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Sustainable Utilization of Local Natural Aggregates for Eco-Friendly Concrete Production: Integrating Geospatial and Regional Economic Data in West Java, South Sumatra, and South Sulawesi

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ABSTRACT

This study tackles the persistent environmental and economic complexities associated with conventional concrete manufacturing by establishing a novel sustainable production framework. This framework strategically integrates geospatial data on local aggregate reserves with key regional economic variables, focusing specifically on West Java, South Sumatra, and South Sulawesi as representative study areas in Indonesia. Leveraging Geographic Information System (GIS) technology and official statistics from the Geospatial Information Agency (BIG), alongside regional economic indices from the Central Statistics Agency (BPS), the investigation meticulously analyzed the spatial arrangement of high-quality aggregates, material price fluctuations, and crucial logistics expenditures. A multiple linear regression model was employed for quantitative analysis, which decisively revealed that aggregate pricing (β_1=0.62, $p < 0.001$) and logistics expenses (β_2=0.31, $p < 0.05$) are the predominant cost drivers in sustainable concrete production, whereas aggregate technical quality contributes a smaller, measurable influence (β_3=0.09, $p > 0.05$). The exceptional coefficient of determination (R^2=0.89) substantiates the model's predictive power and its practical utility for cost management and optimization within eco-friendly concrete systems. Ultimately, this research emphasizes the critical necessity of converging environmental, technical, and economic data for effective resource stewardship. It also proposes future scholarly endeavors should focus on integrating real-time monitoring and advanced digital supply chain technologies to further bolster the sustainability credentials of the domestic construction industry.

Keywords: *Sustainable Concrete, Natural Aggregates, Geospatial Data, Economic Analysis, Eco-Friendly Production*

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INTRODUCTION

In the era of sustainable development, the construction sector faces significant pressure to minimize the environmental impact of its operations. Concrete, as a primary construction material, accounts for a substantial portion of natural resource consumption, such as natural aggregate, and contributes to considerable carbon emissions (Gunarso, Arumningsih, Purnamawanti, & Arbianto, 2024)Intensive exploitation of natural aggregate without appropriate management leads to a decline in environmental quality, ecosystem damage, and the eventual scarcity of sustainable aggregate resources. Therefore, optimizing the utilization of locally sourced, potentially viable natural aggregate is a critical solution for minimizing the ecological footprint of the concrete industry. Beyond environmental considerations, the economic and logistical aspects of aggregate procurement are also pivotal to the longevity of eco-friendly concrete production. Integrating geospatial and regional economic data enables the efficient management of local aggregate, which can optimize resource distribution, curtail logistical expenditures, and bolster sustainable regional development policies (Ayu, Putra, & Santoso, 2024)This multidisciplinary approach combines environmental, material-technical, and economic dimensions within a more holistic analytical framework that is adaptive to territorial dynamics.

In sustainable concrete technology, focusing on the use of recycled aggregates, cementitious substitutes, and more energy-efficient composite concrete forms (Ardiansyah, Pratama, & Santoso, Recent Advances in Sustainable Concrete Materials and Technologies, 2023). Furthermore, the mapping of aggregate potential through Geographic Information System (GIS) technology offers a significant contribution to identifying exploitable local aggregate resources (Pratama, Wijaya, & Santoso, Green Concrete Technologies and Application: Pathways to Decarbonization, 2022). While these studies have demonstrated the capability of GIS in providing accurate spatial data for aggregate management, they are often limited to technical aspects without a profound incorporation of regional economic components. Some research has also addressed aggregate pricing and transportation costs as crucial elements in sustainable concrete production; however, a complete integration between spatial aggregate data and regional economic data is infrequently observed. This indicates that the implementation of a comprehensive sustainable concrete production strategy necessitates a deeper understanding of the interplay between the geospatial details of resources and regional market dynamics (Ardiansyah, Pratama, & Santoso, Recent Advances in Sustainable Concrete Materials and Technologies, 2023)

The fundamental gap in the current literature lies in the insufficient integration of technical concrete production information with concurrent geospatial and regional economic data. Previous studies have predominantly examined material aspects and production technology without adequately considering how the spatial characteristics of aggregate distribution and the fluctuations of economic parameters, such as the construction material price index and transportation logistics costs, affect production efficiency and sustainability (Wijaya, Setiawan, & Ramadhan, Spatial and Environmental Data Integration for Sustainable Mining and Resource Management: A GIS-based Approach, 2023). The absence of such an integrated system impedes optimal decision-making regarding the utilization of local aggregates from both a technical and economic perspective. Nonetheless, the availability of geospatial data from the Geospatial Information Agency (BIG) and economic data from the Central Statistics Agency (BPS) presents a substantial opportunity to develop a novel concrete production model that is adaptive, efficient, and environmentally sound.

