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A Decision-Making Model for Supporting Selection of Sustainable Material for Road Construction in Indonesia

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Abstract: Road construction using large amounts of materials may result in significant environmental concerns. Using sustainable materials can reduce environmental impacts, save energy, reduce costs and improve social systems. This research proposes a decision-making model for selecting sustainable materials for road pavement construction based on sustainability aspects by highlighting key criteria and their weightings. A literature review was undertaken to determine the relevant criteria and subcriteria when selecting environmentally friendly materials for national road projects, which experts then validated and assessed using a Likert scale (1 to 9). The VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method was used to analyse the assessed variables, generating importance rankings for each criterion and subcriterion to construct the model. The results showed that economic criteria were the most important, with a VIKOR index of 0.000, followed by environmental criteria, with an index of 0.754 and social criteria, with an index of 1.000. This study contributes significant knowledge to the field by highlighting the use of VIKOR as a decision-making tool that could aid stakeholders to select materials for sustainable road construction.

Keywords: Sustainable material, Selection model, Road construction, Pavement material selection, VIKOR

INTRODUCTION

Road construction directly supports multiple Sustainable Development Goals (SDGs), from improving infrastructure and economic development to reducing environmental impacts and enhancing social inclusion (Goubran, 2019; Setyandito et al., 2024). Sustainable practices and strategic planning for road construction projects can significantly advanced the United Nations's 2030 Agenda for Sustainable Development (Adshead et al., 2019). Infrastructure development, including roads, plays a critical role in achieving many SDGs, as they influence economic growth, environmental sustainability and social well-being (Mwelu, Watundu and Moya, 2024). Road infrastructure is a key element of SDG 9, which focuses on building resilient infrastructure, promoting sustainable industrialisation and fostering innovation (Singh and

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Ru, 2023). Well-constructed roads improve access to markets, facilitate trade and support industrial growth, especially in developing regions (Dokyi et al., 2024).

Road infrastructure generally provides new access or connects two or more regions, enhancing public accessibility. Road construction not only enhances transportation infrastructure, it also promotes economic, social and environmental improvements in a community or region (Labi et al., 2019). Road infrastructure improves the efficient distribution of goods and services and supporting the shipment of production outputs to the market.

However, road construction generates various types of waste throughout the production process, including excavated materials, demolition waste, material waste, and concrete and asphalt waste. Road construction also generates hazardous waste, dust and airborne particulates (Ali et al., 2019). Therefore, a long-term, environmentally sustainable development approach is required that considers both environmental preservation and human ecology. Extensive road construction requires substantial materials and energy, which can produce significant waste that negatively impacts the environment, including greenhouse gas emissions, during the construction lifecycle. To minimise waste, the use of recycled materials such as reclaimed asphalt pavement and concrete are often encouraged in modern construction projects.

Pavement is a critical component of road construction, as it is designed to bear vehicle load and distribute that weight over a larger area (Yeganeh, Vandoren and Pirdavani, 2022). It serves several essential functions vital to the durability, safety and functionality of the road. Pavement also creates a smooth and even surface for vehicles, allowing for comfortable and efficient travel, reducing wear and tear on vehicles. Road pavement generally uses a large amount of new raw materials (Khade and Wuppulluri, 2024), such as mineral aggregates, that account for more than 80% of concrete pavement and 94% of asphalt pavement (Li et al., 2019). Pavement materials should ideally be sustainable to minimise environmental impacts and ensure long-term viability (Praticò et al., 2020). Sustainable pavement materials and practices are not only environmentally beneficial, but also offer economic advantages, such as reduced maintenance costs and longer-lasting roads (Milad et al., 2022). The implementation of environmentally friendly materials can reduce environmental impacts, conserve energy, lower overall costs and enhance social systems (Bapat, Sarkar and Gujar, 2021; Wang et al., 2025).

This study utilised Indonesia's national road network as a case study. Indonesian roads are classified by their administrative and functional importance. National roads are managed and funded by the central government, in contrast to provincial or district roads managed at local levels. These roads are designated as "national" because they play a crucial role in national connectivity, facilitating the movement of goods, services and people across Indonesia's islands. Therefore, Indonesia's national road network plays a crucial role in connecting its diverse and vast archipelago, and experiences high demand for connectivity to support economic growth, regional development and social mobility (Nawir, Bakri and Syarif, 2023). They are typically high-capacity roads that facilitate long-distance transportation (Hermansyah, Samudra and Satispi, 2024). Indonesia is currently undergoing massive infrastructure development, especially in remote and outer islands, with asphalt as one of the most widely used materials for road pavements.

To ensure cost effective road maintenance, pavement materials must be selected with sustainability in mind by minimising environmental impacts and the associated costs. Unfortunately, Indonesia lacks clear national standards or guidelines for the use of sustainable or alternative materials in road construction (Lendra, Hatmoko and Wibowo, 2024). Sustainable roads are not only environmentally friendly, but also financially prudent (Al Hazaimeh and Alnsour, 2022), ensuring that Indonesia's infrastructure investments continue to support the country's economic development while protecting the environment. In Sarolangun of Province of Jambi, Indonesia, damage has already been detected at various points less than a year after construction. It is suspected that the roadbed's base aggregate material does not meet the required standards.

While the initial cost of sustainable materials may be higher, they often result in long-term cost savings through reduced maintenance, longer life spans and lower energy costs in production. Another benefit is that sustainable materials often provide better durability and longevity for roads, essential in a country like Indonesia, where the climate includes heavy rains, floods and occasional earthquakes. For example, the use of reclaimed asphalt pavement aims to reduce costs and the use of natural resources (Widayanti et al., 2021). However, there has been limited adoption of reclaimed asphalt pavement, industrial by-products (like fly ash or slag) or bio-based binders in Indonesian road construction.

This study therefore focuses on sustainable material criteria selection by developing a framework that supports decision-making to provide effective guidance on evaluating and prioritising sustainable pavement materials. The conceptual framework outlines the key dimensions influencing the selection of sustainable materials in road construction, including environmental impacts, economic feasibility and social acceptability, addressing infrastructures' long-term performance and durability.

