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Siliceous Concrete Materials Management for Sustainability Using Fuzzy-TOPSIS Approach

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Abstract: Concrete manufacturing, a high energy and natural resources demanding process, can play a vital role in sustainable development by offering solutions to environmental and socio-economic issues. Concrete manufactured with siliceous materials can extend concrete life and reduce costs, and judicious management of siliceous utilization can make concrete manufacturing sustainable. A number of industrial and agro-based by-products, waste products, and new engineered materials are being use as siliceous material in concrete. The present research aims to implement the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach, a Multi-Criteria Decision Making (MCDM) technique, for the orderly management of siliceous materials based on sustainable criteria, namely, technical, environmental, social, and economic aspects. The present research adopts twenty indicators of sustainability to evolve a comprehensive model for a sustainability ranking of concrete siliceous materials and to provide siliceous materials management. The present research also provides a methodology for the systematic ranking of sustainable criteria and indicators along with a siliceous materials sustainability order for enhanced sustainable development and management. It can be concluded that the proper material management of siliceous concrete materials, especially nano-engineered materials in construction industry, will help in the conservation of basic concrete materials and environmental protection without direct impact on social development.

Keywords: concrete manufacturing; Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (fuzzy TOPSIS); multi criteria decision making; siliceous materials; management; sustainability

1. Introduction

Concrete is basically manufactured by mixing aggregates with cementitious material. However, a number of construction materials, called admixtures, are added to improve or modify the concrete properties. The selection of such construction materials to provide an all-round performance of concrete is a complex process. Material selection is an important problem attracting theoretical and practical interest [1]. In the construction industry sector, the focus is increasingly on energy efficiency and smart buildings with sustainability in infrastructure design and construction. Subsequently, appropriate materials must also be selected. Zavadskas et al. [2] has pointed out that construction material selection is a significant issue in the construction sector as the materials account for a considerable portion of a structure's total cost. The unmanaged usage of material will not only affect the economy of concrete construction but also badly affect the environment and social development i.e., sustainable development. One of the solutions to reduce the use of basic concrete material and to make concrete economic, durable, and eco-friendly by adding siliceous materials. A number of siliceous materials, found as natural, industry/agro-based by-products, or other engineered materials, can be added as admixtures in concrete. A decade long comprehensive research review has been given by Stojcic et al. [3] for the application of decision-making approaches in sustainability engineering covering the topics from the selection of right stack holders, best process practices, and optimum materials to best options for management.

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Rashid et al. [4] used AHP and TOPSIS methods for the orderly management of building demolished materials such as ceramic waste aggregate and siliceous materials, to get the best performing sustainable concrete. An efficient assessment system using an MCDM-based distance approach (Entropy-TOPSIS) which considers the material energy efficiency aspect for sustainability is due to Bhowmik et al. [5]. Stevic et al. [6] evaluate the potential location of roundabout construction for traffic infrastructure using Rough BWM (Best Worst Method) and Rough WASPAS (Weighted Aggregated Sum Product Assessment) models. The proposed model can capture the interrelationships among multi-input arguments and can provide decision makers more options. Mathiyazhagan et al. [7] frame an assessment model for evaluating and selecting sustainable building materials using a three-phase methodology i.e., triple bottom line (TBL)–best worst methodology (BWM)–Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Khoshnava et al. [8] implemented MCDM techniques to select energy-efficient, environmentally friendly, recyclable construction materials with regard to the technical, social, and environment aspects of sustainability. The model of selection based on environmental, social and economic impact was developed by Abeysundara et al. [9] for sustainable building materials and they found that environmental criteria should be given priority over social and economic criteria for sustainable building construction. Govindan et al. [10] has proposed and validated, via case study and respondent feedback, an integrated multi-criteria decision-making approach to sustainable choices of building materials. Bakhoum and Brown apply an embedded AHP–TOPSIS–entropy approach [11] to the ranking of sustainable structural material. Analytical Hierarch Process (AHP) and Choosing By Advantages (CBA) approaches have been used by Arroyo et al. to compare and select building material based on sustainable criteria [12]. The sustainability criteria related to environment, economic and social performance for residential buildings have been prioritized by Rahman et al. [13] using a Fuzzy Analytic Hierarchical Process. Ahmed et al. [14] applied a combined approach for the selection of siliceous materials satisfying sustainability issues. Erdogan et al. [15] used the Analytic Hierarchy Process (AHP) method and Expert Choice coding to select the best sustainable building management alternative. Akadiri [16] has examined the factors that hinder the selection of sustainable building materials by construction industry stockholders and identified that the perception of extra cost and the lack of information on the materials are the main obstacles for sustainable materials selection. Vinodh et al. [17] has carried out a case study on sustainable concept selection and pointed out that TOPSIS is the suitable MCDM technique for sustainable concept selection. The Fuzzy Extended Analytical Hierarchy Process (FEAHP) based sustainable material selection model is proposed by Akadiri et al. [18]. Dursun and Arslan [19] proposed an integrated decision framework for material selection procedure considering quality function deployment (QFD), 2-tuple fuzzy linguistic representation, and linguistic hierarchies. Zhang et al. [20] proposed a hybrid MCDM method combining decision making and evaluation laboratory (DEMATEL), analytical network process (ANP), grey relational analysis (GRA), and TOPSIS to the strategy selection of material for promoting sustainability development.

Based on the above literature review, it is found that the applications of MCDM for the selection of sustainable construction materials, especially siliceous concrete materials, for construction industry are exceedingly scarce. The management of a vast number of siliceous concrete materials with a sustainable concept should be based on clearly defined sustainable indicators related to technical, environmental, and socio-economic issues. Therefore, the present research objective is to implement the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach, a Multi-Criteria Decision Making (MCDM) technique, for orderly management of siliceous materials based on sustainable criteria, namely, technical, environmental, social and economic aspects and to promote sustainable development.

2. Materials and Methods

2.1. Selection of Sustainability Evaluation Indicators

The sustainability indicators satisfying technical, environmental, and socio-economic criteria are framed to evaluate the sustainable management of siliceous concrete manufacturing material. Sustainability can be enhanced by considering indicators based on environmental, social, and economic aspects. In the present research, wide spectrums of indicators have been employed. In the ranking of siliceous concrete materials, the current model adopts eight, six, and three each of technical, environmental, social, and economic situations indices, respectively. The selected technical sustainability indices for concrete siliceous material includes siliceous material availability, relative proportion of concrete components, consistency of concrete mix, concrete compaction system, cohesiveness of concrete mix, concrete curing system, comply strength requirement of concrete mix, and comply durability requirements of concrete mix. The sustainability indicators for the selection of concrete siliceous material to attain environmental objectives include waste material utilization, concrete material conservation, reduction in carbon footprint, resistance to extreme exposure conditions, and energy conservation conformation to environmental standards. The sustainability indicators for concrete siliceous material to meet socio-economic objectives are considered as public welfare and safety, waste material cleaning, increased employment, life-long maintenance cost, concrete production cost, and siliceous material transportation cost. The Siliceous Concrete Materials Management for Sustainability approach is considered as a way for the concrete construction industry to move towards achieving sustainable development taking into account technical, environmental, socio and economic issues, as shown in Table 1. Sustainable materials management is also a way to portray the construction industry's responsibility towards protecting the environment [21–24]. The practice of sustainable Siliceous Concrete Materials management refers to a process to develop construction industry that causes less harm to the environment—i.e., reducing the natural resources using basic construction materials and waste material management, reducing the environmental burdens of basic construction materials, reducing energy consumption in construction activities, reducing the burden on non-renewable construction materials; increasing durability against extreme exposure conditions; the use of standard recycled/sustainability sourced products, beneficial to the society, and profitable to the conduction industries. Material construction practitioners around the world are beginning to appreciate sustainability and recognize the benefits of implementing sustainable principles in concrete construction. The idea of sustainable materials, for instance, costs less than conventional materials and saves energy. Sustainable concrete material will make a positive contribution to improving quality of life, work efficiency and a good working atmosphere.

