

An Entropy-Weighted VIKOR Approach for Sustainable Selection of Supplementary Cementitious Materials in M25 Concrete

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Abstract

The construction industry contributed significantly to environmental degradation due to the extensive use of conventional materials, leading to high carbon emissions and large amounts of waste generation. According to a 2023 report by the International Trade Administration on India's Solid Waste Management, the country generated approximately 62 million tonnes of waste annually, including industrial by-products such as fly ash, GGBFS, and silica fume. Utilizing these materials in concrete helped address waste management issues while promoting sustainable construction practices. This study applied the Entropy-VIKOR (VlseKriterijumska Optimizacija Kompromisno Resenje) method, a combined multi-criteria decision-making (MCDM) approach, to identify and rank the most suitable waste material for concrete production. Seven parameters were considered: Compressive Strength (7-day), Compressive Strength (28-day), Split Tensile Strength (28-day), Workability (slump), Cost, Embodied carbon, and Embodied energy. Different waste materials at a 10% replacement level in M25 grade concrete were analyzed. The Entropy Weightage Method was used to determine criteria weights based on data dispersion, where higher variation indicated greater importance. The VIKOR method was then applied to obtain a compromise ranking. The results showed that fly ash ranked first, followed by silica fume, glass powder, GGBFS, rice husk ash, and bagasse ash (SCBA). Practically, this approach can help engineers and decision-makers select suitable waste materials for sustainable concrete production while reducing cement consumption and environmental impact.

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1 Introduction

The global construction industry stands as one of the most resource-intensive sectors in the world, exerting immense and growing pressure on natural ecosystems. Concrete, as identified by *SS Volaiy et al. (2025)* as the second most consumed substance on Earth after water—exceeds 4 billion tonnes of annual production, a figure driven by rapid urbanization, expanding infrastructure networks, and sustained economic

growth, especially in developing nations like India. This unprecedented demand for construction materials has intensified environmental degradation, primarily through the cement industry, which is a major source of global greenhouse gas emissions. According to *RM Andrew (2019)*, cement production alone contributes nearly 8% of total global CO₂ emissions, resulting predominantly from two processes: (i) Calcination of limestone, where CaCO₃ decomposes into CaO and CO₂, accounting for 50–60% of total emissions; and (ii) Combustion of fossil fuels required to heat cement kilns to approximately 1450 °C, responsible for the remaining 40–50%.

This energy and carbon-intensive process leads to the release of 0.85–0.95 tonnes of CO₂ per tonne of cement, translating to an annual output of 3.4–3.8 billion tonnes of CO₂ globally, making cement manufacturing one of the most environmentally burdensome industrial operations.

Parallel to the challenge of construction-related emissions, India confronts a critical industrial and agricultural waste management crisis. The country produces over 62 million tonnes of industrial waste annually, including major by-products such as 112–120 million tonnes of fly ash, 40–50 million tonnes of ground-granulated blast furnace slag (GGBFS), 0.7–1.2 million tonnes of silica fume, 20–25 million tonnes of rice husk ash (RHA), and 10–15 million tonnes of waste glass. Limited beneficial reuse of these materials has contributed to the rapid expansion of landfills across the nation. India currently operates more than 3,000 landfill sites occupying over 20,000 hectares, expanding by 500–800 hectares each year. At this rate, landfill areas are projected to exceed 100,000 hectares by 2050. Beyond land scarcity, these sites pose severe environmental hazards: toxic leachate containing heavy metals such as arsenic, cadmium, mercury, and lead infiltrates groundwater up to 500–1000 meters from landfill boundaries, while landfill biogas—comprising 50–55% methane with a global warming potential 28–34 times greater than CO₂ contributes significantly to global climate change. The simultaneous crises of escalating waste generation, unsustainable landfill expansion, and high-carbon construction practices highlight the urgent need for incorporating industrial by-products into concrete to reduce both environmental footprint and waste accumulation.

Over the past two decades, extensive research has been conducted on the incorporation of supplementary cementitious materials (SCMs) into concrete to enhance its mechanical properties and sustainability profile. Early investigations by *Perumal and Sundararajan (2004)* established that incorporating 10% silica fume into high-performance concrete significantly increased compressive strengths, achieving values between 60 and 110 MPa at 28 days. Building on this, *Amudhavalli and Mathew (2012)* and *Roy and Sil (2012)* demonstrated that replacing 10–15% of cement with silica fume led to notable improvements in compressive, tensile, and flexural strengths, with Roy and Sil specifically noting a 17–19% increase in compressive strength over control mixes. Subsequent studies explored a wider range of SCMs. *Ghutke and Bhandari (2014)* identified 10% silica fume as optimal for compressive strength, while *Shilpa Raju and Kumar (2014)* found that replacing 20% of cement with glass powder enhanced both compressive and flexural strengths by approximately 30%, although higher replacement levels diminished these benefits. Similarly, *Parvinder Singh et al. (2014)* and *Patil and Patil (2015)* reported that rice husk ash (RHA) at 12.5% and

