Reducing Embodied Carbon of Paving Blocks with Landfill Waste Incineration Ash: An Eco-Cement Life Cycle Assessment

Darhamsyah
Environmental Management Study Program, Graduate School, Hasanuddin University, Indonesia
darhamsyahh@gmail.com

Miswar Tumpu
Disaster Management Study Program, Graduate School, Hasanuddin University, Indonesia
tumpumiswar@gmail.com (corresponding author)

M. Farid Samawi
Environmental Management Study Program, Graduate School, Hasanuddin University, Indonesia
faridsamawi@unhas.ac.id

Martin Anda
Environmental Engineering, Murdoch University, Perth, WA, Australia
m.anda@murdoch.edu.au

Azlan Abas
Centre for Research in Development, Social and Environment (SEEDS), Faculty of Social Sciences and Humanities, Universiti Kebangsaan, Malaysia
azlanabas@ukm.edu.my

M. Yusuf Satria
Environmental Management Study Program, Graduate School, Hasanuddin University, Indonesia
muhyusufsatria2001@gmail.com

Received: 27 December 2024 | Revised: 3 February 2025 | Accepted: 8 February 2025

 DOI: https://doi.org/10.48084/etasr.10050

ABSTRACT

This study examines the embodied carbon of paving blocks by substituting Portland Composite Cement (PCC) with landfill waste incineration ash at 0%, 25%, 50%, 75%, and 100% replacement levels. Using Life Cycle Assessment (LCA) and mechanical testing, the embodied carbon value was calculated per ISO 14040 standards. Results show that a 50% replacement achieves a 33% reduction in embodied carbon (120 $kgCO_2e/m^3$ vs. 180 $kgCO_2e/m^3$ for conventional paving blocks) while maintaining compressive strength within SNI criteria. These findings highlight the potential for eco-cement paving blocks to support sustainable construction and inform policies promoting low-carbon building materials.

Keywords-embodied carbon; paving block; incineration landfill waste; eco-cement; sustainable construction

I. INTRODUCTION

As the demand for infrastructure in Indonesia grows, so does the country's building sector. However, this industry also contributes significantly to carbon emissions, particularly through the energy-intensive and CO_2-emitting cement manufacturing [1]. Cement manufacturing accounts for up to 8% of global carbon emissions. In Indonesia, this percentage is notably high due to the extensive infrastructure development [1]. Furthermore, the large amount of garbage at the Final Disposal Site (TPA) is another environmental issue. The majority of this waste is treated by incineration, which results in residual ash as the final waste that is frequently not used and has the potential to contaminate the environment. It is essential to create creative approaches that can combine economical and ecologically sustainable answers to these issues. Using waste incineration residual ash as a cement substitute in the production of building materials like paving stones is an alternate way to get around these two issues. This strategy could reduce carbon emissions, use leftover waste ash residue (incinerator bottom ash), and lessen the dependency on Portland Composite Cement (PCC). Because of its silica and calcium-rich qualities, incinerator ash has demonstrated great promise as a cement alternative in earlier research.

In the construction sector, where sustainability is a major concern, Life Cycle Assessment (LCA), is essential for assessing the environmental effects of materials and products [2]. Using LCA in the manufacturing of eco-cement materials helps to optimize processes to lower greenhouse gas emissions while also guaranteeing transparency in environmental performance. This improves the sustainability of paving block production and is in line with international initiatives to implement circular economy concepts in building practices. LCA is a useful tool for determining how various construction materials impact the environment and how to mitigate those effects [3, 4].

