Embodied Carbon in Concrete: Insights from Indonesia and Comparative Analysis with UK and USA

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ABSTRACT

Concrete is the most widely used construction material globally. However, its production, particularly that of cement, is a significant source of carbon dioxide (CO_2) emissions, contributing to approximately 8% - 10% of the global anthropogenic CO_2 emissions. This study aims to analyze and compare the embodied carbon (eCO_2) of various concrete strength grades commonly utilized in Indonesia to offer insights for enhancing sustainability in the construction industry. The methodology involved designing concrete mixes according to Indonesian standards and calculating carbon emissions for each component. The findings revealed that the eCO_2 in the Indonesian concrete mixes was significantly higher than that reported in the UK and US databases. This higher carbon footprint emerges primarily due to the greater cement content found in the Indonesian mixes. Nevertheless, the current study demonstrated that using fly ash as a supplementary cementitious material can substantially reduce the eCO_2, with the mix containing fly ash showing a 42% reduction in emissions compared to the mix without fly ash. This research emphasizes the necessity for the Indonesian construction industry to adopt sustainable practices, including optimized mix designs and the use of low-carbon materials such as fly ash. In doing so, significant reductions in the carbon footprint of concrete can be achieved, contributing to the global efforts to mitigate climate change and to promote sustainability in construction practices.

Keywords-carbon dioxide equivalent; concrete; climate change; portland cement

I. INTRODUCTION

Buildings consume significant amounts of natural resources, potable water, and energy, accounting for 40% of the global energy use. They are also major contributors to global Greenhouse Gas (GHG) emissions [1]. Achieving substantial reductions in global GHG emissions is unattainable without addressing the emissions generated from the building sector. Recognizing this, the Sustainable Building and Climate Initiative (SBCI) of the United Nations Environment Program (UNEP) has integrated the reduction of building-related emissions into a global strategy aimed at combating climate change. This initiative was prominently highlighted during the United Nations Climate Change Conference (COP15) held in

Copenhagen in 2009 [2]. As the operational energy efficiency of new buildings improves, the relative importance of the embodied impacts of the construction materials and processes becomes more pronounced. Consequently, there has been an increasing focus on quantifying and reducing the eCO_2 impacts of buildings and construction products [3-6]. Compared to operational carbon, the quantification of the eCO_2 impacts is more complex and challenging. This complexity mostly arises from varying scoping and methodological assumptions, particularly regarding which life cycle stages are included in the assessment and the methods followed for their quantification. Concrete is the most extensively used construction material globally, with a current consumption rate of 1 m^3 per person per year [7]. Ordinary Portland Cement (OPC) has traditionally been used as the main binder in concrete. However, OPC is associated with a high embodied energy. The carbon dioxide equivalent (CO_2-e)—a metric for comparing the emissions from various greenhouse gases based on their global warming potential—ranges from 0.66 kg to 0.92 kg of CO_2 emitted per kilogram of OPC produced [8-10]. The production of OPC contributes to approximately 8% – 10% of the global anthropogenic CO_2 emissions [11, 12]. The primary sources of the high CO_2 emissions from the OPC production include firstly, the calcination of limestone, a crucial ingredient that results in the release of CO_2, and secondly, the essential energy consumption during the manufacturing process, which involves heating raw materials in a rotary kiln at temperatures exceeding 1400 °C [7].

