

AN AHP-BASED MULTI-CRITERIA DECISION-SUPPORT SYSTEM FOR SUSTAINABLE CIVIL ENGINEERING APPLICATIONS: DEVELOPMENT AND CASE STUDIES

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Abstract:

Decision-making in civil engineering often requires the careful evaluation of multiple, frequently conflicting criteria, encompassing technical performance, cost efficiency, and sustainability considerations. Conventional approaches relying on intuition or single-factor analysis are increasingly insufficient for addressing such multifaceted challenges. This study introduces an Analytic Hierarchy Process (AHP) based multi-criteria decision-support system (DSS) designed to facilitate systematic, transparent, and sustainability-focused decision-making in civil engineering contexts. The research focuses on the creation of a user-friendly, Excel-based platform that allows practitioners to implement AHP without extensive computational expertise. The DSS enables the definition of criteria and choice, execution of pairwise comparisons, consistency assessment, and final ranking through weighted aggregation. Its effectiveness is demonstrated through two real-world case studies involving sustainable concrete material selection: recycled aggregate concrete and waste tire rubber–modified concrete. These applications integrate technical, environmental, and economic factors to identify optimal choice within a sustainability-oriented framework. Findings indicate that the proposed DSS supports objective, structured evaluation, reduces computational effort, and enhances decision transparency. The study emphasizes the significance of applied practice DDS in promoting environmentally responsible practices, offering a versatile solution for researchers, engineers, and students seeking informed, sustainable infrastructure decisions.

Keywords: *Multi-Criteria Decision Making, Analytic Hierarchy Process, Sustainable Civil Engineering, Decision Support Systems, Construction Materials Selection.*

1. Introduction

In most real-world situations, multiple possible courses of action exist, each offering a different way to address the same issue. [1]. Therefore, all human activities inherently involve decision-making, which relies on the systematic evaluation of available options using the decision maker's preferences, prior experience, and relevant information [2]. In such scenarios, decision makers require a sound approach to ensure objective choices, uphold ethical standards, and maintain a comprehensive and transparent decision-making process [3]. From the perspective of a decision maker, the optimal choice is the alternative that enhances benefit-related criteria while reducing cost-related factors [4].

Construction organizations function in a dynamic and complex environment throughout their lifecycle. Stakeholders including industry professionals, regulators, communities, and local authorities, shape system performance through regulation, knowledge sharing, research, and education [3]. Moreover, the pivotal role of the construction sector in economic growth is widely recognized [5]. Construction projects involve numerous interdependent tasks and conflicting factors, making decision-making increasingly complex due to technological advancements and dynamic project conditions [6, 7]. Consequently, decisions must be made scientifically, grounded in qualitative or quantitative analyses, rather than relying solely on intuition, to ensure efficient resource utilization, cost-effectiveness, and sustainable outcomes [8, 9].

In the scope of this analysis, sustainability becomes a critical consideration. Civil infrastructure plays a fundamental role in societal advancement by driving economic development, enhancing living standards, and supporting poverty reduction and competitiveness [10]. At the same time, construction activities exert substantial pressure on natural systems due to intensive demands for materials, land use, and energy throughout both construction and operational phases [11, 12]. Building construction represents a major source of resource and energy consumption, using about 30-40% of primary resources across its lifecycle and generating close to 30% of global greenhouse gas emissions [13, 14]. This dual role positions the construction sector as both a catalyst for progress and a major contributor to environmental degradation, underscoring the need for balanced and well-informed decision-making.

Clearly, halting construction to entirely eliminate its negative environmental and societal impacts is impractical. However, integrating sustainability principles into planning and execution offers a viable strategy to mitigate these effects and promote environmentally responsible infrastructure development [15, 16, and 17].

Researchers have also emphasized the importance of shifting towards environmentally sustainable construction practices [18]. Numerous studies have emphasized that choosing sustainable construction materials is a key component in achieving environmentally responsible construction [19]. Additionally, civil engineering programs have increasingly incorporated sustainable design principles into their curricula [20]. Addressing sustainable design challenges demands that engineers employ holistic thinking and decision making to develop solutions that

balance the economic, environmental, and social pillars that form the foundation of sustainability [21].

From the above text, it is clear that effective DDS are essential to assess and guide the complete decision-making process. Historically, challenges with multiple objectives were resolved by individual experts or small groups. Advances in computer science and numerical methods have since led to the formulation of various DDS, including linear and algorithmic planning, inventory and operational regulation, hypothesis analysis, and MCDM. Among these, MCDM, which is a branch of operations research, stands out for its ability to help decision-makers identify the optimal solution from a set of choice [22].

MCDM provides an effective framework for addressing problems involving multiple evaluation criteria [23]. It is increasingly applied across various fields, providing a structured method for assessing performance and preferences of different management choice with mathematical rigor and transparency [24]. In the past forty years, MCDM approaches have been applied extensively in practice to transform complex problems with multiple, often conflicting or complementary criteria into a single evaluative outcome by systematically ranking available choice [25, 26, 27, and 28].

Within this context, the role of the decision maker becomes central, as one alternative must be selected from a set of feasible options by assessing each against predefined criteria [29]. Such decisions typically require balancing trade-offs among competing factors, which makes intuitive judgment alone insufficient [30]. When multiple criteria simultaneously influence a choice, the process is referred to as MCDM [31]. Practical MCDM problems generally involve two key tasks: determining decision-related information, such as criterion weights and performance values, and using this information to evaluate and rank the available choice [31].

In MCDM, the decision process starts by clearly defining the problem and setting the desired objective. Relevant criteria are then established, and feasible choice is identified. Each alternative is analyzed against the criteria through systematic calculations, and the outcomes are finally presented to support a clear and well-informed decision [32].

To meet both theoretical and practical needs, numerous MCDM methods have been developed, including adaptations or combinations of existing approaches that have led to new research directions [33, 34]. There are some of the broadly used methods in MCDM: Weighted Product Model (WPM), proposed by Bridgman and Miller & Starr [35, 36]; Elimination and Choice Expressing Reality (ELECTRE), proposed by Benayoun, Roy, and Sussman [37]; Weighted Sum Model (WSM), proposed by Fishburne [38]; Analytical Hierarchy Process (AHP), proposed by Saaty [39]; Hwang and Yoon introduced the Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) [25]; Compromise Programming (CP), proposed by Zeleny [40]; Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), proposed by Brans and Vincke [41]; VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), proposed by Opricovic [42]; These methods share a common mathematical structure: each substitute is assessed against the standards, weighted according to importance, and combined to generate an overall score [43]. While these methods share a common framework, they differ in

how criteria are evaluated and aggregated. Each approach has distinct information requirements and mathematical properties, resulting in variations in scores and their interpretation. Consequently, users typically select the method best suited to their specific context, considering the relative strengths and limitations of each [44, 45].

