Note: “W” = water compartment

Table B.19 Substance contributions for Global warming

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		80.70%	4.58%	5.62%	0.04%	7.99%	1.07%
Remaining substances		69.25%	9.29%	8.06%	0.14%	7.87%	5.38%
Carbon dioxide, fossil	Air	80.91%	4.49%	5.57%	0.04%	7.99%	1.00%

Table B.20 Substance contributions for Stratospheric ozone depletion

Substance		Cement	Gravel	Sand	Water	Transp	Electricity
Total of all compartments		31.00%	26.66%	20.69%	0.13%	19.32%	2.20%
Remaining substances		60.08%	20.64%	8.57%	2.38%	6.72%	1.61%
Dinitrogen monoxide	Air	34.83%	32.83%	18.97%	0.16%	10.28%	2.92%
Methane, bromotrifluoro-, Halon 1301	Air	23.38%	15.25%	24.10%	0.02%	36.37%	0.87%

Table B.21 Substance contributions for Ionizing radiation

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		15.25%	17.29%	27.68%	0.09%	39.42%	0.27%
Remaining substances		51.88%	14.10%	20.44%	1.15%	8.31%	4.11%
Carbon-14	Air	14.08%	17.39%	27.91%	0.05%	40.42%	0.15%

Table B.22 Substance contributions for Ozone formation, Human health

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		54.22%	10.78%	13.68%	0.04%	20.76%	0.52%

Remaining substances		45.27%	14.92%	18.60%	0.03%	20.22%	0.96%
Nitrogen oxides	Air	54.35%	10.71%	13.61%	0.04%	20.77%	0.51%

Table B.23 Substance contributions for Fine particulate matter formation

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		61.97%	11.83%	10.84%	0.17%	14.13%	1.06%
Remaining substances		96.90%	1.49%	0.64%	0.04%	0.86%	0.07%
Nitrogen oxides	Air	54.35%	10.71%	13.61%	0.04%	20.77%	0.51%
Particulates, < 2.5 um	Air	63.27%	14.17%	10.89%	0.20%	10.76%	0.72%
Sulfur dioxide	Air	67.48%	11.27%	8.02%	0.30%	10.66%	2.27%

Table B.24 Substance contributions for Ozone formation, Terrestrial ecosystems

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		54.14%	10.81%	13.72%	0.04%	20.76%	0.52%
Remaining substances		45.31%	14.92%	18.59%	0.03%	20.19%	0.96%
Nitrogen oxides	Air	54.35%	10.71%	13.61%	0.04%	20.77%	0.51%

Table B.25 Substance contributions for Terrestrial acidification

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		63.11%	10.23%	10.28%	0.15%	15.03%	1.21%
Remaining substances		13.26%	15.83%	25.79%	4.76%	40.06%	0.30%
Ammonia	Air	97.17%	1.45%	0.56%	0.03%	0.74%	0.06%
Nitrogen oxides	Air	54.35%	10.71%	13.61%	0.04%	20.77%	0.51%
Sulfur dioxide	Air	67.48%	11.27%	8.02%	0.30%	10.66%	2.27%

Table B.26 Substance contributions for Freshwater eutrophication

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		46.47%	12.07%	15.85%	0.09%	23.59%	1.93%
Remaining substances		34.17%	21.58%	16.84%	4.62%	22.41%	0.38%

BOD5 (Biological Oxygen Demand)	W	14.06%	17.28%	27.28%	0.02%	41.20%	0.16%
COD (Chemical Oxygen Demand)	W	14.85%	17.20%	26.99%	0.03%	40.71%	0.22%
Phosphate	W	88.11%	5.34%	1.18%	0.16%	1.02%	4.20%

Table B.27 Substance contributions for Marine eutrophication

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		65.43%	13.80%	6.55%	0.73%	7.28%	6.21%
Remaining substances		50.80%	10.74%	14.28%	0.74%	19.95%	3.49%
Ammonium, ion	W	63.91%	15.55%	7.38%	0.26%	9.68%	3.22%
Nitrate	W	67.56%	12.81%	5.40%	1.06%	4.67%	8.50%