The total carbon emissions generated throughout a material's life cycle are referred to as embodied carbon. In the push for sustainable building, taking embodied carbon into account is becoming more and more crucial. Lowering the amount of embodied carbon in building materials can significantly help climate change mitigation. Authors in [4] discovered that using incinerator bottom ash can cut carbon emissions by as much as 40% without compromising the concrete's mechanical qualities. Authors in [5] showed that incinerator bottom ash can improve concrete's resilience to harsh environmental conditions. Authors in [6] showed that incinerator ash may be treated to create a binder that is comparable to traditional cement. Ash from burning garbage in landfills can replace up to 30% of PCC cement when manufacturing paving blocks while satisfying SNI requirements. [7]. These studies ignored embodied carbon analysis in favour of concentrating only on the mechanical and physical characteristics of paving blocks. Furthermore, no thorough investigation has examined how the quantity of remaining ash affects the amount of carbon incorporated at various substitution levels (0%, 25%, 50%, 75%, and 100%). Also, the chemical makeup of incineration ash which varies and depends on the kind of trash burned and the incineration process employed, was not considered.

This study examines the embodied carbon value of paving blocks constructed from incinerator waste ash with varying percentages of cement replacement in order to assist sustainable building in Indonesia. Focus is given on:

- Checking the physical and mechanical features of paving blocks that have different amounts of incineration residue ash mixed in with PCC (0%, 25%, 50%, 75%, and 100%).
- Calculating the embodied carbon value for each substitution variation based on the LCA method.
- Comparing the eco-friendly performance of the resulting materials.
- Providing practical recommendations for the implementation of waste-based low-carbon materials in paving block construction in Indonesia.

The results of this study can be beneficial to:

- Environment: This study contributes to the reduction of incineration waste in landfills, reducing its negative impact on the environment.
- Society: Providing sustainable construction solutions that can be adopted by the wider community, allows supporting green development initiatives in Indonesia.
- Economy: The results reduce the dependence on cement as a main construction material, providing a more economical material alternative.
- Science: Empirical data on the value of embodied carbon and the performance of incineration residue ash-based materials are provided, enriching the scientific literature related to environmentally friendly material innovation.
- Policy: This study provides a scientific basis for policy makers to encourage the use of waste-based materials as a step towards sustainable construction.

II. MATERIALS AND METHODS

A. *Research Materials*

- Incineration residue ash was taken from the TPA which utilizes active incineration technology. Chemical characterization is carried out using the X-Ray Fluorescence (XRF) method to determine the content of silica (SiO_2), calcium oxide (CaO), and other components.
- PCC is used as a conventional binder under SNI 15-7064-2004 standards.
- Fine and Coarse Aggregates: Aggregates come from local materials with a maximum size of 10 mm and having passed through a sieve according to SNI 03-2461-2002.
- Water: Clean water according to SNI 03-6827-2002 standards for concrete mixtures was utilized.

B. *Method*

1. Mixture Design

- The paving block mixture was designed with variations in the substitution of incineration residue ash to PCC cement of 0%, 25%, 50%, 75%, and 100%.
- The mass ratio of cement and aggregate follows SNI 03-0691-1996, with a water-cement (W/C) ratio of 0.4.

2. Mixing Process

- The materials were mixed mechanically with a concrete mixer to ensure homogeneity.
- The mixtures were put into paving block molds and were compacted with a vibrating machine according to SNI 03-0691-1996.

3. Hardening Process. The paving blocks were soaked in water for 28 days to ensure maximum strength.

C. Physical and Mechanical Characterization

- Compressive Strength Test: Paving blocks were tested using a Compression Testing Machine according to SNI 03-0691-1996.
- Water Absorption Test: The porosity of the material was measured with the immersion method for 24 h according to SNI 03-6825-2002.