Among these, AHP is selected for this study because of its capacity to handle diverse data types and broad data ranges associated with multiple applications in civil engineering projects. Moreover, this method is capable of evaluating numerous choices, criteria, and influencing factors elaborate in the decision-making procedure [4].

AHP is among the most widely used classical MCDM techniques, originally developed by Saaty in 1980. It is a computational method for decision-making [39]. AHP stands out by using pairwise comparisons rather than direct weights. Decision makers evaluate each criterion relative to others, allowing judgments to be made on their comparative importance [24]. The application of AHP to a decision problem involves four essential stages, starting with structuring the problem, performing pairwise comparisons to form the judgment matrix, calculating local weights and checking consistency, and finally aggregating the weights to determine the overall ranking of choice [46, 47]. In AHP, all elements of the hierarchy are treated as independent: decision criteria are assumed to be mutually independent, and choices are considered independent both from the criteria and from one another [48].

Owing to this structured and transparent framework, AHP offers several notable advantages: Effective when accurate and complete data is available [48]; Breaks down complex decision problems into smaller components, providing clear justification for each criterion [49]; Suitable for single or multiple decision problems, integrating both qualitative and quantitative criteria [50]; Incorporates a consistency ratio to ensure the reliability of judgments [51]. Despite its advantages, AHP has certain limitations: Potential loss of information can occur when high scores on some criteria offset low scores on others [49]; The method can be cumbersome to implement due to its complexity [50]; Computations are often intricate and time-consuming [52]. Several studies have investigated decision-making models for complex engineering and management challenges involving multiple variables, conflicting objectives, uncertainty, and risk. An inclusive evaluation of 22 MCDM techniques across 11 construction industry categories found that the AHP was the most frequently applied method, either independently or in combination with other approaches [53]. MCDM frameworks have been successfully applied to optimize concrete mix designs and pavement materials [26, 54], as well as to support critical construction decisions such as detecting unbalanced bidding [55], selecting contractors [56], prioritizing success factors in infrastructure projects [57], choosing appropriate crane type [58], and assessing sustainability in bridge design across life-cycle stages [59].

Building on the evolution of structured decision-support approaches, the origins of MCDM can be traced back to the eighteenth century, with a substantial acceleration in research and application after the 1990s [8]. Since then, MCDM methods have been extensively applied in diverse sectors, including sustainable energy, construction and project management, machinery and material selection, petroleum engineering, supply chain systems, and risk analysis [60–66].

Despite this broad acceptance, their use within core civil engineering areas such as structural, transportation, geotechnical, environmental, and water and waste engineering, remains relatively limited. This shortfall appears to arise primarily from limited practitioner awareness of MCDM capabilities and the availability of practical implementation tools, rather than from methodological inadequacies, pointing to a clear disconnect in knowledge dissemination [67]. Addressing this gap, the present study focuses on developing intuitive, user-oriented computer-based MCDM DSS tailored to civil engineering applications, while also promoting their integration into civil engineering education to strengthen practical, sustainability-oriented decision-making skills.

This study investigates the application of MCDM techniques, with a particular focus on the AHP, to enhance decision-making in civil engineering. A systematic decision-support framework is developed to evaluate competing options based on predefined criteria and is implemented through an intuitive DSS to facilitate practical use without requiring advanced analytical expertise. The framework is demonstrated primarily through sustainable construction material selection and further extended to broader civil engineering applications, including infrastructure planning, resource allocation, and environmental impact assessment. The proposed approach is validated using real-world case studies, ensuring its effectiveness, adaptability, and practical relevance, while also supporting improved decision quality and promoting sustainable and resilient civil engineering practices.

2. Methodology

The study began by systematically reviewing relevant literature to assess the significance and practical applications of MCDM. Based on this review, the AHP was selected as the primary MCDM method to apply, given its widespread global preference and suitability for the problem scope. While AHP can be applied manually for a limited number of choice and criteria, its application becomes increasingly time-consuming as the number of options and criteria increases.

To overcome this limitation and recognizing the computational demands of AHP for larger sets of option and criteria, a DDS was developed to streamline calculations, reduce time, and minimize manual effort. Excel was chosen for its user-friendly interface, coding flexibility, and ability to handle the required computations efficiently. Data from selected peer-reviewed studies on sustainable development parameters were compiled and analyzed using the developed AHP framework to identify the best possible choice.

The primary objective was to gain a thorough understanding of MCDM and its application within civil engineering, particularly to identify sustainable construction materials. The developed DSS allows entry of up to ten choice and criteria, producing results in both descriptive and graphical formats, facilitating easy interpretation and future application to other AHP-based MCDM problems.

For AHP application, firstly data was sourced from Hurrah Rashid et al. (2020), who produced 25 concrete mixes by partially substituting natural coarse aggregate with recycled concrete

aggregate (RCA) at 0%, 25%, 50%, 75%, and 100% by mass, spanning compressive strengths of 17–35 MPa. High-quality RCA obtained from clean precast components was used. Mechanical properties were assessed through fresh and hardened tests, with varying super plasticizer contents to maintain workability and examine correlations comparing the 1-day strength with super plasticizer to the 7- and 28-day strengths without it. Environmental and economic factors, including CO₂ footprint, material usage and associated cost, were also measured. AHP and TOPSIS were applied to integrate technical, environmental, and economic criteria, using target compressive strengths of 20, 25, and 30 MPa to identify the most sustainable RCA mixes systematically, supporting cost-effective and environmentally responsible concrete selection [68].

Secondly, data was collected from another published paper written by Zafar et al. (2022). They carried out the study by including waste tire rubber (WTR) replacing up to 20% by volume of cement, sand, and gravel with three types of rubber: powder, crumb, and chip. Mechanical performance was assessed through fresh properties, compressive, splitting tensile and flexural strengths, as well as durability. Environmental and economic aspects including CO₂ emissions, raw material consumption, and cost were also quantified. MCDM techniques were applied, integrating technical, environmental, and economic criteria. The results identified 5% rubber chip concrete as the top-ranked mixture. This framework provides guidance for selecting rubberized concrete for various applications such as structural, non-structural, and geotechnical, and supports policy decisions for sustainable use of WTR in construction [69].

2.1 Procedure for Applying AHP

First, clearly define the overall goal of the decision. Next, identify the criteria that will influence the choice. Finally, list the choice to be evaluated against these criteria. The relative significance of each pair of decision-making options is rated using a pairwise comparison matrix, which positions the option both horizontally and vertically and assigns numerical values that compare the horizontal substitute with the vertical substitute. To apply AHP, pairwise comparison matrices were developed for the choice by assigning relative importance based on specific criteria. This allows the decision-maker to choose the highest-ranked substitute or set of optimal. Similarly, a pairwise assessment matrix was constructed for the measures by determining their relative priorities. Established guidelines from the literature [70] were consulted to prepare these matrices, with the table 1 provided below for clarity.