Table B.28 Substance contributions for Terrestrial ecotoxicity

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		19.15%	12.98%	24.94%	0.10%	42.75%	0.07%
Remaining substances		64.53%	7.19%	10.66%	0.24%	16.94%	0.45%
Antimony	Air	16.31%	13.10%	25.80%	0.01%	44.77%	0.01%
Copper	Air	13.09%	13.89%	26.86%	0.12%	46.00%	0.04%
Zinc	Air	40.41%	9.76%	18.26%	0.14%	31.26%	0.17%

Table B.29 Substance contributions for Freshwater ecotoxicity

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		25.19%	12.16%	22.86%	0.13%	38.74%	0.93%
Remaining substances		34.46%	11.44%	19.69%	0.92%	31.13%	2.37%
Antimony	Air	16.31%	13.10%	25.80%	0.01%	44.78%	0.00%
Barium	W	75.82%	4.03%	6.17%	0.02%	9.17%	4.78%
Silver	W	90.38%	1.08%	1.25%	0.04%	1.41%	5.84%
Zinc	W	15.84%	13.70%	25.96%	0.06%	44.27%	0.16%

Table B.30 Substance contributions for Marine ecotoxicity

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		20.78%	12.77%	24.38%	0.11%	41.65%	0.32%
Remaining substances		61.52%	7.31%	11.12%	0.41%	16.93%	2.71%
Antimony	Air	16.31%	13.10%	25.80%	0.01%	44.77%	0.01%
Copper	Air	13.09%	13.89%	26.87%	0.12%	46.00%	0.04%
Zinc	Air	40.40%	9.76%	18.26%	0.14%	31.26%	0.17%
Zinc	W	15.83%	13.73%	25.97%	0.06%	44.25%	0.16%

Table B.31 Substance contributions for Human carcinogenic toxicity

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		69.32%	4.89%	8.86%	0.80%	13.41%	2.73%
Remaining substances		80.00%	5.43%	4.53%	0.56%	5.59%	3.89%
Arsenic	Air	93.70%	1.48%	1.68%	0.41%	2.48%	0.26%
Chromium VI	W	61.90%	7.44%	16.26%	2.16%	4.87%	7.36%
Formaldehyde	Air	72.23%	2.47%	4.70%	0.00%	20.60%	0.01%
Nickel	Air	43.62%	11.76%	16.96%	0.72%	26.08%	0.87%

Table B.32 Substance contributions for Human non-carcinogenic toxicity

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		38.72%	9.60%	17.48%	0.37%	32.39%	1.45%
Remaining substances		64.36%	6.37%	10.45%	0.22%	17.24%	1.35%
Acrolein	Air	8.68%	7.72%	15.18%	0.00%	68.42%	0.00%
Antimony	Air	16.31%	13.10%	25.80%	0.01%	44.77%	0.01%
Arsenic	Air	92.39%	2.00%	1.80%	0.77%	2.55%	0.48%
Arsenic	W	36.47%	10.17%	13.49%	2.76%	16.35%	20.75%
Lead	Air	44.31%	9.46%	16.78%	0.52%	28.56%	0.36%
Zinc	Air	40.40%	9.76%	18.26%	0.14%	31.26%	0.17%
Zinc	W	15.84%	13.71%	25.96%	0.06%	44.27%	0.16%

Table B.33 Substance contributions for Land use

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		12.59%	1.34%	85.41%	0.15%	0.27%	0.24%
Remaining substances		83.69%	11.37%	0.00%	1.26%	2.07%	1.60%
Occupation, mineral extraction site	Raw	3.70%	0.09%	96.09%	0.01%	0.04%	0.07%

Table B.34 Substance contributions for Mineral resource scarcity

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		98.89%	0.31%	0.36%	0.14%	0.30%	0.01%
Remaining substances		82.88%	5.11%	4.45%	2.48%	4.94%	0.14%
Clay, unspecified	Raw	99.94%	0.02%	0.02%	0.00%	0.02%	0.00%
Iron	Raw	99.48%	0.03%	0.43%	0.01%	0.05%	0.00%

Table B.35 Substance contributions for Fossil resource scarcity

Substance		Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments		59.29%	9.18%	11.98%	0.07%	17.45%	2.03%
Remaining substances		51.08%	19.89%	2.41%	0.56%	0.33%	25.75%
Coal, hard	Raw	93.44%	3.15%	1.12%	0.09%	1.13%	1.07%
Gas, natural/m3	Raw	86.62%	3.29%	2.13%	0.09%	2.58%	5.29%
Oil, crude	Raw	13.10%	17.62%	27.80%	0.02%	41.38%	0.08%

