

## Research Article

# Decision Support Model for Design of High-Performance Concrete Mixtures Using Two-Phase AHP-TOPSIS Approach

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Received 23 January 2019; Accepted 27 February 2019; Published 13 March 2019

Academic Editor: Behzad Esmaeili

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Concrete mix design is the science to obtain concrete proportions of cement, water, and aggregate, based on the particular concrete design method and their mix design parameters. However, the suitability of concrete proportion for high-performance concrete depends on resulting mix factors, namely, water, cement, fine aggregate, and coarse aggregate ratios. This paper implements the multicriteria decision-making techniques (MCDM) for ranking concrete mix factors and representative mix design methods. The study presents a framework to identify critical mix factors found from the concrete mix design methods for high-performance concrete using the two-phase AHP and TOPSIS approach. Three methods of concrete mix design, namely, American Concrete Institute (ACI) mix design method, Department of Energy (DOE) method, and Fineness Modulus (FM) method, are considered for ranking mix design methods and the resulting mix factors. Three hierarchy levels, having three criteria and seven subcriteria, and three alternatives are considered. The present research is attempted to provide MCDM framework to rank the concrete mix guidelines for any given environment such as concrete under sulphate and chloride attack and for evolving the performance-based concrete mix design techniques. Sensitivity and validation analysis is also provided to demonstrate the effectiveness of the proposed approach.

## 1. Introduction

Concrete mix design is the process of deciding the proportioning of the ingredients of concrete using well-experimented design guidelines to get the specific performance of concrete. The various design guidelines that include the mix parameters such as properties of cement, minimum and maximum cement quantity, water-to-cement ratio, mixing water requirements, aggregates-to-cement ratio, properties of aggregates, aggregates grading, and proportions of aggregate may change with different concrete exposure conditions, with required properties of concrete in green or hardened state, and with performance requirement. The mix factors significantly affecting the suitability of mix proportion for high-performance concrete are taken into consideration for ranking decision model. The concrete workability, strength and durability affecting mix factor, water-cement ( $w/c$ ) ratio, concrete denseness indicators, density and fine aggregate to total aggregate ( $FA/T$ ) ratio, concrete quality indicators, fine aggregate to cement ( $FA/c$ )

ratio, and total aggregate to cement ( $T/c$ ) ratio are considered. Other factors that may affect the suitability of mix proportion for high-performance concrete are coarse aggregate to cement ( $CA/c$ ) and cost of concrete. Due to interdependency among the concrete mix factors, it is not an easy task to select the concrete mix factors and mix design methods guidelines for particular environment and for high-performance concrete. Multi-Criteria Decision Making (MCDM) techniques may be employed to ascertain the criticality of mix factors and grading of mix design techniques. The research work related to the implementation of MCDM techniques in civil engineering is mainly devoted to construction technology. The application of MCDM approaches in the civil engineering theoretical concepts and methods are very scarce. An integrated model of median ranked sample set (MRSS) and an analytic network process (ANP) has been proposed by Younes et al. [1] to select a suitable landfill site. Kabir et al. [2] present a review of the application of MCDM procedures and their taxonomy in the field of infrastructure management. Caterino et al. [3]

studied the applicability and performance of most widely adopted MCDM methods for the seismic retrofitting technologies of structures. They have concluded that the technique for order of preference by similarity to ideal solution (TOPSIS) and VIKOR methodologies are more suitable for the retrofit technology selection because of potentiality to deal with each kind of judgment criteria, parameters, and involving choices. Zavadskas et al. [4] studied the accuracy of ranking in a particular situation obtained in the TOPSIS methods. AHP is implemented by Do and Kim [5] to select an optimal patching material for concrete repair satisfying chemical performance and physical performance. Cheng and Kang [6] have proposed a fuzzy preference relation-based Multi-Criteria Prospect Model (MCPM) for the construction contractor selection. A multiattribute fuzzy weighted average approach-assisted MCDM process is used by Alhumaidi [7] for the selection of construction contractors having a set of attributes. AHP model-based MCDM methodology has successfully been applied for the sustainability assessment in civil engineering [8, 9]. Antucheviciene et al. [10] have presented a review of decision-making methods and applications in civil engineering. Monghasemi et al. [11] have developed a new MCDM model to optimize the time-cost-quality in construction projects. Do and Kim [5] applied AHP to select an optimal repair material for a chloride-deteriorated concrete member by focusing on the chemical and physical performance quantitatively. Ozbay et al. [12] use Taguchi's experiment design methodology for optimal design for analysis of mix proportion parameters of high-strength self-compacting concrete. The optimal levels for mix proportions are determined for maximization of ultrasonic pulse velocity (UPV), compressive strength, and splitting tensile strength, and for the minimization of air content, water permeability, and water absorption values. De Angelis et al. [13] propose Multi-Criteria Decision Making (MCDM) analysis based on the TOPSIS method for comparing four building components with conflicting structural and environmental performance criteria. Hamdia et al. [14] present fuzzy Analytic Hierarchy Process- (FAHP-) based assessment model to estimate the importance of structural assessment criteria of damages and deteriorations for concrete buildings.