Table 1: The fundamental scale applied for pairwise evaluations in the AHP method

Importance Rating	Definition	Clarification
1	Equal importance	Two activities contribute equally to the objective.
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another.

5	Essential or strong importance	Experience and judgment strongly favor one activity over another.
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice.
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed.
Reciprocals	If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	--
Rationales	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

Data from previously published studies were used, and various parameters, described later in the methodology section, were considered to set the pairwise comparison ratings. Reciprocal values (e.g., 1/9, 1/8, etc.) were assigned when the alternative in the horizontal row was less preferred than the vertical alternative, with a value of 1 consistently assigned when an option was compared with itself.

To obtain the normalized matrix, each element of a column in the pairwise comparison matrix is divided by the sum of that column. The row averages of the resulting normalized matrix are then computed and used to form the priority vector, which represents the relative preferences of alternatives for each criterion and is scaled to sum to 1.

Compute the weighted sum for each row of the pairwise comparison matrix by multiplying each element of the original matrix with the corresponding priority vector value of its column and summing across the row. Then, for each row, divide its weighted sum by the priority vector value of the corresponding alternative. The average of these ratios gives λ_{max} . Subsequently, the Consistency Index (C.I) is calculated using the formula below, where n represents the number of alternatives.

$$C.I = \frac{\lambda_{max} - n}{n - 1} \tag{1}$$

Determine the Random Index, R.I, as per your n value from the table 2. These values are taken from the guidelines of literature [39].

Table 2: Standard Reference Values of the Random Index

n	1	2	3	4	5	6	7	8	9	10
Random Index (R.I.)	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Then determine the Consistency Ratio (C.R):

$$C.R = \frac{C.I}{R.I} \quad (2)$$

A consistency ratio above 0.10 indicates that the pairwise comparison matrix is unreliable. A consistency ratio of 0.10 reflects that the judgments contain approximately 10% inconsistency and are only acceptable at or below this threshold [39]. However, in some research contexts, higher consistency ratio thresholds, such as C.R values below 0.20 or even above, have been considered acceptable; particularly in studies based on questionnaire surveys involving many respondents or comparison matrices with a large number of attribute [71].

Once above all points are completed for all criteria, the priority vectors of choice are compiled into a priority matrix with each column containing the priority vector for that specific criterion. This process mirrors the development of alternative pairwise comparison matrices: the criteria are compared using the preference guidelines, the resulting matrix is normalized, and the criteria priority vector is calculated.

The global priority vector is derived by multiplying the priorities of the alternative's matrix (obtained in step 6) with the criteria priority vector (obtained in step 7), producing the final ranking of all choice.

2.2 AHP Method on Khurram Rashid et al. (2020) Paper

AHP Method applied on recycled aggregate concrete after collecting required data from Khurram Rashid et al. (2020) Paper for 35 MPa target strength concrete.

2.2.1 Data Collected

The data was gathered by reading the paper thoroughly and by consulting the graphs at the presented in the paper for 35 MPa concrete. The table 3 below presents a summarized version of the collected data and associated notations, which served as the basis for constructing the pairwise comparison matrix. The 5 alternative concrete samples (C-35, 25R-35, 50R-35, 75R-35, 100R-35, respectively) were evaluated considering four criteria: cost to prepare, compressive strength, volume of raw material used, and CO₂ footprint, corresponding to criteria 1 through 4, respectively.

Table 3: Summary of Collected Concrete Mix Data and Evaluation Criteria (Example 1)

Alternative	Description	Cost	Compressive	Volume of	CO ₂
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		(PKR)	Strength (MPa)	Raw Material (Wt. %)	Footprint (kg/m ³)
C-35	Concrete with 0% RCA and 35 MPa target strength	5900	35.5	100	250
25R-35	Concrete with 25% RCA and 35 MPa target strength	5800	33.6	88	248
50R-35	Concrete with 50% RCA and 35 MPa target strength	5700	31	76	246
75R-35	Concrete with 75% RCA and 35 MPa target strength	5620	30.7	66	244
100R-35	Concrete with 100% RCA and 35 MPa target strength	5530	29.7	54	242

2.2.2 Development of hierarchy in order to apply AHP

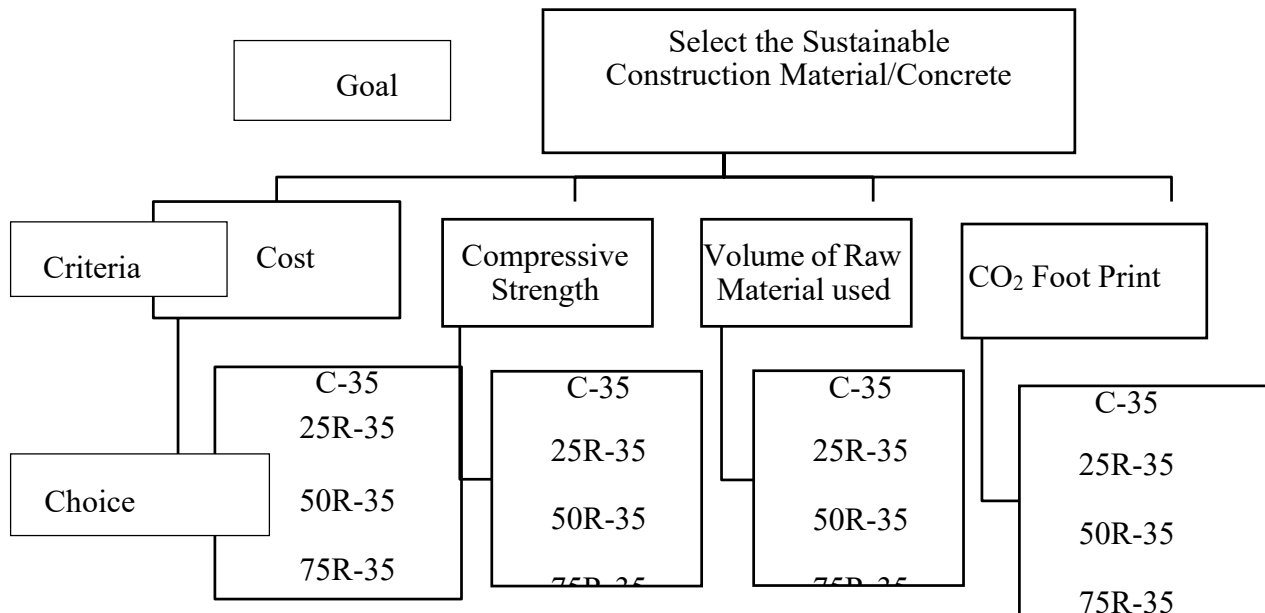


Figure 1: Development of hierarchy for an application of AHP Method

2.2.3 Pair-Wise Comparison Matrices

In AHP, preference values range from 1 to 9, including reciprocals. Replacing conventional concrete entirely with recycled aggregate concrete represents the upper practical limit, allowing the full scale to be considered. To maintain a safety margin and avoid extreme judgments, values were capped at 7. Relative priorities were assigned by considering both the limits and differences between successive choices, ensuring meaningful weight allocation. For example, choices with similar performance for a criterion were assigned preference values close to 1 to reflect minimal distinction.