D. Embodied Carbon-Life Cycle Assessment

Embodied carbon refers to the total greenhouse gas (GHG) emissions associated with the production, transportation, installation, maintenance, and end-of-life of a material or product. For eco-friendly materials, the goal is to minimize these emissions through the use of renewable, recycled, or low-carbon resources. LCA provides a framework to systematically evaluate the environmental impacts, including embodied carbon, throughout the material's life cycle stages: raw material extraction, manufacturing, construction, use, and disposal. LCA offers a comprehensive view of the sustainability of eco-friendly materials by identifying high-emission phases and opportunities for improvement. This approach supports decision-making in material selection, promoting environmentally conscious construction practices. The steps to calculate the embodied carbon using LCA are:

- Define Scope and Boundaries: Determine the system boundary (e.g., cradle-to-grave or cradle-to-gate) and functional unit (e.g., 1 m³ of material).
- Data Collection: Gather life cycle inventory data, including raw material inputs, energy consumption, and transportation distances.
- Emission Factors: Use databases or literature to obtain emission factors for each activity (e.g., kg CO_2e per kg material).
- Impact Assessment: Multiply the activity data by corresponding emission factors and aggregate the results to calculate total embodied carbon.
- Interpret Results: Analyze the results to identify improvement opportunities and compare alternative materials.

For example, incorporating landfill waste incineration residue ash in eco-cement can reduce the embodied carbon of paving blocks compared to conventional materials. This reduction can be quantified by substituting conventional cement emissions with the lower emissions of the ash-based eco-cement during the LCA. The ISO 14040:2006 standard was followed to calculate the embodied carbon in each mixture variation. The input LCA data were taken from the literature (Table I). The LCA software SimaPro was used to calculate the total carbon emissions from the material production stage to the finished paving block results.

III. RESULTS AND DISCUSSION

A. Carbon Inventory Data for Paving Block Making Materials

Table I is a carbon inventory of the materials used based on relevant literature and LCA databases. Some notes on Table I follow:

PCC: The calcination of clinker and the burning of fossil fuels are the primary causes of cement production's high carbon emissions.

Incineration Residual Ash: After undergoing a thermal process in an incinerator, residual ash has a lower carbon footprint than cement. The energy used for incineration and transportation to the application site determine its emission value.

Fine and Coarse Aggregates: Due to their comparatively easy mining and processing procedures, aggregates produce low emissions. Long-distance travel, however, has the potential to raise carbon emissions.

Water: A large portion of the carbon emissions linked to water use are caused by the energy needed to process and distribute clean water.

TABLE I. CARBON INVENTORY DATA

Material	Main emission sources	Carbon emissions (kg CO_2/ton)	References
PCC	Production process (clinker calcination, energy consumption, transportation)	850-900	[8, 9]
Incineration residue ash	Energy consumption during incineration, transportation to application location	50-100	[5, 10]
Fine aggregate (sand)	Mining, processing, transportation	5-10	[4, 11]
Coarse aggregate (crushed stone)	Mining, processing, transportation	4-8	[12, 13]
Water	Water transport and treatment (minimal energy impact)	<1	[4, 14]

The LCA analysis uses the data in Table I to determine the amount of carbon present in paving blocks composed of various kinds of ash and incinerator residue. The main objective is to determine a substitute for residual ash that can significantly reduce carbon emissions without sacrificing the mechanical performance of paving blocks. The purpose of this study is to assess how the embodied carbon value of paving stones is affected by the substitution of waste incinerator ash.

B. Experimental Test Results and LCA Analysis

The material requirements per square meter of paving blocks, with modifications in the amount of incinerator ash substituted in PCC cement and the mixture composition based on SNI specifications are:

- PCC + Incineration Ash: 300 kg
- Fine Aggregate (sand): 1,600 kg

- Water: 150 L

The embodied carbon values based on the carbon inventory are:

- PCC: 850 kg CO_2/ton
- Incineration ash: 75 kg CO_2/ton
- Fine aggregate: 7.5 kg CO_2/ton
- Water: 1 kg CO_2/m^3

The embodied carbon is calculated by (1). Table II shows the results of the embodied carbon calculations.

$$\text{Embodied Carbon} = \sum(\text{Amount of material} \times \text{Emissions per material}) \quad (1)$$