2.2. Fuzzy TOPSIS Methodology

Zadeh [25] implemented the concept of fuzzy sets theory to express the linguistic terms used in decision-making to alleviate the difficulty of operational management. Hwang and Yoon [26] first suggested the TOPSIS method, a linear weighting technique. The weights can be assigned to the criteria using various methods such as mean weight (MW), entropy analysis, eigenvector method, standard deviation (SD), analytical network process (ANP), and analytical hierarchy process (AHP). The proposed MCDM based Fuzzy TOPSIS approach is implemented to the problem of ranking the sustainable concrete siliceous material. Based on an in-depth literature review, eleven of the most common siliceous concrete materials were identified. It includes Nano-Cement, Nano-Particles of Siliceous Material, Natural Pozzolana, Metakaolin, Silica Fume, Fly Ash, Rice Husk Ash, Lime Stone, Blast Furnace Slag, Recycled Aggregate, and Waste Glass. Figure 1 illustrates the fuzzy-TOPSIS based framework for the ranking of sustainable siliceous concrete materials management.

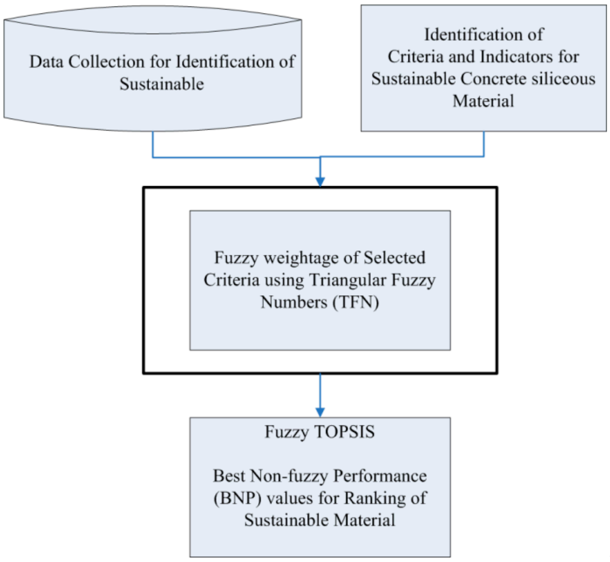

Figure 1. Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (fuzzy-TOPSIS) based framework for ranking of sustainable siliceous concrete material management.

Table 1. Sustainable criteria along with sustainability indicators (sub-criteria) for selection of siliceous concrete materials and their principal issues.

Title	Sustainability Criteria	Principal Issues
technical sustainability	• siliceous material availability • relative proportion of concrete components • consistency of concrete mix • concrete compaction system • Cohesiveness of concrete mix • Concrete curing system • Comply strength requirement of concrete mix • Comply durability requirements of concrete mix	properly managed construction materials utilization; protection of sensitive ecosystems through good construction practices and supervision; technically proven high preformation construction materials; low water consumption during production.
Environmental sustainability	• Waste material utilization • Concrete material conservation • Reduction in carbon foot print • Resistance to extreme exposure conditions • Energy conservation • Conformation to environmental standards	Reduction of natural resources using basic construction materials and waste material management; reduction of the environmental burdens of basic construction materials; reduction of energy consumption in construction activities; reduction of the burdens on non-renewable construction materials; increased durability against extreme exposure conditions; use of standard recycled/sustainability sourced products.
Social sustainability	• Public welfare and safety • Waste material cleaning • Increased employment	Health, safety and conducive working environment; minimizing local nuisance and disruption; contributing to the local economy through local employment and procurement; building long-term relationships with local suppliers; minimizing strain on land resources and improving of overall quality of life.
Economic sustainability	• Life-long maintenance cost • Concrete production cost • Siliceous material transportation cost	Improved productivity; employee economic satisfaction; lower cost projects with increased cost predictability; delivering services that provide best value to clients; supplier satisfaction; client satisfaction with minimum defects; low cost maintenance; low cost product through minimum transportation cost; optimized life-cycle economic performance.

The experts with commendable experience in concrete technology were asked to judge and rank the selected sustainable criteria and sustainable indicators. A questionnaire (Sample Questionnaire-1, Appendix A) based on linguistics terms and triangular fuzzy number (TFN) was offered for establishing the importance of the criteria and role of siliceous concrete material towards sustainability. Questionnaire-1 used five linguistic terms [27], namely, Very Low, Low, Medium, High, and Very High, along with corresponding triangular fuzzy numbers (TFN) of (0,0.1,0.3), (0.1,0.3,0.5), (0.3,0.5,0.7), (0.5,0.7,0.9), and (0.7,0.9,1), respectively, reflecting the importance weights of each performance criteria in providing sustainability in siliceous concrete material. Later, on Questionnaire-2 (Appendix B) was administered which used five linguistic terms [28], namely, Very Poor, Poor, Fair, Good and Very Good, along with corresponding triangular fuzzy numbers (TFN) of (0,1,3), (1,3,5), (3,5,7), (5,7,9), and (7,9,10) to ascertain the role of each concrete siliceous material to provide the much needed sustainability on the selected set of twenty criteria. The overall performance of each concrete siliceous material was documented. In order to find the preferential sustainable concrete siliceous material, the selected criteria were further utilized to rate the performance of each preferential concrete siliceous material using Zeleny's [29] opinion. According to Hwang and Yoon [26], in comparison with others, the selected option should have the optimal distance (most close to positive and farthest from adverse) i.e., alternatives should not only be the shortest distance from the positive ideal reference point (PIRP) but also the longest distance from the negative ideal reference point (NIRP). The algorithm used in this method is described in the following section.

2.2.1. Construction of the Fuzzy Decision Matrix for Sustainability Problem

Given m alternatives for sustainable concrete siliceous material, n selection criteria, and k expert group of professionals, a typical fuzzy decision matrix for sustainability problem can be expressed as below:

$$\widetilde{D}= \begin{array}{cc} & \mathrm{SC}^1\mathrm{SC}^2\ldots\ldots\mathrm{SC}^\mathrm{n} \\ \begin{array}{c} A_1 \\ A_2 \\ \vdots \\ A_3 \end{array} & \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \end{array}, \ \mathrm{i} = 1,\ 2, \ldots\ldots, \ \mathrm{m};\ \mathrm{j} = 1,\ 2,\ \ldots\ldots, \mathrm{n} \tag{1}$$

where A_1, A_2, ... , A_n are the alternatives materials to be chosen, SC_1, SC_2, ... , SC_n denote the sustainability evaluation criteria for concrete siliceous material, $\widetilde{D}_{ij}$ represents the rating of alternative materials A_i with respect to sustainability criterion SC_j evaluated by k experts. Since the perception toward ranking the sustainable concrete siliceous material is subject to an individual's experience, intuition, or knowledge, this study, therefore, uses the technique of average value to integrate the fuzzy performance score $\widetilde{x}_{ij}$ for k experts concerning the same evaluation criteria, that is

$$\widetilde{x}_{ij} = \frac{1}{k}\left(\widetilde{x}_{ij}^1 + \widetilde{x}_{ij}^2 + \ldots + \widetilde{x}_{ij}^k\right) \tag{2}$$

where $\widetilde{x}_{ij}^k$ is the rating of alternative Ai with respect to criterion SCj evaluated by the k expert and