The applications of MCDM to civil engineering are limited to the general problems, and they are not illustrative enough to evaluate the specific problems such as design methods, guidelines, and theoretical concept. The present study is the maiden attempt to apply MCDM techniques to select the mix design technique in concrete technology for high-performance concrete. Two popular MCDM techniques, namely, AHP and TOPSIS approach, which have demonstrated their applicability in different fields, are implemented for the problem of preferential mix design method applicable to high-performance concrete.

## 2. AHP and TOPSIS

While designing a concrete mix for achieving particular performance, the designer chooses the mix design method from the available methods and considers the mix parameters

as per the requirement of the method. The number of MCDM methods has been developed for value measurement, goal, preference level, and outranking selection. The different MCDM method depends on the distinct types of inputs and results in equally distinct outputs but the most suitable method is which best satisfies decision-making and puts forward sufficient confidence to translate their decisions into actions [15]. Among the available MCDM techniques, the integrated AHP [16] and TOPSIS [17] approach has been chosen for the present study. The selected approach exploits the advantages of both the AHP and TOPSIS method. The advantage of using the integrated two-phase AHP-TOPSIS approach over the individual MCDM methods [18] is presented in Table 1.

## 3. Methodology

The selection of the preferential mix design method for achieving particular performance is an MCDM process. The proposed model decomposes the process into three levels, concrete mix objective criteria, resulting mix factors as subcriteria, and mix design methods as alternatives. Problem formulation determines the problem aims, assessment criteria, and experts. The problem criteria are identified based on experts' opinion [19–23]. The study adopted an integrated and more realistic MCDM methodology, two-phase AHP and TOPSIS approach, to select the priority concrete mix for high performance. For this purpose, the weights that are obtained from AHP calculations are used in TOPSIS calculations. The selection steps determine the weights (importance) of the mix factors and the prioritization of the mix design method.

*3.1. Proposed Approach.* The main steps of the proposed approach to select the preferential mix design method are as follows.

*Step 1.* Develop the problem criteria hierarchy and normalize the decision matrix and calculate the weights of matrix by AHP following the procedure outlines by Saaty [16].

In this step, the criteria of the problem (preferential mix design method for extreme environment) are identified as per the methodology, and the problem is decomposed into three levels as per experts' opinion, authors' experience, and literature review. In level 1, the most important factors of mix design, namely, workability, strength, and durability are considered as a criterion of the problem. The concrete mix parameters for extreme environment (level 2 subcriteria) are identified as water-cement ( $w/c$ ) ratio, density, coarse aggregate-cement ( $CA/c$ ) ratio, total aggregate-cement ( $T/c$ ) ratio, fine aggregate-cement ( $FA/c$ ) ratio, fine aggregate-total aggregate ( $FA/T$ ) ratio, and cost. In level 3, three mix design methods, namely, the ACI mix design method, DOE mix design method, and FM mix design method, are considered as alternatives. The hierarchical structure of the preferential mix design method for an extreme environment is depicted in Figure 1. The pairwise comparisons of various criteria and subcriteria are done as shown in Tables A1–A3

TABLE 1: Comparison of proposed with individual AHP and TOPSIS methods [18].