4–12% replacement, respectively, yielded maximum compressive, tensile, and flexural strengths, though excessive RHA reduced workability. Research in the late 2010s further refined SCM utilization. *Golewski (2017)* highlighted that 20% fly ash replacement optimizes strength in mature concrete, while *Rahman and Uddin (2018)* observed that 20% glass powder maximized compressive strength and 30% maximized split tensile strength. *Mallesha et al. (2019)* showed the synergistic effect of combining 20% GGBS with 25% foundry sand, resulting in a 57% increase in compressive strength compared to control. In the 2020s, the focus shifted towards optimizing SCM blends and evaluating their sustainability impacts. *Chandio et al. (2020)* demonstrated that 5% fly ash with 50% recycled aggregate produced the best compressive strength, albeit slightly lower than control. *Jha and Jain (2020)* and *Kumar and Dhaka (2020)* confirmed that 10% glass powder and 9–12% silica fume, respectively, provided optimal improvements in compressive, flexural, and split tensile strengths. *Khoshnava et al. (2020)* and *Li et al. (2020)* advanced the field by introducing hybrid multi-criteria decision-making (MCDM) frameworks for evaluating green building materials and planning, emphasizing the increasing complexity of sustainability considerations.

Recent studies have continued to expand the palette of SCMs and their applications. *Baikerikar et al. (2021)* and *Ali Ajwad et al. (2022)* demonstrated that glass powder (5–10%) and RHA (6%) can significantly enhance strength and durability, while *Al-Awabdeh et al. (2022)* found that 50% glass waste as fine aggregate increases early compressive strength. In 2023, Hathiram and Hardhika showed that combining 25% fly ash with EPS beads increased compressive strength by over 25%, and *Khotele et al. (2023)* reported that 15% silica fume achieved the highest compressive strength in M20 concrete. *Ma et al. (2023)* and *Bimantara Putra Nugraha et al. (2023)* further validated the benefits of glass powder and rubber blends for both strength and workability. The most recent research underscores the value of blended SCM systems and advanced evaluation methods. *Yadav et al. (2024)* and *Ganta Mounika et al. (2024)* found that glass powder and combined fly ash–RHA systems can improve workability and split tensile strength, though compressive strength may decrease at higher replacement levels. *Ajay Yadav et al. (2024)* highlighted the suitability of glass powder blends for moderate-strength applications, while *Rudra Pratap Singh et al. (2025)* and *Luan et al. (2023)* confirmed that optimized SCM blends, including fly ash, GGBS, and silica fume, can achieve high compressive strength and significantly reduce environmental impacts. Collectively, these studies demonstrate that partial replacement of cement or fine aggregate with SCMs consistently enhances mechanical and durability properties while supporting sustainable construction practices. They also indicate that the selection of SCMs must be based on a careful balance of performance, environmental benefit, and economic feasibility.

Despite these advancements, a key challenge persists: no single waste-derived SCM consistently excels across all technical, environmental, and economic criteria. Each possesses distinct advantages but also critical limitations. This makes the selection of the most sustainable material inherently multidimensional, requiring structured evaluation tools rather than subjective judgment.

Given the conflicting nature of SCM performance parameters—strength, durability, workability, availability, cost, and environmental impact—conventional single-criterion

selection approaches are insufficient. Multi-Criteria Decision-Making (MCDM) frameworks provide a systematic and quantitative method to: i) assess alternatives across numerous criteria simultaneously, ii) handle trade-offs transparently, iii) standardize diverse parameter scales, iv) integrate expert judgment consistently, and v) derive defensible rankings of sustainable materials. Thus, MCDM is essential for determining which SCM should be prioritized for sustainable concrete production.