This study makes a significant contribution to both theory and practice by bridging the gap between sustainability principles and construction material decision-making. While previous research has primarily focused on materials for specific construction elements, such as AlKheder, AlKandari and AlYatama (2022), who identified three aspects of sustainable material selection for runway pavement, and Al-Atesh et al. (2023) who identified three aspects of sustainable material selection for building structures, this study expands the focus by investigating sustainable material selection for specific road pavement materials. Despite the construction sector operating at full capacity, limited literature has explored sustainable construction practices within the Indonesian context (Widayanti et al., 2021; Sumabrata, Iskandar and Abiyoga, 2022; Lendra, Hatmoko and Wibowo, 2024).

This study aims to select sustainable construction material criteria based on their weightings as a priority indicator in the Indonesian context. Several previous studies used the Analytic Hierarchy Process (AHP) method (Ibrahim and Shaker, 2019; Torres-Machi et al., 2019; Peng, Feng and Guo, 2021). In addition, Torres-Machi et al. (2019) used the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method and AlKheder, AlKandari and AlYatama (2022) used the Statistical Package for the Social Sciences (SPSS). Based on previous research, the use of VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) analysis is still limited. The VIKOR method has the advantage of allowing for ranking of several samples with conflicting criteria, which can assist decision-makers in reaching a final decision (Wang et al., 2021). Therefore, the VIKOR method was chosen for the selection of environmentally friendly materials for sustainable development in this study. The VIKOR method is superior in ranking the best alternatives, although it is less efficient in assigning criterion weighting (Wang et al., 2021; Al-Atesh et al., 2023).

The remainder of this article is presented as follows. The next section provides a detailed explanation of pavement materials. This is followed by an outline of the research method, which establishes the weighting of the criteria and subcriteria for a decision-making method for sustainable pavement materials. The discussion then presents the analysis of the weightings and results. Finally, the conclusion summarises the study findings, including recommendations for future research.

LITERATURE REVIEW

Sustainable Development

Sustainable development in the construction industry describes measures to improve safety, minimise resources, reduce environmental impact, enhance aesthetics and increase stakeholder satisfaction (Al-Atesh et al., 2023). Environmentally friendly materials (green materials) achieve maximum functionality while minimising resource use, integrating well into ecosystem processes, reducing dependence on other materials and energy sources, and promoting a service-oriented economy (Pelli, 2021). Material selection plays an important role in design and construction processes. Inappropriate material selection can lead to damage or implementation failure and significantly reduce product performance, thereby negatively impacting an organisation's productivity, profitability and reputation (Omer and Noguchi, 2020; Wang, 2023). Choosing the best materials leads to optimal design and performance at minimum cost (Wang et al., 2025). The selection of environmentally friendly materials (green materials), also referred to as sustainable material selection, aims to ensure performance and reduce the overall lifecycle impact on the environment and public health (Yaro et al., 2023). In addition to benefiting the environment and society, environmentally friendly materials also promote business development and offer significant opportunities for the advancement of construction management (Chakravarthy et al., 2022).

The selection of materials is largely cost-oriented and is required to improve product quality and accelerate the construction process, which increases public concerns about sustainable development (Peng, Feng and Guo, 2021). However, the process for selecting materials in large quantities, coupled with the complex relationships between different selection parameters, remains a major challenge for the construction industry, as multiple criteria must be considered (Ismaeel, 2023). Additionally, the application of environmentally friendly materials remains a challenge for contractors (Chakravarthy et al., 2022).

AlKheder, AlKandari and AlYatama (2022) examined criteria for selecting sustainable materials and identified three aspects of sustainable material selection for runway pavement: (1) technical, with a weighting of 64%, (2) socio-economic, with a weighting of 23% and (3) environmental, with a weighting of 13%. Meanwhile, Al-Atesh et al. (2023) identified three aspects of sustainable material selection for building structures: (1) environment, with a weighting of 44.68%, (2) economy, with a weighting of 44.67% and (3) social, with a weighting of 10.65%. Other variables include several aspects, such as technical (Sahlol et al., 2021), economic, environmental (Sandanayake et al, 2020) and social (AlKheder, AlKandari and AlYatama, 2022). Technical aspects encompass both long-term and short-term properties, while economic aspects include purchase costs, processing costs and transportation costs. Environmental aspects relate to resource use, pollution, energy consumption, recycling (AlKheder, AlKandari and AlYatama, 2022) and the reduction of waste generated during the construction process (Peng, Feng and Guo, 2021). Social aspects include social interests related to drivers' comfort and safety (Torres-Machi et al., 2019). Correct material selection enhances product quality and expedites the construction process, leading to increased public concern for sustainable development (Peng, Feng and Guo, 2021). Table 1 summarises the

14 criteria identified for pavement material selection. There are five criteria under the economic category, six in the environmental category, and three in the social category.

Table 1. Criteria for pavement material selection

Code	Criteria and Subcriteria	Description	Source
A	Economic	Includes costs related to purchase, processing and transportation.	
A1	Investment costs	Potential for high initial costs due to better quality road pavement design.	Plati (2019); Al-Atesh et al. (2023); Wang et al. (2025)
A2	Design costs	Potential for high design costs due to better quality road pavement design.	Torres-Machi et al. (2019)
A3	Local materials	The use of local materials in highway projects depends on the project location.	Sahlol et al. (2021)
A4	Cost effectiveness	Effective financing is possible due to the high quality of materials, reducing the need for additional maintenance costs.	Plati (2019); Wang et al. (2025)
A5	Pavement lifespan	Potential for a durable pavement lifespan to avoid frequent rehabilitation, depending on the average daily traffic and the type of pavement to be constructed.	Hamim et al. (2021)
B	Environmental	Covers the management of natural resources, pollution control, energy consumption and recycling to reduce waste generated during the construction process.	
B1	Ecological benefits	Positive benefits are provided by the natural environment to humans and the overall ecosystem.	Szpotowicz and Tóth (2020)
B2	Material waste management	Provides management of construction and demolition waste during road construction.	AlKheder, AlKandari and AlYatama (2022); Plati (2019)
B3	Impact on air quality	Utilises construction equipment that reduces air pollution emissions.	AlKheder, AlKandari and AlYatama (2022)
B4	Emission reduction	Reduces the use of fossil fuels.	Torres-Machi et al. (2019)
B5	Energy efficiency	Optimal use of energy and resource conservation, thereby reducing unnecessary energy consumption or waste.	AlKheder, AlKandari and AlYatama (2022)