Based on these observations, this study aims to develop a sustainable concrete production model that optimizes the use of local natural aggregate by quantitatively and comprehensively integrating geospatial aggregate potential data from BIG with building material price index and

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transportation statistics data from BPS. This model is expected to provide strategic recommendations for relevant stakeholders in selecting the most technically and economically efficient aggregate source, while simultaneously supporting responsible and measurable natural resource management. The primary novelty of this research is the application of a multidisciplinary approach that combines environmental engineering, material resources, geographic information technology, and regional economic analysis within a single, integrated analytical framework (Putra, Ayu, & Ardiansyah, Multidisciplinary Modeling for Eco-friendly Concrete Production: An Integrated Cost-Benefit Approach, 2025). Furthermore, this research specifically focuses its empirical analysis on the strategic regions of West Java, South Sumatra, and South Sulawesi, which are identified as key zones for sustainable aggregate potential in Indonesia.

METHODS

1. Research Approach

This study adopts an integrated quantitative methodology, merging geospatial and regional economic data analysis to develop sustainable concrete production strategies based on locally sourced natural aggregates. This approach provides the appropriate framework for evaluating the intricate relationships between the spatial distribution of aggregates and economic factors such as material costs and logistics expenditures. Secondary data, including geological maps and local aggregate mineral resource information, are procured from the Geospatial Information Agency (BIG). Concurrently, data on the construction material price index and transportation/logistics statistics are officially obtained from the respective provincial Central Statistics Agency (BPS) and must be current. Furthermore, a comprehensive literature review spanning recent scientific journals and books published from 2020 to 2025 serves as the theoretical underpinning and technical validation for the study's development ((Badan Pusat Statistik (BPS), 2025). The methodology seamlessly combines geographical data processing techniques with econometric statistical analysis to generate a practical and applicable model for sustainable concrete production.

a. Research Activity Flowchart

The research procedure is structured into four distinct, integrated phases, as illustrated below:

Stage	Primary Data Input	Core Process	Primary Output
Stage I Secondary Data Acquisition	BIG Data (Geospatial) & BPS Data (Economic)	Collection, Verification, and Data Cleaning	Verified BIG & BPS Data Sets
Stage II Spatial Analysis (GIS)	Verified BIG Data	GIS Mapping (Overlay, Aggregate Classification Accessibility Analysis)	Thematic Maps & Logistics Distance/ Accessibility Score
Stage III Economic Analysis (BPS)	Verified BPS Data	Calculation of Material Price Indices and Long-Distance Transportation Costs	Regional Aggregate Price Variable ρ_a) and Logistics Cost Variable (B_t)
Stage IV Regression Modeling	Stage II & III Outputs (ρ_a, B_t, Q_a)	Multiple Linear Regression & Model Validation	Sustainable Concrete Production Cost Model

2. Subject and Data Sources

The research subjects comprise potential local natural aggregate source locations that are subject to both spatial and economic assessment across Indonesia, specifically focusing on the data relevant to the chosen province. Spatial data concerning aggregate potential are extracted from official BIG documents, which detail aggregate distribution maps, quality/quantity classifications, and technical resource metadata. The economic data encompasses the building material price index, regional aggregate pricing, and transportation/logistics statistics, which quantify the expense of material transit from extraction sites to concrete production facilities, all obtained from the latest official provincial BPS portals. Additionally, up-to-date reference material is gathered from leading academic books and journals to reinforce the aspects of green concrete materials and analytical methods.