$$\widetilde{x}_{ij}^k = \left(a_{ij}^k,\ b_{ij}^k,\ c_{ij}^k\right). \tag{3}$$

2.2.2. Normalization of the Fuzzy Decision Matrix for Sustainability Problem

The various criteria required to select the sustainable concrete siliceous material are measured in different units and therefore need to be normalized. The current study adopts linear scales to transform the normalization function for preserving the property of the ranges of normalized TFN to be included in [0, 1]. If $\widetilde{R}$ denotes the normalized fuzzy decision matrix, then

$$\widetilde{R}= \left[\widetilde{r}_{ij}\right]_{mxn},\ I = 1,\ 2, \ldots\ldots, m;\ j = 1,\ 2,\ \ldots\ldots, n \tag{4}$$

where $\widetilde{r}_{ij} = \left(\frac{a_{ij}}{sc_j^+}, \frac{b_{ij}}{sc_j^+}, \frac{c_{ij}}{sc_j^+}\right)$

$$SC_j^+ = \max_i SC_{ij} \tag{5}$$

2.2.3. Construction of Weighted Normalized Fuzzy Decision Matrix for Sustainability Problem

Considering the different weight of each sustainability criterion, the weighted normalized decision matrix can be computed by multiplying the importance weights of the evaluation criteria and the values in the normalized fuzzy decision matrix. The weighted normalized decision matrix $\widetilde{v}$ is defined as

$$\widetilde{v} = \left[\widetilde{v}_{ij}\right]_{mxn}, \; i = 1, \; 2, \ldots\ldots, m; \; j = 1, \; 2, \; \ldots\ldots, n \tag{6}$$

$$\widetilde{v}_{ij} = r_{ij} \otimes \widetilde{w}_j \tag{7}$$

where $\widetilde{w}_j$ represents the importance weight of criterion C_j obtained through

$$\widetilde{w}_j = \frac{1}{K}\left(\widetilde{w}_j^1 + \widetilde{w}_j^2 + \ldots + \widetilde{w}_j^k\right) \tag{8}$$

where k is the number of expert members in a group and $\widetilde{w}_j^k$ represents the fuzzy weight of j criteria assessed by kth expert"

2.2.4. Determination of the FPIRP and FNIRP

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

$$A^+ = \left(\widetilde{v}_1^+, \; \widetilde{v}_2^+, \ldots \widetilde{v}_n^+\right) \tag{9}$$

$$A^- = \left(\widetilde{v}_1^-, \; \widetilde{v}_2^-, \ldots \widetilde{v}_n^-\right) \tag{10}$$

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

2.2.5. Calculation for the Distances of Each Concrete Siliceous Material to FPIRP and FNIRP

The distance of each concrete siliceous material alternate from the fuzzy positive ideal reference point (FPIRP) and the fuzzy negative ideal reference point (FNIRP) can be derived respectively as

$$d_i^+ = \sum\nolimits_{j=1}^{n} d\left(\widetilde{v}_{ij}, \; \widetilde{v}_j^+\right), \; \mathrm{i} = 1, \; 2, \ldots\ldots, \mathrm{n}; \; \mathrm{j} = 1, \; 2, \; \ldots\ldots, \mathrm{n} \tag{11}$$

$$d_i^- = \sum\nolimits_{j=1}^{m} d\left(\widetilde{v}_{ij}, \; \widetilde{v}_j^-\right), \; \mathrm{i} = 1, \; 2, \ldots\ldots, \mathrm{m}; \; \mathrm{j} = 1, \; 2, \; \ldots\ldots, \mathrm{n} \tag{12}$$

where, $d\left(\widetilde{v}_{ij}, \; \widetilde{v}_j\right)$, denotes the distance measurement between two fuzzy numbers, d_i^+ represents the distance of alternative L_i from FPIRP, and d_i^- is the distance of alternative L_i from FNIRP.

2.2.6. Process to Obtain the Closeness Coefficient and Rank the Order of Alternatives

Once the closeness coefficient (*CC*) is determined, the ranking order of all alternatives can be obtained, allowing the decision-makers to select the most feasible alternative. The closeness coefficient of each alternative is calculated as

$$cc_i = \frac{d_i^-}{d_i^+ + D_i^-} \; \mathrm{i} = 1, 2, 3, \; \ldots\ldots \mathrm{m} \tag{13}$$

An option with index cc_i approaching 1 shows that the option is near to the fuzzy positive ideal reference point and far from the fuzzy negative ideal reference point. A large proximity index value indicates a good performance of the option *Ai*.

2.2.7. Assessment of Sustainable Concrete Siliceous Material

The ranking of concrete siliceous materials with sustainability objectives is a multi-criteria decision-making process. After the initial problem formulation, expert advice and opinion may be sought to determine the sustainable assessment criteria and indicators. Experts may employ their vast experience and expertise while ranking concrete siliceous material according to their merits in sustainability. The use of linguistic terms and corresponding TFN will help to make their decision in fuzzy based assessment. The fuzzy TOPSIS methodology was employed. The five experts were asked to judge the role of the criteria in providing sustainability. They were also asked to judge the role of each concrete siliceous material in providing sustainability. The detailed methodology adopted in ranking the concrete siliceous material, as per the closeness to sustainability goals, is documented in the following section.

3. Results

3.1. Calculation of the Synthetic Importance Weights of Evaluation Criteria

The expert group expressed their opinion in linguistics terms for their preference of sustainability evaluation indicators [27], namely Very Low, Low, Medium, High, and Very High, corresponding to its TFN. An integrated fuzzy importance weight matrix for evaluation criteria was generated using the method of average value described in Equation (7). To understand the importance order of these selection criteria, the center of area (COA) method [30] was utilized to de-fuzzify TFN into corresponding best non-fuzzy performance (BNP) values. The twenty most important sustainable indicators for assessing concrete siliceous materials for sustainability with corresponding BNP values are presented in Table 2 as SC_1 (0.66), SC_2 (0.72), SC_3 (0.70), SC_4 (0.7267), SC_5 (0.76), SC_6 (0.72), SC_7 (0.6867), SC_8 (0.42), SC_9 (0.7667), SC_{10} (0.8667), SC_{11} (0.80), SC_{12} (0.7667), SC_{13} (0.7333), SC_{14} (0.7667), SC_{15} (0.4133), SC_{16} (0.3933), SC_{17} (0.38), SC_{18} (0.4267), SC_{19} (0.40), and SC_{20} (0.46). The maximum BNP value was obtained for the sustainable indicator of "concrete material conservation (SC_{10})", while the minimum BNP value was obtained for the sustainable indicator of "increased employment (SC_{17})".

3.1.1. Construction of the Fuzzy Decision Matrix

The ranking of concrete siliceous materials is an important issue for sustainable concrete objectives. In order to accomplish sustainability goals, a systematic performance analysis of various sustainability criteria and their indicators was carried out. The experts gave their feedback in linguistic terms. The experts used the linguistic terms Very Poor, Poor, Fair, Good and Very Good along with TFN, as depicted in Appendix A, to express their opinions for each concrete siliceous material based on their individual capability against each sustainability evaluation indicator. The fuzzy performance ratings of each concrete siliceous material regarding evaluation indicators were averaged to synthesize the various individual judgments. With Equation (1), the synthetic fuzzy decision matrix can be computed, as shown in Table 3. Fuzzy weights were obtained after normalizing the BNP values.

Table 2. Fuzzy importance weight, best non-fuzzy performance (BNP), and rank of each indicator.