2.2.3.1 Cost as a Criterion

Cost should be minimized to enhance construction affordability and efficiency. As 100R-35 had the lowest cost and C-35 the highest, 100R-35 was strongly preferred over C-35. Accordingly, in the AHP pairwise comparison matrix, the C-35 entry in the 100R-35 row was assigned 7, while the 100R-35 entry in the C-35 row was 1/7. The remaining entries were determined similarly, based on the preparation costs of the other concrete samples.

Table 4: Pairwise Evaluation Matrix for Criteria 1 (Cost)

Cost	C-35	25R-35	50R-35	75R-35	100R-35
C-35	1	1/2	1/3	1/5	1/7
25R-35	2	1	1/2	1/3	1/5
50R-35	3	2	1	1/2	1/3
75R-35	5	3	2	1	1/2
100R-35	7	5	3	2	1

2.2.3.2 Compressive strength as a Criterion

Compressive strength should be maximized to ensure strong and durable structures. Since C-35 had the highest strength, it was assigned greater weight. With C-35 moderately preferred over 50R-35, the 50R-35 entry in the C-35 row was set to 3, and the C-35 entry in the 50R-35 row was 1/3. The remaining entries were determined following AHP Step 2, considering the relative differences among all samples.

Table 5: Pairwise Evaluation Matrix for Criteria 2 (Compressive Strength)

Compressive Strength	C-35	25R-35	50R-35	75R-35	100R-35
C-35	1	2	3	5	7

25R-35	$\frac{1}{2}$	1	2	3	5
50R-35	$\frac{1}{3}$	$\frac{1}{2}$	1	2	3
75R-35	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{2}$	1	2
100R-35	$\frac{1}{7}$	$\frac{1}{5}$	$\frac{1}{3}$	$\frac{1}{2}$	1

2.2.3.3 Volume of raw material as a Criterion

To conserve natural resources, the use of natural aggregates should be minimized. Since 100R-35 had the lowest raw material usage, it received the highest weight in the pairwise comparison for criterion 3 (volume of raw material), while C-35, with the highest usage (100%), received the lowest. As 100R-35 was strongly preferred over C-35, the C-35 entry in the 100R-35 row was set to 7, and the 100R-35 entry in the C-35 row was $\frac{1}{7}$, following AHP Step 2.

Table 6: Pairwise Evaluation Matrix for Criteria 3 (Volume of Raw Material)

Volume of Raw Material	C-35	25R-35	50R-35	75R-35	100R-35
C-35	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{7}$
25R-35	2	1	$\frac{1}{2}$	$\frac{1}{4}$	$\frac{1}{6}$
50R-35	3	2	1	$\frac{1}{3}$	$\frac{1}{5}$
75R-35	5	4	3	1	$\frac{1}{3}$
100R-35	7	6	5	3	1

2.2.3.4 CO₂ footprint as a Criterion

To minimize environmental impact, CO₂ emissions should be reduced. Since 100R-35, using 100% recycled aggregate, had the lowest CO₂ footprint, it was strongly preferred over other choice. The pairwise comparison matrix for criterion 4 (CO₂ footprint) was constructed following AHP Step 2, assigning a relative importance of 7 for C-35 versus 100R-35 and $\frac{1}{7}$ for 100R-35 versus C-35, with other comparisons completed similarly.

Table 7: Pairwise Evaluation Matrix for Criteria (CO₂ Footprint)

CO₂ Footprint	C-35	25R-35	50R-35	75R-35	100R-35
C-35	1	$\frac{1}{2}$	$\frac{1}{3}$	$\frac{1}{5}$	$\frac{1}{7}$
25R-35	2	1	$\frac{1}{3}$	$\frac{1}{4}$	$\frac{1}{5}$
50R-35	3	3	1	$\frac{1}{3}$	$\frac{1}{4}$
75R-35	5	4	3	1	$\frac{1}{3}$

100R-35	7	5	4	3	1
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At this stage, relative priorities of the evaluation criteria were determined based on project-specific requirements. Since the focus was on selecting sustainable construction materials and concrete mixes, greater weight was given to criteria directly supporting sustainability. Carbon dioxide emissions were prioritized due to their environmental impact, while minimizing raw material use was emphasized to conserve natural resources. Compressive strength and cost remained relevant but were assigned lower importance to highlight environmental protection and sustainable construction objectives.

2.2.4 Decision Matrix for Choice

The decision matrix below in table 8 is a key element of AHP, a structured method for analyzing complex decisions. It evaluates choice against multiple criteria through pairwise comparisons, quantified to reflect decision-maker preferences. This systematic approach ensures objective and comprehensive assessment, facilitating the identification of the most suitable alternative.

Table 8: Decision Matrix for Choice (Example 1)

Criteria	C-35	25R-35	50R-35	75R-35	100R-35
Cost	5900	5800	5700	5620	5530
Compressive Strength	35.5	33.6	31	30.7	29.7
Volume of Raw Materials	100	88	76	66	54
CO₂ Footprint	250	248	246	244	242

2.3 AHP Method on Zafar et al. (2022) Paper

AHP Method Application on data collected from published paper of Zafar et al. (2022).

2.3.1 Data Collected

The data was obtained through a detailed review of the published study, including analysis of the graphs for various concrete samples. The table 9 below summarizes the collected data and notations, forming the basis for the pairwise comparison matrix. The 13 choice concrete mixes (C-C, RP-5, RP-10, RP-15, RP-20, RS-5, RS-10, RS-15, RS-20, RG-5, RG-10, RG-15, RG-20, respectively) were assessed based on four criteria: workability (slump in mm), 28-day compressive strength (MPa), durability (normalized 90-day compressive strength in MPa), and environmental impact (CO₂ footprint), corresponding to criteria 1 through 4, respectively.