Table B.36 Substance contributions for Water consumption

Substance	Cement	Gravel	Sand	Water	Transpo	Electricity
Total of all compartments	78.69%	1.20%	12.19%	7.08%	0.27%	0.56%

APPENDIX C
MIDPOINT IMPACTS OF 65GGBS AND 50FA MASS THAILAND CONCRETE MIXTURES

Table C.1 Midpoint impacts of slag and fly ash concrete with transportation

Impact category	**Unit**	**GGBS65 (Import)**	**GGBS65 (600km)**	**GGBS65 (190km)**	**FA50 (600km)**	**FA50 (190km)**
Global warming	kg CO_2 eq	2.98E+02	1.58E+02	1.46E+02	1.77E+02	1.68E+02
Stratospheric ozone depletion	kg CFC11 eq	1.38E-04	3.25E-05	2.72E-05	2.66E-05	2.35E-05
Ionizing radiation	kBq Co-60 eq	1.25E+00	3.49E-01	2.64E-01	2.77E-01	2.11E-01
Ozone formation, Human health	kg NO_x eq	3.91E+00	4.58E-01	4.04E-01	5.18E-01	4.49E-01
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.24E+00	1.65E-01	1.53E-01	1.55E-01	1.41E-01
Ozone formation, Terrestrial ecosystems	kg NO_x eq	3.93E+00	4.66E-01	4.11E-01	5.23E-01	4.53E-01
Terrestrial acidification	kg SO_2 eq	3.76E+00	3.66E-01	3.34E-01	3.59E-01	3.24E-01
Freshwater eutrophication	kg P eq	2.37E-02	8.75E-03	7.31E-03	7.79E-03	6.63E-03
Marine eutrophication	kg N eq	9.70E-04	9.57E-04	9.50E-04	1.17E-04	1.12E-04
Terrestrial ecotoxicity	kg 1,4-DCB	9.21E+02	9.32E+02	6.89E+02	7.09E+02	5.23E+02
Freshwater ecotoxicity	kg 1,4-DCB	2.33E-01	2.42E-01	2.06E-01	1.17E-01	8.94E-02
Marine ecotoxicity	kg 1,4-DCB	8.28E-01	8.13E-01	6.41E-01	5.19E-01	3.85E-01

Human carcinogenic toxicity	kg 1,4-DCB	2.11E+00	1.59E+00	1.58E+00	2.34E-01	2.15E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	3.08E+01	3.04E+01	2.69E+01	1.51E+01	1.20E+01
Land use	m^2a crop eq	2.97E+00	2.95E+00	2.94E+00	2.77E+00	2.76E+00
Mineral resource scarcity	kg Cu eq	1.38E+00	1.38E+00	1.38E+00	6.54E-01	6.53E-01
Fossil resource scarcity	kg oil eq	6.95E+01	2.82E+01	2.42E+01	2.77E+01	2.46E+01
Water consumption	m^3	1.60E+00	1.60E+00	1.59E+00	1.60E+00	1.60E+00

Table C.2 Midpoint impacts of slag and fly ash concrete without transportation

Impact category	**Unit**	**GGBS**	**Fly Ash**	**OPC**
Global warming	kg CO_2 eq	1.41E+02	1.63E+02	3.56E+02
Stratospheric ozone depletion	kg CFC11 eq	2.47E-05	2.21E-05	3.13E-05
Ionizing radiation	kBq Co-60 eq	2.25E-01	1.81E-01	2.21E-01
Ozone formation, Human health	kg NO_x eq	3.79E-01	4.17E-01	7.75E-01
Fine particulate matter formation	kg $PM_{2.5}$ eq	1.47E-01	1.34E-01	2.58E-01
Ozone formation, Terrestrial ecosystems	kg NO_x eq	3.86E-01	4.21E-01	7.81E-01
Terrestrial acidification	kg SO_2 eq	3.19E-01	3.08E-01	6.02E-01
Freshwater eutrophication	kg P eq	6.65E-03	6.10E-03	1.06E-02
Marine eutrophication	kg N eq	9.47E-04	1.09E-04	2.06E-04
Terrestrial ecotoxicity	kg 1,4-DCB	5.77E+02	4.36E+02	5.81E+02
Freshwater ecotoxicity	kg 1,4-DCB	1.89E-01	7.63E-02	1.10E-01
Marine ecotoxicity	kg 1,4-DCB	5.61E-01	3.23E-01	4.41E-01
Human carcinogenic toxicity	kg 1,4-DCB	1.57E+00	2.07E-01	4.05E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	2.53E+01	1.06E+01	1.78E+01
Land use	m^2a crop eq	2.94E+00	2.76E+00	2.87E+00
Mineral resource scarcity	kg Cu eq	1.38E+00	6.52E-01	1.56E+00
Fossil resource scarcity	kg oil eq	2.24E+01	2.32E+01	4.42E+01
Water consumption	m^3	1.59E+00	1.60E+00	3.26E+00