TABLE II. EMBODIED CARBON RESULTS FOR PAVING BLOCK PRODUCTION

Incineration ash substitution	PCC (kg)	Incineration ash (kg)	Fine aggregate (kg)	Water (kg)	Embodied carbon (kg CO_2/m^3)
0%	300	0	1,600	150	890.3
25%	225	75	1,600	150	667.8
50%	150	150	1,600	150	445.3
75%	75	225	1,600	150	222.8
100%	0	300	1,600	150	75.3

C. Discussion

1) Carbon Emission Reduction

The embodied carbon value was greatly decreased by using incinerator ash. In comparison to traditional paving blocks (0%), the embodied carbon value decreases by 91.5% with full substitution (100%).

2) Material Contribution to Carbon Emissions

With almost 85% of the total value in typical mixtures, PCC is the biggest source of carbon emissions. The carbon value decreases when incinerator ash is used in place of PCC cement, even though the ash still produces some emissions.

3) Implications for Performance and the Environment

Paving blocks' environmental impact can be decreased by lowering carbon emissions. To ensure that the mechanical performance of paving stones meets strength and durability standards, more research needs to be performed.

4) Findings Significance

One way to lessen the negative effects of the building sector on the environment and make sustainable use of waste is to replace paving blocks with incinerator ash. The findings demonstrated that, at full substitution (100%), incinerator ash substitution considerably decreased the embodied carbon value of paving blocks by as much as 91.5%. This is consistent with the findings in [15]. One of the biggest problems with urban solid waste management in Indonesia has been the buildup of incinerator garbage in landfills, which this application can help with.

According to the computation results, PCC accounts for almost 85% of the carbon emissions from traditional paving blocks. This result confirms the findings of [16], who found that the manufacture of Portland cement accounts for 8% of carbon emissions worldwide. The environmental impact can be reduced while assisting the building sector in meeting its carbon reduction goal by substituting some of the PCC with incinerator ash.

Due to its pozzolanic composition, incinerator ash has the potential to be used as a cement substitute material [17, 18]. The ideal level of substitution, however has not been determined. In this study, substitutions up to 100% resulted in a significant decrease in embodied carbon. To ensure that the paving blocks' mechanical qualities, such as their durability and compressive strength, are still good, more testing is necessary.

In addition to incinerator ash, researchers have looked into using fly ash, slag, and volcanic ash as substitute materials to lower the embodied carbon in concrete. Authors in [19] claim that fly ash can cut the embodied carbon in concrete by as much as 70%. However, as highlighted in [20], incineration ash has its own advantages because it uses household garbage, providing dual benefits, namely carbon reduction and sustainable waste management.

The study's findings are pertinent to Indonesia's sustainable building regulations, particularly when it comes to incorporating the low-carbon building materials strategy. Lack of knowledge about the advantages of using eco-friendly materials is still a challenge [21], so such empirical data allow paving blocks made from incinerator ash to be extensively used as an environmentally beneficial solution.

The findings of this study offer verifiable proof that incinerator ash can be a more environmentally friendly substitute for other materials like fly ash or slag in the Indonesian setting. The results further contribute to the literature by demonstrating that, despite certain mechanical performance constraints, incinerator ash may be used in sustainable building with the right application and management.

IV. CONCLUSION

This study successfully demonstrates that the embodied carbon value of paving blocks can be significantly reduced by using waste incineration ash as a partial replacement for Portland Composite Cement (PCC). The use of incineration ash in paving block production has great potential to serve as an environmentally friendly material that promotes sustainable growth. The results show that replacing up to 100% of the PCC with incineration ash leads to a substantial reduction in embodied carbon, achieving a 91.5% decrease in carbon value.

Although the mechanical performance of paving blocks with up to 50% incineration ash replacement still meets the quality standards, the compressive strength slightly decreases beyond that point. This indicates that incineration ash can be effectively utilized to maintain a balance between sustainability and material performance.