Table 9: Summary of Collected Concrete Mix Data and Evaluation Criteria (Example 2)

Alternative	Description	Workability (mm)	Compressive Strength (MPa)	Durability (MPa)	Environmental Impact (kg/m ³)
C-C	Cement Concrete	78	21.5	0.41	180
RP-5	Concrete with 5% cement replaced by rubber powder	69	16.9	0.30	177
RP-10	Concrete with 10% cement replaced by rubber powder	62	12.8	0.23	173.5
RP-15	Concrete with 15% cement replaced by rubber powder	56	10.9	0.21	170.5
RP-20	Concrete with 20% cement replaced by rubber powder	51	9.5	0.18	167
RS-5	Concrete with 5% sand replaced by rubber crumbs	74	18.7	0.32	173.5
RS-10	Concrete with 10% sand replaced by rubber crumbs	70	16.7	0.26	166.5
RS-15	Concrete with 15% sand replaced by rubber crumbs	65	14.6	0.22	160
RS-20	Concrete with 20% sand replaced by rubber crumbs	61	13.8	0.20	153.5
RG-5	Concrete with 5% gravel replaced by rubber chips	71	16.9	0.35	170
RG-10	Concrete with 10% gravel replaced by rubber chips	64	13.5	0.31	160
RG-15	Concrete with 15% gravel replaced by rubber chips	59	11.8	0.27	150.5
RG-20	Concrete with 20% gravel replaced by rubber chips	54	10.4	0.26	139.5

2.3.2 Development of Hierarchy in order to apply AHP

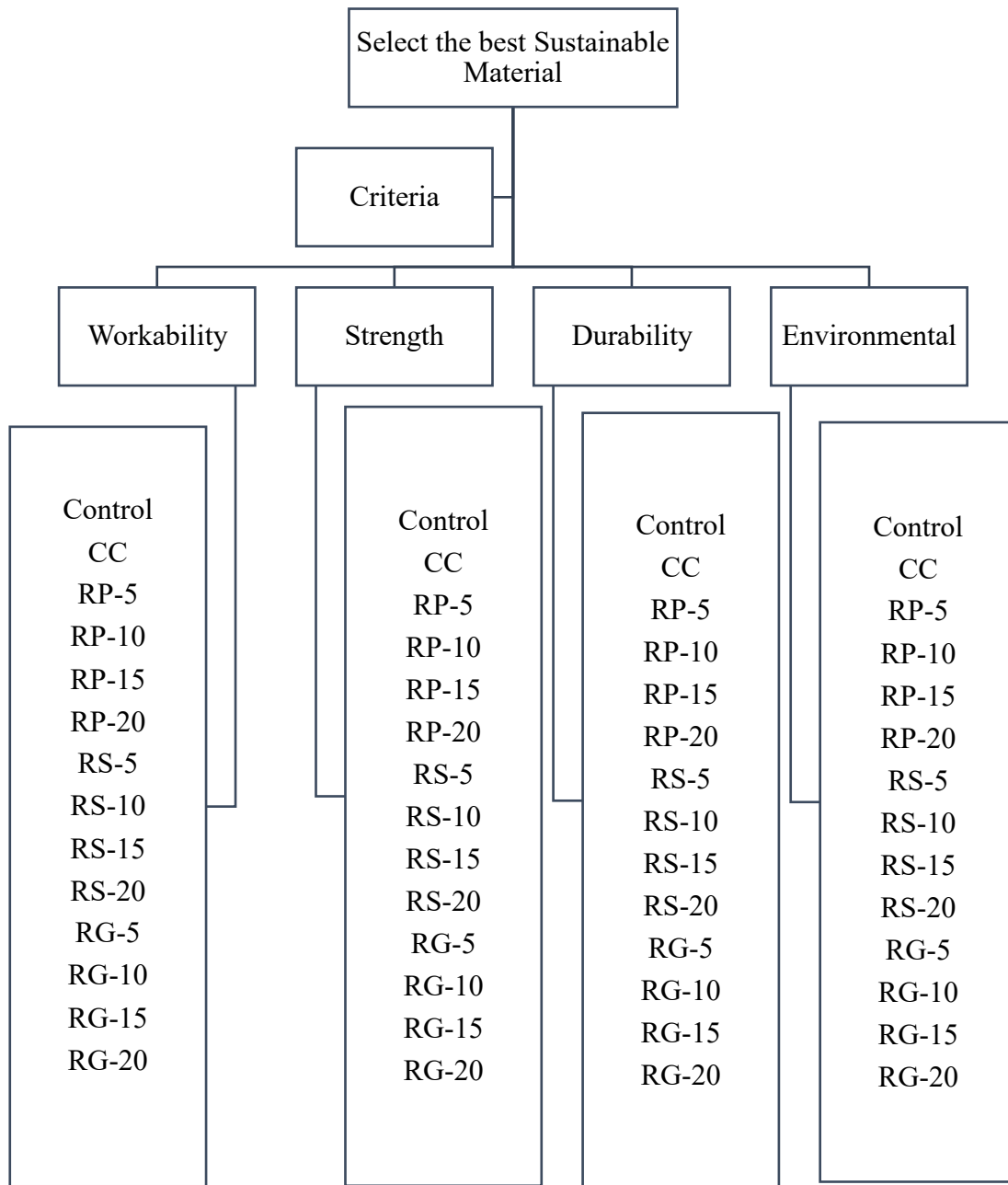


Figure 2: Development of Hierarchy for application of AHP Method

2.3.3 Decision Matrix for Choice

The decision matrix for example 2 is given below in table 10.

Table 10: Decision Matrix for Choice (Example 2)

Criteria	CC	RP-5	RP-10	RP-15	RP-20	R S-5	RS-10	RS-15	RS-20	RG-5	RP-10	RG-15	RG-20
Workability	78	69	62	56	51	74	70	65	61	71	64	59	54
Strength	21	17	12.8	10.9	9.5	19	16.7	14.6	13.8	16.9	13.5	11.8	10.4
Durability	0.4	0.3	0.23	0.21	0.18	0.3	0.26	0.22	0.2	0.35	0.31	0.27	0.26
Environmental	180	177	174	170	167	173	166	160	154	170	160	150	139

2.4 Development of DSS

Once all pairwise comparison matrices were established, the next stage involved performing calculations in accordance with the AHP methodology. To facilitate this process, an intuitive and user-friendly platform was developed to reduce computational effort, improve efficiency, reduce computation time, eliminate tedious manual work, and allow repeated use for applying AHP to a wide range of decision-making challenges in the future.

2.4.1 Initialization Concept

As highlighted in methodology, minimizing error and achieving an acceptable consistency ratio (less than 0.1) is most feasible when the number of criteria or choice remains limited. Accordingly, pairwise comparison matrices were formulated for cases where consistency evaluation was required. The literature defines n as the matrix size, representing the number of choice when a single criterion is applied, or the number of criteria when criteria are compared with each other. When n is kept below 10, the relative differences between successive entries typically exceed about 10%, and a consistency ratio below 0.1 does not significantly influence the final outcomes, ensuring dependable results. Several studies further recommend restricting AHP applications to a maximum of eight choices to maintain robustness and reliability.