APPENDIX D

MIDPOINT IMPACTS OF MASS CONCRETE MIXTURES FROM THE PHILIPPINES

Table D.1 Global warming potential of various concrete mixtures with 0% (0FA), 10% (10FA), 15% (15FA) and 20% (20FA) fly ash as cement replacement.

Compressive strength	0FA (OPC)	10FA	15FA	20FA
MPa	kg CO_2 eq	kg CO_2 eq	kg CO_2 eq	kg CO_2 eq
13.8	254.57	232.26	-	248.49
20.7	271.50	247.47	264.38	262.23
24.1	297.22	271.58	272.27	275.97
27.6	339.84	310.87	286.85	289.71
34.5	341.86	310.97	310.41	330.94
41.4	426.76	388.05	338.51	344.68
48.3	464.26	421.16	377.07	-
55.2	481.25	436.65	-	-
69.0	549.82	498.34	480.48	-

Table D.2 Environmental impacts for 13.8 MPa concrete with different percentages of fly ash as cement replacement

Impact category	Unit	0FA (OPC)	10FA	20FA
Global warming	kg CO_2 eq	2.55E+02	2.32E+02	2.48E+02
Stratospheric ozone depletion	kg CFC11 eq	2.81E-05	2.68E-05	2.72E-05
Ionizing radiation	kBq Co-60 eq	2.31E-01	2.24E-01	2.15E-01
Ozone formation, Human health	kg NO_x eq	6.01E-01	5.58E-01	5.80E-01
Fine particulate matter formation	kg $PM_{2.5}$ eq	2.03E-01	1.88E-01	1.97E-01
Ozone formation, Terrestrial ecosystems	kg NO_x eq	6.07E-01	5.64E-01	5.86E-01
Terrestrial acidification	kg SO_2 eq	4.66E-01	4.32E-01	4.53E-01

Freshwater eutrophication	kg P eq	8.90E-03	8.35E-03	8.52E-03
Marine eutrophication	kg N eq	1.78E-04	1.66E-04	1.71E-04
Terrestrial ecotoxicity	kg 1,4-DCB	5.45E+02	5.25E+02	5.11E+02
Freshwater ecotoxicity	kg 1,4-DCB	9.92E-02	9.49E-02	9.35E-02
Marine ecotoxicity	kg 1,4-DCB	4.08E-01	3.93E-01	3.84E-01
Human carcinogenic toxicity	kg 1,4-DCB	3.11E-01	2.88E-01	3.01E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	1.46E+01	1.37E+01	1.39E+01
Land use	m^2a crop eq	3.44E+00	3.41E+00	2.99E+00
Mineral resource scarcity	kg Cu eq	1.04E+00	9.40E-01	1.03E+00
Fossil resource scarcity	kg oil eq	3.69E+01	3.44E+01	3.52E+01
Water consumption	m^3	2.42E+00	2.24E+00	2.37E+00

Table D.3 Environmental impacts for 27.6 MPa concrete with different percentages of fly ash as cement replacement

Impact category	**Unit**	**0FA (OPC)**	**10FA**	**15FA**	**20FA**
Global warming	kg CO_2 eq	3.40E+02	3.11E+02	2.87E+02	2.90E+02
Stratospheric ozone depletion	kg CFC11 eq	3.20E-05	3.09E-05	2.93E-05	2.92E-05
Ionizing radiation	kBq Co-60 eq	2.44E-01	2.43E-01	2.31E-01	2.23E-01
Ozone formation, Human health	kg NO_x eq	7.53E-01	7.00E-01	6.53E-01	6.55E-01
Fine particulate matter formation	kg $PM_{2.5}$ eq	2.58E-01	2.40E-01	2.23E-01	2.24E-01
Ozone formation, Terrestrial ecosystems	kg NO_x eq	7.60E-01	7.08E-01	6.60E-01	6.61E-01
Terrestrial acidification	kg SO_2 eq	5.96E-01	5.54E-01	5.15E-01	5.16E-01
Freshwater eutrophication	kg P eq	1.09E-02	1.03E-02	9.62E-03	9.51E-03
Marine eutrophication	kg N eq	2.28E-04	2.19E-04	2.01E-04	1.96E-04