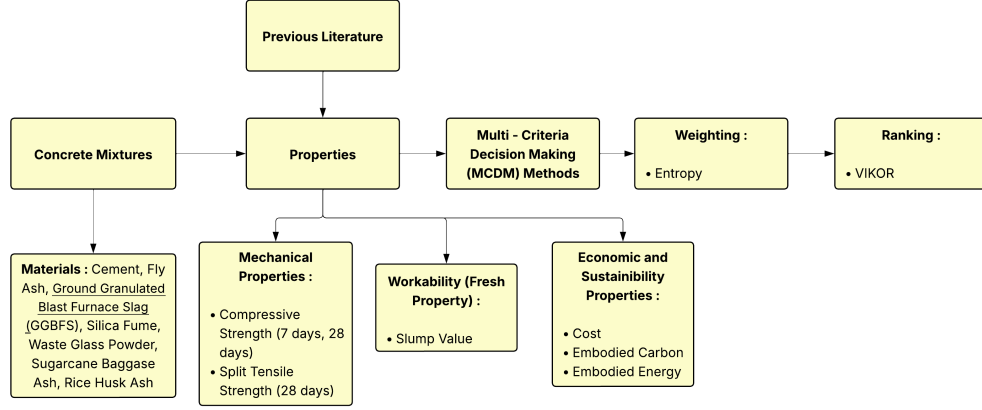


Fig. 1 Workflow Diagram

In this study, the Entropy method is adopted to assign weights to the evaluation criteria. This method is chosen because it objectively measures the level of uncertainty and variability present in the decision matrix. Criteria that show greater differences among the alternatives contain more useful information for distinguishing between options and therefore receive higher weights, reflecting their stronger discriminatory ability. On the other hand, criteria with very similar values across alternatives contribute less information and are assigned lower weights. By deriving weights directly from the data rather than relying on subjective judgment, the Entropy method ensures a more unbiased, transparent, and reliable weighting process, thereby improving the robustness of the MCDM analysis.

Among MCDM techniques, the VIKOR (Vlsekriterijumska Optimizacija Kompromisno Resenje) method is particularly suitable because it focuses on identifying a compromise solution—the most realistic decision when no single alternative is superior in all criteria. VIKOR balances group utility (overall performance) with individual regret (worst-case weakness), ensuring that recommendations avoid materials with hidden critical deficiencies. It also provides clear ranking metrics, along with validation conditions to confirm the reliability of results. These features make VIKOR especially effective for sustainable material selection in construction. The overall workflow followed in this study is illustrated in Figure 1.

The novelty of this study lies in developing a comprehensive VIKOR-based multi-criteria evaluation framework that integrates technical, environmental, and economic

parameters to determine which industrial or agricultural waste material should be given top priority as the most sustainable option for concrete production, addressing a critical gap in decision-making for sustainable construction materials.

2 Materials and methods

2.1 Data collection

The data for this study was primarily obtained through an extensive and systematic review of existing literature. Therefore, the study relies on secondary, yet reputable data sources, including peer-reviewed journal articles, technical reports, and recognized construction materials databases. The data was further analyzed to gather information on performance parameters (such as workability, compressive strength, and tensile strength) and environmental impact metrics. This methodology ensures a comprehensive understanding of material behaviour, environmental considerations, and sustainable practices currently adopted in the field of green construction (Table 2).

Economic data, including material costs and local availability, were collected through a targeted market survey conducted in Bidhannagar Area of Kolkata, West Bengal, India, along with online surveys for other areas across the country. The survey involved direct interactions with local suppliers, contractors, and retailers to obtain up-to-date pricing, procurement challenges, and market trends. This localized economic assessment provided context-specific insights into the feasibility of material adoption in the region (Table 2).

Table 1 presents the data matrix comprising performance, cost, and environmental criteria for the different alternatives considered in this study. The values included in the matrix have been compiled based on an extensive review of existing literature [15 - 70].

Table 1 Performance, Cost, and Environmental Criteria for Different Alternatives

Alternatives	Beneficial Criteria				Nonbeneficial Criteria		
	CS (7 Days) (MPa)	CS (28 Days) (MPa)	Split Tensile (MPa)	Slump (mm)	Cost (Rs.)	Embodied Energy (kgCO ₂ /m ³)	Embodied Carbon (MJ/m ³)
GGBS	20.50	34.80	2.80	80	5195.6	263.14	1506.2
Fly Ash	17.80	29.50	3.50	95	5010.8	260.92	1555.8
Silica Fume	21.20	35.60	4.63	53	6060.4	261.26	1555.8
WGP	20.60	31.70	3.75	60	5162.0	261.19	1555.8
RHA	31.98	36.90	1.92	89	5296.4	260.96	1560.5
SGBS	22.56	37.85	2.20	80	5128.4	261.12	1560.5

2.2 Waste - Based Supplementary Materials incorporated in Sustainable Green Concrete

This section reviews the primary waste-based supplementary materials incorporated in sustainable green concrete, focusing on their origins, environmental benefits, and key performance characteristics which will be presented in a tabular form (Table 2).