2.4.2 DSS Description

An Excel-based DDS was developed for MCDM application using the AHP. The developed DSS enables a structured, transparent, and consistent evaluation of choice, supporting objective and reliable decision-making.

- **Input Criteria and Choice:** Users begin by entering the criteria and choice that will be evaluated. Criteria represent the factors against which the choices are judged, and choices are the options among which the decision is to be made.
- **Form Pairwise Comparison Matrix for Criteria:** Users compare each criterion against every other criterion in pairs, assigning relative importance values. This pairwise evaluation matrix reflects the preferences and judgments of the decision maker.
- **Normalize the Comparison Matrix:** The DSS automatically normalizes the pairwise comparison matrix. Normalization converts the raw comparison values into a scale that sums to 1 for each criterion, facilitating consistent and meaningful comparisons.
- **Determine Criteria Weights:** The DSS derives the weights for each criterion from the normalized matrix, indicating their significance in the decision-making process.
- **Check Consistency:** The DSS performs a uniformity check on the pairwise evaluations to ensure that the judgments are logically consistent. It calculates the Consistency Ratio (CR), which must be less than 0.1 to indicate acceptable consistency. If the CR exceeds this threshold, users may need to revise their comparisons.
- **Form Decision Matrix for Choice:** After determining the criteria weights, the DSS forms a decision matrix where each alternative is evaluated against each criterion. Users provide scores reflecting how well each alternative meets each criterion.
- **Create Weighted Normalized Decision Matrix:** The DSS then applies the criteria weights to the decision matrix, followed by the construction of weighted normalized decision matrix. This matrix adjusts the alternative scores according to the significance of each criterion, ensuring that more critical criteria contribute more to the overall decision.
- **Calculate Final Scores and Rank Choice:** The DSS calculates the final scores for each substitute by adding the weighted normalized scores. These scores provide a clear ranking of the choice, indicating which option best meets the criteria based on their assigned weights.

3. Results and Discussion

First, AHP methodology was applied to data reported in a peer-reviewed study by Khurram Rashid, and the resulting calculations are presented and discussed in this section. Five concrete options (C-35, 25R-35, 50R-35, 75R-35, and 100R-35) were evaluated against four criteria: cost, compressive strength, volume of raw materials, and CO₂ footprint.

A decision matrix was introduced in the methodology section, in which the options were evaluated with respect to each evaluation standard. To enable meaningful comparison, a normalization procedure was applied, converting all criteria values to a common scale. This step ensures uniformity across diverse measures and supports a fair, objective, and coherent evaluation process.

Table 11 represents the standardized decision matrix corresponding to the original matrix discussed in the methodology section.

Table 11: Standardized Decision Matrix for Example 1

Criteria	C-35	25R-35	50R-35	75R-35	100R-35
Cost	0.59	0.70	0.81	0.90	1.00
Compressive Strength	1.00	0.89	0.74	0.72	0.66
Volume of Raw Material	0.60	0.70	0.81	0.89	1.00
CO₂ Footprint	0.60	0.70	0.80	0.90	1.00

Following normalization of the decision matrix, weights are allocated to each criterion according to their relative importance in guiding the decision. This approach integrates the significance of each criterion into the evaluation, allowing for a balanced and comprehensive assessment of choice. Table 12 presents the weighted standardized decision matrix.

Table 12: Weighted Standardized Decision Matrix for Example 1

Criteria	Weightage	C-35	25R-35	50R-35	75R-35	100R-35
Cost	0.08	0.05	0.06	0.06	0.07	0.08
Compressive Strength	0.13	0.13	0.11	0.09	0.09	0.08
Volume of Raw Material	0.49	0.29	0.34	0.40	0.44	0.49
CO₂ Footprint	0.31	0.18	0.21	0.24	0.27	0.31

The final decision matrix for Example 1, presented in Table 13, is obtained from the weighted normalized matrix, which accounts for both the performance of each alternative and the relative significance of the criteria. Composite scores are calculated by aggregating the weighted values across all criteria for each alternative. These scores provide a clear quantitative basis for ranking, with the highest score indicating the most preferred option. This systematic process ensures that the final selection is transparent, objective, and consistent with the priorities defined in the AHP framework.

Table 13: Final Decision Matrix for Example 1

Criteria	C-35	25R-35	50R-35	75R-35	100R-35
Cost	0.05	0.06	0.06	0.07	0.08

Compressive Strength	0.13	0.11	0.09	0.09	0.08
Volume of Raw Material	0.29	0.34	0.40	0.44	0.49
CO₂ Footprint	0.18	0.21	0.24	0.27	0.31
Score	0.65	0.72	0.80	0.87	0.96
Rank	5th	4th	3rd	2nd	1st
Final	100R-35				

The final significance vector values are 0.65, 0.72, 0.8, 0.87, and 0.96. The final significance vector value for alternative is 0.96 (Highly preferred). The graph given below show the graphical representation of final priority vector and different choice; and the alternative 5 is selected to be the best choice keeping the sustainability and environmental effects as of highest weightage and it has highest position on the graph.

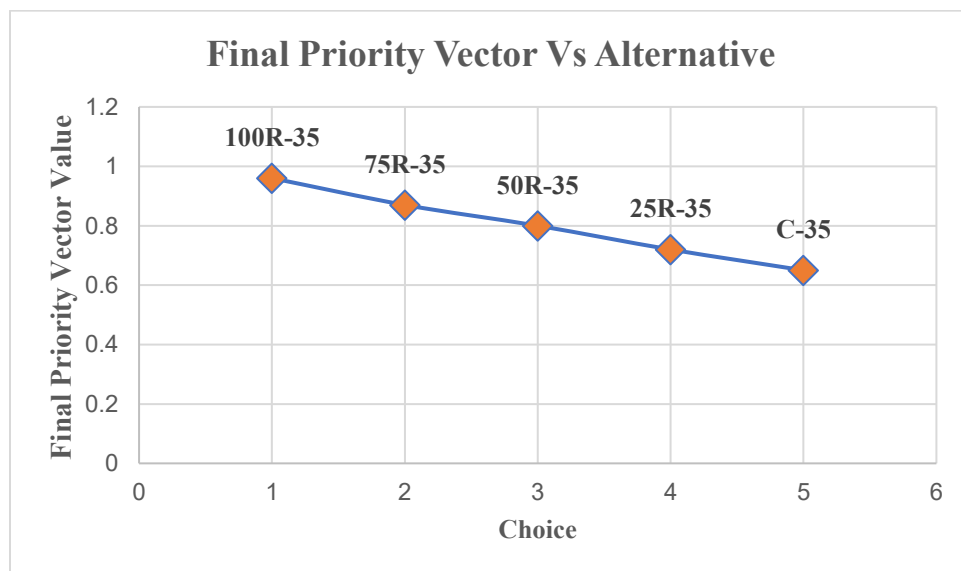


Figure 3: Graph between Final Priority Vector and Choice for Example 1

Secondly, the AHP framework was applied to data reported in the peer-reviewed study by Zafar et al. (2022), and the resulting analyses are presented and discussed in this section. A total of thirteen concrete choices (C-C, RP-5, RP-10, RP-15, RP-20, RS-5, RS-10, RS-15, RS-20, RG-5, RG-10, RG-15, and RG-20) were evaluated using four criteria: workability, compressive strength, durability, and environmental impact. The original decision matrix was standardized using the method outlined earlier. The resulting normalized values, weighted normalized values and final decision for this case study are presented in Table 14, and 15 and 16 respectively.