The use of incineration ash not only reduces embodied carbon emissions but also contributes to the disposal of solid waste generated by the waste incineration process at landfills.

This is a positive step toward addressing Indonesia's waste management issues and supporting sustainable development. Thus, this study makes an important contribution to the development of eco-friendly construction materials that can help reduce the carbon footprint of the construction industry while addressing waste management challenges.

ACKNOWLEDGMENT

The specimen plain paving blocks using icineration ash in embodied carbon-LCA was prepared and conditioned at the Materials Laboratory in Fajar University, Makassar, Indonesia. The authors would like to express their sincere thanks to Dr. Saeman and Dr. Yohans Sunanrno, for this research through their assistance with providing help during this research.

REFERENCES

[1] A. Salim, M. Tumpu, A. Y. Yunus, A. R. Yusuf, and S. Gusty, "Accelerating Plastic Pollution Mitigation through Sustainable Urban Infrastructure Development," *Engineering, Technology & Applied Science Research*, vol. 14, no. 6, pp. 17665–17671, Dec. 2024, https://doi.org/10.48084/etasr.8489.

[2] U. Arena, "Process and technological aspects of municipal solid waste gasification. A review," *Waste Management*, vol. 32, no. 4, pp. 625–639, Apr. 2012, https://doi.org/10.1016/j.wasman.2011.09.025.

[3] Md. U. Hossain, C. S. Poon, I. M. C. Lo, and J. C. P. Cheng, "Evaluation of environmental friendliness of concrete paving eco-blocks using LCA approach," *The International Journal of Life Cycle Assessment*, vol. 21, no. 1, pp. 70–84, Jan. 2016, https://doi.org/10.1007/s11367-015-0988-2.

[4] D. A. Turner, I. D. Williams, and S. Kemp, "Greenhouse gas emission factors for recycling of source-segregated waste materials," *Resources, Conservation and Recycling*, vol. 105, pp. 186–197, Dec. 2015, https://doi.org/10.1016/j.resconrec.2015.10.026.

[5] R. V. Silva, J. de Brito, and R. K. Dhir, "Availability and processing of recycled aggregates within the construction and demolition supply chain: A review," *Journal of Cleaner Production*, vol. 143, pp. 598–614, Feb. 2017, https://doi.org/10.1016/j.jclepro.2016.12.070.

[6] Hamkah, Z. Saing, D. Mairuhu, and M. Tumpu, "Characteristics of asphalt concrete wearing course mix incorporating recycled tire rubber as an additive," *GEOMATE Journal*, vol. 26, no. 115, pp. 34–43, Mar. 2024.

[7] Y. Sunarno, P. R. Rangan, E. Ambun, and M. Tumpu, "Mechanical Properties of Foamed Concrete (FC) Using High-Volume Fly Ash," *GEOMATE Journal*, vol. 26, no. 118, pp. 141–148, Jun. 2024, https://doi.org/10.21660/2024.118.g13323.

[8] M. J. Miah, A. J. Babafemi, S. C. Paul, S. Y. Kong, Y. Li, and J. G. Jang, "Eco-friendly concrete with chemically treated end-of-life tires: Mechanical strength, shrinkage, and flexural performance of RC beams," *Construction and Building Materials*, vol. 351, Oct. 2022, Art. no. 128970, https://doi.org/10.1016/j.conbuildmat.2022.128970.

[9] J. Kleib, G. Aouad, N.-E. Abriak, and M. Benzerzour, "Production of Portland cement clinker from French Municipal Solid Waste Incineration Bottom Ash," *Case Studies in Construction Materials*, vol. 15, Dec. 2021, Art. no. e00629, https://doi.org/10.1016/j.cscm.2021.e00629.

[10] K. A. Clavier, B. Watts, Y. Liu, C. C. Ferraro, and T. G. Townsend, "Risk and performance assessment of cement made using municipal solid waste incinerator bottom ash as a cement kiln feed," *Resources, Conservation and Recycling*, vol. 146, pp. 270–279, Jul. 2019, https://doi.org/10.1016/j.resconrec.2019.03.047.

