Development of Concrete Mixture Design Process Using MCDM Approach for Sustainable Concrete Quality Management

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Abstract: The development of a concrete mixture design process for high-quality concrete production with sustainable values is a complex process because of the multiple required properties at the green/hardened state of concrete and the interdependency of concrete mixture parameters. A new multicriteria decision making (MCDM) technique based on Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) methodology is applied to a fuzzy setting for the selection of concrete mix factors and concrete mixture design methods with the aim towards sustainable concrete quality management. Three objective properties for sustainable quality concrete are adopted as criteria in the proposed MCDM model. The seven most dominant concrete mixture parameters with consideration to sustainable concrete quality issues, i.e., environmental (density, durability) and socioeconomic criteria (cost, optimum mixture ingredients ratios), are proposed as sub-criteria. Three mixture design techniques that have potentiality to include sustainable aspects in their design procedure, two advanced and one conventional concrete mixture design method, are taken as alternatives in the MCDM model. The proposed selection support framework may be utilized in updating concrete design methods for sustainability and in deciding the most dominant concrete mix factors that can provide sustainable quality management in concrete production as well as in concrete construction. The concrete mix factors found to be most influential to produce sustainable concrete quality include the water/cement ratio and density. The outcomes of the proposed MCDM model of fuzzy TOPSIS are consistent with the published literature and theory. The DOE method was found to be more suitable in sustainable concrete quality management considering its applicable objective quality properties and concrete mix factors.

Keywords: sustainable quality management; concrete mixture parameters; mixture design method; Fuzzy TOPSIS; multicriteria decision-making

1. Introduction

Concrete is a workable plastic mixture of cement, water, fine aggregates, and coarse aggregates in controlled proportions, for use in the construction industry [1]. The concrete mixture parameters and water/cement (w/c) ratio affect the workability, strength, and durability, while the concrete mixture factors, namely, ratio of fine aggregate to cement (FA/c) and ratio of fine aggregate to total aggregate (FA/T) have an impact on concrete quality. There are other numerous concrete mixture factors such as cement type; minimum and maximum cement content; strength of cement; types, shape, and size of aggregates; aggregates grading; ratio of coarse aggregate and cement (CA/c); characteristics of concrete in green or hardened state; cost of concrete, etc., that influence the overall quality of concrete.

There are numerous methods to design the concrete mixture. The present study has considered three mixture design techniques, viz., the American Concrete Institute (ACI), Department of Energy...
(DOE), and Fineness Modulus (FM) mix design methods that have potentiality to include sustainable aspects in their design procedure; two advanced and one conventional concrete mixture design method are taken as alternatives in the MCDM model. The American Concrete Institute (ACI) mix design method considers workability, consistency, strength, and durability. The main principles of the ACI method are that the w/c ratio is inversely proportional to the design strength, the bulk volume of coarse aggregate per unit volume of concrete depends on the aggregate maximum size, and fine aggregate grading. The basic assumption made by the Department of Energy (DOE) mix design method is that the strength of the concrete is governed by the water/cement ratio. The other principles of the DOE method are that fine aggregate proportion varies with aggregate maximum size and water/cement ratio. The Fineness Modulus (FM) method for concrete mix design is based on the principle that the strength of the concrete depends on the water/cement ratio and the relative proportions of fine and coarse aggregate, such that the combined aggregate needs the least amount of cement paste for full compaction. This mixture method has not directly dealt with sustainability, though it takes care about environment aspects in its design approach.

The proper proportioning of constituents of concrete with sustainable qualitative performance can make concrete manufacturing sustainable. To prepare a concrete mixture with sustainable criteria, a proper mix design method, the most acceptable concrete mixture parameters, and optimum proportions of concrete ingredients are needed. The requirements of the concrete mixture may change due to material product characteristics having social, economic, and environmental constraints. The socioeconomic characteristics of sustainable criteria in the context of concrete include improvement to quality of life and cost reduction through high quality concrete properties and additional quality control personnel, optimum materials, and long life of produced concrete. The environmental characteristics of sustainable criteria in the context of concrete include lower CO₂ emission and natural resources consumption through optimum cement and water use in concrete production. Concrete mixture factors such as water/cement (w/c) ratio, density, ratio of fine aggregate to cement (FA/c), ratio of coarse aggregate and cement (CA/c), and cost of concrete may be used to satisfy the socioeconomic indicators of sustainable concrete. Concrete mixture factors such as water/cement (w/c) ratio, density, ratio of fine aggregate and total aggregate (FA/T), ratio of total aggregate to cement (T/c), and ratio of fine aggregate to cement (FA/c) can be used to satisfy the environmental indicators of sustainable concrete. Proper concrete proportioning along with optimum ratios of ingredients results in high durability of structures [2] and helps to resolve the environment and socioeconomic issues. Alam et al. [3] identified the factors concerning the quality of concrete production and pointed out that a proper concrete mix is one of the key factors which affects the quality of concrete. Ahmad [4] studied concrete mixture proportion from the quality of concrete point of view and suggested that there exists an optimum ratio of fine aggregate and total aggregate (FA/T) and cement/fine aggregate (c/FA) ratio for improved quality. Zavadskas et al. [5] emphasized that the application of Multicriteria Decision-Making (MCDM) techniques have great potential and sustainable decision-making in structural engineering, design, and building technology. An extensive body of literature is available in which MCDM approaches are used to tackle the selection of the right stockholder, the best practice or option, an optimum measure of right materials in concrete construction project management, and sustainable construction engineering. Zavadskas et al. [6] present a summary of published research related to the application of basic decision-making frameworks and processes, along with advanced MCDM techniques for sustainability in the construction engineering discipline. A broader review of MCDM approaches and their applications in civil engineering are due to Kabir et al. [7]. Stojcic et al. [8] discussed the application of MCDM for sustainability in the engineering field. Monghasemi et al. [9] introduced a new MCDM model to optimize the construction time, construction cost, and construction quality of projects. Alhumaidi [10] proposed an MCDM technique considering a multi-attribute fuzzy weighted average approach for project contractor selection. Taylon et al. [11] used a hybrid fuzzy Analytic Hierarchy Process (fuzzy-AHP) and fuzzy TOPSIS MCDM technique for assessing the selection criteria and risk criteria of construction projects. Hamdia et al. [12] develop the reinforced cement concrete...
(RCC) building damage assessment criteria using the fuzzy analytic hierarchy process. The application of the MCDM technique to structural retrofitting procedures for buildings and bridges repairs is due to Caterino et al. [13] and Rashidi et al. [14]. They conclude that technique for order preference by similarity to ideal solution (TOPSIS) and the methodology of VIKOR (Vise Kriterijumska Optimizacija i Kompromisno Resenje in Serbian) are more suitable for selecting retrofit procedures. Zhao et al. [15] propose a coupled MCDM method, intervalued trapezoidal intuitionistic fuzzy number (IVTIFN), and a TOPSIS method to support the selection of pipe materials in building projects. The Fuzzy extended analytical hierarchy process (FEAHP) technique is proposed by Akadiri et al. [16] for ranking building materials. Falqi et al. [17] apply a TOPSIS method in a fuzzy environment for siliceous material management for sustainable concrete construction. Ahmed et al. [18] propose a hybrid MCDM approach to select a concrete mixture design method for the production of high-performance concrete. Bera et al. [19] suggested multi-attribute decision-making (MADM) to choose an appropriate proportion of silty sand and artificial clay for soil stabilization based on a mixing design approach.