Criteria	AHP	TOPSIS	Two-phase AHP-TOPSIS (proposed)
Use hierarchical structure	✓		✓
To provide objective criteria's weight	✓		✓
Comparison of ideal solution		✓	✓
Ranking method	✓	✓	✓
Be easy to understand	✓	✓	✓

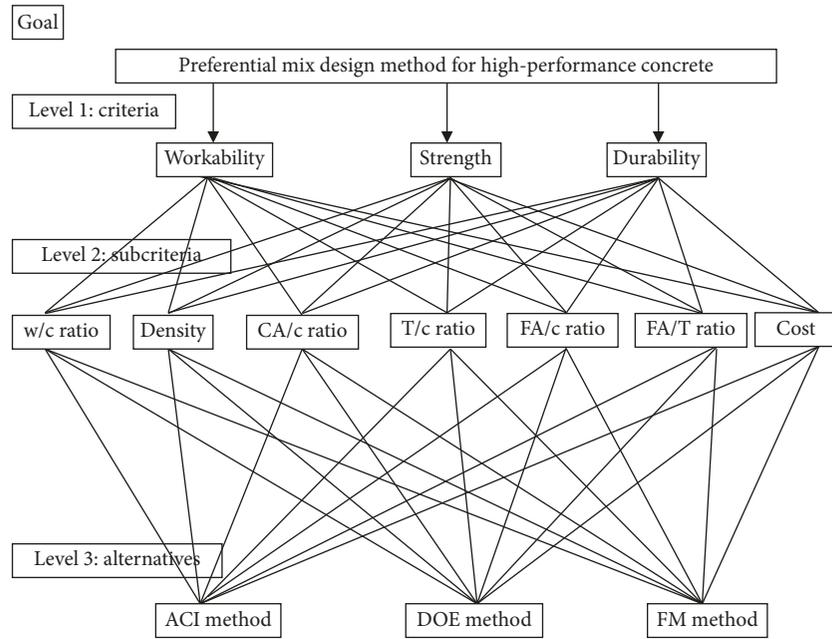


FIGURE 1: Hierarchical structure of the preferential mix design method and mix factors for high performance concrete.

(Appendix-A). The pairwise comparison matrix of the main criteria of Table A1 is then used to normalize the decision matrix, and the weights of the matrix are calculated.

*Step 2.* Consistency check of each pairwise comparison matrix using AHP [16].

The consistency of the assessment process is checked by calculating the CI and CR value of each pairwise comparison matrix and the aggregate matrix [16] and [24]. The calculated values of CI and CR are below 0.10 (maximum permissible value), indicating a satisfactory degree of consistency.

*Step 3.* Estimate the relative weights of the alternatives with respect to each weight of subcriterion.

The relative weights of the objective criteria, namely, workability, strength and durability, and design mix parameters are obtained from the aggregated values using the eigenvector method [16], and afterward, the design mix methods weight for each mix factors are calculated. The relative weights of three design methods with respect to weight of each design mix factor are given in Table A4 (Appendix-A).

*Step 4.* Conduct TOPSIS by normalizing the decision matrix using AHP [16].

Calculate the normalized decision matrix and calculate the weighted normalized decision matrix, following the methodology is given by Hwang and Yoon [17]. The obtained normalized decision matrix and weighted normalized decision matrix are shown in Tables A5 and A6 (Appendix-I).

*Step 5.* Determine the ideal and negative ideal solutions and calculate the separation measures.

The ideal solution ( $A^*$ ) and negative ideal solution ( $A^-$ ) is determined from weighted normalized decision matrix and separation distances of each alternative are calculated from the positive ( $D_j^+$ ) and from a negative ideal solution ( $D_j^-$ ) [17]. The separation distances from an ideal solution ( $D_j^+$ ) and negative ideal solution ( $D_j^-$ ) are given in Table A7.

*Step 6.* Calculate the relative closeness to the ideal solution and rank the preference order.

The relative closeness of each alternative ( $C_j^*$ ) determination to the ideal solution is the final step of the TOPSIS methodology [17]. The two-phase AHP and TOPSIS approach results including the ranking of alternative as per values of the relative closeness to the ideal solution are shown in Table 2. The ranking of the alternatives in descending order is the DOE method, ACI method, and FM method of concrete mix design for an extreme environment.

TABLE 2: Final score obtained by TOPSIS.