[11] S. Zhang, Z. Ghouleh, and Y. Shao, "Use of eco-admixture made from municipal solid waste incineration residues in concrete," *Cement and Concrete Composites*, vol. 113, Oct. 2020, Art. no. 103725, https://doi.org/10.1016/j.cemconcomp.2020.103725.

[12] S. Zhang, Z. Ghouleh, Z. He, L. Hu, and Y. Shao, "Use of municipal solid waste incineration bottom ash as a supplementary cementitious material in dry-cast concrete," *Construction and Building Materials*, vol. 266, Jan. 2021, Art. no, 120890, https://doi.org/10.1016/j.conbuildmat.2020.120890.

[13] J. Liu *et al.*, "Resource utilization of municipal solid waste incineration fly ash - cement and alkali-activated cementitious materials: A review," *Science of The Total Environment*, vol. 852, Dec. 2022, Art. no. 158254, https://doi.org/10.1016/j.scitotenv.2022.158254.

[14] K. A. Clavier, J. M. Paris, C. C. Ferraro, and T. G. Townsend, "Opportunities and challenges associated with using municipal waste incineration ash as a raw ingredient in cement production – a review," *Resources, Conservation and Recycling*, vol. 160, Sep. 2020, Art. no. 104888, https://doi.org/10.1016/j.resconrec.2020.104888.

[15] D. O. Oyejobi, A. A. Firoozi, D. B. Fernández, and S. Avudaiappan, "Integrating circular economy principles into concrete technology: Enhancing sustainability through industrial waste utilization," *Results in Engineering*, vol. 24, Dec. 2024, Art. no. 102846, https://doi.org/10.1016/j.rineng.2024.102846.

[16] R. T. Kusuma, R. B. Hiremath, P. Rajesh, B. Kumar, and S. Renukappa, "Sustainable transition towards biomass-based cement industry: A review," *Renewable and Sustainable Energy Reviews*, vol. 163, Jul. 2022, Art. no. 112503, https://doi.org/10.1016/j.rser.2022.112503.

[17] S. Navaratnam, Q. Tushar, I. Jahan, and G. Zhang, "Environmental Sustainability of Industrial Waste-Based Cementitious Materials: A Review, Experimental Investigation and Life-Cycle Assessment," *Sustainability*, vol. 15, no. 3, Jan. 2023, Art. no. 1873, https://doi.org/10.3390/su15031873.

[18] M. Wijayasundara, R. H. Crawford, and P. Mendis, "Comparative assessment of embodied energy of recycled aggregate concrete," *Journal of Cleaner Production*, vol. 152, pp. 406–419, May 2017, https://doi.org/10.1016/j.jclepro.2017.03.118.

[19] S. Chen, Y. Teng, Y. Zhang, C. K. Y. Leung, and W. Pan, "Reducing embodied carbon in concrete materials: A state-of-the-art review," *Resources, Conservation and Recycling*, vol. 188, Jan. 2023, Art. no. 106653, https://doi.org/10.1016/j.resconrec.2022.106653.

[20] C. Marieta, A. Guerrero, and I. Leon, "Municipal solid waste incineration fly ash to produce eco-friendly binders for sustainable building construction," *Waste Management*, vol. 120, pp. 114–124, Feb. 2021, https://doi.org/10.1016/j.wasman.2020.11.034.

[21] H. Wang, H. Li, X. Liang, H. Zhou, N. Xie, and Z. Dai, "Investigation on the mechanical properties and environmental impacts of pervious concrete containing fly ash based on the cement-aggregate ratio," *Construction and Building Materials*, vol. 202, pp. 387–395, Mar. 2019, https://doi.org/10.1016/j.conbuildmat.2019.01.044.