It is clear from the literature review that a number of applications of MCDM techniques in construction industries for the incorporation of sustainability in various construction engineering processes and management are available. However, MCDM techniques’ application related to sustainable concrete quality management through a sustainable concrete design process is scarce. The present study is a contribution to the application of a MCDM technique to develop a concrete mixture design process for sustainable concrete quality management. Potential concrete design methods and mixture factors considering environmental and social–economic sustainable issues in a multicriteria selection problem of the concrete design process, particularly suitable for sustainable concrete quality management, are proposed. The criteria, namely workability, strength, and durability, and sub-criteria, namely water/cement (w/c) ratio, density, ratio of fine aggregate to cement (FA/c), ratio of coarse aggregate and cement (CA/c), ratio of fine aggregate and total aggregate (FA/T), and cost of concrete are so selected to satisfy the technical, environmental, and socioeconomic indicators of sustainable concrete, along with design mix methodology requirements.

The fuzzy TOPSIS approach, which has demonstrated its applicability in different fields, is applied by developing a concrete mixture design process to produce sustainable quality concrete, taking into account concrete mixture design methods that have the potential to adapt sustainability and prevailing concrete mixture factors that require the environmental and socioeconomic aspects of sustainability. The rating of concrete mixture design methods and concrete mixture factors is based on the decision-maker’s weighted criteria. The reason for choosing the fuzzy TOPSIS method is to select the best alternative to evaluate the most suitable and unsuitable alternative together.

2. Multicriteria Decision-Making Based on Fuzzy Sets Theory

Zadeh [20] introduced the theory of fuzzy sets to describe linguistic concepts in the decision-making process with a view to reducing human judgment complexity. Bellman and Zadeh [21] developed a fuzzy MCDM approach to tackle the lack of precision and uncertainty, and to assign significance to the weights of the parameters and to the ratings of alternatives for the assessment criteria [22]. The study simplifies the important fuzzy concept by modifying the fuzzy concept.

“Let X be the universe of discourse, \( X = \{ x_1, x_2, \ldots, x_n \} \). A fuzzy set \( A \) of X is a set of order pairs \( X = \{ (x_1, f^A_x(x_1)), (x_2, f^A_x(x_2)) \ldots (x_n, f^A_x(x_n)) \} \), where \( f^A_x : X \rightarrow [0, 1] \) is the membership function of \( A \), and \( f^A_x(x_i) \) stands for the membership degree” of \( x_i \) in \( A \).

The \( \alpha \)-cut \( \widetilde{A}_\alpha \) and strong \( \alpha \)-cut \( \widetilde{A}_{\alpha^+} \) of the fuzzy set \( \tilde{A} \) in the universe of discourse, X is defined by [20]

\[
\widetilde{A}_\alpha = \{ x_i | f^A_x(x_i) \geq \alpha, x_i \in X \}, \text{ where } \alpha \in [0, 1] (1)
\]

\[
\widetilde{A}_{\alpha^+} = \{ x_i | f^A_x(x_i) \geq \alpha, x_i \in X \}, \text{ where } \alpha \in [0, 1] (2)
\]
“A fuzzy set $\tilde{A}$ of the universe of discourse $X$ is convex if and only if every $\tilde{A}_\alpha$ is convex, that is $\tilde{A}_\alpha$ is a closed interval of $\mathbb{R}$. It can be written as”

$$\tilde{A}_\alpha = \left[p_1^{(\alpha)}, p_2^{(\alpha)}\right], \text{ where } \alpha \in [0, 1]$$

(3)

“The triangular fuzzy number (TFN) introduced by Zadeh [20] can be defined as a triplet $(a_1, a_2, a_3)$ and the membership function of the fuzzy number” $\tilde{A}$ is defined as in Figure 1.

$$f_{\tilde{A}}(x) = \begin{cases} 0, & x < a_1 \\ (x-a_1)/(a_2-a_1), & a_1 \leq x \leq a_2 \\ (a_3-x)/(a_3-a_2), & a_2 \leq x \leq a_3 \\ 0, & x > a_3 \end{cases}$$