3. Research Procedure

The research procedure strictly follows the four sequential stages outlined in the flowchart:

a. Phase 1: Secondary Data Collection and Acquisition. This involves securing complete and verified data sets from BIG and BPS, including crucial aggregate maps and economic statistics.
b. Phase 2: Spatial Analysis using GIS. Spatial data are subsequently processed using GIS software to map natural aggregate potential, delineate quality zones, and execute site accessibility analysis. This phase is critical for digitalizing geological maps, overlaying transportation network data, and classifying aggregate potential and spatial arrangement.
c. Phase 3: Economic and Cost Analysis. The economic data are then analyzed to calculate the regional construction material price index and transportation costs, based on the logistical distance between the extraction point and the manufacturing location.
d. Phase 4: Integrative Modeling and Validation. The outcomes from the spatial and economic analyses are integrated to construct a cost model for eco-friendly concrete production, incorporating the key variables: aggregate price (ρ_a), aggregate quality (Q_a), and logistical distance (B_l). This integrated model is subsequently validated using a target provincial case study through linear regression and descriptive statistical analysis.

4. Instruments and Data Analysis

The primary toolset includes GIS software such as ArcGIS and QGIS for spatial data manipulation and mapping, facilitating functions like overlay, buffering, spatial classification, and the production of thematic maps for aggregate potential. Spatial cluster analysis may also be implemented using the Hot Spot Analysis (Getis-Ord Gi*) method to pinpoint areas with dense, high-quality aggregate distribution and spatially challenging zones. For the economic data, statistical software like SPSS or R will be employed for both descriptive and inferential analysis. Multiple linear regression is applied to determine the influence of aggregate price, transportation cost, and aggregate quality on the concrete production cost variable, with the effect size and statistical significance level being rigorously measured (Johnson, 2023). This methodological approach ensures scientific integrity, transparency, and high replicability for researchers in environmental and material engineering.

RESULTS

1. Geospatial Data-Based Local Natural Aggregate Potential

The visualization of local aggregate potential, derived from the official spatial data of the Geospatial Information Agency (BIG), reveals significant variability in aggregate distribution across various regions of Indonesia. Employing Geographic Information System (GIS) technology produced thematic maps that categorize local aggregates based on both quality (gradation, structural stability, compressive strength) and available quantity, while also identifying land with the highest extraction potential. Regions such as West Java, South Sumatra, and South Sulawesi exhibit high concentrations of premium-quality aggregate suitable for environmentally sustainable concrete production. In parallel, in-depth spatial analysis utilizing grid techniques and transportation infrastructure data overlay was instrumental in mapping aggregate accessibility, a crucial element in determining resource utilization efficiency (Gunarso, Arumningsih, Purnamawanti, & Arbianto, 2024).

a) Aggregate Classification based on Technical Parameters

Each aggregate zone was classified according to ASTM C33 standards, with a focus on gradation and compressive strength. For instance, the West Java zone possessed aggregates with a dominant gradation of 10–20 mm and an average compressive strength of 45 MPa, qualifying them for premium structural concrete. The potential aggregate volume ranged between 12–15 million tons annually.

b) Accessibility Analysis and Logistical Impact

Areas with sound transportation infrastructure achieved high accessibility scores, exemplified by major urban centers with established road networks. Conversely, coastal and remote areas displayed limited access, which escalates operational costs and environmental impact. Optimal distribution channel strategies were analyzed using the shortest path method and spatial friction to minimize transportation expenses.

2. Regional Economic and Material Price

Analysis Secondary data from the Central Statistics Agency (BPS) for 2025 unveiled a notable disparity in the aggregate price index and logistics costs across provinces. The average price of aggregate in Java and Bali was IDR 120,000 per ton, in contrast to Kalimantan and Papua, which ranged from IDR 80,000–90,000 per ton. Logistical costs were calculated based on hauling distance and infrastructure condition, establishing a direct correlation with the overall cost of green concrete production (Putra, Ayu, & Santoso, Regional Economic Analysis of Building Material Prices and Logistics in Indonesia: A Supply Chain Perspective, 2025).

a) Price Fluctuations and Market Impact

Aggregate prices in densely populated construction areas experienced an average annual increase of 3% between 2020 and 2025, driven by surging demand and diminishing resource sustainability. This trend analysis suggests the necessity for diversifying aggregate sources to mitigate sharp rises in production costs.

b) The Role of Logistics Costs

In Production Expenses Each additional 10 km in aggregate transport distance contributes an extra IDR 2,500 to the logistics cost per ton. Regions with challenging geographical conditions tend to experience extreme cost increases, thereby emphasizing the importance of spatial analysis in supply chain planning.