Indicator	Description of the Indicator	Fuzzy Importance Weight	BNP Values	Rank
SC_1	Concrete curing system	(0.460,0.660,0.860)	0.6600	13
SC_2	Concrete compaction system	(0.540,0.740,0.880)	0.7200	9
SC_3	Cohesiveness of concrete mix	(0.500,0.700,0.900)	0.7000	11
SC_4	Consistency of concrete mix	(0.540,0.740,0.900)	0.7267	8
SC_5	Comply strength requirement of concrete mix	(0.580,0.780,0.920)	0.7600	6
SC_6	Comply durability requirements of concrete mix	(0.5400.740,0.880)	0.7200	9
SC_7	Relative proportion of concrete components	(0.500,0.700,0.860)	0.6867	12
SC_8	Siliceous material availability	(0.220,0.420,0.620)	0.4200	16
SC_9	Energy conservation	(0.580,0.780,0.940)	0.7667	3
SC_{10}	Concrete material conservation	(0.700,0.900,1.000)	0.8667	1
SC_{11}	Waste material utilization	(0.620,0.820,0.960)	0.8000	2
SC_{12}	Conformation to environmental standards	(0.580,0.780,0.940)	0.7667	5
SC_{13}	Reduction in carbon foot print	(0.540,0.740,0.920)	0.7333	7
SC_{14}	Resistance to extreme exposure conditions	(0.580,0.780,0.940)	0.7667	3
SC_{15}	Waste material cleaning	(0.220,0.420,0.600)	0.4133	17
SC_{16}	Public welfare and safety	(0.240,0.380,0.560)	0.3933	19
SC_{17}	Increased employment	(0.220,0.420,0.500)	0.3800	20
SC_{18}	Concrete production cost	(0.240,0.420,0.6200	0.4267	15
SC_{19}	Siliceous material transportation cost	(0.240,0.400,0.560)	0.4000	18
SC_{20}	Lifelong maintenance cost	(0.260,0.460,0.660)	0.4600	14

3.1.2. Calculation of Normalized Fuzzy Decision Matrix and Weighted Normalized Matrix

To ensure that the normalized triangular fuzzy numbers are included in the interval [0, 1], the linear scale transforms function is used. The synthetic fuzzy decision matrices were normalized using the Equations (2)–(4), and the results are shown in Table 4. Normalization process was carried out by dividing each row by the maximum of that row. The normalized values are shown in the table. The normalized fuzzy numbers were later applied on importance weights and since the importance weights of criteria are different, Equations (6) and (7) was employed for the fuzzy weighted normalized decision matrix, results are shown in Table 5.

3.1.3. Determination of the Fuzzy Positive and Fuzzy Negative Ideal Reference Points

As the positive TFN are in the range of [0, 1], so the fuzzy positive ideal reference point and fuzzy negative ideal reference point can be defined as

$$\mathrm{A}^{+}= [(1,1,1),\ (1,1,1),\ (1,1,1),\ (1,1,1),\ (1,1,1)] \tag{14}$$

$$\mathrm{A}^{-}= [(0,0,0),\ (0,0,0),\ (0,0,0),\ (0,0,0),\ (0,0,0)] \tag{15}$$

3.1.4. Calculation for the Distance of Each Concrete Siliceous Material to FPIRP and FNIRP and Determining the Closeness Coefficient (CC) for Ranking of Concrete Siliceous Material

The distance of each concrete siliceous material to the FPIRP and FNIRP can be calculated using Equations (10) and (11). Once the distances of concrete siliceous material from FPIRP and FNIRP are determined, the closeness coefficient for the concrete siliceous material alternatives can be obtained with Equation (12). Closeness coefficients are calculated based on the obtained FPIRP and FNIRP. The distances of concrete siliceous material from FPIRP and FNIRP, the closeness coefficient and ranking of various concrete siliceous materials are shown in Table 6. Figure 2 depicts the graphical representation of concrete siliceous materials ranking as per the obtained Closeness Coefficients.

Table 3. The fuzzy decision matrix of sustainable siliceous materials alternatives.

Criteria	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
SC_1	(3.400,5.400,7.400	(0.600,2.200,4.200)	(0.800,2.600,4.600)	2.600,4.600,6.600)	(0.800,2.600,4.600)	(0.200,1.400,3.400)	(3.800,5.800,7.800)	(2.200,4.200,6.200)	(1.200,2.600,4.600)	(0.200,1.400,3.400)	(0.200,1.400,3.400)
SC_2	(1.000,3.000,5.000	(2.600,4.600,6.600)	(0.600,2.200,4.200)	2.200,4.200,6.200)	(1.000,3.000,5.000)	(0.400,1.800,3.800)	(2.600,4.600,6.600)	(2.800,4.600,6.600)	(0.400,1.800,3.800)	(0.400,1.800,3.800)	(0.400,1.800,3.800)