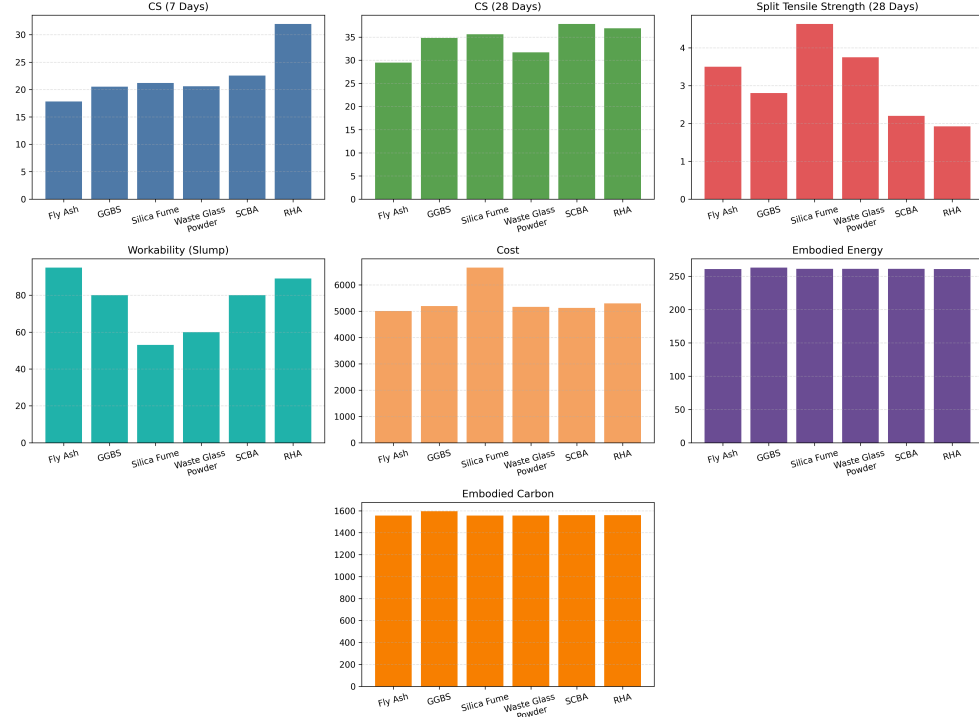


Fig. 2 Comparative visualization of mechanical, workability, economic, and environmental criteria for different SCM-based concrete mixes with 10% replacement.

2.3 Framework used for the Strategic Selection of Waste Materials

The Entropy - VIKOR approach is an advanced multi-criteria decision-making (MCDM) technique developed to evaluate and rank alternatives in scenarios involving conflicting criteria and uncertain or imprecise information. By implementing the VIKOR method, this approach enables the effective handling of vagueness, ambiguity, and subjectivity in both the assessment of criteria and the evaluation of alternatives. As a result, it offers a more realistic and flexible decision-making framework, particularly well-suited for complex problems in sustainability and engineering applications.

Table 2 Materials Used in Green Concrete and Their Key Characteristics

Material	Origin	Environmental Benefit	Key Performance Characteristics
Fly Ash	Coal combustion byproduct (power plants)	Reduces landfill waste and CO ₂ emissions	Improves workability; increases durability; reduces permeability; lowers cement and water demand
GGBFS	Blast furnace iron production byproduct	Utilizes industrial waste; lowers carbon footprint	Enhances durability and service life; improves workability; reduces heat of hydration; improves sulfate resistance
Silica Fume	Silicon/ferrosilicon alloy production byproduct	Repurposes silicon industry waste	Significantly increases strength; improves durability; reduces permeability; enhances corrosion resistance
Rice Husk Ash (RHA)	Rice husk combustion residue	Utilizes agricultural waste; promotes resource valorization	High silica (86–96%); improves compressive strength; reduces permeability; enhances chemical resistance
Waste Glass Powder	Finely ground recycled glass	Supports circular economy; reduces glass waste	Enhances compressive strength; improves workability; lowers environmental footprint
Sugarcane Bagasse Ash	Burnt residue of sugarcane bagasse	Reduces landfill waste; lowers CO ₂ emissions	High amorphous silica; improves compressive strength; reduces permeability; optimal replacement 10–25%

Stepwise Procedure:

Shannon Entropy Weighting Method

Given a decision matrix $X = [x_{ij}]$ with $i = 1, 2, \dots, m$ alternatives and $j = 1, 2, \dots, n$ criteria, the Shannon Entropy method proceeds as follows.

Step 1: Construct the decision matrix

Organise the raw performance data into a matrix:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

Step 2: Normalise the decision matrix

Normalise each criterion column by dividing each element by the column sum:

$$p_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}} \quad (2)$$

This converts each column into a probability distribution, i.e., the values in each column sum to 1.

Step 3: Calculate entropy of each criterion

Apply Shannon's entropy formula to each criterion:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^m p_{ij} \ln(p_{ij}) \quad (3)$$

where $\frac{1}{\ln m}$ is a normalising constant ensuring $0 \leq e_j \leq 1$. If $p_{ij} = 0$, then $p_{ij} \ln(p_{ij}) = 0$ by convention.

Step 4: Degree of diversification

Calculate the divergence (departure from maximum entropy) for each criterion:

$$d_j = 1 - e_j \quad (4)$$

A higher d_j indicates that a criterion provides more discriminating information.

Step 5: Calculate final Entropy weights

Normalise the d_j values to obtain the final weights:

$$w_j = \frac{d_j}{\sum_{j=1}^n d_j} \quad (5)$$

The resulting weights w_j satisfy $\sum_{j=1}^n w_j = 1$.

VIKOR

Step 1: Construct the Decision Matrix:

The initial step involves constructing a comprehensive decision matrix that systematically organizes alternatives and evaluation criteria.

$$D = [x_{ij}] \quad (6)$$

$$i = 1, 2, \dots, m \text{ (alternatives)}, \quad j = 1, 2, \dots, n \text{ (criteria)}$$

Where x_{ij} represents the performance value of alternative i with respect to criterion j , m denotes the total number of alternatives under consideration (6 materials) and n represents the total number of evaluation criteria (7 parameters).