Table 14: Standardized Decision Matrix for Example 2

Criteria	CC	RP-5	RP-10	RP-15	RP-20	RS-5	RS-10	RS-15	RS-20	RG-5	RG=10	RG-15	RG-20
Workability	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Strength	0.4	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.2
Durability	0.3	0.3	0.2	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Environmental	0.3	0.3	0.3	0.3	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3

Table 15: Weighted Standardized Decision Matrix for Example 2

Criteria	Weightage	CC	RP-5	RP-10	RP-15	RP-20	RS-5	RS-10	RS-15	RS-20	RG-5	RG=10	RG-15	RG-20
Workability	0.15	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.04
Strength	0.23	0.08	0.07	0.06	0.05	0.05	0.07	0.07	0.06	0.06	0.07	0.07	0.06	0.06
Durability	0.38	0.12	0.11	0.10	0.10	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.10
Environmental	0.23	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.06	0.06	0.07	0.06	0.06	0.06

Table 16: Final Decision Matrix for Example 2

Criteria	CC	RP-5	RP-10	RP-15	RP-20	RS-5	RS-10	RS-15	RS-20	RG-5	RG=10	RG-15	RG-20
Workability	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.04
Strength	0.08	0.07	0.06	0.05	0.05	0.07	0.07	0.06	0.06	0.07	0.07	0.06	0.06
Durability	0.12	0.11	0.10	0.10	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.10
Environmental	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.06	0.06	0.07	0.06	0.06	0.06
Score	0.31	0.28	0.26	0.25	0.24	0.30	0.28	0.28	0.28	0.29	0.28	0.27	0.27
Rank	1st	8th	11th	12th	13th	2nd	4th	6th	7th	3rd	5th	9th	10th

The final priority vector value for alternative C-C is = 0.31 (Highly preferred). Final selection is alternative 1 i.e. C-C concrete.

The graph given below shows a detailed graphical representation of the final priority vector alongside various choices. Each alternative is evaluated based on specific criteria, with sustainability and environmental impacts given the highest weightage in the decision-making

method. This prioritization reflects the importance of choosing options that align with sustainable development goals and minimize negative environmental consequences.

Among the choice considered, Alternative 1 emerges as the most favorable choice. The high placement of Alternative 1 suggests that it excels in meeting the prioritized sustainability and environmental standards, making it the most suitable option based on the defined criteria. This decision underscores the emphasis on selecting solutions that not only meet functional requirements but also contribute positively to long-term ecological and social well-being.

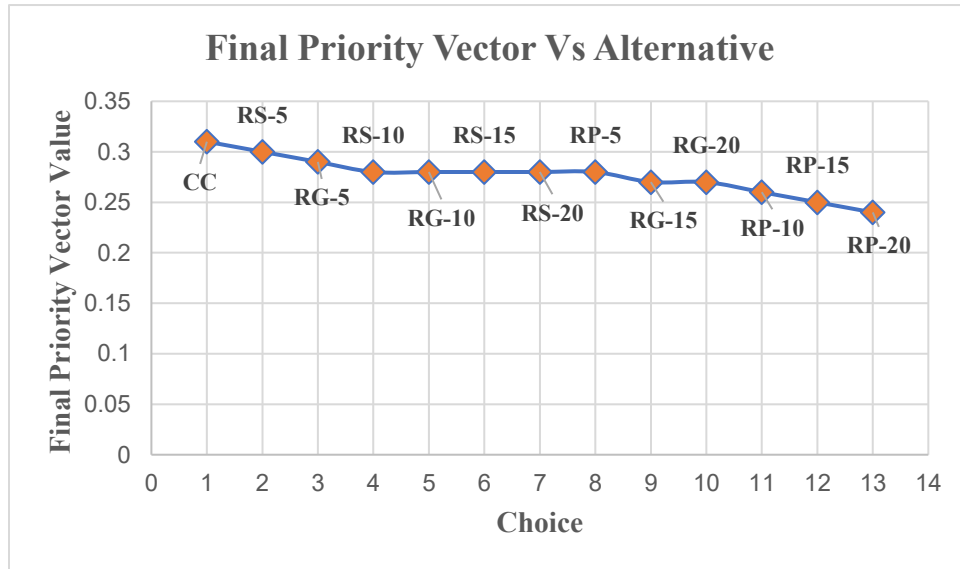


Figure 4: Graph between Final Priority Vector and Choice for Example 2

Finally, the DDS’s screenshots show a clearly presented and well-organized dataset. Excel’s strong capabilities for data organization, analysis, and presentation make it a valuable tool for both research and professional applications. The results generated by the developed DSS are illustrated in figures 5 and 6.

AHP Application on Khurram Rashid et al. (2020)

1 ASSIGN CRITERIA WEIGHTS

Weights	cost	Compressive Strength	Volume of Raw Mat.	CO ₂
	0.0786	0.1264	0.4836	0.3054

2 FORM DECISION MATRIX FOR ALTERNATIVES

Criteria	C-35	25R-35	50R-35	75R-35	100R-35	Criteria Type
cost	5900	5900	5700	5620	5530	Non-Beneficial
Compressive Strength	35.5	33.6	31	30.7	29.7	Beneficial
Volume of Raw Mat.	100	88	76	66	54	Non-Beneficial
CO ₂	250	248	246	244	242	Non-Beneficial

For Beneficial Criteria:

$$X'_{ij} = 1 - \frac{x_j^{max} - x_{ij}}{\sum (x_j^{max} - x_{ij})}$$

For Non-Beneficial Criteria:

$$X'_{ij} = 1 - \frac{x_{ij} - x_j^{min}}{\sum (x_{ij} - x_j^{min})}$$

Criteria	C-35	25R-35	50R-35	75R-35	100R-35	Max.	Min.
cost	5900	5900	5700	5620	5530	5900	5530
Compressive Strength	35.5	33.6	31	30.7	29.7	35.5	29.7
Volume of Raw Mat.	100	88	76	66	54	100	54
CO ₂	250	248	246	244	242	250	242