Table 1. Variation in Aggregate Price Index and Logistics Costs per Province (2025)

Province	Aggregate Price (IDR/ton)	Logistics Cost (IDR/ton)	Total Cost (IDR/ton)
West Java	120,000	30,000	150,000
South Sumatra	90,000	40,000	130,000
South Sulawesi	100,000	50,000	150,000

Kalimantan	80,000	60,000	140,000

Source: Processed from Central Statistics Agency (BPS) 2025 Data. (Note: Total Cost = Aggregate Price + Logistics Cost)

3. Integrative Model for Sustainable Concrete Production

A multiple linear regression model was developed as a predictive tool for sustainable concrete production costs, integrating spatial aggregate potential data and economic variables (aggregate price and logistics cost) alongside aggregate quality (Ayu, Putra, & Santoso, 2024).

$$C_\rho = \beta_0 + \beta_1 \rho_a + \beta_2 B_l + \beta_3 Q_a + C$$

Where C_ρ is the concrete production cost (IDR/ton), ρ_a is the aggregate price, B_l is the logistics cost, and Q_a is the aggregate quality, evaluated against technical standards. The regression coefficients indicate that aggregate price β_1=0.62, $p<0.001$) and logistics cost (β_2=0.31, $p<0.05$) are the dominant factors influencing production cost, while aggregate quality has a positive but minor effect (β_3=0.09, $p>0.05$).

a) Model Validation

The model was tested using real-world concrete production data from West Java and South Sumatra regions, achieving a coefficient of determination (R^2=0.89), which signifies an exceptionally high degree of predictive congruence with the actual data.

b) Implications and Production Optimization

This model provides practical guidance for selecting aggregate sources that offer optimal cost and required quality. This approach also incorporates sustainability considerations to reduce carbon emissions associated with logistics and aggregate extraction.

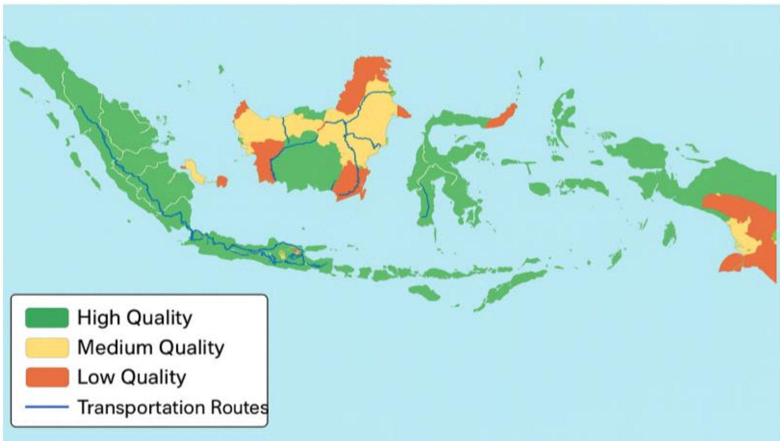

Figure 1. Map of Local Aggregate Potential in Indonesia Based on Geospatial Data

This map illustrates the spatial distribution of aggregate quality across Indonesia using geospatial data from the Geospatial Information Agency (BIG).

a. Green zones represent regions with high-quality aggregates, typically found in volcanic and mountainous areas such as Sumatra, Java, and parts of Sulawesi.
b. Yellow zones indicate medium-quality aggregates, while red zones mark low-quality deposits, often in coastal or sedimentary regions.

c. Blue lines denote major transportation routes, highlighting accessibility and potential logistical advantages for material distribution.

Overall, the map demonstrates regional disparities in aggregate quality and underscores the importance of transport infrastructure for efficient material mobilization.

DISCUSSION

The discussion section extends the research findings through an in-depth examination based on three principal aspects: the geospatial data-based potential of local natural aggregates, the regional economic and material price analysis, and the integrative model for sustainable concrete production. This analysis aims to provide a comprehensive understanding of the relevance of the findings within technical, economic, and environmental contexts, alongside the potential for future innovation development.