Each row corresponds to a specific material alternative (Fly Ash, GGBFS, Silica Fume, Glass Powder, Glass Powder, Bagasse Ash, Rice Husk Ash), while each column represents an evaluation criterion (Compressive strength (7 days, 28 days), Split tensile strength (28 days), Slump (Workability), Cost, Embodied Carbon, Embodied Energy).

Step 2: Determine the Best and Worst Values for Each Criterion:

For each evaluation criterion, the methodology identifies optimal and worst-case performance values.

Best Values

For benefit criteria (higher values are preferable):

$$f_j^* = \max_i x_{ij} \quad (7)$$

For cost criteria:

$$f_j^* = \min_i x_{ij} \quad (8)$$

Worst Values

For benefit criteria:

$$f_j^- = \min_i x_{ij} \quad (9)$$

For cost criteria:

$$f_j^- = \max_i x_{ij} \quad (10)$$

Where f_j^* represents the best value and f_j^- represents the worst value for criterion j .

Step 3: Compute the Utility and Regret Measures:

The methodology calculates two fundamental measures for each alternative.

Utility Measure (S_i):

$$S_i = \sum_{j=1}^n w_j \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \quad (11)$$

This measure represents the overall satisfaction level achieved by alternative i across all criteria, weighted by their relative importance.

Regret Measure (R_i):

$$R_i = \max_j \left[w_j \frac{f_j^* - x_{ij}}{f_j^* - f_j^-} \right] \quad (12)$$

This measure identifies the maximum dissatisfaction for alternative i across all criteria, representing the worst-case scenario for that alternative.

Here, w_j represents the weight assigned to criterion j , reflecting its relative importance.

Step 4: Compute the VIKOR Index:

The VIKOR index combines utility and regret measures to provide a comprehensive ranking metric:

$$Q_i = v \cdot \frac{S_i - S^*}{S^- - S^*} + (1 - v) \cdot \frac{R_i - R^*}{R^- - R^*} \quad (13)$$

Where

$$S^* = \min S_i, \quad S^- = \max S_i$$

$$R^* = \min R_i, \quad R^- = \max R_i$$

v represents the weight for the majority rule strategy (typically set to 0.5). The parameter v controls the balance between group utility maximization and individual regret minimization. A value of $v = 0.5$ provides equal consideration to both aspects.

Step 5: Rank the Alternatives:

Alternatives are ranked based on their Q_i values, with lower values indicating better performance. The ranking provides a clear hierarchy of material alternatives based on their overall performance across all evaluation criteria.

Step 6: Validation Conditions:

The methodology includes two critical validation conditions to ensure solution robustness.

Condition 1: Acceptable Advantage

$$Q(A_2) - Q(A_1) \geq DQ \quad (14)$$

Where

$Q(A_1)$ represents the Q value of the best-ranked alternative.

$Q(A_2)$ represents the Q value of the second-best alternative.

$$DQ = \frac{1}{m - 1} \quad (15)$$

where m is the number of alternatives.

This condition ensures that the top alternative has a sufficient advantage over the second-best option.

Condition 2: Acceptable Stability

The top-ranked alternative must also achieve the best ranking in either the utility measure (S_i) or the regret measure (R_i). This condition ensures consistency across different evaluation perspectives.

Based on the validation conditions, the methodology provides different solution scenarios :

- *Both Conditions Satisfied:* Alternative A_1 represents the unique compromise solution with clear superiority over other options.

- *Only Stability Condition Met:* Both A_1 and A_2 are considered compromise solutions, indicating comparable performance levels.
- *Neither Condition Met:* A set of compromise solutions is proposed, typically including the top-ranked alternatives, suggesting that multiple materials may be suitable depending on specific project requirements.

3 Results & Discussion

3.1 MCDM Methods

3.1.1 Entropy

Table 3 presents the weights assigned under different scenarios. These weights help illustrate how variations in their values influence the final decision and provide a basis for conducting sensitivity analysis.

Table 3 Criterion weights obtained using the Entropy method for the considered performance

Criterion	Weight
Compressive Strength (7 day)	0.2025
Compressive Strength (28 day)	0.0398
Split Tensile Stress (28 day)	0.4837
Slump	0.2184
Cost	0.0551
Embodied Carbon	0.000048
Embodied Energy	0.000506

The weights obtained through the Entropy method (Figure 3) reflect the relative importance of each criterion based on the degree of variation observed across the alternatives. Criteria that exhibit larger variability among alternatives provide greater discriminatory information and therefore receive higher weights, whereas criteria with nearly similar values across alternatives contribute less to distinguishing between options and consequently receive lower weights.