(*Continued on next page*)

Table 1. *Continued*

Code	Criteria and Subcriteria	Description	Source
B6	Recycling	Reduction, reuse and recycling of operational and maintenance materials.	AlKheder, AlKandari and AlYatama (2022)
C	Social	Includes social interests related to driver comfort and safety.	
C1	Road surface characteristics	Road surface characteristics depend on smoothness, texture roughness and also deflection.	Plati (2019); Sahlol et al. (2021)
C2	Ease of construction	Ease of efficiently implementing materials during the construction process.	AlKheder, AlKandari and AlYatama (2022)
C3	Aesthetics	Evaluation of the aesthetics and visual appeal of material selection.	Al-Atesh et al (2023) Sahlol et al. (2021) and AlKheder, AlKandari and AlYatama (2022)

Pavement

Pavement design and materials are carefully selected based on factors such as traffic load, climate and budget, as these greatly impact a road's longevity and performance (Mendoza-Sanchez et al., 2024). Road pavement consists of several layers of different aggregates, aiming to improve the durability and stability of the road surface. Common pavement types include:

1. Flexible pavement construction

   Flexible pavements use asphalt as a binder utilising a layered system. Flexible pavements are typically prone to rutting caused by heavy traffic and harsh environmental conditions (Nawir, Bakri and Syarif, 2023). This type of pavement has almost negligible flexural strength and is flexible in structural behavior when subjected to loads (Khade and Wuppulluri, 2024).

2. Rigid pavement construction

   Rigid pavements use Portland cement as a binder for concrete slabs, with or without reinforcement, placed over a subgrade, with or without a subbase layer. Also known as cement concrete pavements, rigid pavements use cement as the adhesive material, making them relatively more rigid than asphalt pavements. The structure consists of a cement concrete surface layer, a base layer, and, if necessary, a subbase course layer (Nawir, Bakri and Syarif, 2023). Table 2 describes the key differences between rigid and flexible pavement.

Table 2. Features of rigid and flexible pavement

Feature	Rigid	Flexible
Main material	Concrete	Asphalt
Load distribution	Surface/slab action	Layered distribution
Thickness	Thinner	Thicker
Initial cost	Higher	Lower
Maintenance	Less frequent	More frequent
Lifespan	20 years to 30 years	10 years to 15 years
Application	Highways, airport and heavy loads	Local roads and lighter traffic

In road construction, pavement materials play an important role in supporting transportation infrastructure and economic development. Negative impacts of conventional materials include high energy consumption during production, significant greenhouse gas emissions and non-recyclable waste production (Zheng et al., 2020). Construction accounts for large amounts of carbon, energy (39%) and water (12%), and generates substantial carbon dioxide emissions (38%) (Fei et al., 2021). Some studies have focused on creating pavement composite materials that involves concrete pavement, such as alkali-activated concrete (Fernandes et al., 2023) and geopolymer mortar (Pratap, Mondal and Rao, 2024). The SDGs illustrate how sustainable principles can be integrated into the construction cycle: building, decorating, servicing and repairing structures (Fei et al., 2021). Sustainable development involves three main aspects, namely, social, economic and environmental, aiming to meet economic growth needs while enhancing ecological benefits and social welfare (Luo and Yang, 2023).

One principle of pavement sustainability includes choosing environmentally friendly materials at low cost while considering their social impact (Al-Atesh et al., 2023). Pavement sustainability largely depends on the appropriate selection of materials. One main goal of pavement sustainability is reusing aggregates, primarily through recycling strategies. When existing pavement experiences severe damage, defects, decline or disruption, milling and recycling processes are considered sustainable rehabilitation methods. By recycling pavement and utilising waste structural materials, many sustainable materials can be used as aggregates for road pavement (Plati, 2019). Other environmentally friendly materials commonly implemented include the following:

1. Plastic asphalt

   The use of plastic asphalt not only effectively extends lifespan, but also supports efforts to recycle non-biodegradable plastic materials (Kataki et al., 2022).

2. Rubber asphalt

   The use of rubber from used tires in asphalt helps reduce issues related to the disposal of non-degradable used tires and decreases waste volume in landfills. In the production process, rubber from used tires is crushed into small particles and mixed with hot asphalt. This not only reduces waste, but also lowers greenhouse gas emissions and energy consumption compared to conventional asphalt mixtures (Pouranian and Shishehbor, 2019). Rubber asphalt can also significantly reduce traffic noise compared to regular road pavement, making it an environmentally friendly choice that reduces impacts on nearby communities (Sahlol et al., 2021).

3. Reclaimed asphalt pavement

   The reclaimed asphalt pavement is an asphalt material obtained from existing asphalt pavement layers, which is then processed and reused to create new asphalt mixtures. The use of reclaimed asphalt pavement in road pavements is a sustainable practice that reduces the need for new materials and minimises environmental impacts from construction waste disposal (Plati, 2019). However, the use of reclaimed asphalt pavement in surface mixtures is typically recommended only up to 30% because the crack resistance of asphalt mixtures tends to decrease with higher reclaimed asphalt pavement content.

4. Recycled concrete aggregate

   Recycled concrete aggregate is primarily used as a coarse aggregate in base or subbase layers, improving modulus and stiffness; however, it can also replace conventional aggregates in asphalt and concrete mixtures (Plati, 2019).

VIKOR Method

The VIKOR method was first introduced by Serafim Opricovic in 1998. It provides more accurate ranking results and focuses on ranking and selecting a number of alternatives and determining a compromise solution for problems with conflicting criteria, which can help decision-makers reach a final decision (Wang et al., 2021).

This method is especially useful in situations where decision-makers face difficulty making choices when designing a system. Several researchers have used the VIKOR method as a multi-criteria compromise ranking, including for material selection (Wang et al., 2021) and design concept selection (Ayyildiz and Taskin, 2022; Luo and Yang, 2023). The steps used in the VIKOR method (Luo and Yang, 2023) are as follows:

1. Create a decision matrix (*F*).
2. Determine criteria weightings (*w*).
3. Create a normalisation matrix (*N*).
4. Normalise weightings (*F*).
5. Calculate utility measures (*S*) and regret measures (*R*).
6. Calculate the VIKOR index (*Q*).
7. Rank the alternatives.