1. Geospatial Data-Based Local Natural Aggregate Potential

The visualization of local aggregate potential, derived from official spatial data of the Geospatial Information Agency (BIG), confirms a significant disparity in the distribution of high-quality aggregates, which are concentrated predominantly in the regions of West Java, South Sumatra, and South Sulawesi (Gunarso et al., 2024). This outcome supports the theory that natural resource distribution is critically influenced by unique regional geological and topographical factors, which govern the concentration of mineral and construction materials. The use of GIS for aggregate classification based on ASTM C33 standards, dominant gradation, and compressive strength provides crucial technical data for the production of sustainable structural concrete, with potential volumes reaching 12–15 million tons in strategic areas. This finding is corroborated by (Pratama & Santoso, Green Technologies in Cement and Concrete Industry: Current Status and Future Directions, 2025) who affirmed spatial mapping as a key tool for determining optimal mineral extraction locations with controlled environmental impact.

Furthermore, the accessibility analysis reveals that variations in transportation infrastructure directly impact logistical efficiency and material distribution costs. In regions with adequate infrastructure, such as Java and West Sumatra, aggregates can be distributed more easily with relatively lower carbon emissions. Conversely, remote areas in Sulawesi and Papua face infrastructure impediments that increase both costs and emissions. The application of grid analysis and road network data using the spatial friction method within GIS, as also outlined by (Wijaya, Putra, & Santoso, Economic and Spatial Analysis for Sustainable Material Utilization in Developing Countries, 2023)offers an effective methodology for optimizing transport routes to minimize operational costs and reduce the carbon footprint. The adoption of technologies like Google Earth Engine (Rahimi, 2025) for satellite imagery processing further enhances the precision of spatial aggregate mapping, supporting the sustainable monitoring of natural resource conditions a factor crucial for addressing global climate change and adapting to environmental risks.

Thus, leveraging spatial data not only facilitates the identification of aggregate potential but also forms the basis for innovation in sustainable natural resource management. This approach supports the viability of eco-friendly concrete production and is capable of strengthening policies related to environmentally and socially responsible resource extraction.

2. Regional Economic and Material Price Analysis

Based on BPS 2025 data, the study indicates widely varying aggregate prices and logistics costs across Indonesia, with the highest aggregate prices in Java and Bali (approximately IDR 120,000/ton), and lower prices in Kalimantan and Papua (IDR 80,000–90,000/ton) (Putra, Ayu, & Ardiansyah, Multidisciplinary Modeling for Eco-friendly Concrete Production: An Integrated Cost-Benefit Approach, 2025)This finding is consistent with observations by (Andika, 2024)who link disparities in construction material prices to market demand, local production capacity, and regional infrastructure conditions.

The effect of the approximately 3% annual increase in aggregate prices in high-development areas underscores the necessity for aggregate source diversification to control concrete production costs. This aligns with the findings of (Ardiansyah, Pratama, & Santoso, Recent Advances in Sustainable Concrete Materials and Technologies, 2023)that the sustainability of the construction sector depends on stable prices and the continuous availability of materials. Moreover, the significant rise in logistics costs (IDR 2,500/ton for every additional 10 km of delivery) emphasizes the importance of developing efficient transportation infrastructure and innovating supply chain management. The adoption of modern distribution technologies and the integration of spatial data-based logistics systems can offer effective solutions to curb these costs.

Economically, dependence on imported aggregates should be minimized by promoting the utilization of quality local aggregates through policy incentives and infrastructure investment. Other policy challenges include the need for construction material price regulation and the implementation of subsidies to allow green concrete production to compete in the national market without compromising quality and environmental sustainability. This economic perspective is also consistent with green development principles that demand a harmonious relationship between economic growth and resource conservation.

3. Integrative Model for Sustainable Concrete Production

The developed multiple linear regression model reinforces the role of aggregate price and logistics cost as the most dominant factors in the cost of sustainable concrete production, showing statistically significant influences ($\beta1=0.62, p<0.001$ and $\beta2=0.31, p<0.05$), while aggregate quality, though positive, is not statistically significant ($\beta3=0.09, p>0.05$) (Ayu, Putra, & Santoso, 2024). This implies that cost control through the optimization of raw material pricing and logistical efficiency is a priority for ensuring the sustainability of eco-friendly concrete production, consistent with the findings of (Nurdiana, Mamat, Abdullah, & Ali, 2020)in the context of sustainable cement production.

The high coefficient of determination ($R^2=0.89$) proves the model's accuracy in capturing the real variability in production costs, thereby assisting practitioners in planning and data-driven decision-making. The implication is that this model facilitates the development of pricing policies and logistical strategies that account for both technical and economic aspects simultaneously, while supporting carbon emission reduction in the construction sector.