SC_3	(1.400,3.400,5.400)	(2.200,4.200,6.200)	(2.600,4.600,6.600)	3.000,5.000,7.000)	(0.800,2.600,4.600)	(2.600,4.600,6.600)	(3.000,5.000,7.000)	(2.600,4.600,6.600)	(2.400,4.200,6.200)	(3.000,5.000,7.000)	(3.000,5.000,7.000)
SC_4	(1.000,3.000,5.000)	(4.600,6.600,8.600)	(2.200,4.200,6.200)	1.000,3.000,5.000)	(1.400,3.400,5.400)	(2.600,4.600,6.600)	(6.200,8.200,9.600)	(3.000,5.000,7.000)	(1.800,3.800,5.800)	(2.600,4.600,6.600)	(2.600,4.600,6.600)
SC_5	(1.000,3.000,5.000)	(0.800,2.400,4.000)	(4.600,6.600,8.600)	3.800,5.800,7.800)	(0.600,1.800,3.800)	(0.200,1.400,3.400)	(3.800,5.800,7.800)	(4.600,6.600,8.600)	(0.200,1.400,3.400)	(0.200,1.400,3.400)	(0.200,1.400,3.400)
SC_6	0.200,1.200,3.400)	(0.600,2.200,4.200)	(0.800,2.400,4.600)	2.400,4.000,5.600)	(0.000,0.800,2.400)	(0.200,1.200,3.800)	(2.400,4.000,5.600)	(1.600,3.200,5.400)	(0.200,1.200,2.800)	(0.200,1.200,2.800)	(0.200,1.200,2.800)
SC_7	(0.200,1.400,3.400)	(2.600,4.600,6.600)	(0.600,2.200,4.200)	3.000,5.000,7.000)	(0.000,1.000,3.000)	(2.600,4.600,6.600)	(3.000,5.000,7.000)	(0.600,2.200,4.200)	(1.000,2.600,4.600)	(2.600,4.600,6.600)	(2.600,4.600,6.600)
SC_8	(0.200,1.400,3.400)	(2.200,4.200,6.200)	(2.600,4.600,6.600)	1.800,3.800,5.800)	(0.000,1.000,3.000)	(2.600,4.600,6.600)	(6.200,8.200,9.600)	(3.400,5.400,7.400)	(1.600,3.400,5.400)	(2.600,4.600,6.600)	(2.600,4.600,6.600)
SC_9	(0.000,1.000,3.000)	(4.000,5.800,7.800)	(2.200,4.200,6.200)	1.800,3.800,5.800)	(0.000,1.000,3.000)	(0.200,1.400,3.400)	(3.800,5.800,7.800)	(2.600,4.600,6.600)	(0.000,1.000,3.000)	(0.200,1.400,3.400)	(0.200,1.400,3.400)
SC_{10}	(0.200,1.400,3.400)	(4.000,5.800,7.800)	(4.000,5.800,7.800)	2.600,4.600,6.600)	(1.000,3.000,5.000)	(0.400,1.800,3.800)	(2.600,4.600,6.600)	(4.000,5.800,7.800)	(0.200,1.400,3.400)	(0.400,1.800,3.800)	(0.400,1.800,3.800)
SC_{11}	(0.000,1.000,3.000)	(0.800,2.600,4.600)	(0.800,2.600,4.600)	1.400,3.400,5.400)	(1.000,3.000,5.000)	(2.600,4.600,6.600)	(3.000,5.000,7.000)	(2.000,3.800,5.800)	(1.000,2.600,4.600)	(2.600,4.600,6.600)	(2.600,4.600,6.600)
SC_{12}	(0.400,1.800,3.800)	(2.600,4.600,6.600)	(0.800,2.600,4.600)	1.800,3.800,5.800)	(1.000,3.000,5.000)	(2.600,4.600,6.600)	(6.200,8.200,9.600)	(0.400,1.800,3.800)	(1.200,3.000,5.000)	(2.600,4.600,6.600)	(2.600,4.600,6.600)
SC_{13}	(1.000,3.000,5.000)	(2.600,4.600,6.600)	(2.600,4.600,6.600)	1.800,3.800,5.800)	(1.200,3.000,5.000)	(4.600,6.600,8.600)	(6.600,8.600,9.800)	(2.600,4.600,6.600)	(4.200,6.200,8.200)	(4.600,6.600,8.600)	(4.600,6.600,8.600)
SC_{14}	(1.000,3.000,5.000)	(4.200,6.200,8.200)	(2.600,4.600,6.600)	1.800,3.800,5.800)	(1.000,3.000,5.000)	(1.400,3.400,5.400)	(3.400,5.400,7.400)	(4.200,6.200,8.200)	(1.000,3.000,5.000)	(1.400,3.400,5.400)	(1.400,3.400,5.400)
SC_{15}	(1.800,3.800,5.800)	(2.600,4.600,6.600)	(4.200,6.200,8.200)	1.800,3.800,5.800)	(1.000,3.000,5.000)	(0.800,2.600,4.600)	(3.800,5.800,7.800)	(2.600,4.600,6.600)	(1.800,3.800,5.800)	(0.800,2.600,4.600)	(0.800,2.600,4.600)
SC_{16}	(2.200,4.200,6.000)	(4.600,6.600,8.600)	(2.600,4.600,6.600)	2.200,4.200,6.000)	(1.000,3.000,5.000)	(0.400,1.800,3.800)	(5.400,7.400,9.200)	(1.800,3.800,5.800)	(1.800,3.400,5.200)	(0.400,1.800,3.800)	(0.400,1.800,3.800)
SC_{17}	(1.800,3.800,5.800)	(2.600,4.600,6.600)	(1.400,3.400,5.400)	2.600,4.600,6.600)	(1.000,3.000,5.000)	(0.400,1.800,3.800)	(3.400,5.400,7.400)	(2.600,4.600,6.600)	(1.200,2.600,4.600)	(0.400,1.800,3.800)	(0.400,1.800,3.800)
SC_{18}	(3.400,5.400,7.400)	(4.600,6.600,8.600)	(2.600,4.600,6.600)	1.800,3.800,5.800)	(1.000,3.000,5.000)	(0.200,1.400,3.400)	(3.800,5.800,7.800)	(2.600,4.600,6.600)	(1.200,2.600,4.600)	(0.200,1.400,3.400)	(0.200,1.400,3.400)
SC_{19}	(3.800,5.800,7.800	(4.600,6.600,8.600)	(1.400,0.400,5.400)	1.800,3.800,5.800)	(1.400,3.400,5.400)	(0.400,1.800,3.800)	(3.800,5.800,7.800)	(2.200,4.200,6.200)	(1.400,3.000,5.000)	(0.400,1.800,3.800)	(0.400,1.800,3.800)
SC_{20}	(5.400,7.400,9.200)	(0.600,2.200,4.200)	(1.800,3.800,5.800)	5.400,7.400,9.200)	(1.800,3.800,5.800)	(0.200,1.400,3.400)	(5.400,7.400,9.200)	(2.200,4.200,6.200)	(1.200,2.600,4.600)	(0.200,1.400,3.400)	(0.200,1.400,3.400)