Terrestrial ecotoxicity	kg 1,4-DCB	5.88E+02	5.72E+02	5.47E+02	5.36E+02
Freshwater ecotoxicity	kg 1,4-DCB	1.11E-01	1.08E-01	1.02E-01	1.00E-01
Marine ecotoxicity	kg 1,4-DCB	4.46E-01	4.33E-01	4.13E-01	4.05E-01
Human carcinogenic toxicity	kg 1,4-DCB	4.01E-01	3.75E-01	3.47E-01	3.45E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	1.75E+01	1.65E+01	1.55E+01	1.54E+01
Land use	m^2a crop eq	3.18E+00	3.29E+00	3.19E+00	2.94E+00
Mineral resource scarcity	kg Cu eq	1.44E+00	1.30E+00	1.19E+00	1.22E+00
Fossil resource scarcity	kg oil eq	4.68E+01	4.45E+01	4.09E+01	4.02E+01
Water consumption	m^3	3.15E+00	2.93E+00	2.73E+00	2.72E+00

Table D.4 Environmental impacts for 41.4 MPa concrete with different percentages of fly ash as cement replacement

Impact category	**Unit**	**0FA (OPC)**	**10FA**	**15FA**	**20FA**
Global warming	kg CO_2 eq	4.27E+02	3.88E+02	3.39E+02	3.45E+02
Stratospheric ozone depletion	kg CFC11 eq	3.66E-05	3.45E-05	3.19E-05	3.18E-05
Ionizing radiation	kBq Co-60 eq	2.68E-01	2.58E-01	2.43E-01	2.34E-01
Ozone formation, Human health	kg NO_x eq	9.15E-01	8.39E-01	7.46E-01	7.54E-01
Fine particulate matter formation	kg $PM_{2.5}$ eq	3.15E-01	2.89E-01	2.57E-01	2.59E-01
Ozone formation, Terrestrial ecosystems	kg NO_x eq	9.24E-01	8.48E-01	7.54E-01	7.61E-01
Terrestrial acidification	kg SO_2 eq	7.32E-01	6.72E-01	5.95E-01	6.01E-01
Freshwater eutrophication	kg P eq	1.31E-02	1.22E-02	1.09E-02	1.08E-02
Marine eutrophication	kg N eq	2.81E-04	2.65E-04	2.36E-04	2.29E-04
Terrestrial ecotoxicity	kg 1,4-DCB	6.55E+02	6.18E+02	5.77E+02	5.70E+02
Freshwater ecotoxicity	kg 1,4-DCB	1.28E-01	1.20E-01	1.11E-01	1.09E-01

Marine ecotoxicity	kg 1,4-DCB	5.01E-01	4.72E-01	4.39E-01	4.33E-01
Human carcinogenic toxicity	kg 1,4-DCB	4.95E-01	4.57E-01	4.04E-01	4.03E-01
Human non-carcinogenic toxicity	kg 1,4-DCB	2.08E+01	1.93E+01	1.74E+01	1.74E+01
Land use	m^2a crop eq	3.25E+00	3.18E+00	3.12E+00	2.88E+00
Mineral resource scarcity	kg Cu eq	1.84E+00	1.66E+00	1.43E+00	1.47E+00
Fossil resource scarcity	kg oil eq	5.75E+01	5.36E+01	4.77E+01	4.67E+01
Water consumption	m^3	3.90E+00	3.59E+00	3.16E+00	3.18E+00

APPENDIX E
ENDPOINT IMPACTS OF MASS CONCRETE MIXTURES FROM THE PHILIPPINES AND STATISTICAL CALCULATIONS

Table E.1 Human health (H) impact of various concrete mix and corresponding reduction percentage