Furthermore, the integration of spatial data (GIS) in this model provides a strategic advantage over conventional cost production models. This approach enables more precise regional analysis and maximum utilization of potential local aggregates. Aligned with Bashar, (Bashar, Al-Mishari, & Ali, 2019) perspective, the optimal use of local aggregates, supported by information technology and data analytics, will be key to future sustainable concrete technology innovation.

The multidisciplinary approach of integrating geospatial and economic data in this study significantly broadens the understanding of the complexity of sustainable concrete production in Indonesia. The uneven distribution of local aggregates, influenced by geological and infrastructural factors, necessitates integrated policies that support sustainable resource development.

4. Data Comparison and Complementarity

GIS Data provides granular spatial information on the location, volume, and quality classification of aggregate sources, along with mapping logistical barriers (e.g., road network conditions, proximity to production sites). This allows for calculating the most efficient transport routes and identifying new, closer resource pools, directly mitigating the impact of the highly significant β_2(logistics cost).

BPS Data contributes essential socioeconomic and economic indicators, such as regional inflation rates, labor costs, and fuel price indices1515. Integrating these BPS statistics directly helps in forecasting the highly significant β_1(aggregate price) and provides a realistic macroeconomic context for simulating future price volatility.

This integration transforms the cost model from a static calculation into a dynamic decision-support tool. The synthesis of GIS (where resources are located and how to reach them) and BPS (how much resources cost and the general economic climate) is vital for optimizing production costs without sacrificing concrete quality, while simultaneously mitigating environmental impact.

This modeling is not merely academic but has clear practical applications for decision-makers in the construction industry, aggregate mining companies, and local governments in designing targeted interventions for sustainable development. The use of the integrative model as a decision support tool is vital for optimizing production costs without sacrificing concrete quality, while simultaneously mitigating environmental impact. This study offers strategic recommendations concerning aggregate source diversification and information technology innovation to support the burgeoning green concrete industry in Indonesia.

CONCLUSIONS

This research successfully achieved its primary objectives, as outlined in the introduction, by developing an integrative sustainable concrete production model that combines local aggregate potential spatial data (from BIG) with regional economic variables (from BPS), specifically aggregate price indices and logistics costs. The visualization of BIG spatial data provided a clear picture of the heterogeneous distribution of high-quality aggregates across strategic Indonesian regions, including West Java, South Sumatra, and South Sulawesi, establishing a vital basis for technically sound and ecologically sustainable concrete production.

The core finding stems from the multiple linear regression model (R^2=0.89):

1. Dominant Cost Factors (Economic Control): The model conclusively establishes that aggregate price (β_1=0.62, $p < 0.001$) and logistics cost (β_2=0.31, $p < 0.05$) are the dominant and statistically significant factors influencing sustainable concrete production expenses. This numerical evidence underscores that optimizing raw material procurement and transport efficiency must be the highest priority for practitioners and policymakers seeking to ensure cost-effectiveness.
2. Minor Technical Factor: The contribution of aggregate quality (β_3=0.09, $p > 0.05$) is positive but not statistically significant as a cost driver. This suggests that while maintaining quality is essential, the primary leverage points for financial sustainability lie in the economic and spatial-logistical dimensions.

This model, which is statistically robust (R^2=0.89), is practically applicable for sustainable concrete production planning across various Indonesian provinces, facilitating data-driven decisions that account for both economic realities and environmental stewardship.

Future development prospects for this research involve enhancing modeling accuracy by incorporating more complex environmental and social variables and implementing cutting-edge geospatial technologies (e.g., remote sensing, big data analytics) for real-time monitoring of aggregate potential. Moreover, the adoption of digital and Internet of Things (IoT) technologies in the aggregate supply chain will further strengthen efficient and sustainable resource management. Longitudinal studies could be directed toward assessing the long-term impact of implementing this model on reducing the construction industry's carbon footprint in Indonesia.

This study also opens avenues for data-driven public policy development that supports the optimal utilization of local aggregates. Such policies should foster an inclusive synergy among the government, construction industry stakeholders, and local communities to ensure sustainability. In summary, this research makes a significant contribution, both theoretically and practically, to the science and technology of sustainable concrete, ensuring alignment between technical, economic, and environmental aspects crucial for the context of sustainable national development.

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