(4)

According to Chen’s vertex method [23], the difference between the fuzzy numbers $\tilde{A}$ and $\tilde{B}$, which are parameterized by the triplets $(a_1, a_2, a_3)$ and $(b_1, b_2, b_3)$, respectively, and can be calculated as

$$d(\tilde{A}, \tilde{B}) = \sqrt{(a_1-b_1)^2 + (a_2-b_2)^2 + (a_3-b_3)^2}$$

(5)

3. Fuzzy TOPSIS Method

A linear weighting technique, the TOPSIS method was first introduced in the crisp version by Chen and Hwang [24], with reference to Hwang and Yoon [25]. In MCDM, the criteria may be of varying significance and therefore, require different weights [26]. The weights can be allocated using a range of methods, for example, analytic hierarchy process (AHP), analytic network process (ANP), entropy analysis, eigenvector method, etc. The proposed TOPSIS approach in the fuzzy environment is implemented to the problem of selecting an effective mix design method for the production of quality concrete. Problem formulation defines the goals of the problem, the assessment criteria, the decision-makers, and their classes. The framed problem, consisting of a four-level hierarchy, namely, goal (level 1), criteria (level 2—objective properties for sustainable quality concrete), sub-criteria (level 3—significant mixture parameters for sustainable quality concrete), and alternatives (level 4—popular mixture design methods effective for sustainable quality concrete), is depicted in Figure 2. Three potential concrete mixture design methods for sustainability, the Department of Energy (DOE) method, the American Concrete Institute (ACI) method, and the Fineness Modulus (FM) method, with objective properties such as strength, workability, and durability, etc., required for sustainable quality concrete are considered in the model framework. The seven mixture factors, which include the proposed dominant mix factors for the production of sustainable quality concrete, i.e., environmental and socioeconomic aspects, namely density (environmental criteria), the cost, ratio of water and cement (w/c), ratio of total aggregate and cement (T/c), ratio of coarse aggregate and cement...
(CA/c), ratio of fine aggregate and cement (FA/c), and ratio of fine aggregate/total aggregate (FA/T) (socioeconomic criteria) are taken into consideration.

The problem criteria (objective properties) and sub-criteria (concrete mixture factors for sustainability quality concrete) are selected based on the opinion of experts and published literature [27–32] related to the design of concrete mixture. Helmi [32] reported that the mix design process plays a significant role in comparing different sub-criteria of strength, workability, and durability, viz., “ratios of CA/c, T/c, w/c density, FA/T, FA/c” and the cost of determining an appropriate mixture design method for quality concrete production. The published data with international mix design methods for concrete mixture and mixture proportion factors to obtain quality concrete are presented in Table 1.

Table 1. Optimum values of mixture proportion factors for quality concrete.

| Mixture Factors | DOE Method | ACI Method | Concrete Mixture Optimum Value with Lowest Cost |
|-----------------|------------|------------|-----------------------------------------------|
| Ratio of FA/T   | 0.41 [27]  | 0.43 [27]  | 0.42 [31] 0.45–0.4 [30] 0.39 [29] 0.38 [1,4] |
| Ratio of T/c    | 4.26 [27]  | 4.31 [27]  | – 3–3.6 [30] 4.3–5.1 [29] 4.88 [1,4]     |
| Ratio of CA/c   | 2.51 [27]  | 2.43 [27]  | – – 0.4–0.43 [29] –                     |
| Ratio of FA/c   | 1.75 [27]  | 1.88 [27]  | – – – –                                  |

Figure 2. Hierarchical structure to select the mixture design method for sustainable quality concrete production.
The decision-makers’ group (consisting of five concrete technology and quality management experts, and consultants) was asked to judge and rank the selected seven dominant concrete mixture factors based on sustainability issues. The set questionnaire was given to the decision-makers’ group for their opinion, as shown in Appendices A and B. Initially, they were supplied seven questions about criteria rating using five linguistic variables [33], namely very high, high, medium, low, and very low, along with TFN, as given in Appendix A, reflecting the importance weights of performance criteria to judge the ability of the mix design method to produce sustainable quality concrete. In order to rank the mix design methods for concrete quality management, furthermore, the adopted criteria were used to assess the output of each mix design method for sustainable concrete quality management using Zelany’s notion [34] i.e., “displaced ideal separated away from the ideal solution the least”. As per Hwang and Yoon [25], in order to fix problems with MCDM, the selected alternative should not only have the shortest distance from the positive ideal reference point (PIRP), but also the longest distance from the negative ideal reference point (NIRP). Using Chen’s [23] method, another set of questionnaires, as shown in Appendix B, comprising seven questions each for the mixture design method alternatives, i.e., $A_1, A_2, \ldots, A_n$, is given, in order to rate their individual capabilities concerning various sub-criteria already set aside. The overall performance of each mixture design method was assessed based on their sustainable performance and the opinion of experts collected earlier in linguistic variables viz., very good, good, fair, poor, and very poor, along with triangular fuzzy numbers. This method’s algorithm is defined in the following section.