Table 4. The fuzzy normalized decision matrix of sustainable siliceous materials alternatives.

Criteria	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
SC_1	(0.436,0.692,0.949)	(0.103,0.333,0.590)	(0.103,0.333,0.590)	(0.333,0.590,0.846)	(0.103,0.333,0.590)	(0.026,0.179,0.436)	(0.487,0.744,1.000)	(0.282,0.538,0.795)	(0.154,0.333,0.590)	(0.026,0.179,0.436)	(0.026,0.179,0.436)
SC_2	(0.152,0.455,0.758)	(0.091,0.333,0.636)	(0.091,0.333,0.636)	(0.333,0.636,0.939)	(0.152,0.455,0.758)	(0.061,0.273,0.576)	(0.394,0.697,1.000)	(0.424,0.697,1.000)	(0.061,0.273,0.576)	(0.061,0.273,0.576)	(0.061,0.273,0.576)
SC_3	(0.200,0.486,0.771)	(0.371,0.657,0.943)	(0.371,0.657,0.943)	(0.429,0.714,1.000)	(0.114,0.371,0.657)	(0.371,0.657,0.943)	(0.429,0.714,1.000)	(0.371,0.657,0.943)	(0.343,0.600,0.886)	(0.429,0.714,1.000)	(0.429,0.714,1.000)
SC_4	(0.104,0.313,0.521)	(0.229,0.438,0.646)	(0.229,0.438,0.646)	(0.104,0.313,0.521)	(0.146,0.354,0.563)	(0.271,0.479,0.688)	(0.646,0.854,1.000)	(0.313,0.521,0.729)	(0.188,0.396,0.604)	(0.271,0.479,0.688)	(0.271,0.479,0.688)
SC_5	(0.116,0.349,0.581)	(0.535,0.767,1.000)	(0.535,0.767,1.000)	(0.442,0.674,0.907)	(0.070,0.209,0.442)	(0.023,0.163,0.395)	(0.442,0.674,0.907)	(0.535,0.767,1.000)	(0.023,0.163,0.395)	(0.023,0.163,0.395)	(0.023,0.163,0.395)
SC_6	(0.036,0.214,0.607)	(0.143,0.429,0.714)	(0.143,0.429,0.821)	(0.429,0.714,1.000)	(0.000,0.143,0.429)	(0.036,0.214,0.679)	(0.429,0.714,1.000)	(0.286,0.571,0.964	(0.036,0.214,0.500)	(0.036,0.214,0.500)	(0.036,0.214,0.500)
SC_7	(0.029,0.200,0.486)	(0.086,0.314,0.600)	(0.086,0.314,0.600)	(0.429,0.714,1.000)	(0.000,0.143,0.429)	(0.371,0.657,0.940)	(0.429,0.714,1.000)	(0.086,0.314,0.600)	(0.143,0.371,0.657)	(0.371,0.657,0.943)	(0.371,0.657,0.943)
SC_8	(0.021,0.146,0.354)	(0.271,0.479,0.688)	(0.271,0.479,0.688)	(0.188,0.396,0.604)	(0.000,0.104,0.313)	(0.271,0.479,0.688)	(0.646,0.854,1.000)	(0.354,0.563,0.771)	(0.167,0.354,0.563)	(0.271,0.479,0.688)	(0.271,0.479,0.688)
SC_9	(0.000,0.128,0.385)	(0.282,0.538,0.795)	(0.282,0.538,0.795)	(0.231,0.487,0.744)	(0.000,0.128,0.385)	(0.026,0.179,0.436)	(0.487,0.744,1.000)	(0.333,0.590,0.846)	(0.000,0.128,0.385)	(0.026,0.179,0.436)	(0.026,0.179,0.436)
SC_{10}	(0.026,0.179,0.436)	(0.513,0.744,1.000)	(0.513,0.744,1.000)	(0.333,0.590,0.846)	(0.128,0.385,0.641)	(0.051,0.231,0.487)	(0.333,0.590,0.846)	(0.513,0.744,1.000)	(0.026,0.179,0.436)	(0.051,0.231,0.487)	(0.051,0.231,0.487)
SC_{11}	(0.000,0.128,0.385)	(0.513,0.744,1.000)	(0.103,0.333,0.590)	(0.179,0.436,0.692)	(0.128,0.385,0.641)	(0.333,0.590,0.846)	(0.385,0.641,0.897)	90.256,0.487,0.744	(0.128,0.333,0.590)	(0.333,0.590,0.846)	(0.333,0.590,0.846)
SC_{12}	(0.042,0.188,0.396)	(0.083,0.271,0.470)	(0.083,0.271,0.479)	(0.188,0.396,0.604)	(0.104,0.313,0.521)	(0.271,0.479,0.688)	(0.646,0.854,1.000)	(0.042,0.188,0.396)	(0.125,0.313,0.521)	(0.271,0.479,0.688)	(0.271,0.479,0.688)
SC_{13}	(0.102,0.306,0.510)	(0.265,0.469,0.673)	(0.265,0.469,0.673)	(0.184,0.388,0.592)	(0.122,0.306,0.510)	(0.469,0.673,0.878)	(0.673,0.878,1.000)	(0.265,0.469,0.673)	(0.429,0.633,0.837)	(0.469,0.673,0.878)	(0.469,0.673,0.878)
SC_{14}	(0.135,0.405,0.676)	(0.351,0.622,0.892)	(0.351,0.622,0.892)	(0.243,0.514,0.784)	(0.135,0.405,0.676)	(0.189,0.459,0.730)	(0.459,0.730,1.000)	(0.351,0.622,0.892)	(0.135,0.405,0.676	(0.189,0.459,0.730)	(0.189,0.459,0.730)
SC_{15}	(0.220,0.463,0.707)	(0.512,0.756,1.000)	(0.512,0.756,1.000)	(0.220,0.463,0.707)	(0.122,0.366,0.610)	(0.098,0.317,0.561)	(0.463,0.707,0.950)	(0.512,0.756,1.000)	(0.220,0.463,0.707)	(0.098,0.317,0.561)	(0.098,0.317,0.561)
SC_{16}	(0.239,0.457,0.652)	(0.283,0.500,0.717)	(0.283,0.500,0.717)	(0.239,0.457,0.652)	(0.109,0.326,0.540)	(0.043,0.196,0.413)	(0.587,0.804,1.000)	(0.283,0.500,0.717)	(0.196,0.370,0.565)	(0.043,0.196,0.413)	(0.043,0.196,0.413)
SC_{17}	(0.209,0.442,0.674)	(0.535,0.767,1.000)	(0.163,0.395,0.628)	(0.302,0.535,0.767)	(0.116,0.349,0.581)	(0.047,0.209,0.442)	(0.395,0.628,0.860)	(0.209,0.442,0.674)	(0.140,0.302,0.535)	(0.047,0.209,0.442)	(0.047,0.209,0.442)
SC_{18}	(0.436,0.692,0.949)	(0.333,0.590,0.846)	(0.333,0.590,0.846)	(0.231,0.487,0.744)	(0.128,0.385,0.641)	(0.026,0.179,0.436)	(0.487,0.744,1.000)	(0.333,0.590,0.846)	(0.154,0.333,0.590)	(0.026,0.179,0.436)	(0.026,0.179,0.436)
SC_{19}	(0.442,0.674,0.907)	(0.535,0.767,1.000)	(0.163,0.395,0.628)	(0.209,0.442,0.674)	(0.163,0.395,0.628)	(0.047,0.209,0.442)	(0.442,0.674,0.907)	(0.302,0.535,0.767)	(0.163,0.349,0.581)	(0.047,0.209,0.442)	(0.047,0.209,0.442)
SC_{20}	(0.587,0.804,1.000)	(0.500,0.717,0.935)	(0.196,0.413,0.630)	(0.587,0.804,1.000)	(0.196,0.413,0.630)	(0.022,0.152,0.370)	(0.587,0.804,1.000)	(0.239,0.457,0.674)	(0.130,0.283,0.500)	(0.022,0.152,0.370)	(0.022,0.152,0.370)

Table 5. The fuzzy weighted normalized decision matrix of Sustainable Siliceous materials alternatives.