Calculating the eCO_2 of concrete is less contentious, but considerably more complex. This involves contributions from cement, aggregates, water, and admixtures, with the cement component typically dominating. These components are combined in an almost infinite variety of proportions to satisfy specific structural design requirements. Although some researchers have employed single values for eCO_2 [13, 14], it has been demonstrated that the eCO_2 of concrete is substantially influenced by the structural design and loading conditions [15]. Regarding plain concrete, eCO_2 is critically dependent on the mix design and the compressive strength grade [16]. Numerous studies have reported eCO_2 values for concrete, either as individual figures or as ranges based on specific properties, principally the compressive strength grade and the use of supplementary cementitious materials. Authors in [17] reported a general eCO_2 value of 0.107 kg CO_2/kg and a monotonic relationship between eCO_2 (0.061 kg CO_2/kg – 0.188 kg CO_2/kg) and the characteristic cube strength (8 MPa – 50 MPa) for CEM I (100% OPC mix) and CEM II (65% OPC and 35% supplementary cementitious materials) concrete. However, they were cautious about the indiscriminate use of these values. The first author in [13] utilized a value of 0.20 kg CO_2/kg without having differentiated it by strength, conversely the other authors in [13] assigned a value of 0.13 kg CO_2/kg for plain concrete and 0.24 kg CO_2/kg for 2% reinforced concrete, having attributed the additional CO_2 to the steel reinforcement. Authors in [18] reported volumetric eCO_2 values of 0.225 kg/m^3 – 0.322 kg/m^3 for normal and blended cement concretes, corresponding to eCO_2 values of approximately 0.09 kg CO_2/kg – 0.12 kg CO_2/kg. However, none of these studies provided systematic details of the mix designs, such as the relative proportions of constituent materials. The present study presents a comprehensive analysis of eCO_2 associated with various concrete strength grades in Indonesia, where specific mix designs are commonly employed to achieve the desired compressive strength. The results are compared with corresponding data from other countries, specifically the UK and the US. The primary objective of this study was to enhance the understanding of eCO_2 in concrete, thereby contributing to the broader goal of sustainability in the construction industry. This study offers practical insights and recommendations to support the construction industry in its efforts to mitigate climate change and promote sustainability.

II. METHODOLOGY

This study provides a detailed and systematic approach for assessing the eCO_2 of various concrete strength grades in Indonesia, facilitating comparative analysis with data collected from other countries. The methodology involves three key phases: mix design, carbon emission calculation, and data integration. A range of concrete mixes was designed in accordance with the Indonesian standard SNI 7656-2012 [19], which is based on ACI 211.1-91 [20]. The mix design process followed a systematic sequence of steps aimed at determining the optimal composition for achieving the desired strength, workability, and durability of concrete structures. A slump value of 100 mm ± 2 mm was selected to ensure the workability of concrete. Table I summarises the proportions of the constituent materials for each concrete grade. The mix design process adopted OPC Type I cement with a focus on achieving the desired 28-day cylinder compressive strength [21]. As it would be expected, higher compressive strength grades required a greater proportion of cement. This increase in cement content is necessary to achieve enhanced strength characteristics, underlining the role of cement as the main binding material. The relationship between the compressive strength and cement content was carefully considered to optimize the mix designs for each concrete grade evaluated in this study.

TABLE I. THE PROPORTIONS OF CONSTITUENT MATERIALS PER CUBIC METER

Components	**Unit**	**fc' 20 MPa**	**fc' 25 MPa**	**fc' 28 MPa**	**fc' 32 MPa**	**fc' 35 MPa**
OPC Type I	kg	348	407	437	468	509
Fine aggregate	kg	790	731	701	671	629
Coarse aggregate	kg	1009	1009	1009	1009	1009
Water	l	202	202	202	202	202

eCO_2 was calculated as a ‘cradle to gate’ mass of CO_2 emitted per unit mass of reinforced concrete considering all major emissions during mining (A1), transport to site (A2), and processing (A3), as illustrated in Figure 1. The Functional Unit, defined as eCO_2 emitted (kg eCO_2/kg) owing to the activities necessary to construct 1 m^3 of concrete, was the unit constant used in this study.

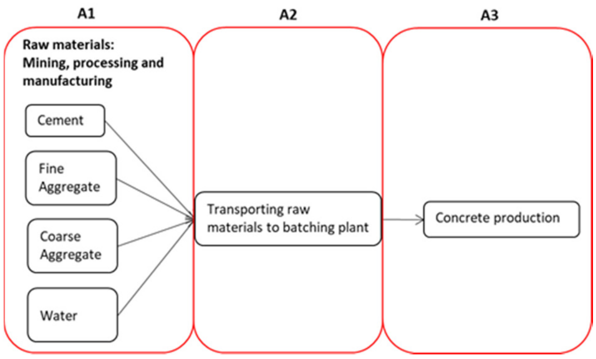

Fig. 1. CO_2 emissions system diagram for concrete production.