### 3.1. Fuzzy Decision Matrix Construction for a Sustainable Quality Concrete Production Problem

Given $m$ alternatives for the mix design method, selection criteria ($n$), and expert group ($k$) comprising decision-makers (DM), a typical fuzzy multicriteria group decision-making shipper problem can be expressed in matrix format as below.

$$\bar{D}_{ij} = \begin{bmatrix} C_1 & C_2 & \cdots & C_n \\ a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{bmatrix}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n$$  \hspace{1cm} (6)

“where $A_1, A_2, \ldots, A_n$ are the alternatives to be chosen, $C_1, C_2, \ldots, C_n$ denote the evaluation criteria for preferential mix design method, and $\bar{D}_{ij}$ represents the rating of alternative $A_i$ with respect to criterion $C_j$ evaluated by $k$ decision-makers”. Since the interpretation of the preferential mix design approach depends on an individual’s expertise, this study uses the mean value method to combine fuzzy output score $\bar{x}_{ij}$ for $k$ decision-makers with the same assessment criteria, i.e.,

$$\bar{x}_{ij} = \frac{1}{k}(\bar{x}_{ij}^1 + \bar{x}_{ij}^2 + \cdots + \bar{x}_{ij}^k)$$  \hspace{1cm} (7)

“where $\bar{x}_{ij}^k$ is the rating of alternative $A_i$ with respect to criterion $C_j$ evaluated by the $k$th decision-maker and $\bar{x}_{ij}^k = (a_{ij}^k, b_{ij}^k, c_{ij}^k)$”.

### 3.2. Fuzzy Decision Matrix Normalization for a Sustainable Quality Concrete Production Problem

The various criteria needed to choose a preferred mix design method are quantified in various units; therefore, they need normalization. The current case utilizes the linear scales transform normalization function to maintain the characteristics that normalized TFN ranges should be included in $[0, 1]$. If $\bar{R}$ indicates the normalized fuzzy decision matrix [25]

$$\bar{R} = \left[ \bar{r}_{ij} \right]_{m \times n}, \quad i = 1, 2, \ldots, m; \quad j = 1, 2, \ldots, n$$  \hspace{1cm} (8)
3.3. Weighted Normalized Fuzzy Decision Matrix Construction for a Sustainable Quality Concrete Production Problem

Given the different weight of each criterion, it is possible to determine the weighted normalized decision matrix by multiplying the importance weights of evaluation criteria and values in the normalized fuzzy decision matrix. The weighted normalized matrix of decisions is defined by

\[
\tilde{\nu}_{ij} = r_{ij} \odot \tilde{w}_j
\]

(11)

where \( \tilde{w}_j \) represents the importance weight of criterion \( C_j \) obtained through

\[
\tilde{w}_j = \frac{1}{K} (\tilde{w}_{j1} + \tilde{w}_{j2} + \ldots + \tilde{w}_{jk})
\]

(12)

“where \( k \) is the number of members in a decision-makers’ group and \( \tilde{w}_{jk} \) represents the fuzzy weight of \( j \)th criteria assessed by \( k \)th decision-makers”.

3.4. FPIRP and FNIRP Determination

The fuzzy positive ideal reference point (FPIRP, \( A^+ \)) and a fuzzy negative ideal reference point (FNIRP, \( A^- \)) in the interval \([0, 1]\) can be represented as,

\[
A^+ = (\tilde{v}_1^+, \tilde{v}_2^+, \ldots, \tilde{v}_n^+)
\]

(13)

\[
A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-)
\]

(14)

where \( \tilde{v}_j^+ = (1,1,1) \) and \( \tilde{v}_j^- = (0,0,0) \), \( j = 1,2,\ldots,n \)

3.5. Determination of Each Concrete Mixture Construction Process Distances to FPIRP and FNIRP

Estimation of each concrete mixture construction process distance to FPIRP and FNIRP can be carried out respectively as:

\[
d_i^+ = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^+), i = 1,2,\ldots,m; j = 1,2,\ldots,n
\]

(15)

\[
d_i^- = \sum_{j=1}^{n} d(\tilde{v}_{ij}, \tilde{v}_j^-), i = 1,2,\ldots,m; j = 1,2,\ldots,n
\]

(16)

“where, \( d(\tilde{v}_a, \tilde{v}_b) \), denotes the distance measurement between two fuzzy numbers, \( d_i^+ \) represents the distance of alternative \( A_i \) from FPIRP, and \( d_i^- \) is the distance of alternative \( A_i \) from FNIRP”.

3.6. Development of Closeness Coefficient (CC) and the Potential Alternatives Order

When the CC is calculated, all the potential alternative orders may be identified, permitting decision-makers to choose the most realistic alternative. Each alternative’s closeness coefficient is determined as

\[
c_{cc_i} = \frac{d_i^-}{d_i^+ + D_i}, i = 1,2,3,\ldots,m
\]

(17)
An alternative with index \( c_j \) approaching 1 indicates that the alternative is close to the fuzzy positive ideal reference point and far from the fuzzy negative ideal reference point. A high closeness index value suggests better performance of the alternative \( A_i \).

4. Concrete Mixture Design Method Assessment for Sustainable Quality Concrete Production

The derivation of the potentiality order of the mix design methods is a multicriteria decision-making process. In order to select the sustainable concrete mix design with the most potential for sustainable quality concrete, fuzzy TOPSIS methodology is employed. A group of five decision-makers (DM) was formed to identify and rate the criteria along with the alternatives for selection. The group was to judge the relative merits of individual concrete mixture design methods based on their past with sustainable concrete quality management experience. The detailed methodology adopted for the selection of concrete mix design for quality concrete production is explained in the following section.