Some advantages of the VIKOR method include:

1. It includes preference values for ranking and can handle the ranking of many alternatives.
2. Additionally, it can handle conflicting criteria in ranking. Conflicting criteria mean that there are several criteria, but each criterion uses a different evaluation. The evaluation may see the highest value as better or the lowest value as better (Wang et al., 2021).

METHODOLOGY

The purpose of this study was to identify and analyse various relevant criteria in the selection of sustainable materials used in road projects, as well as to develop a model for selecting those materials. The first stage of this study comprised a literature review to determine the relevant criteria and subcriteria in selecting environmentally friendly materials for national road projects (see Table 1). Fourteen research variables were grouped into three main aspects: economic, environmental and social. First, a survey was sent to respondents. Interviews were then conducted with participants to validate the model.

The majority of national roads in Indonesia, approximately 6,500 km of 47,603 km, are concentrated on Java (Minister of Public Works and Public Housing Regulation Number 1688/KPTS/M/2022). This road is a major infrastructure project aimed at improving connectivity across Java from the Western city of Merak in Banten to Banyuwangi in East Java. National roads are built and managed by the Ministry of Public Works and Housing through the National Road Implementation Center; therefore, 25 respondents were selected from this institution. The respondents were Pejabat Pembuat Komitmen, or Commitment Making Officers, who played a crucial role in the management and execution of public sector projects, including road construction. The respondents' profiles are described in Table 3. The respondents were selected using a purposive sampling method based on their experiences and capability to plan and to manage national road projects. Their responsibilities spanned the entire project lifecycle, from procurement to financial management, ensuring that the project adhered to both legal and procedural requirements.

Having significant experience, they were expected to provide deeper insights into the challenges and best practices in construction projects. The interviews included four Pejabat Pembuat Komitmen who completed the survey and were specifically involved in the on-going projects.

Table 3. Respondents' profile

Characteristic		**Number of Respondents**	**%**
Education background	Doctorate (PhD)	–	–
	Master's degree	24	96
	Bachelor's degree	1	4
Working experience	3 years to 6 years	3	12
	6 years to 9 years	9	36
	More than 9 years	13	52

In the survey, the respondents were asked to assess the importance of criteria and subcriteria using a Likert scale (1 to 9), with a scale of 1 indicating "Absolute Low Importance" and 9 indicating "Absolute High Importance", as shown in Table 4.

Table 4. Rating scale for the importance of criteria and subcriteria

Rating Scale	**Definition**
9	Absolutely more important
8	Much more important
7	Very important
6	Slightly more important
5	Equally important
4	Slightly less important
3	Less important
2	Much less important
1	Absolutely less important

The data obtained from this questionnaire survey were then analysed using the VIKOR method, resulting in importance rankings for each criterion and subcriterion. A decision matrix was then created, and weighting normalisation was performed. Next, utility measures (S) and regret measures (R) were calculated, and the VIKOR index (Q) was computed to rank the alternatives based on the results. The stages for data analysis are described as follows (Luo and Yang, 2023):

1. Create a decision matrix (F)

   C_1 C_2 C_3 ... C_c

$$F = \begin{array}{c} A_1 \\ A_2 \\ A_3 \\ \vdots \\ A_n \end{array} \begin{bmatrix} X_{11} & X_{12} & X_{13} \\ X_{21} & X_{22} & X_{23} \\ X_{31} & X_{32} & X_{33} \\ \vdots & \vdots & \vdots \\ X_{n1} & X_{n2} & X_{n3} \end{bmatrix} \qquad \text{Eq. 1}$$

   where:

   Ai = i-th alternative,

   I = 1, 2, 3, ..., n is the sequence number of the alternatives,

   C_j = j-th criterion and

   X_{ij} = Element of the matrix representing the performance level of the i-th alternative.

2. Determine the criteria weights (w)

$$\sum_{j=1}^{n} w_j = 1 \qquad \text{Eq. 2}$$

   where:

   W_j = criteria weight and

   j = 1, 2, 3, ..., n is the sequence number of attributes or criteria.

3. Calculate utility measures (S) and regret measures (R)

$$S_i = \sum_{j=1}^{n} w_j \frac{(f^+ - f_{ij})}{f^+ - f_j^-} \qquad \text{Eq. 3}$$

$$R_i = \max_j \left[\frac{(f^+ - f_{ij})}{f^+ - f_j^-} \right] \qquad \text{Eq. 4}$$

   where:

   Si = Weighted and normalised Manhattan distance and

   Ri = Weighted and normalised Chebyshev distance.

4. Calculating VIKOR index (Q)

$$Q_i = v\left[\frac{S_i - S^+}{S^+ - S^-}\right] + (1-v)\left[\frac{R_i - R^+}{R^+ - R^-}\right] \quad \text{Eq. 5}$$

where:

$S-$ = Mini (Si),

$S+$ = Maxi (Si),

$R-$ = Mini (Ri),

$R+$ = Maxi (Ri) and

v = Weighting ranging from 0 to 1 (usually valued at 0.5).

To validate the generated rankings, an acceptable advantage was conducted using Eq. 6. This test assists decision-makers in determining which criteria or subcriteria are the most important or relevant.

$$Q_2 - Q_1 \geq DQ \quad \text{Eq. 6}$$

$$DQ = \frac{1}{m-1} \quad \text{Eq. 7}$$

where:

m = Number of alternatives,

Q_1 = First alternative or rank from Qi and

Q_2 = Second alternative or rank from Qi.

If the acceptable advantage test is met, the next step is to conduct the acceptable stability in decision-making test. This test is performed to observe ranking criteria and subcriteria that are unstable with respect to changes in the variable v. The test uses values v = 0.00, 0.25, 0.75 and 1.00, and then compares the consistency with the ranking results Qi when v = 0.50. The model will then be built from the criteria and subcriteria using the weightings resulting from VIKOR.

Interview participants were then asked to validate the model, as well as to provide insights and perspectives regarding the selected variables. The detailed methodology is illustrated in Figure 1.