Criteria	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	A_{11}
SC_1	(0.201,0.457,0.816)	(0.047,0.220,0.507)	(0.047,0.220,0.507)	(0.153,0.389,0.728)	(0.047,0.220,0.507)	(0.012,0.118,0.375)	(0.224,0.491,0.860)	(0.130,0.355,0.684)	(0.071,0.220,0.507)	(0.012,0.118,0.375)	(0.012,0.118,0.375)
SC_2	(0.082,0.336,0.667)	(0.049,0.247,0.560)	(0.049,0.247,0.560)	(0.180,0.471,0.827)	(0.082,0.3360.652)	(0.033,0.202,0.507)	(0.213,0.516,0.880)	(0.229,0.516,0.880)	(0.033,0.202,0.507)	(0.033,0.202,0.507)	(0.033,0.202,0.507)
SC_3	(0.100,0.340,0.694)	(0.186,0.460,0.849)	(0.186,0.460,0.849)	(0.214,0.500,0.900)	(0.057,0.260,0.565)	(0.186,0.460,0.849)	(0.214,0.500,0.900)	(0.186,0.460,0.849)	(0.171,0.420,0.797)	(0.214,0.500,0.900)	(0.214,0.500,0.900)
SC_4	(0.056,0.231,0.469)	(0.124,0.324,0.581)	(0.124,0.324,0.581)	(0.056,0.231,0.469)	(0.079,0.262,0.484)	(0.146,0.355,0.619)	(0.349,0.632,0.900)	(0.169,0.385,0.656)	(0.101,0.293,0.544)	(0.146,0.355,0.619)	(0.146,0.355,0.619)
SC_5	(0.067,0.272,0.535)	(0.310,0.599,0.920)	(0.310,0.599,0.920)	(0.256,0.526,0.834)	(0.040,0.163,0.380)	(0.013,0.127,0.364)	(0.256,0.526,0.834)	(0.310,0.599,0.920)	(0.013,0.127,0.364)	(0.013,0.127,0.364)	(0.013,0.127,0.364)
SC_6	(0.019,0.159,0.534)	(0.077,0.317,0.629)	(0.077,0.317,0.723)	(0.231,0.529,0.880)	(0.000,0.106,0.369)	(0.019,0.159,0.597)	(0.231,0.529,0.880)	(0.154,0.423,0.849)	(0.019,0.159,0.440)	(0.019,0.159,0.440	(0.019,0.159,0.440)
SC_7	(0.014,0.140,0.418)	(0.043,0.220,0.516)	(0.043,0.220,0.516)	(0.214,0.500,0.860)	(0.000,0.100,0.369)	(0.186,0.460,0.811)	(0.214,0.500,0.860)	(0.043,0.220,0.516)	(0.071,0.260,0.565)	(0.186,0.460,0.811)	(0.186,0.460,0.811)
SC_8	(0.005,0.061,0.220)	(0.060,0.201,0.426)	(0.060,0.201,0.426)	(0.041,0.166,0.375)	(0.000,0.044,0.269)	(0.060,0.201,0.426)	(0.142,0.359,0.620)	(0.078,0.236,0.478)	(0.037,0.149,0.349)	(0.060,0.201,0.426)	(0.060,0.201,0.426)
SC_9	(0.000,0.100,0.362)	(0.164,0.420,0.747)	(0.164,0.420,0.747)	(0.134,0.380,0.699)	(0.000,0.100,0.331)	(0.015,0.140,0.410)	(0.283,0.580,0.940)	(0.193,0.460,0.795)	(0.000,0.100,0.362)	(0.015,0.140,0.410)	(0.015,0.140,0.410)
SC_{10}	(0.018,0.162,0.436)	(0.359,0.669,1.000)	(0.359,0.669,1.000)	(0.233,0.531,0.846)	(0.090,0.346,0.551)	(0.036,0.208,0.487)	(0.233,0.531,0.846)	(0.359,0.669,1.000)	(0.018,0.162,0.436)	(0.036,0.208,0.487)	(0.036,0.208,0.487)
SC_{11}	(0.000,0.105,0.369)	(0.318,0.610,0.960)	(0.064,0.273,0.566)	(0.111,0.357,0.665)	(0.079,0.315,0.551)	(0.207,0.484,0.812)	(0.238,0.526,0.862)	(0.159,0.399,0.714)	(0.079,0.273,0.566)	(0.207,0.484,0.812)	(0.207,0.484,0.812)
SC_{12}	(0.024,0.146,0.372)	(0.048,0.211,0.450)	(0.048,0.211,0.450)	(0.109,0.309,0.568)	(0.060,0.244,0.448)	(0.157,0.374,0.646)	(0.375,0.666,0.940)	(0.024,0.146,0.372)	(0.073,0.244,0.490)	(0.157,0.374,0.646)	(0.157,0.374,0.646)
SC_{13}	(0.055,0.227,0.469)	(0.143,0.347,0.620)	(0.143,0.347,0.620)	(0.099,0.287,0.544)	(0.066,0.227,0.439)	(0.253,0.498,0.807)	(0.364,0.649,0.920)	(0.143,0.347,0.620)	(0.231,0.468,0.770)	(0.253,0.498,0.807)	(0.253,0.498,0.807)
SC_{14}	(0.078,0.316,0.635)	(0.204,0.485,0.838)	(0.204,0.485,0.838)	(0.141,0.401,0.737)	(0.078,0.316,0.581)	(0.110,0.358,0.686)	(0.266,0.569,0.940)	(0.204,0.485,0.838)	(0.078,0.316,0.635)	(0.110,0.358,0.686)	(0.110,0.358,0.686)
SC_{15}	(0.048,0.195,0.424)	(0.113,0.318,0.600)	(0.113,0.318,0.600)	(0.048,0.195,0.424)	(0.027,0.154,0.524)	(0.021,0.133,0.337)	(0.102,0.297,0.571)	(0.113,0.318,0.600)	(0.048,0.195,0.424)	(0.021,0.133,0.337)	(0.021,0.133,0.337)
SC_{16}	(0.057,0.173,0.365)	(0.068,0.190,0.402)	(0.068,0.190,0.402)	(0.057,0.173,0.365)	(0.026,0.124,0.467)	(0.010,0.074,0.231)	(0.141,0.306,0.560)	(0.068,0.190,0.402)	(0.047,0.140,0.317)	(0.010,0.074,0.231)	(0.010,0.074,0.231)
SC_{17}	(0.046,0.186,0.337)	(0.118,0.322,0.500)	(0.036,0.166,0.314)	(0.067,0.225,0.384)	(0.026,0.147,0.500)	(0.010,0.088,0.221)	(0.087,0.264,0.430)	(0.046,0.186,0.337)	(0.031,0.127,0.267)	(0.010,0.088,0.221)	(0.010,0.088,0.221)
SC_{18}	(0.105,0.291,0.588)	(0.080,0.248,0.525)	(0.080,0.248,0.525)	(0.055,0.205,0.461)	(0.031,0.162,0.551)	(0.006,0.075,0.270	(0.117,0.312,0.620)	(0.080,0.248,0.525)	(0.037,0.140,0.366)	(0.006,0.075,0.270)	(0.006,0.075,0.270)
SC_{19}	(0.106,0.270,0.508)	(0.128,0.307,0.560)	(0.039,0.158,0.352)	(0.050,0.177,0.378)	(0.039,0.158,0.540)	((.011,0.084,0.247	(0.106,0.270,0.508)	(0.073,0.214,0.430)	(0.039,0.140,0.326)	(0.011,0.084,0.247)	(0.000,0.084,0.247)
SC_{20}	(0.153,0.370,0.660)	(0.130,0.330,0.617)	(0.051,0.190,0.416)	(0.153,0.370,0.660)	(0.051,0.190,0.542)	0(.006,0.070,0.244	(0.153,0.370,0.660)	(0.062,0.210,0.445)	(0.034,0.130,0.330)	(0.006,0.070,0.244)	(0.006,0.070,0.244)

Table 6. The fuzzy positive ideal reference point (FPIRP) and fuzzy negative ideal reference point (FNIRP) distances, closeness coefficients and rank of each sustainable siliceous materials.

Supplementary Material	Alternatives	d_i^+	d_i^-	cc_i	Ranking
Limestone	A_1	15.2620	6.3464	0.2937	9
Blast Furnace Slag	A_2	13.2325	8.6205	0.3945	3
Metakaolin	A_3	13.8836	7.9110	0.3630	5
Fly Ash	A_4	13.3874	8.4508	0.3870	4
Rise Husk Ash	A_5	15.6305	6.0714	0.2798	10
Silica Fume	A_6	15.1549	6.4536	0.2987	6
Nano-Cement	A_7	11.3468	10.790	0.4874	1
Nano-Particles Supp. Mat.	A_8	13.2058	8.6757	0.3965	2
Recycled Aggregate	A_9	15.4692	6.0042	0.2796	11
Waste Glass	A_{10}	15.1564	6.4067	0.2971	7
Natural Pozolona	A_{11}	15.1606	6.4065	0.2971	8

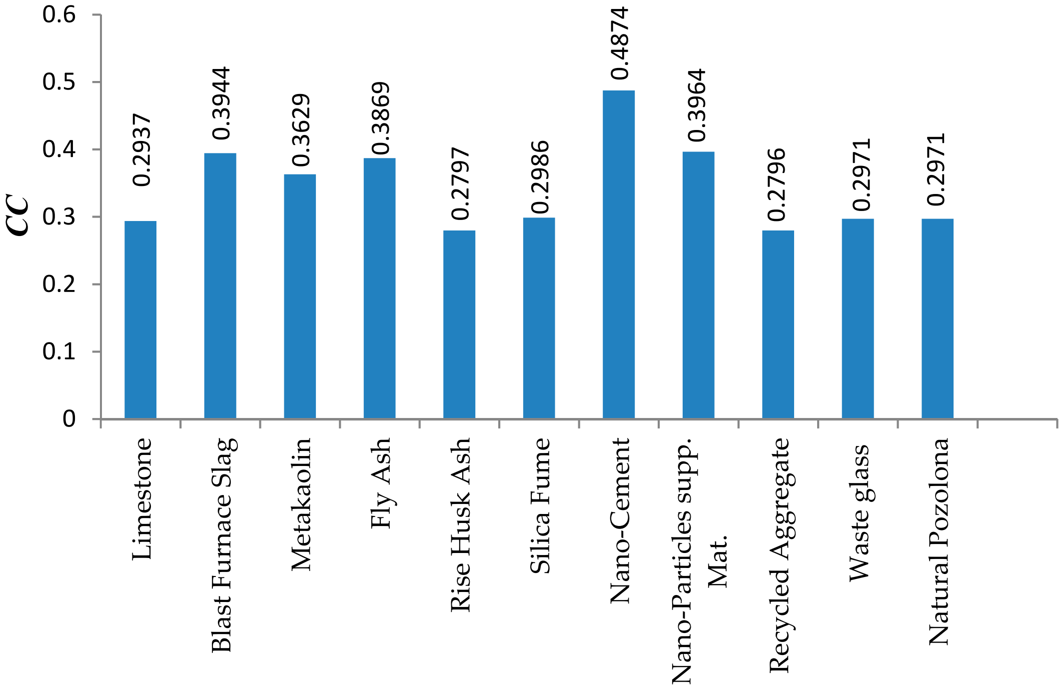

Figure 2. Ranking of each alternative material based on closeness coefficient.