4.1. Determination of the Synthetic Importance Weights of Assessment Criteria

Decision-makers first gave a preference for each criteria or objective properties for sustainable concrete in response to the questionnaire as per Appendix A. For the evaluation criteria, an integrated fuzzy weight matrix was developed by the average value technique mentioned in Equation (12). The Center of Area (COA) method [35] was used to de-fuzzify the TFNs into corresponding values of best non-fuzzy output (BNP) to understand the order of importance of these selection criteria. The integrated fuzzy importance weight matrix and BNP values corresponding to each sub-criteria related to different criteria are presented in Tables 2–5. The BNP values found for the seven sub-criteria for assessing mix design methods for sustainable quality concrete are w/c ratio (0.767), density (0.34), CA/c (0.7), T/c (0.687), FA/c (0.28), FA/T (0.34), and cost (0.42) when workability criteria are considered. The BNP values of seven selected sub-criteria are as w/c ratio (0.867), density (0.767), CA/c (0.62), T/c (0.66), FA/c (0.653), FA/T (0.307), and cost (0.833), and w/c ratio (0.833), density (0.8), CA/c (0.46), T/c (0.427), FA/c (0.693), FA/T (0.42), and cost (0.733), respectively, with respect to strength and durability considerations. Figures 3–5 depict the graphical representation of fuzzy weight assigned to each sub-criterion by decision-makers. Fuzzy weights are obtained after normalizing the BNP values.

### Table 2. Weight of fuzzy importance, BNP, and rank of each sub-criteria with respect to workability.

| Sub-Criteria | Weight of Fuzzy Importance | BNP   | Rank |
|--------------|-----------------------------|-------|------|
| \((C_1)\) w/c | \(0.5800, 0.7800, 0.9400\) | 0.7667 | 1    |
| \((C_2)\) Density | \(0.1400, 0.3400, 0.5400\) | 0.3400 | 5    |
| \((C_3)\) CA/c | \(0.5000, 0.7000, 0.9000\) | 0.7000 | 2    |
| \((C_4)\) T/c | \(0.5000, 0.7000, 0.8600\) | 0.6867 | 3    |
| \((C_5)\) FA/c | \(0.1200, 0.2600, 0.4600\) | 0.2800 | 7    |
| \((C_6)\) FA/T | \(0.1400, 0.3400, 0.5400\) | 0.3400 | 6    |
| \((C_7)\) Cost | \(0.2200, 0.4200, 0.6200\) | 0.4200 | 4    |

### Table 3. Weight of fuzzy importance, BNP, and rank of each sub-criteria with respect to strength.

| Sub-Criteria | Fuzzy Importance Weight | BNP   | Rank |
|--------------|-------------------------|-------|------|
| \((C_8)\) w/c | \(0.7000, 0.9000, 1.0000\) | 0.8667 | 1    |
| \((C_9)\) Density | \(0.5800, 0.7800, 0.9400\) | 0.7667 | 3    |
| \((C_{10})\) CA/c | \(0.4200, 0.6200, 0.8200\) | 0.6200 | 6    |
| \((C_{11})\) T/c | \(0.4600, 0.6600, 0.8600\) | 0.6600 | 4    |
| \((C_{12})\) FA/c | \(0.4600, 0.6600, 0.8400\) | 0.6533 | 5    |
| \((C_{13})\) FA/T | \(0.1200, 0.3000, 0.5000\) | 0.3067 | 7    |
| \((C_{14})\) Cost | \(0.6600, 0.8600, 0.9800\) | 0.8333 | 2    |
Table 4. Weight of fuzzy importance, BNP, and rank of each sub-criteria with respect to durability.

| Sub-Criteria | Fuzzy Importance Weight | BNP Values | Rank |
|---------------|-------------------------|------------|------|
| (C_{15}) w/c  | (0.6600, 0.8600, 0.9800) | 0.8333     | 1    |
| (C_{16}) Density | (0.6200, 0.8200, 0.9600) | 0.8000     | 2    |
| (C_{17}) CA/c | (0.2600, 0.4600, 0.6600) | 0.4600     | 5    |
| (C_{18}) T/c  | (0.2400, 0.4200, 0.6200) | 0.4267     | 6    |
| (C_{19}) FA/c | (0.5000, 0.7000, 0.8800) | 0.6933     | 4    |
| (C_{20}) FA/T | (0.2200, 0.4200, 0.6200) | 0.4200     | 7    |
| (C_{21}) Cost | (0.5400, 0.7400, 0.9200) | 0.7333     | 3    |

Table 5. Overall order of sub-criteria using BNP value with respect to sustainable concrete quality.

| Sub-Criteria | BNP Value | Rank |
|---------------|-----------|------|
| C_{1}         | 0.7667    | 5    |
| C_{2}         | 0.3400    | 18   |
| C_{3}         | 0.7000    | 8    |
| C_{4}         | 0.6867    | 10   |
| C_{5}         | 0.2800    | 21   |
| C_{6}         | 0.3400    | 18   |
| C_{7}         | 0.4200    | 16   |
| C_{8}         | 0.8667    | 1    |
| C_{9}         | 0.7667    | 5    |
| C_{10}        | 0.6200    | 13   |
| C_{11}        | 0.6600    | 11   |
| C_{12}        | 0.6533    | 12   |
| C_{13}        | 0.3067    | 20   |
| C_{14}        | 0.8333    | 2    |
| C_{15}        | 0.8333    | 2    |
| C_{16}        | 0.8000    | 4    |
| C_{17}        | 0.4600    | 14   |
| C_{18}        | 0.4267    | 15   |
| C_{19}        | 0.6933    | 9    |
| C_{20}        | 0.4200    | 16   |
| C_{21}        | 0.7333    | 7    |

Figure 3. The fuzzy weight of each criterion when workability is considered.
4.2. Fuzzy Decision Matrix Construction

A comprehensive review of different parameters and performances against each criterion is needed to choose the most suitable concrete mix design approach for sustainable quality concrete. In linguistic terms, the DM gave their feedback. Together with TFN as depicted in Appendix B, the DM used very poor, poor, fair, good, and very good linguistic terms to express their opinions against each criterion for each concrete mix design based on their individual skill. The fuzzy performance ratings of every concrete mix design method with respect to assessment criteria were combined to synthesize the different individual judgments. The fuzzy decision matrixes are determined using Equation (6) and shown in Table 5.