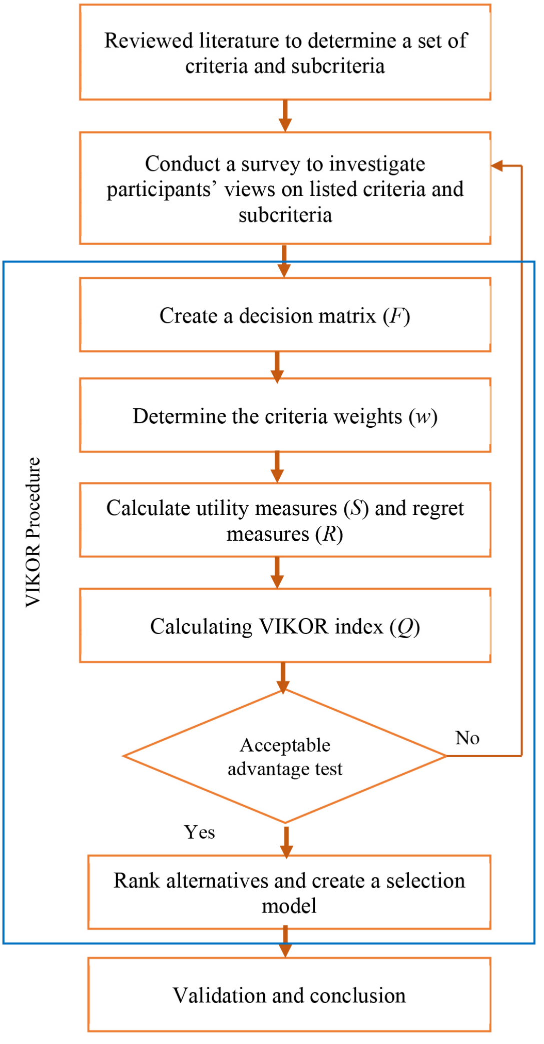

Figure 1. Flow chart of the methodology

RESULTS

Determination of Criteria and Subcriteria Priorities

The following outlines a detailed calculation to determine the level of importance of the "criteria" variable in the selection of environmentally friendly materials for national road projects, which can also serve as a calculation example for other subcriteria:

1. Create a decision matrix (F) using the formula provided in Equation 1. The results of this matrix are presented in Table 5.

Table 5. Decision matrix (F)

$$F = \begin{vmatrix} 6 & 8 & 7 & 8 & 8 & 9 & 8 & 7 & 8 & 8 & 3 & 3 & 5 & 3 & 7 \\ 7 & 7 & 8 & 7 & 8 & 8 & 6 & 6 & 9 & 5 & 7 & 7 & 6 & 5 & 5 \\ 5 & 5 & 5 & 8 & 6 & 8 & 7 & 5 & 7 & 6 & 5 & 7 & 5 & 6 & 4 \end{vmatrix}$$

2. Determine the criteria weightings (w), with the weightings based on the respondents' work experience. The determination of the criteria weightings is shown in Table 6.

Table 6. Criteria weightings

	Determination Value														
$\Sigma w = 1$	0.04	0.08	0.08	0.04	0.08	0.04	0.08	0.04	0.06	0.06	0.08	0.08	0.08	0.08	0.08

3. Calculate the utility measures (S) and regret measures (R) using the formulas provided in Equations 3 and 4. The results of these calculations are shown in Table 7.

Table 7. Results of utility measures (S) and regret measures (R)

Code	Criteria	Si	Ri
A	Economic	62.520	12.5
B	Environmental	108.333	25.0
C	Social	152.818	25.0

4. Calculate the VIKOR index (Q) and ranking. The index calculation uses the formula provided in Eq. 5. The results of the calculations are presented in Table 8.

Table 8. VIKOR index (Q) and the rank

Code	Criteria	*Si*	*Ri*	*Qi*	Rank
A	Economic	62.520	12.5	0.000	1
B	Environmental	108.333	25.0	0.754	2
C	Social	152.818	25.0	1.000	3
	$S+$, $R+$	152.818	25.0		
	$S-$, $R-$	62.520	12.5		

The recapitulation of the VIKOR index results for the criteria and subcriteria in the selection of green materials for national road projects is shown in Table 9.

Table 9. VIKOR index results for criteria and subcriteria

Criteria	Vikor Index (*Qi*)	Ranking	Subcriteria	Vikor Index (*Qi*)	Ranking
Economic	0.000	1	Investment costs	0.653	2
			Design costs	0.798	3
			Local materials	1.000	5
			Cost effectiveness	0.881	4
			Pavement lifespan	0.000	1
Environmental	0.754	2	Ecological benefits	0.000	1
			Material waste management	0.618	3
			Impact on air quality	0.651	4
			Emission reduction	0.602	2
			Energy efficiency	0.708	5
			Recycling	1.000	6
Social	1.000	3	Road surface characteristics	0.752	2
			Ease of construction	0.000	1
			Aesthetics	1.000	3

Based on Table 9, the criterion with the lowest VIKOR index value in this study was the economic criterion, with a value of 0.00. In the VIKOR method, the lowest index value indicates a high level of importance, making the economic criterion the most important factor in decision-making. This result emphasises that economic considerations have the greatest influence in determining the final decision regarding material selection for sustainability purposes. Therefore, the economic criterion should rank first in the selection of environmentally friendly materials. Decisions prioritising economic aspects have the potential to enhance the overall competitiveness of the project.

Additionally, focusing on this criterion can encourage more efficient resource use in the construction process.

The second rank in the selection of environmentally friendly materials in this study was the environmental criterion, with a VIKOR index value of 0.754. This indicates that while economic factors are very important, environmental factors also play a significant role in decision-making. Thus, the chosen materials must not only be economical, but also environmentally friendly, supporting overall sustainability goals. The use of materials that consider environmental aspects can reduce negative impacts on ecosystems. This can also enhance perception of an organisation being concerned about environmental issues.

The social criterion ranked third, with a VIKOR index value of 1.00. This highlights the importance of social aspects, indicating that selected materials should provide benefits for community welfare. Choosing materials that consider social aspects can improve relations with the surrounding community. Additionally, socially friendly materials can contribute to inclusive and sustainable development, benefiting all parties involved.