Among all the criteria considered, Split Tensile Strength (hereafter STS) received the highest weight of 48.37%, indicating its dominant influence in the decision-making process. The STS values varied significantly across the alternatives, ranging from 1.92 MPa for RHA to 4.63 MPa for Silica Fume, corresponding to a ratio of 2.41:1, which represents the largest proportional spread among all criteria. This substantial variation indicates that STS effectively differentiates between alternatives in terms of their tensile crack resistance. The coefficient of variation ($CV = 29.74\%$) further confirms the high dispersion in STS values. Such variation arises because different supplementary cementitious materials (SCMs) influence the concrete microstructure differently, particularly the interfacial transition zone (ITZ), thereby affecting tensile performance. As a result, the Entropy method assigns the highest weight to this criterion.

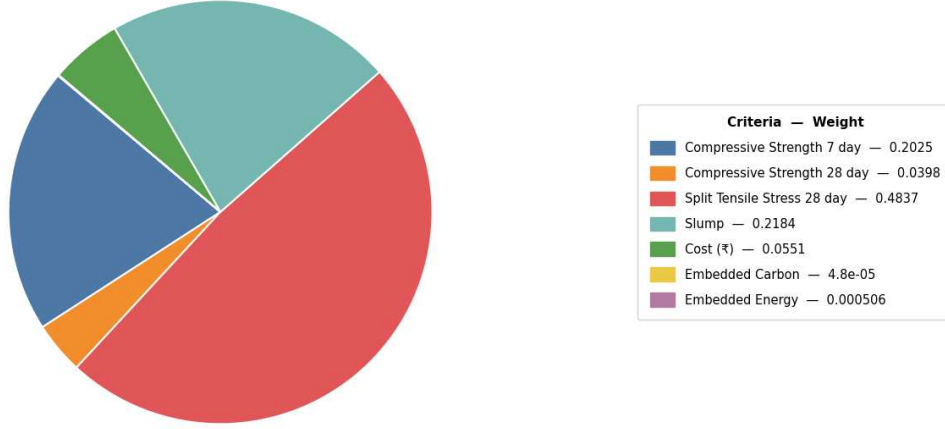


Fig. 3 Entropy-based weight distribution of criteria used in the MCDM analysis

The second most influential criterion is Slump, with a weight of 21.84%. Slump values ranged from 53 mm for Silica Fume to 95 mm for Fly Ash, yielding a ratio of 1.79:1 and a coefficient of variation of 19.67%. This notable variation arises primarily from the physical characteristics of the materials. Silica Fume possesses an extremely high specific surface area, which reduces workability, whereas Fly Ash contains spherical particles that enhance flowability. Because workability plays an important role in the practical usability of concrete during construction, the observed variation across alternatives results in a relatively high entropy-based weight.

The 7-day Compressive Strength (hereafter CS7) was assigned a weight of 20.25%, ranking third among the criteria. The CS7 values ranged from 17.8 MPa for Fly Ash to 31.98 MPa for RHA, corresponding to a ratio of 1.80:1 and a coefficient of variation of 20.03%. This variation is largely attributed to the differing early-age reaction characteristics of the SCMs. RHA exhibits relatively high early-age strength due to its highly reactive silica content, while Fly Ash generally shows slower pozzolanic activity at early curing ages. Since early compressive strength influences construction scheduling and formwork removal, this criterion demonstrates moderate discriminatory ability.

The Cost criterion received a weight of 5.51%, placing it fourth in importance. Cost values ranged from Rupee 5010.8 for Fly Ash to Rupee 6640.4 for Silica Fume, corresponding to a ratio of 1.33:1 and a coefficient of variation of 10.34%. Although Silica Fume is considerably more expensive due to specialized production processes, the remaining alternatives fall within a relatively narrow cost range (Rupee 5128 – Rupee 5296). This clustering reduces the overall variability among alternatives, limiting the influence of cost in the entropy-based weighting process.

The 28-day Compressive Strength (hereafter CS28) received a comparatively low weight of 3.98%, with a coefficient of variation of 8.48%. The values ranged from 29.5 MPa for Fly Ash to 37.85 MPa for SGBS, corresponding to a ratio of 1.28:1. At the 10% replacement level considered in this study, most SCMs tend to produce similar 28-day compressive strengths because the pozzolanic reactions of the materials generally

converge by this curing period. This reduced variation results in a low divergence value and, consequently, a lower entropy-based weight.

The environmental criteria, Embodied Energy and Embodied Carbon, received extremely low weights of 0.05% and approximately 0.00%, respectively. The values for embodied carbon ranged only from 1552.7 to 1596.2, with a ratio of 1.03:1 and a coefficient of variation of 0.30%, indicating near-uniform values across all alternatives. Similarly, embodied energy exhibited minimal variation with a coefficient of variation of 0.97%. This limited variability occurs because all concrete mixes contain 90% ordinary Portland cement (hereafter OPC) and only 10% SCM replacement, meaning the environmental impact is largely dominated by the OPC component. As a result, these criteria provide minimal discriminatory information, leading the Entropy method to assign them negligible weights.