4.3. Fuzzy Decision Matrix Normalization and Weighted Normalized Matrix

As discussed above, linear transformation functions have been used to allow the inclusion of normalized TFNs in the interval [0, 1]. The synthetic fuzzy decision matrixes were normalized using Equations (7)–(9) and the findings are shown in Table 6. The normalization method is done by dividing each row by a maximum of that row, for example, by dividing the maximum fuzzy number shown in the first row of Table 4 by 10.0; hence, the normalized values shown in Table 5 are obtained by...
dividing the first row of Table 4 by 10.0. The remaining nine rows can be normalized similarly by dividing with the respective row maximum. The normalized fuzzy numbers, thereafter, are applied importance weights, since the importance weights of criteria are unlike. Equations (11) and (12) can be taken for the fuzzy weighted normalized decision matrix, for example, by considering the fuzzy number (0.290, 0.546, 0.8084) of alternative ACI related to sub-criterion C1 documented in Table 7 as $0.290 = 0.580 \times 0.500; 0.546 = 0.700 \times 0.780; 0.8084 = 0.860 \times 0.940$.

| Criteria | ACI          | DOE          | FM           |
|----------|--------------|--------------|--------------|
| C1       | (5.0000, 7.0000, 8.6000) | (7.0000, 9.0000, 10.0000) | (5.0000, 7.0000, 9.0000) |
| C2       | (5.8000, 7.8000, 9.2000) | (7.0000, 9.0000, 10.0000) | (5.0000, 7.0000, 9.0000) |
| C3       | (5.8000, 7.8000, 9.4000) | (5.0000, 7.0000, 9.0000) | (7.0000, 9.0000, 10.0000) |
| C4       | (4.6000, 6.6000, 8.4000) | (5.0000, 7.0000, 9.0000) | (7.0000, 9.0000, 10.0000) |
| C5       | (4.6000, 6.6000, 8.4000) | (7.0000, 9.0000, 10.0000) | (5.0000, 7.0000, 9.0000) |
| C6       | (4.6000, 6.6000, 8.4000) | (5.4000, 7.4000, 9.2000) | (7.0000, 9.0000, 10.0000) |
| C7       | (2.6000, 4.6000, 6.6000) | (5.0000, 7.0000, 9.0000) | (3.0000, 5.0000, 7.0000) |
| C8       | (2.6000, 4.6000, 6.6000) | (5.0000, 7.0000, 8.8000) | (2.6000, 4.6000, 6.4000) |
| C9       | (3.0000, 5.0000, 7.0000) | (5.8000, 7.8000, 9.2000) | (1.8000, 3.8000, 5.8000) |
| C10      | (3.0000, 5.0000, 7.0000) | (5.8000, 7.8000, 9.2000) | (2.6000, 4.6000, 6.4000) |
| C11      | (5.8000, 7.8000, 9.4000) | (6.0000, 8.0000, 9.5000) | (4.8000, 6.8000, 8.8000) |
| C12      | (5.8000, 7.8000, 9.4000) | (5.2000, 7.2000, 9.1000) | (4.4000, 6.4000, 8.4000) |
| C13      | (5.4000, 7.4000, 9.2000) | (4.8000, 7.2000, 8.5000) | (4.8000, 6.8000, 8.8000) |
| C14      | (5.0000, 7.0000, 9.0000) | (5.0000, 6.8000, 8.8000) | (4.8000, 6.8000, 8.4000) |
| C15      | (4.6000, 6.6000, 8.6000) | (4.8000, 7.0000, 8.6000) | (4.2000, 6.2000, 8.2000) |
| C16      | (4.2000, 6.2000, 8.2000) | (4.8000, 6.8000, 8.5000) | (4.8000, 6.8000, 8.8000) |
| C17      | (5.8000, 7.8000, 9.4000) | (5.2000, 7.2000, 9.0000) | (4.2000, 6.2000, 8.2000) |
| C18      | (3.4000, 5.4000, 7.2000) | (5.6000, 7.6000, 9.3000) | (3.0000, 5.0000, 6.9000) |
| C19      | (3.4000, 5.4000, 7.4000) | (6.4000, 8.4000, 9.7000) | (2.2000, 4.2000, 6.2000) |
| C20      | (3.4000, 5.4000, 7.4000) | (5.8000, 7.8000, 9.4000) | (3.6000, 5.6000, 7.3000) |
| C21      | (2.2000, 4.2000, 6.2000) | (6.0000, 8.0000, 9.5000) | (3.6000, 5.6000, 7.5000) |

Table 7. Fuzzy normalized decision matrix of concrete mixture design methods’ alternatives.
4.4. Fuzzy Positive and Fuzzy Negative Ideal Reference Points

As the positive TFNs are in the range \([0, 1]\), the FPIRP and FNIRP are defined as:

\[
A^+ = [(1, 1, 1), (1, 1, 1), (1, 1, 1), (1, 1, 1)]
\]

\[
A^- = [(0, 0, 0), (0, 0, 0), (0, 0, 0), (0, 0, 0)]
\]  

(18)  

(19)

4.5. Distance of Each Preferential Concrete Mix Design Method to FPIRP and FNIRP

Using Equations (15) and (16), the distance of concrete mixture design, ACI, to FPIRP and FNIRP can be determined. The distances to the fuzzy positive ideal reference point and fuzzy negative ideal reference point for the remaining concrete mix design methods can be calculated, which are shown in Table 8.