4. Discussion

The Fuzzy-TOPSIS based approach has been implemented to manage the use of siliceous concrete materials for sustainable development. Mahmoudkelaye et al. [21] applied the Analytic Network Process (ANP) as a multi-criteria decision-making method for sustainable material selection for building, considering the holistic impact of materials on the environment through sustainable criteria which are marked as economic, technical, socio-cultural, and environmental factors. The importance of the criteria and sub-criteria in choosing sustainable materials was determined through this model. Whereas, the present study implements the Fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) approach, a Multi-Criteria Decision Making (MCDM) technique, for orderly management of siliceous materials based on sustainable criteria, namely, technical, environmental, social and economic aspects and to promote sustainable development. Various sustainable criteria viz. technical, environmental and socio-economical, are considered. It has been observed that, in accomplishing the sustainable goals for siliceous concrete materials, the environmental criteria play a central role, whereas the social criteria play the minor role. It has also been observed that the most effective sustainable indicator for the ranking of siliceous concrete materials is “concrete material conservation". It indicates that concrete material conservation is a major issue in sustainable material management and the use of siliceous concrete material should be mandatory in the construction industry for sustainable development. The least effective sustainable indicator observed is the "enhanced employment", and siliceous concrete materials application has no major impact on social development. Among the eleven selected siliceous concrete materials, nano-engineered materials, namely, nano-cement and nano-particles of siliceous material should be given top priority in material management for the manufacturing of sustainable concrete product. The siliceous materials come next for sustainable concrete construction. The recycled material to be used as siliceous concrete materials occupies the lowest rank among the sustainable concrete materials. The ranking of the material in descending order of preference to produce sustainable concrete is: Nano-cement > Nano-particles of siliceous material > Blast Furnace Slag > Fly Ash > Metakaolin > Silica Fume > Waste Glass > Natural Pozolona > Lime Stone > Rice Husk Ash > Recycled Aggregate, where '>' represents preference over other concrete material. The corresponding closeness coefficients of the eleven siliceous concrete materials are: 0.4874 > 0.3965 > 0.3945 > 0.3870 > 0.3630 > 0.2987 > 0.2971 > 0.2971 > 0.2937 > 0.2798 > 0.2796 where '>' represents the preference over other concrete material.

5. Conclusions

The construction industry must look for a sustainability framework to overcome global resources scarcity and environmental impact by adopting sustainable material management in the concrete manufacturing processes. The proper material management is required to select the siliceous material for the production of concrete product from the ever increasing sources of siliceous materials such as industrial waste products, agro-waste products, building recycled material, natural pozolonic material, and siliceous engineered material. The much needed sustainability may be accrued by considering factors related to technique and the environment as well as socio-economic factors while selecting siliceous concrete materials. Concrete manufacturing, through material management, must adapt to environmental friendly material and processes, which should not only be cost-effective but also provide economic value and safety for society. In the present study, more comprehensive criteria are selected in order to provide sustainability. Moreover, the study adopts twenty sustainability indicators for siliceous concrete materials, thus covering the material management sustainability aspects to a larger extent. It is found from the adopted MCDM approach that among the selected sustainable indicators, the most effective sustainable indicator for managing siliceous materials is concrete material conservation. The least governing sustainable indicator is enhanced employment. It can be concluded from the study that the large scale use of siliceous concrete materials in construction industry will help in the conservation of basic concrete materials and environmental protection, though it will not have direct impact on social development.

The proposed material management model for siliceous materials suggests that the material could be best utilized for sustainable development by the classifying the various siliceous materials into two groups i.e., Group I with CC > 0.35 and Group II with CC < 0.35. The selected siliceous concrete materials, namely, Nano-cement and Nano-particles of siliceous material, Blast Furnace Slag, Fly Ash, and Metakaoline exhibit larger CC value and are hence classified as Group I materials, which possess higher potential of providing sustainability. The siliceous concrete materials of Silica Fume, Waste Glass, Natural Pozolona, Lime Stone, and Rice Husk Ash exhibit lower values of CC, and hence may be regarded as having lower capability towards achieving sustainability in comparison to the Group II. The nano-engineered material, although costly, will prove to be the best material for sustainable concrete construction and development.

The current research provides just a preliminary framework for the selection of basic materials for concrete construction in alignment with sustainability. In selecting sustainable siliceous concrete materials, this research has opened opportunities for further research in sustainable materials. The results of this study can be further expanded and modified to achieve the ultimate objective of encouraging and improving sustainable construction methods. The present research will be of great importance for the concrete industry dealing with concrete manufacturing and to tackle the challenges like increased manufacturing costs, higher concrete performance requirements, and being risk-free to the environment and society.

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Appendix A

Questionaire for Fuzzy TOPSIS

With respect to the overall goal of "Selection of the Sustainable Siliceous Materials"

Sample questions included in questionnaire

Q1. How importance is the Sustainable Indicator Support for Concrete Curing System in the rating of 1–9 scale? (C_1)

Q2. What importance do you assign to Sustainable Indicator *Support to Concrete Compaction System* in the rating of 1–9 scale? (C_2)?

Q3. What importance do you assign to Sustainable Indicator *Support to Cohesiveness of Concrete Mix* in the rating of 1–9 scale? (C_3)?

Q4. What importance do you assign to Sustainable Indicator *Support to Consistency of Concrete Mix* in the rating of 1–9 scale? (C_4)?

Q5. What importance do you assign to Sustainable Indicator *Comply Strength Requirement of Concrete Mix* in the rating of 1–9 scale? (C_5)?

With Respect to Sustainable Siliceous Materials.		**Importance (or Preference) of Each Criterion**				
Questions	Sustainable Indicator	(0,0.1,0.3) Very Low	(0.1,0.3,0.5) Low	(0.3,0.5,0.7) Medium	(0.5,0.7,0.9) High	(0.7,0.9,1) Very High
Q1	C_1			√		
Q2	C_2				√	
Q3	C_3	√				
Q4	C_4			√		

Appendix B

Scoring of Alternatives with Respect to Sustainable Indicator for Overall Goal of "Sustainable Siliceous Materials"

Q2-1. What scores do you assign to A_1 with reference to Sustainable Indicator *Support to Concrete Curing System* (C_1) in the rating of 1–9 scale?

Q2-2. What scores do you assign to A_1 with reference to Sustainable Indicator *Support to Concrete Compaction System* (C_2) in the rating of 1–9 scale?

Q2-3. What scores do you assign to A_1 with reference to Sustainable Indicator *Support to Cohesiveness of Concrete Mix* (C_3) in the rating of 1–9 scale?

Q2-4. What scores do you assign to A_1 with reference to Sustainable Indicator *Support to Consistency of Concrete Mix* (C_4) in the rating of 1–9 scale?

Q2-5. What scores do you assign to A_1 with reference to Sustainable Indicator *Comply Strength Requirement of Concrete Mix* (C_5) in the rating of 1–9 scale?

With Respect to the Sustainable Siliceous Materials			**Performance of Each Sustainable Siliceous Materials Alternative with Respect to Each Sustainable Indicator**				
Questions	Sustainable Indicator	Sustainable Siliceous Materials	(0,1,3) Very Poor	(1,3,5) Poor	(3,5,7) Fair	(5,7,9) Good	(7,9,10) Very Good
Q2-1	C_1	A_1				√	
Q2-2	C_2	A_1				√	
Q2-3	C_3	A_1			√		
Q2-4	C_4	A_1			√		
Q2-5	C_5	A_1			√		

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