Overall, the entropy-based weighting results demonstrate that criteria with greater variability across alternatives—such as STS, Slump, and CS7 play a more significant role in distinguishing the performance of the SCM-based concrete mixes, whereas criteria with nearly uniform values contribute less to the decision-making process.

3.1.2 VIKOR

In the VIKOR methodology, the final recommendation is not always a single alternative. Instead, the method evaluates whether the top-ranked alternative is significantly better than the others using two acceptance conditions: C1 (Acceptable Advantage) and C2 (Acceptable Stability in Decision Making). These conditions determine whether a unique best alternative exists or whether a set of compromise solutions should be proposed.

From the computed VIKOR indices, the alternatives are ranked according to the compromise index Q_i . The ranking obtained in this study is shown in Table 4 and corresponding visualizations are being represented in Figure 4.

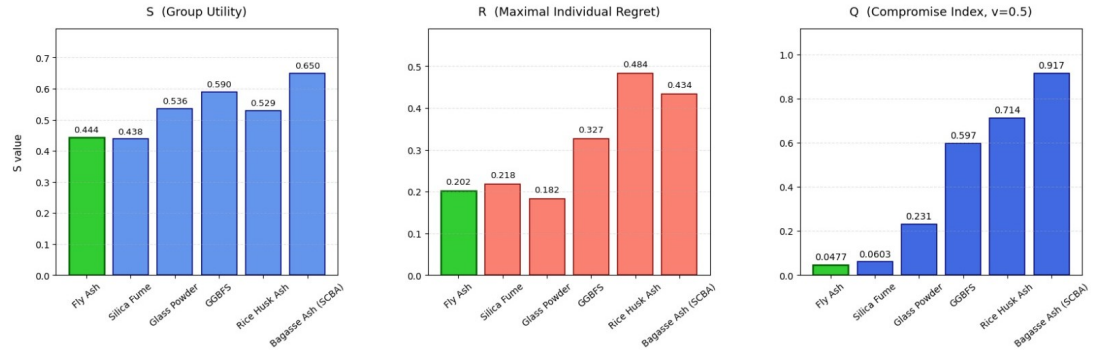


Fig. 4 Final Results

The alternative with the lowest Q_i value is considered the best compromise solution. In this analysis, Fly Ash obtained the lowest value of $Q_i = 0.0457$, followed closely by Silica Fume with $Q_i = 0.0603$.

However, the validity of selecting Fly Ash as the single optimal alternative must be tested using the VIKOR acceptance conditions. Condition C1 evaluates whether the difference between the first and second ranked alternatives is sufficiently large.

Table 4 VIKOR ranking results using entropy-based weights

Material	Rank	S	R	Q
Fly Ash	1	0.4440	0.2025	0.0477
Silica Fume	2	0.4382	0.2184	0.0603
Glass Powder	3	0.5360	0.1820	0.2306
GGBFS	4	0.5899	0.3266	0.5973
Rice Husk Ash	5	0.5291	0.4837	0.7142
Bagasse Ash (SCBA)	6	0.6503	0.4337	0.9172

$$DQ = \frac{1}{n-1} \quad (16)$$

where n represents the number of alternatives. Since six alternatives were evaluated in this study, the threshold becomes:

$$DQ = \frac{1}{6-1} = 0.20 \quad (17)$$

The difference between the compromise indices of the two best alternatives is:

$$Q(A'') - Q(A') = 0.0603 - 0.0457 = 0.0146 \quad (18)$$

Since $0.0146 < 0.20$, the acceptable advantage condition is not satisfied. This indicates that the performance difference between Fly Ash and Silica Fume is statistically insignificant in terms of the compromise index.

The acceptable stability condition (C2) requires that the best-ranked alternative (A') should also be ranked first in either group utility (S_i) or individual regret (R_i).

In the present case:

- The lowest S_i value belongs to Silica Fume ($S_i = 0.4389$).
- The lowest R_i value belongs to WGP ($R_i = 0.1820$).

Fly Ash ranks second in both S_i and R_i , therefore the stability condition is also not satisfied.

Since Condition C1 is not satisfied, the VIKOR methodology recommends identifying all alternatives that satisfy the following condition:

$$Q(A^M) - Q(A') < DQ \quad (19)$$

Applying this criterion indicates that Fly Ash, Silica Fume and Waste Glass Powder fall within the acceptable threshold:

Thus, the final compromise solution set is:

$$\{\text{Fly Ash, Silica Fume, WGP}\} \quad (20)$$

These three alternatives are considered statistically close in their compromise performance and represent valid solutions for the decision maker.

The VIKOR analysis was applied to evaluate and rank six supplementary cementitious materials (SCMs), namely GGBS, Fly Ash, Silica Fume, Waste Glass Powder (WGP), Rice Husk Ash (RHA), and SGBS, based on multiple performance, economic, and environmental criteria. The method employs three indices: group utility (S_i), individual regret (R_i), and compromise index (Q_i).