The carbon emissions for this assessment were obtained from an inventory of carbon and energy data provided by Circular Ecology [22]. Table II lists the carbon emissions values for each component of the concrete mix. Additionally, carbon emissions associated with transportation and processing were considered in the assessment. For transportation, the carbon emission factor was 0.005 kg CO_2/kg of material per 50 km travelled. In this study, a transport distance of 200 km was assumed to reflect the common situation for batching plants in Indonesia. For processing, the carbon emission factor was 0.007 kg CO_2/kg of material. These factors were applied to account for the emissions generated during the transport of raw materials to the construction site and for the processing of these materials into the final concrete product.

TABLE II. CARBON EMISSIONS VALUE

Components	eCO_2 Contribution (kg eCO_2/kg)
OPC Type I	0.912
Fine aggregate	0.00747
Coarse aggregate	0.0157
Water	0.000344

This study integrated the calculated carbon emission data with the specific mix design. This integration allowed for a comprehensive assessment of the total eCO_2 for each concrete grade evaluated in this study. The integration process ensured that both the material composition and the associated emissions from transportation and processing were estimated in the final eCO_2 values.

III. RESULTS AND DISCUSSIONS

This section presents the findings of the analysis and investigation of the eCO_2 emissions associated with various concrete grades commonly used in Indonesia. As previously discussed, this study focuses on the contributions of different life cycle phases, namely raw material extraction (A1), transportation (A2), and concrete production (A3), to the total carbon emissions. Figure 2 shows the total carbon emissions per m^3 for each concrete grade. The data revealed that the raw material phase (A1) was the most significant contributor, accounting for more than 80% of the total carbon emissions. Notably, within the raw material phase, cement alone contributed to more than 90% of carbon emissions, underscoring its substantial impact on the overall carbon footprint of concrete. In contrast, the emissions from transportation (A2) and concrete production (A3) were relatively uniform across all the concrete grades. Both phases contributed equally to the remaining carbon emissions with a comparatively small effect on the total carbon footprint. Although a 200 km transport distance was assumed, the minimal impact of transportation emissions suggests that logistical variations have limited influence within the context of this assumption. Similarly, the concrete production phase (A3) had a consistent and minor impact on total emissions, highlighting the efficiency of the production processes.

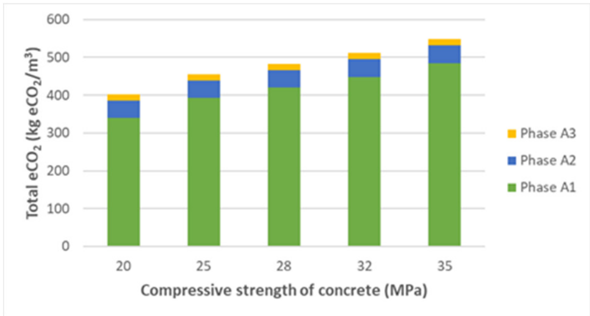

Fig. 2. Total eCO_2 for each concrete grade.

The results of the eCO_2 analysis in this study were compared with the data obtained from the UK [23] and the US [24] databases. The US data were attained from Industry-average Environmental Product Declarations, which incorporate 20% fly ash substitution for cement. Meanwhile, the UK data, sourced from the ICE database, include a 15% fly ash replacement for cement. The comparison involves concrete with various compressive strengths, and the findings are summarised in Figure 3. This comparison indicated that the eCO_2 values in this study were consistently higher than those reported in the UK and US databases. This discrepancy is principally attributed to the differences in the cementitious contents used in the concrete mixes. A higher cement content directly correlates with increased carbon emissions because cement production is one of the most carbon-intensive processes in the construction material supply chain. Variations in eCO_2 can be influenced by differences in the regional practices, material sourcing, and technological advancement in cement production. For instance, the UK and US may benefit from more efficient production techniques, greater use of supplementary cementitious materials, and optimized mix designs that collectively reduce the overall carbon footprint. In particular, the UK has witnessed an increased emphasis placed on blended cements and the use of supplementary cementitious materials over the past 20 years. This shift was largely driven by legislative requirements aimed at reducing eCO_2 levels in construction projects. Conversely, there are currently no legislative requirements for the reduction of eCO_2 in Indonesian construction projects. As a result, conventional concrete mixes with high cement content remain the norm. By learning from practices in regions with lower eCO_2, such as the UK and US, and implementing these strategies, the construction industry in Indonesia can move towards more sustainable and environmentally friendly practices. Adopting supplementary cementitious materials and optimizing mix designs can significantly mitigate the environmental impacts of concrete production in Indonesia.