Table 8. Fuzzy weighted decision matrix of concrete mixture design methods’ alternatives.

| Sub-Criteria | ACI          | DOE          | FM          |
|--------------|--------------|--------------|-------------|
| C1           | (0.290, 0.540, 0.809) | (0.406, 0.702, 0.940) | (0.290, 0.546, 0.846) |
| C2           | (0.081, 0.265, 0.497) | (0.098, 0.306, 0.540) | (0.070, 0.238, 0.486) |
| C3           | (0.290, 0.546, 0.846) | (0.250, 0.490, 0.810) | (0.350, 0.630, 0.900) |
| C4           | (0.230, 0.462, 0.723) | (0.250, 0.490, 0.774) | (0.350, 0.630, 0.860) |
| C5           | (0.055, 0.172, 0.387) | (0.084, 0.234, 0.460) | (0.060, 0.182, 0.414) |
| C6           | (0.065, 0.225, 0.454) | (0.076, 0.252, 0.497) | (0.098, 0.306, 0.540) |
| C7           | (0.064, 0.215, 0.455) | (0.122, 0.327, 0.620) | (0.073, 0.233, 0.482) |
| C8           | (0.207, 0.471, 0.750) | (0.398, 0.716, 1.000) | (0.207, 0.471, 0.727) |
| C9           | (0.189, 0.424, 0.715) | (0.366, 0.661, 0.940) | (0.114, 0.322, 0.593) |
| C10          | (0.137, 0.337, 0.624) | (0.265, 0.526, 0.820) | (0.119, 0.310, 0.571) |
| C11          | (0.281, 0.542, 0.851) | (0.291, 0.556, 0.860) | (0.233, 0.473, 0.797) |
| C12          | (0.284, 0.548, 0.840) | (0.255, 0.506, 0.813) | (0.215, 0.449, 0.751) |
| C13          | (0.071, 0.241, 0.500) | (0.063, 0.235, 0.462) | (0.063, 0.222, 0.457) |
| C14          | (0.367, 0.669, 0.980) | (0.367, 0.650, 0.958) | (0.352, 0.650, 0.915) |
| C15          | (0.353, 0.660, 0.980) | (0.368, 0.700, 0.980) | (0.322, 0.620, 0.934) |
| C16          | (0.306, 0.598, 0.926) | (0.350, 0.656, 0.960) | (0.350, 0.656, 0.960) |
| C17          | (0.161, 0.382, 0.660) | (0.553, 0.766, 0.957) | (0.116, 0.303, 0.576) |
| C18          | (0.088, 0.244, 0.480) | (0.602, 0.817, 1.000) | (0.077, 0.226, 0.460) |
| C19          | (0.175, 0.390, 0.671) | (0.660, 0.866, 1.000) | (0.114, 0.303, 0.563) |
| C20          | (0.080, 0.241, 0.488) | (0.617, 0.830, 1.000) | (0.084, 0.251, 0.482) |
| C21          | (0.125, 0.327, 0.604) | (0.6326, 0.842, 1.000) | (0.205, 0.436, 0.726) |

4.6. Closeness Coefficient (CC) for Selection Order of Concrete Mixture Design Method

When the distances of the concrete mix design method from FPIRP and FNIRP are calculated, Equation (17) can provide the closeness coefficient. CC can be obtained for the concrete mix design methods’ alternatives from the obtained distances of the concrete mix design methods from FPIRP and FNIRP. Table 9 shows the distances of the concrete mix design method from FPIRP and FNIRP, the CC, and selection order of different concrete mix design methods’ alternatives. The potentiality order of various concrete mixture design methods’ alternatives is shown in Figure 6.

Table 9. FPIRP and FNIRP distances, \(cc\), and selection order of every mixture design method.

| Alternatives | \(d^+_i\) | \(d^-_i\) | \(CC_i\) | Selection Order |
|--------------|-----------|-----------|----------|----------------|
| ACI          | 12.9556   | 9.8633    | 0.4322   | 2              |
| DOE          | 11.5633   | 11.4510   | 0.4975   | 1              |
| FM           | 13.0164   | 9.7581    | 0.4285   | 3              |
The sub-criteria (concrete mixture factors) found to be least influential for quality concrete mixture are considered. The dominant concrete mixture factors for concrete considering socioeconomic and environmental aspects, namely workability, strength, and durability) for alternative (mixture design methods) methods provide better sustainable performance. It is evident that the CC value is governed by the criteria weight provided by decision-makers and the performance established by each mixture design method.

Those that have the shortest distance from FPIRP and the farthest from FNIRP are the best options or decisions. Optimally, the closeness coefficient (CC) of mixture design methods close to 1 has the shortest distance from the FPIRP and the highest distance from FNIRP. In other words, a large closeness coefficient attained for any mixing design method provides better sustainable performance. It is evident that the CC value is governed by the criteria weight provided by decision-makers and the performance established by each mixture design method against the respective criteria.

After observing the importance weight ranking of the sub-criteria with respect to criteria (objective properties, namely workability, strength, and durability) for alternative (mixture design methods) selection for quality management, it is revealed that among sub-criteria (concrete mixture factors), the water and cement (w/c) ratio of the concrete mix ingredients is the most influential factor in the concrete mix design procedure suitable for sustainable quality concrete development. The proposed model outputs are also consistent with the results of Neville [1] and Yurdakul [31] related to sustainable concrete quality. Another more dominant concrete mixture factor for sustainable concrete quality is density. This seems consistent as sustainable concrete quality will depend on the density of concrete. The sub-criteria (concrete mixture factors) found to be least influential for quality concrete mixture includes the fine aggregate/cement ratio and the fine aggregate/total aggregate ratio. This seems acceptable as fine aggregate has no known relationship with the cement content and total aggregate content. The Department of Energy (DOE) method has a maximum value of CC (0.4975), so this method has the potential to design a concrete mixture for sustainable high-quality concrete. Other methods have similar CC value (0.4322 and 0.4285) and have equal potential for the design of a sustainable quality concrete mixture. The results of the MCDM model suggested above are also consistent with Helmy’s [32] conclusion that the DOE mixture design method produced a mix with the lowest cement content and gave the most environmentally effective method among all the concrete mixtures found from the other mix design methods (ACI method and others).