Fly Ash achieved the lowest compromise index ($Q_i = 0.0457$), indicating the most balanced performance across all evaluated criteria. Despite having relatively lower early compressive strength compared to some alternatives, Fly Ash demonstrates strong performance in workability, cost efficiency, and environmental indicators. Its spherical particle morphology improves the flowability of fresh concrete and reduces water demand, resulting in higher slump values. Furthermore, as an industrial by-product of thermal power plants, Fly Ash offers economic and environmental advantages due to its low cost and reduced embodied carbon.

Silica Fume ranked second in the analysis and recorded the lowest group utility score ($S_i = 0.4389$), indicating superior overall performance across the evaluated criteria. The ultra-fine particle size and high silica content of Silica Fume enhance pozzolanic reactivity, producing a dense microstructure that improves compressive strength, durability, and permeability resistance. However, its lower workability and higher cost increase its individual regret value (R_i), preventing it from achieving the top compromise ranking.

Waste Glass Powder (WGP) secured the third position and achieved the lowest individual regret value ($R_i = 0.1820$), indicating that no single criterion severely penalizes its performance. The amorphous silica present in recycled glass participates in secondary hydration reactions, contributing to improved strength and durability. Additionally, the use of waste glass as a supplementary cementitious material supports sustainability by diverting waste from landfills and reducing the environmental impact of concrete production.

GGBS ranked fourth in the overall analysis. Although it provides advantages such as long-term strength development and improved durability, its comparatively lower tensile strength and slightly higher environmental impact values resulted in increased penalty scores in the VIKOR evaluation.

Rice Husk Ash (RHA) ranked fifth despite exhibiting high compressive strength values. This result is primarily attributed to its poor split tensile strength performance, which carries significant importance in the weighted decision model. Consequently, the high individual regret value associated with tensile performance reduces its overall ranking.

SGBS was identified as the least preferred alternative, ranking sixth in the analysis. While it demonstrated excellent 28-day compressive strength, its low tensile strength and accumulated penalties across multiple criteria produced the highest group utility and compromise index values.

Overall, the results demonstrate that tensile strength plays a decisive role in determining the final ranking of SCMs in this study. Materials exhibiting strong tensile performance, such as Silica Fume, Fly Ash, and WGP, achieved higher rankings, while those with weaker tensile properties were penalized more heavily in the decision-making framework.

The VIKOR analysis ultimately recommends Fly Ash as the primary compromise solution due to its lowest Q_i value and balanced multi-criteria performance. However, Silica Fume and WGP also belong to the compromise solution set and remain viable alternatives depending on project-specific priorities such as structural performance, cost considerations, or environmental sustainability.

4 Limitations & Future Work

This study applied the VIKOR method using entropy weightage for all criteria, which may not fully reflect the varying priorities of real construction projects. A detailed sensitivity analysis is therefore essential to examine how different weight combinations influence material rankings and to ensure robustness of results. Future work should incorporate advanced weighting techniques and explore uncertainty-handling methods such as fuzzy VIKOR, AHP VIKOR or other hybrid MCDM approaches to better capture real-world decision variability.

Additionally, expanding the scope to include life cycle assessment (LCA) would provide a more comprehensive understanding of environmental impacts. Incorporating emerging green binders, recycled aggregates, and region-specific waste materials can improve the model's adaptability across diverse contexts. Experimental validation through laboratory testing is also necessary to confirm predicted performance and address practical challenges like workability or curing behavior. Finally, developing an interactive decision-support tool would enable practitioners to input project requirements and receive optimized material recommendations, strengthening the practical applicability of the framework and supporting broader adoption of sustainable construction practices.

5 Conclusion

The strategic selection of waste-derived supplementary cementitious materials is essential for advancing sustainable construction. Using the VIKOR multi-criteria decision-making method, this study evaluated the technical, environmental, and economic performance of Fly Ash, GGBFS, Silica Fume, Rice Husk Ash, Waste Glass Powder and Sugarcane Bagasse Ash across various concrete grades and curing periods. The results showed that no single material is universally optimal; instead, performance is context-dependent, varying with project needs such as early strength, long-term durability, or cost efficiency. By integrating multiple performance parameters into a unified ranking approach, the VIKOR framework effectively reconciled trade-offs between mechanical performance and sustainability. Overall, the findings reinforce the potential of industrial and agricultural waste materials as viable, environmentally responsible alternatives to traditional cement, supporting carbon reduction, resource conservation, and circular economy goals.

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Declarations

Ethical Approval and accordance

Not applicable.

Competing Interests

The authors declare that they have no competing interests regarding the publication of this paper.

Consent to publish

Not applicable.

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Not applicable.

Data Availability

The datasets generated during and/or analysed during the current study are not publicly available, because the data was collected from extensive literature review but the comprehensive dataset is not publicly available. Hence the same can be made available from the corresponding author on reasonable request.

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