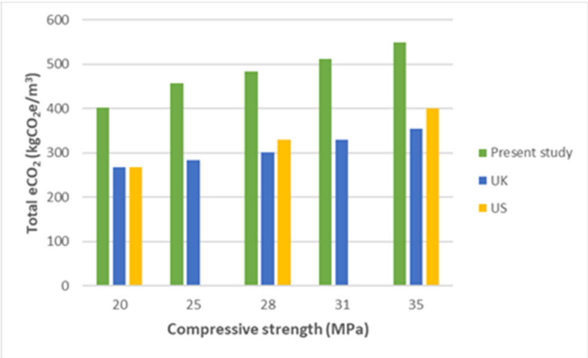

Fig. 3. Comparison of eCO_2 in concrete: Present Study vs. UK vs. US.

Furthermore, in the context of the eCO_2 in concrete, a recent study conducted by ARUP and Innovate UK [25] introduced an eCO_2 classification scheme. The scheme in [25] categorizes concrete from A to G based on the relationship between compressive strength and eCO_2. According to this classification, concrete is rated from A (low eCO_2) to G (high eCO_2). This classification scheme provides a useful framework for understanding and comparing eCO_2 in different concrete mixes. By categorizing concrete based on its eCO_2, this scheme helps highlight the environmental impact of high-strength concrete mixes, which are prevalent in many modern construction projects. The analysis in the present study reveals that the evaluated concrete mixes fall into the G classification, indicating a relatively high eCO_2 [25]. The predominance of the raw-material phase in carbon emissions can be attributed to the high eCO_2 content of cement, which is a major component of concrete. Cement production is inherently carbon-intensive because of the calcination of limestone and the high temperatures required in kilns. As higher compressive strength grades need more cement, the carbon emissions proportionally increase with the strength grade.

In [25], the classification of commonly used Indonesian concretes in this study can be seen as G, this highlights the significant environmental impact of the current standard concrete mixes. Addressing this issue requires a multifaceted approach that combines material innovation, process optimization, and strategic planning to move towards more sustainable construction practices. By leveraging the eCO_2 classification scheme, stakeholders can better understand the carbon implications of their material choices and take informed actions to reduce the carbon footprint of their projects. In Indonesia, it is common practice to use fly ash as a Supplementary Cementitious Material (SCM) to reduce the cement content of concrete. Properly designed concrete mixes incorporating fly ash can significantly improve the workability of plastic concrete and enhance the strength and durability of hardened concrete. The inclusion of fly ash not only lowers the eCO_2 by replacing a portion of the cement, but also contributes to better performance characteristics. To illustrate this, the Indonesian Ministry of Public Works and Housing recommends proportions of the constituent materials of concrete with a compressive strength of 35 MPa, as depicted in Table III. Notably, the cement proportion was lower than that of the concrete mix without fly ash. The use of fly ash in concrete not only reduces the reliance on cement, but also improves the workability and durability of concrete. Fly ash particles fill the voids in the concrete matrix leading to a denser and more cohesive mixture, which enhances both the fresh and hardened properties of the concrete. The addition of a superplasticizer further assists in achieving the desired workability without increasing the water content, which is essential for maintaining the strength and durability of concrete.

TABLE III. PROPORTIONS OF CONSTITUENT MATERIALS FOR 35 MPA CONCRETE MIXES WITH AND WITHOUT FLY ASH

Components	Unit	Concrete with fly ash	Concrete without fly ash
Cement	kg	273	348
Fine aggregate	kg	669	790
Coarse aggregate	kg	1035	1009
Water	l	143	202
Fly Ash	kg	182	-
Superplasticizer	kg	5	-