Acceptable Advantage Testing

Acceptable advantage testing was used to validate the generated rankings. This test is used to enhance decision-maker's confidence that the chosen criteria or subcriteria are the most important or relevant. After obtaining the *Qi* value or VIKOR index, a compromise solution is then determined. The compromise solution is identified from the criteria and subcriteria with the best rankings by measuring the minimum VIKOR index. To understand the compromise solution and acceptable advantage, it is necessary to review the conditions in Eq. 6 as follows (Ayyildiz and Taskin, 2022; Luo and Yang, 2023):

1. If using a value of v = 0.5 (consensus) for the criteria, then the following is obtained:

   $Q_2 - Q_1 = 0.754 - 0.000 - 0.754$

   Since the value of $Q_2 - Q_1 = 0.754 > DQ = 0.500$ it can be concluded that the acceptable advantage condition is met.

2. If using a value of v = 0.5 (voting by majority rule) for the economic subcriteria, then the following is obtained:

   $Q_2 - Q_1 = 0.653 - 0.000 - 0.653$

   Since the value of $Q_2 - Q_1 = 0.653 > DQ = 0.250$ it can be concluded that the acceptable advantage condition is met.

3. If using a value of v = 0.5 (voting by majority rule) for the environmental subcriteria, then the following is obtained:

   $Q_2 - Q_1 = 0.602 - 0.000 - 0.602$

   Since the value of $Q_2 - Q_1 = 0.602 > DQ = 0.200$ it can be concluded that the acceptable advantage condition is met.

4. If using a value of v = 0.5 (voting by majority rule) for the social subcriteria, then the following is obtained:

   $Q_2 - Q_1 = 0.752 - 0.000 - 0.752$

   Since the value of $Q_2 - Q_1 = 0.752 > DQ = 0.500$ it can be concluded that the acceptable advantage condition is met.

The results of the acceptable advantage test analysis in this study indicated that the use v = 0.5 met the criteria (acceptable advantage), allowing the compromise solution of the alternative rankings (acceptable stability) to be used in determining the appropriate green materials for national road pavement. Selected criteria and subcriteria demonstrated adequate stability under various conditions, ensuring that the decisions were widely acceptable. This compromise solution would also help optimise resource use, maximise environmental benefits and reduce costs, making it highly beneficial in guiding policies and strategies for sustainable national road development projects.

Acceptable Stability in Decision-making Testing

This test was used to evaluate the stability of the rankings of criteria and subcriteria against changes in the value of the variable v. This study compared the values v = 0.00, 0.25, 0.75 and 1.00 with the consistency of the ranking results *Qi* when v = 0.50. The calculation results and rankings of the criteria and subcriteria based on the changes in the value of the variable v are shown in Table 10.

Based on Table 10, changes in the values v = 0.00, 0.25, 0.75 and 1,00 for each criterion and subcriterion resulted in varying VIKOR index values (*Qi*). If the *Qi* values generated for each v were greater than the minimum value (*DQ*) for each criterion and subcriterion, then those criteria and subcriteria were considered stable. This stability was indicated by the consistency of *Qi* values, which did not undergo significant changes despite variations in the value of v. The results of the calculations and testing using the VIKOR method were then normalised to obtain weightings for each criterion, as described in Table 11. The weightings were derived from the normalised VIKOR index, as shown in Table 9. The model is illustrated by the criteria and subcriteria weightings as the priority for selecting environmentally friendly materials, as shown in Figure 2.

Table 10. Results of the acceptable stability in decision-making test on criteria and subcriteria

Code	Qi	Qi	Qi	Qi	Qi	Ranking	Code	Qi	Qi	Qi	Qi	Qi	Ranking
	v = 0.00	v = 0.25	v = 0.50	v = 0.75	v = 1.00			v = 0.00	v = 0.25	v = 0.50	v = 0.75	v = 1.00	
A	0.00	0.00	0.00	0.00	0.00	1	A5	0.00	0.00	0.00	0.00	0.00	1
							A1	0.90	0.83	0.65	0.48	0.31	2
							A2	0.96	0.90	0.80	0.70	0.60	3
							A4	0.98	0.94	0.88	0.82	0.76	4
							A3	1.00	1.00	1.00	1.00	1.00	5
B	0.99	0.88	0.75	0.63	0.51	2	B1	0.00	0.00	0.00	0.00	0.00	1
							B4	0.90	0.80	0.60	0.40	0.20	2
							B2	0.91	0.81	0.62	0.43	0.24	3
							B3	0.94	0.83	0.65	0.48	0.30	4
							B5	0.99	0.85	0.71	0.56	0.42	5
							B6	1.00	1.00	1.00	1.00	1.00	6
C	1.00	1.00	1.00	1.00	1.00	3	C2	0.00	0.00	0.00	0.00	0.00	1
							C1	0.97	0.88	0.75	0.63	0.50	2
							C3	1.00	1.00	1.00	1.00	1.00	3

Table 11. Weight calculation for criteria and subcriteria

Criteria	Normalisation	Weight	Subcriteria	Normalisation		Weight	Final Weight
Economic	$= \frac{1}{0.0001 + 1}$ $= 1.00$	$= \frac{1}{1 + 0.570 + 0.5}$ $= 0.48$	Investment costs	0.605	3.193	0.189	0.092
			Design costs	0.556		0.174	0.084
			Local materials	0.500		0.157	0.076
			Cost effectiveness	0.532		0.166	0.080
			Pavement lifespan	1.000		0.313	0.151
Environmental	0.57	0.28	Ecological benefits	1.000	3.933	0.254	0.070
			Material waste management	0.618		0.157	0.043
			Impact on air quality	0.606		0.154	0.042
			Emission reduction	0.624		0.159	0.044
			Energy efficiency	0.585		0.149	0.041
			Recycling	0.500		0.127	0.035
Social	0.50	0.24	Road surface characteristics	0.571	2.071	0.276	0.067
			Ease of construction	1.000		0.483	0.117
			Aesthetics	0.500		0.241	0.058

The application of environmentally friendly materials in the field is often regarded as an innovation, particularly concerning the addition of materials in the asphalt mixing plant mixture (Milad et al., 2022). The results of this study also show that the use of environmentally friendly materials aims to enhance sustainability and efficiency in national road construction. Several aspects need to be considered in selecting these materials, including funding, material availability, and the quality of the final product. The funding required to implement the use of environmentally friendly materials should ideally be more efficient than that for conventional materials, if possible. Additionally, the quality of the final product using green materials must meet applicable standards to ensure the safety and durability of the roads. The use of environmentally friendly materials is also expected to reduce negative environmental impacts, such as greenhouse gas emissions and the use of natural resources. Thus, the use of these materials not only supports sustainable development but also provides long-term benefits for road infrastructure.