3 FORM NORMALISED DECISION MATRIX

Criteria	C-35	25R-35	50R-35	75R-35	100R-35
cost	0.53	0.70	0.81	0.90	1.00
Compressive Strength	1.00	0.89	0.74	0.72	0.66
Volume of Raw Mat.	0.60	0.70	0.81	0.83	1.00
CO ₂	0.60	0.70	0.80	0.90	1.00

4 FORM WEIGHTED NORMALISED DECISION MATRIX

Criteria	Weightage	C-35	25R-35	50R-35	75R-35	100R-35
cost	0.08	0.05	0.06	0.06	0.07	0.08
Compressive Strength	0.13	0.13	0.11	0.09	0.09	0.08
Volume of Raw Mat.	0.49	0.29	0.34	0.40	0.44	0.49
CO ₂	0.31	0.18	0.21	0.24	0.27	0.31

5 Final Decision

Criteria	C-35	25R-35	50R-35	75R-35	100R-35
cost	0.05	0.06	0.06	0.07	0.08
Compressive Strength	0.13	0.11	0.09	0.09	0.08
Volume of Raw Mat.	0.29	0.34	0.40	0.44	0.49
CO ₂	0.18	0.21	0.24	0.27	0.31
Score	0.65	0.72	0.80	0.87	0.96
Rank	5th	4th	3rd	2nd	1st
Final			100R-35		

Figure 5: DSS Results for Example 1

AHP Application on Zafar et al. (2022)															
1 ASSIGN CRITERIA WEIGHTS															
	Weights	Workability 0.154	Strength 0.231	Durability 0.384	Enviromental 0.231										
2 FORM DECISION MATRIX FOR ALTERNATIVES															
	Criteria	CC	RP-5	RP-10	RP-15	RP-20	RS-5	RS-10	RS-15	RS-20	RG-5	RG-10	RG-15	RG-20	-----
	Workability	78	69	62	56	51	74	70	65	61	71	64	59	54	Non-Beneficial
	Strength	21.5	16.9	12.8	10.9	9.5	18.7	16.7	14.6	13.8	16.9	13.5	11.8	10.4	Beneficial
	Durability	0.41	0.3	0.23	0.21	0.18	0.32	0.26	0.22	0.2	0.35	0.31	0.27	0.26	Beneficial
	Enviromental	180	177	173.5	170.5	167	173.5	166.5	160	153.5	170	160	150.5	139.5	Beneficial
3 FORM NORMALISED DECISION MATRIX FOR ALTERNATIVES															
	Criteria	CC	RP-5	RP-10	RP-15	RP-20	RS-5	RS-10	RS-15	RS-20	RG-5	RG-10	RG-15	RG-20	
	Workability	0.26	0.26	0.27	0.27	0.29	0.28	0.28	0.29	0.32	0.26	0.26	0.27	0.28	
	Strength	0.36	0.29	0.25	0.22	0.21	0.32	0.29	0.26	0.24	0.32	0.29	0.26	0.25	
	Durability	0.31	0.27	0.25	0.25	0.24	0.29	0.28	0.28	0.27	0.29	0.28	0.28	0.27	
	Enviromental	0.29	0.28	0.27	0.26	0.25	0.29	0.28	0.28	0.28	0.29	0.28	0.28	0.28	
4 FORM WEIGHTED NORMALISED DECISION MATRIX															
	Criteria	Weightage	CC	RP-5	RP-10	RP-15	RP-20	RS-5	RS-10	RS-15	RS-20	RG-5	RG-10	RG-15	RG-20
	Workability	0.15	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.04
	Strength	0.23	0.08	0.07	0.06	0.05	0.05	0.07	0.07	0.06	0.06	0.07	0.07	0.06	0.06
	Durability	0.38	0.12	0.11	0.10	0.10	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.10
	Enviromental	0.23	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.06	0.06	0.07	0.06	0.06	0.06
5 Final Decision															
	Criteria	CC	RP-5	RP-10	RP-15	RP-20	RS-5	RS-10	RS-15	RS-20	RG-5	RG-10	RG-15	RG-20	
	Workability	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.04	0.04	0.04	0.04	
	Strength	0.08	0.07	0.06	0.05	0.05	0.07	0.07	0.06	0.06	0.07	0.07	0.06	0.06	
	Durability	0.12	0.11	0.10	0.10	0.09	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.10	
	Enviromental	0.07	0.06	0.06	0.06	0.06	0.07	0.07	0.06	0.06	0.07	0.06	0.06	0.06	
	Score	0.31	0.28	0.26	0.25	0.24	0.30	0.28	0.28	0.28	0.29	0.28	0.27	0.27	
	Rank	1st	8th	11th	12th	13th	2nd	4th	6th	7th	3rd	5th	9th	10th	
	Final	CC													

Figure 6: DSS Results for Example 2

4. Conclusions

Following conclusions are drawn from this research:

- Choosing an alternative is largely determined by the weights derived from the pairwise comparison matrices
- AHP is time-consuming and lengthy if the number of choice and criteria increases, but this can be easily managed with the developed DSS.
- CO₂ footprint and natural resource usage are considered to achieve sustainability.
- The consistency ratios for individual criteria are less than 0.1, so input weights don't need to be revised. If the consistency check isn't satisfied, the pairwise comparison matrices must be revised.
- A DSS was used to apply the AHP method to recycled aggregate concrete, which saves time in identifying the most preferred alternative.
- Using computer-based tools is crucial today. The developed DSS can be used in the industry for any decision-making problem involving AHP.
- The priority vector changes based on preferences set in the pairwise comparison matrices, influenced by experience and requirements.
- To move towards sustainability, we may need to compromise on factors like compressive strength or cost. Fulfilling sustainability requirements might involve significant cost compromises, but this is less important than conserving natural resources and the environment for future generations.

5. Recommendations and Future Research Directions

It is essential to raise awareness among society and decision-makers in the construction industry regarding the critical importance of environmental preservation and sustainability in project planning and execution. When applying the AHP, it is recommended to limit the number of choices to a maximum of eight and the number of criteria to eight, or at most ten, as exceeding these limits may introduce small consistency errors that could influence the results.

Although this study focused solely on the AHP method, emerging research highlights the advantages of hybrid MCDM approaches for enhancing accuracy. Future studies are encouraged to adopt hybrid methods or incorporate additional MCDM techniques to validate and cross-check outcomes for improved reliability.

Furthermore, while the developed DSS in this study treats all criteria as primary criteria, its functionality can be enhanced to accommodate hierarchical structures, allowing sub-criteria to be incorporated under main criteria. This improvement would enable a more comprehensive and precise application of AHP, supporting better-informed decisions in complex civil engineering scenarios.

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