	Human health (Disability Adjusted Life Years)					Reduction, %		
Strength (MPa)	OPC	10FA	15FA	20FA		OPC vs 10FA	OPC vs 15FA	OPC vs 20FA
13.79	3.70E-04	3.39E-04	-	3.60E-04		8.18%	-	2.56%
20.68	3.92E-04	3.60E-04	3.82E-04	3.79E-04		8.30%	2.55%	3.46%
24.1	4.27E-04	3.93E-04	3.93E-04	3.97E-04		7.97%	7.94%	6.95%
27.58	4.84E-04	4.46E-04	4.13E-04	4.16E-04		7.94%	14.79%	14.15%
34.47	4.88E-04	4.46E-04	4.45E-04	4.71E-04		8.58%	8.74%	3.44%
41.37	6.02E-04	5.50E-04	4.83E-04	4.90E-04		8.69%	19.85%	18.65%
48.26	6.54E-04	5.95E-04	5.35E-04	-		8.98%	18.14%	-
55.16	6.77E-04	6.16E-04	-	-		8.93%	-	-
68.95	7.69E-04	6.99E-04	6.75E-04	-		9.08%	12.22%	-

Table E.2 Ecosystem (E) impact of various concrete mix and corresponding reduction percentage

	Ecosystem (species-yr)					Reduction, %		
Strength (MPa)	E OPC	E 10FA	E 15FA	E 20FA		OPC vs 10FA	OPC vs 15FA	OPC vs 20FA
13.79	9.43E -07	8.66E -07	-	9.15E -07		8.14%	-	2.97%
20.68	9.97E -07	9.14E -07	9.74E -07	9.62E -07		8.29%	2.33%	3.55%
24.1	1.09E -06	1.00E -06	1.00E -06	1.01E -06		7.92%	7.90%	7.21%

27.58	1.23E-06	1.13E-06	1.05E-06	1.05E-06		7.86%	14.71%	14.26%
34.47	1.24E-06	1.13E-06	1.13E-06	1.19E-06		8.56%	8.75%	3.68%
41.37	1.53E-06	1.40E-06	1.22E-06	1.24E-06		8.71%	19.86%	18.77%
48.26	1.66E-06	1.51E-06	1.36E-06	-		8.78%	18.12%	-
55.16	1.72E-06	1.56E-06	-	-		8.93%	-	-
68.95	1.95E-06	1.77E-06	1.71E-06	-		9.09%	12.28%	-

Table E.3 Resources (R) impact of various concrete mix and corresponding reduction percentage

	Resources (USD 2013)					Reduction, %		
Strength (MPa)	R OPC	R 10FA	R 15FA	R 20FA		OPC vs 10FA	OPC vs 15FA	OPC vs 20FA
13.79	10.18	9.64	-	9.58		5.36%	-	5.89%
20.68	10.65	10.07	10.45	9.95		5.51%	1.89%	6.57%
24.1	11.31	10.80	10.70	10.33		4.51%	5.44%	8.71%
27.58	12.39	12.05	11.10	10.67		2.72%	10.43%	13.64%
34.47	12.80	12.04	12.13	11.82		5.90%	5.23%	7.67%
41.37	14.87	14.12	12.73	12.19		5.09%	14.43%	18.04%
48.26	16.53	15.42	14.07	-		6.69%	14.86%	-
55.16	16.92	15.83	-	-		6.43%	-	-
68.95	18.81	17.55	17.15	-		6.69%	8.81%	-

Table E.4 Results of paired t-test for comparison (p-values) for human health impacts

	OPC	10FA	15FA	20FA
OPC	-			
10FA	0.000	-		
15FA	0.005	0.112	-	
20FA	0.054	0.814	0.211	-

Table E.5 Results of paired t-test for comparison (p-values) for ecosystem impacts

	OPC	10FA	15FA	20FA
OPC	-			
10FA	0.000	-		
15FA	0.005	0.114	-	
20FA	0.050	0.761	0.271	-

Table E.6 Results of paired t-test for comparison (p-values) for resources impacts

	OPC	10FA	15FA	20FA
OPC	-			
10FA	0.000	-		
15FA	0.007	0.094	-	
20FA	0.011	0.079	0.001	-

Table E.7 Spearman correlation of human health (H), ecosystem (E), and resources (R) impacts to various concrete ingredients for cement-only mixtures (OPC).