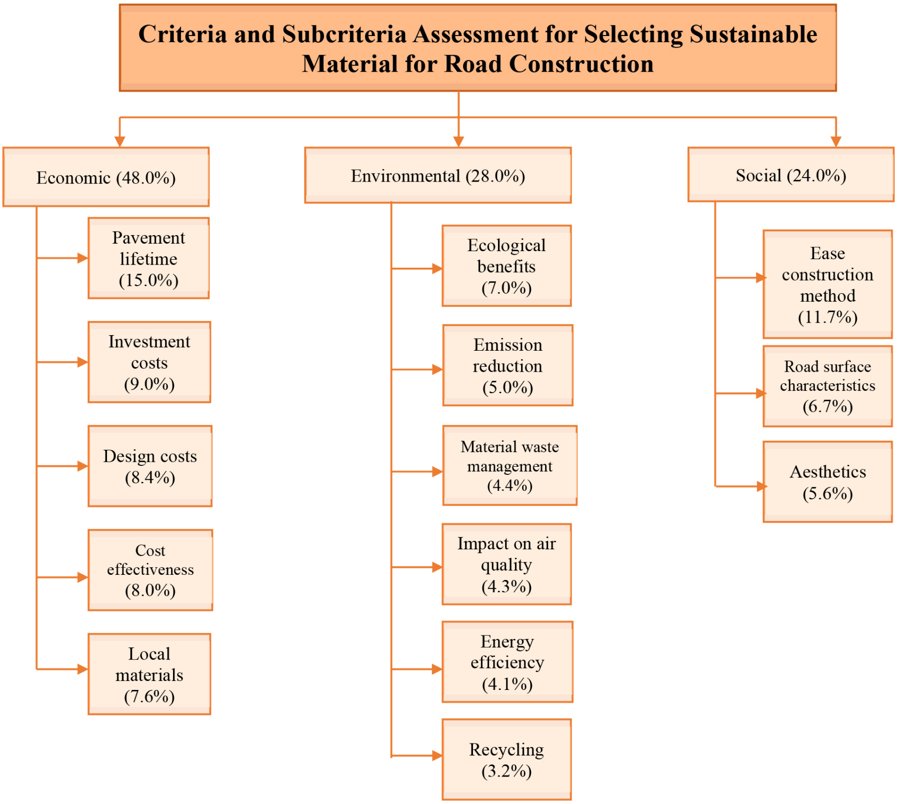

Figure 2. Decision-making model

DISCUSSION

The VIKOR calculation in this study revealed the prioritisation of the three sustainability criteria in the selection of green materials for road construction. The economic criterion emerged as the most critical factor, receiving a weighting of 48%. This suggests that cost effectiveness is the primary driver when selecting materials for sustainable road construction projects. The VIKOR index for the economic criterion was 0.00, indicating its highest level of importance in the decision-making process, as lower VIKOR values denote a more favourable ranking.

Second, the environmental criterion held a significant weighting of 28%, with a VIKOR index value of 0.754. This suggests that while economic considerations are crucial, environmental factors, such as material sustainability and ecological impact, also play a significant role in the decision process. Although not as highly prioritised as the economic factor, the environmental criterion is essential for achieving the broader sustainability goals.

Finally, the social criterion, representing aspects like social equity, community impact and stakeholder interests, was the least prioritised, accounting for 24% of the overall weighting. The VIKOR index for the social criterion was 1.00, indicating that it ranked the lowest in terms of importance for material selection. However, while it ranked third, its role remains significant, particularly in ensuring social responsibility and long-term community benefits.

Economic Criteria

The first aspect in the application of green materials identified in this study was the economic aspect. Based on the analysis results, the economic criterion ranked as the most important factor to consider in selecting green materials, with a VIKOR index of 0.00. This supports research by Plati (2019), Torres-Machi et al. (2019) and Szpotowicz and Tóth (2020).

The economic aspect in the application of green materials encompasses various factors that must be considered including pavement lifespan (15.0%), investment costs (9.0%), design costs (8.4%), cost effectiveness (8.0%), and the utilisation of local materials (7.6%). These aim to ensure sustainability and cost efficiency in road infrastructure development. In this study, the economic subcriteria had VIKOR indices of 0.000, 0.653, 0.798, 0.881 and 1.000.

The pavement lifespan, which refers to the effective life of road pavement, is influenced by the initial design, materials used and maintenance strategies (Hamim et al., 2021). High-quality materials require a higher initial investment;

however, their use results in significant savings in lifecycle cost (Hamim et al., 2021; Wang et al., 2025). Additionally, investing in quality materials can reduce maintenance frequency, which minimises traffic disruptions. Considering these factors, the selection of appropriate materials is crucial to ensure the sustainability and efficiency of long-term projects.

Initial investment costs may be higher due to the technology used for mixing green materials with asphalt; however, long-term savings in maintenance costs can offset this, making it a profitable long-term investment. An optimal pavement design is also crucial in planning for sustainable pavements, as good design can extend the lifespan of the pavement while keeping total costs down during its lifetime. The quality of materials reduces the need for periodic maintenance costs, creating cost efficiencies (Plati, 2019; Szpotowicz and Tóth, 2020). Therefore, a holistic approach to the selection of materials and pavement design is essential to achieve optimal results. Additionally, the implementation of innovative technologies can further enhance the efficiency and sustainability of infrastructure projects.

Using local materials increases cost efficiency by reducing transportation costs, which constitute a significant portion of construction expenses, while also supporting the local economy (Plati, 2019). The use of recycled materials sourced locally reduces transportation costs and benefits the local economy. The closer the material source is to the project site, the lower the costs incurred for transportation. Additionally, utilising local materials contributes to the reduction of the carbon footprint from transportation, supporting sustainability goals (Sahlol et al., 2021). Thus, this strategy is not only economically beneficial, but also has a positive impact on the environment. Countries worldwide are effectively utilising locally sourced materials in road construction, promoting sustainability and reducing environmental impact. These practices not only address waste management issues but also enhance the durability and functionality of road infrastructure. For example, India has extensively implemented the use of recycled plastics in road construction (Kataki et al., 2022), while Australia is utilising reclaimed asphalt pavement, which works well in asphalt concrete (Gallage and Jayakody, 2023).