The eCO_2 analysis of concrete mixes with and without fly ash is presented in Figure 4. This comparison provides valuable insights into the environmental impacts of these materials. From this analysis, it is evident that the use of fly ash in concrete significantly reduced the total eCO_2 from 484 kg eCO_2 for the mix without fly ash to 280 kg eCO_2 for the mix with fly ash. This substantial reduction, amounting to approximately 42%, mostly occurs owing to the decreased need for cement in the concrete mix when fly ash is deployed as a supplementary cementitious material. The significant reduction in carbon emissions achieved by incorporating fly ash highlights its potential as a sustainable material for the construction industry in Indonesia. This practice not only lowers the carbon footprint of concrete, but also contributes to the overall sustainability of construction practices by utilizing industrial by-products and enhancing the performance characteristics of concrete. By adopting such material innovations, the construction industry in Indonesia can make substantial progress towards reducing its environmental impact and promoting sustainable development.

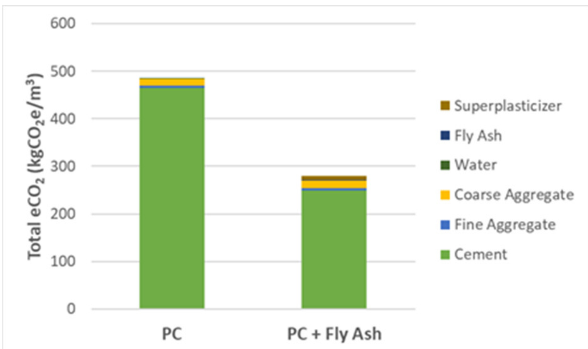

Fig. 4. Comparison of eCO_2 of concrete with and without Fly Ash.

However, the widespread use of fly ash in concrete in Indonesia poses several challenges. First, fly ash is not readily available and therefore is expensive. This limited availability restricts its use in large-scale construction projects. Furthermore, the quality of fly ash in Indonesia is not uniform, which makes it challenging to maintain consistent quality standards for concrete. Variability in the properties of fly ash can lead to inconsistencies in the performance of concrete mixes, thereby posing a significant hurdle in the construction industry. Addressing these issues requires the development of reliable supply chains and quality control mechanisms to ensure that fly ash can be effectively used as a supplementary cementitious material. Overcoming these challenges is crucial for maximising the environmental benefits of fly ash in concrete and for advancing sustainable construction practices in Indonesia.

IV. CONCLUSIONS

This study provides a comprehensive analysis of embodied carbon (eCO_2) in various concrete strength grades in Indonesia, with comparisons to data from the UK and the US. Several key findings and associated implications for the construction industry in the pursuit of sustainability are as follows:

1. The analysis revealed that raw material extraction, particularly cement, was the dominant contributor to the total carbon footprint, accounting for more than 90% of the emissions in the concrete production process. This confirms that the eCO_2 from the transportation and concrete production stages has a relatively minor impact compared to the raw material phase.

2. The embodied eCO_2 values for concrete mixes in Indonesia were significantly higher than those reported in the UK and US databases. This disparity is primarily attributed to the higher cement content used in Indonesian concrete mixes, because cement production is a major source of carbon emissions.

3. The comparison with the ARUP and Innovate UK classification schemes further underscores the relatively high eCO_2 of Indonesian concrete classified as category G. This classification calls for urgent attention to optimize mix designs and adopt low-carbon technologies.

4. This study demonstrated the potential of using supplementary cementitious materials, such as fly ash, to reduce the eCO_2 in concrete. By partially replacing cement with fly ash, the concrete mix not only reduces its carbon footprint, but also improves its workability and durability. The concrete mix with fly ash showed a significant reduction in the total eCO_2, emphasizing the importance of adopting sustainable materials and practices.

The work presented here demonstrates that incorporating fly ash into concrete mixes significantly reduces eCO_2, with a reduction of approximately 42% compared to mixes without fly ash. These findings align with global research, indicating that supplementary cementitious materials, such as fly ash, can effectively lower carbon emissions and enhance concrete performance. However, challenges such as fly ash availability and quality variability must be addressed to fully realize these benefits. By comparing practices in the UK and the US, this study stresses the potential for similar sustainable practices worldwide, offering valuable insights for advancing environmentally responsible concrete production.

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DATA AVAILABILITY

The calculation data sheet can be found at: https://zenodo.org/records/13762296.

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