	H OPC	E OPC	R OPC	Cement	Water	Gravel	Sand
Cement	0.996	0.996	0.996				
Water	-0.392	-0.392	-0.392	-0.372			
Gravel	0.353	0.353	0.353	0.354	-0.249		
Sand	-0.917	-0.917	-0.917	-0.937	0.341	-0.546	
Admixture	1.000	1.000	1.000	0.996	-0.392	0.353	-0.917

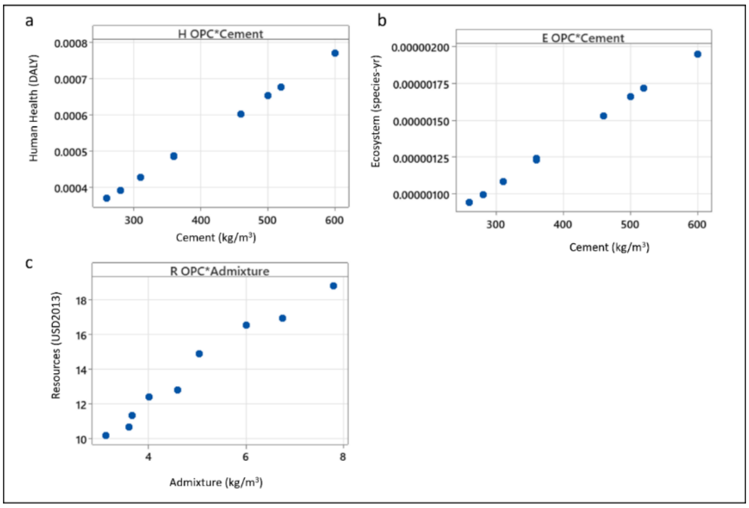

Figure E.1 Scatterplot of (a) human health vs cement content, (b) ecosystem vs cement content, and (c) resources vs admixture

APPENDIX F
CASE STUDIES OF CONCRETE CONSTRUCTION PROJECTS

An analysis of six recently completed construction projects was carried out to understand the prevalence of using waste as cement replacing materials in general construction as listed in Table F.1.

Table F.1 Concrete construction projects surveyed in Philippines

No	Type	Concrete Volume Used (m^3)	Construction Period	Waste material used in concrete	Construction Completion
1	Midrise (15-storey)	87,399	48 months	15-20% fly ash	2020
2	High Rise (40-storey)	62,651	48 months	20% fly ash	2020
3	High Rise (32-storey)	22,845	42 months	15% fly ash	2018
4	Infrastructure (girder for elevated road)	36,143	20 months	-	2021
5	Infrastructure (sewage treatment plant)	63,000	36 months	fly ash (% not given)	2020
6	Infrastructure (airport)	42, 867	39 months	-	2018

In the Philippines, large construction projects are often supplied with concrete via in-house or third-party ready-mix batching plants. This system gives the contractor flexibility in selecting concrete components based on the planned usage and desired qualities. The investigated projects were constructed between 2018 and 2021 and included high-rise (above 15 stories), midrise (up to 15 stories), and infrastructure projects. Infrastructure projects studied include an elevated road, an airport, and a sewage treatment plant. The categorization is based on the one used by the American Concrete Institute in their program for concrete excellence. As indicated in Table F.1, four of the surveyed projects included up to 20% fly ash from coal-fired power plants in their concrete design mix. All of these projects are vertical in nature (buildings).

When asked why they use fly ash, almost all users state that they do it to increase sustainability and lower their carbon impact, which benefits their company's reputation. Apart from that, the key factor considered is cost savings. The use of fly ash reduces the amount of cement used, hence lowering the cost. According to one project, fly ash usage helps reinforce the concrete material and end product. Additional sustainability measures included the utilization of recycled steel bars and surplus concrete in construction. Excess concrete materials from pouring batches throughout the building period were not disposed of in one project. Rather than discarding them, they were recycled and made into other valuable construction parts, such as wheel stops, concrete blocks, and concrete pedestals.

During the planning stage of one of the projects that did not use fly ash, highly reactive pozzolans derived from industrial by-products such as silica fume and/or slags were considered to achieve the high early strength requirement. This plan was abandoned because of the country’s unstable source of slag and silica fume. Currently, these resources are imported from other countries. As a result, the contractor views this as a potential issue, particularly considering the project's budget. Finally, they employ only 100 percent pure cement and a specialized concrete admixture manufactured by a business partner specializing in chemical admixture production, which met the high early strength requirement without using a boiler or steam to accelerate the curing process.

BIOGRAPHY

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