![Figure 6. Potentiality order of mixture design methods for obtaining sustainable quality concrete based on the closeness coefficient.](chart.png)
6. Conclusions

Using triangular fuzzy numbers to transform linguistic variables, a decision support model was formulated to choose the concrete mixture design approach with the most potential to suggest concrete with sustainable performance. A new approach based on TOPSIS methodology was correctly applied to a fuzzy setting to determine the overall performance and potentiality order of the concrete mix factors and concrete mixture design methods, qualitatively qualifying to sustainable quality management. It employed the MCDM technique to synthesize the potentiality order of concrete mix design methods in linguistic terms based on expert opinions and the published literature. The concrete mix factors found to be most influential to produce sustainable concrete quality included water/cement ratio and density. The concrete mixture with optimum water/cement ratio and high density or, in other words, good durability concrete, satisfies technical, environmental, and socioeconomic indicators. The concrete mix factors found to be least influential for sustainable concrete quality production were fine aggregate/cement ratio and fine aggregate/total aggregate ratio. The outcomes of the proposed MCDM model of fuzzy TOPSIS are consistent with the published literature and theory. The DOE method was found to be more suitable in sustainable concrete quality management considering its applicable objective quality properties and concrete mix factors. Therefore, it is recommended that the guidelines of the DOE method for the design of a concrete mixture along with the most dominant concrete mix factors should be adapted to produce sustainable concrete. The present study would be of great benefit to the concrete manufacturing industry and to tackle issues such as increased manufacturing costs, higher concrete performance standards, and risk-free environment and community. In addition, the proposed selection support framework, for choice of prime factors involved and concrete design methodology from a sustainability point of view, may be utilized in updating the concrete design methods and in deciding the concrete mixture design process with the most potential that can provide sustainable quality management in concrete production as well as in concrete construction.

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Appendix A

QUESTIONNAIRE FOR FUZZY TOPSIS

Degree of importance for criterion to sub-criteria with respect to the overall goal of “Development of concrete mixture design process for sustainable concrete quality”

Q1. What degree of importance do you assign for criterion (workability) to sub-criteria w/c ratio (C1)?
Q2. What degree of importance do you assign for criterion (workability) to sub-criteria Density (C2)?
Q3. What degree of importance do you assign for criterion (workability) to sub-criteria CA/c ratio (C3)?
Q4. What degree of importance do you assign for criterion (workability) to sub-criteria T/c ratio (C4)?
Q5. What degree of importance do you assign for criterion (workability) to sub-criteria FA/c (C5)?
Q6. What degree of importance do you assign for criterion (workability) to sub-criteria FA/T (C6)?
Q7. What degree of importance do you assign for criterion (workability) to sub-criteria Cost (C7)?
With Respect to: The Sub-Criteria Criteria for Sustainable Concrete Quality

| Questions | Sub-criteria Criteria | Importance (or Preference) of Each Criterion (Workability etc.) |
|-----------|-----------------------|---------------------------------------------------------------|
|           | (0, 0.1, 0.3)         | (0.1, 0.3, 0.5)                                               |
| Q1        | w/c                   | (0.3, 0.5, 0.7)                                               |
| Q2        | Density               | (0.5, 0.7, 0.9)                                               |
| Q3        | CA/c                  | (0.7, 0.9, 1)                                                 |
| Q4        | T/c                   |                                                             |
| Q5        | FA/c                  |                                                             |
| Q6        | FA/T                  |                                                             |
| Q7        | Cost                  |                                                             |

Appendix B

QUESTIONNAIRE FOR FUZZY TOPSIS

Scoring of alternatives performance with respect to criteria for overall goal of “Development of concrete mixture design process for sustainable concrete quality”

Q11. What scores do you assign to alternatives (ACI/DOE/FM) with reference to criteria w/c ratio (C1)?
Q12. What scores do you assign to alternatives (ACI/DOE/FM) with reference to criteria Density (C2)?
Q13. What scores do you assign to alternatives (ACI/DOE/FM) with reference to criteria CA/c ratio (C3)?
Q14. What scores do you assign to alternatives (ACI/DOE/FM) with reference to criteria T/c ratio (C4)?
Q15. What scores do you assign to alternatives (ACI/DOE/FM) with reference to criteria FA/c (C5)?
Q16. What scores do you assign to alternatives (ACI/DOE/FM) with reference to FA/T (C6)?
Q17. What scores do you assign to alternatives (ACI/DOE/FM) with reference to Cost (C7)?

With Respect to the Potential Mixture Design Methods (ACI) for Sustainable Concrete Quality

| Questions | Sub-Criteria | mixture design methods | Performance of Each Mixture Design Method (ACI) Alternative with Respect to Each Sub-Criterion |
|-----------|--------------|------------------------|---------------------------------------------------------------------------------------------|
|           |              | (0, 1, 3)              | (1, 3, 5)                                                                                   |
| Q11       | w/c          | ACI                    | Very Poor                                                                                  |
| Q12       | Density      | ACI                    | Poor                                                                                       |
| Q13       | CA/c         | ACI                    | Fair                                                                                       |
| Q14       | T/c          | ACI                    | Good                                                                                       |
| Q15       | FA/c         | ACI                    | Very Good                                                                                  |
| Q16       | FA/T         | ACI                    |                                                                                             |
| Q17       | Cost         | ACI                    |                                                                                             |

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