Based on the interview results, several important considerations have emerged in the selection of environmentally friendly materials for national road construction. As funding for national road projects in Indonesia is entirely sourced from the state budget, material choices often focus on the lowest costs to ensure that the project can be completed within the available budget, with the aim of maximising the efficient use of public funds. However, the selection of inexpensive materials must still consider the pavement's lifespan to meet established standards, as well as considering quality and environmental sustainability.

Environmental Criteria

The next aspect from the results was the environmental aspect, which ranked second in this study, with a VIKOR index of 0.754. In the interviews, participants stated that in infrastructure projects, especially national road projects, the ecological aspect is expected to enhance environmental quality and prevent negative impacts from construction waste. The environmental aspect of national road construction involves various important factors, including ecological benefits (7.0%), emission reduction (5.0%), waste material management (4.4%), impact on air quality (4.3%), energy efficiency (4.1%) and material recycling (3.2%). The environmental subcriteria in this study had VIKOR indices of 0.00, 0.602, 0.618, 0.651, 0.708 and 1.00.

This aligns with previous research indicating that the environmental aspect should consider ecological benefits to reduce energy and water consumption during the construction process (Szpotowicz and Tóth, 2020). By emphasising ecological benefits, road construction projects can enhance sustainability, conserve resources and mitigate negative environmental impacts (Yaro et al., 2023; Dokyi et al., 2024). Efficient energy use and resource conservation help reduce energy waste (Peng, Feng and Guo, 2021). Utilising recycled materials in construction also provides various ecological benefits, such as reducing energy and water consumption during the building process (Almusaed et al., 2024). This step not only contributes to resource efficiency, but also supports efforts to create a cleaner and more sustainable environment. Therefore, from the analysis, it could be concluded that the implementation of environmentally friendly construction practices is increasingly important to address climate change challenges. These efforts can also enhance a company's image as an environmentally responsible industry player.

Additionally, emission reductions can be achieved by decreasing the use of fossil fuels; for example, by employing more efficient and environmentally friendly construction equipment. The use of innovative materials in construction also plays a role in reducing emissions by decreasing reliance on fossil fuels. This emission reduction significantly impacts air quality, including lowering concentrations of harmful pollutants in the atmosphere, mitigating global warming and improving overall air quality (Alkheder, AlKandari and AlYatama, 2022). The use of more efficient and environmentally friendly construction equipment is therefore essential (Hamim et al., 2021). Applying new technologies in the construction process can also further optimise efficiency and reduce environmental impacts. Thus, sustainable strategies in the construction industry are crucial for achieving broader environmental goals.

Road construction generates a significant amount of construction waste, necessitating effective waste management. The use of innovative materials contributes to more effective waste management (Widayanti et al., 2024), which can be implemented by applying an efficient system throughout the construction process (Alkheder, AlKandari and AlYatama, 2022). Additionally, the use of recycled materials helps reduce the amount of construction waste; thus, decreasing the environmental impact of waste disposal (Peng, Feng and Guo, 2021). Through this approach, construction projects can be more sustainable and environmentally friendly. Implementing good waste management strategies can also enhance the efficiency of the resources used in construction.

Based on the interviews, the most important factors to consider in the environmental aspect of national road project development include air quality, emissions, energy, ecology, material waste and recycling. Maintaining air quality is crucial, as poor air can lead to health issues. Emissions from fossil fuels are a major concern due to their contribution to climate change. Energy usage must be optimised to avoid waste and support efficiency. Additionally, ecological considerations are necessary to protect biodiversity and ecosystems. Effective management of material waste is required to minimise negative environmental impacts, while recycling practices should be implemented to reduce waste and support resource sustainability.

Social Criteria

The model showed that the application of green materials in road paving should include consideration of social aspects, including ease of construction processes (11.7%), road surface characteristics (6.7%) and aesthetics (5.6%). These social factors are important parameters that add complexity to pavement sustainability and contribute to community well-being and satisfaction. These social criteria also influence the selection of sustainable materials, impacting the social aspects of the overall construction project.

Surface characteristics, including smoothness, texture roughness and deflection, play a crucial role in determining the performance and comfort of road users (Plati, 2019; Dokyi et al., 2024). Interview participants noted that the use of innovative materials in road paving provides significant economic, environmental and social benefits. One advantage of these materials is the smoother and more elastic road surface, which enhances comfort and safety for road users. The elasticity of the materials also helps reduce noise generated by passing vehicles, creating a quieter and more comfortable environment for residents.

Ease of implementation of materials is essential for improving construction efficiency (Ibrahim and Shaker, 2019). These green materials excel in terms of ease of construction, as their mixing and application are relatively straightforward and can be carried out with existing construction equipment, without requiring additional investment in new technologies. This increases efficiency and reduces construction time, which is critical in national road projects to minimise traffic disruption.

Assessment of the aesthetic aspects and visual appeal of the materials is also important for creating an attractive environment for road users (Sahlol et al., 2021). Interview participants further noted that these green materials have similar appearances to conventional asphalt, while offering better surface quality and durability. They also excel in maintaining the colour and texture of the road surface, making them visually appealing in the long term.

CONCLUSION

This study aimed to develop a model to choose sustainable construction materials, focusing on road materials to support sustainable development in national road projects in Indonesia. The results indicate that three main criteria must be considered in the selection of sustainable materials, namely, economic, environmental and social aspects. The economic aspect includes pavement lifespan, investment costs, the use of local materials, cost effectiveness and design costs. The environmental aspect involves ecological benefits, material waste management, emission reduction, impact on air quality, energy efficiency and recycling practices. Meanwhile, the social aspect encompasses ease of construction, aesthetics and road surface characteristics. The significant contribution of this research lies in its ability to translate sustainability principles into actionable selection criteria and foster consistency in assessment, which will encourage the use of locally available and eco-friendly materials.

Based on this research, several recommendations are proposed for future studies. Future research should examine other stakeholders' perspectives to produce more comprehensive and accurate decisions. Second, subsequent research is advised to explore the potential of other environmentally friendly materials that could be used in construction projects, with a focus on cost analysis, long-term performance and environmental impact in greater depth.

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