Criteria	$D_j^*$	$D_j^-$	$C_j^*$	Ranking
ACI	0.117	0.233	0.502	2
DOE	0.130	0.246	0.530	1
FM	0.096	0.219	0.439	3

**3.2. Sensitivity Analysis.** The sensitivity analysis demonstrates the influence and stability of criterion's weight (mix factors weights) on alternative (mix design method) selection. Thus, the concrete method selection robustness may be verified by exchanging criterion weight. Each criterion's weight has been exchanged with another criterion's weights which gives various combinations resulting from the three main criteria. The weight of three main criteria, i.e., (workability, strength, and aggregate size) considered as  $w_1$ ,  $w_2$ , and  $w_3$  are obtained as 0.297, 0.539, and 0.164. On using these weights, the model gives the  $C_j^*$ , for ACI, DOE, and FM as 0.502, 0.530, and 0.439. Similarly, by exchanging weight,  $w_1$ ,  $w_2$ , and  $w_3$  may further be used in sensitivity analysis. The sensitivity analysis output is summarized in Table 3 and Figure 2. The first condition of Table 3 expresses the original results of the two-phase AHP and TOPSIS methodology. The DOE method has the highest  $C_j^*$  value of 0.541 from 0.530 when the first and third criteria weights are exchanged in condition 2. Also, the DOE method has the lowest value of 0.472 when the first and second criteria weights are exchanged in condition 4. The ACI method will have the highest  $C_j^*$  value of 0.559 from 0.502 when the first and second criteria weights are exchanged in condition 4. The ACI method is having the lowest value of 0.502 in the first condition. The FM method will have the highest  $C_j^*$  value of 0.542 from 0.439 when the first and second criteria weights are exchanged in condition 4. The FM method will have the lowest value of 0.439 when the first condition is met.

**3.3. Validation.** The quantitative optimum values of concrete mix factors found in the literature (Table 4). Helmy [28] may play a significant role while comparing various subcriteria of workability, strength, and durability, i.e., w/c density, CA/c, T/c, FA/c, FA/T, and cost for identifying a preferential mix design method for high-performance concrete. Thus, the various mix design guidelines for optimum values giving dense concrete with the lowest cost could be realized. The study reveals that the DOE mix design method produces a mix with the lowest cement content and gives the best workability in comparison to the other mix design method of ACI and FM. Moreover, from the published literature, it has been found that the performance of the DOE mix design method is better than the other mix design technique which is in line with the obtained result in the present study. Thus, the ranking obtained in the present research matches with the literature results.

## 4. Discussion

The results of the two-phase AHP and TOPSIS approach implemented to preferential mix design technique to develop high-performance concrete suggested that the

TABLE 3: Sensitivity analysis output.

Conditions	Criteria weight			$C_j^*$		
	$w_1$	$w_2$	$w_3$	ACI	DOE	FM
1	0.297	0.539	0.164	0.502	0.530	0.439
2	0.164	0.539	0.297	0.514	0.541	0.447
3	0.297	0.164	0.539	0.509	0.509	0.456
4	0.539	0.297	0.164	0.559	0.472	0.542

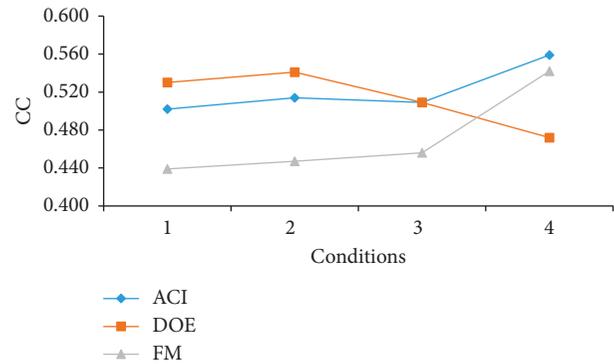


FIGURE 2: Sensitivity analysis with respect to mix objective criteria.

Department of Energy (DOE) method of mix design is the best choice for high-performance concrete having objective factors as workability, strength, and durability, and mix design parameters as w/c ratio, density, CA/c ratio, T/c ratio, FA/c ratio, FA/T ratio, and cost. The ranking of the mix design method predicted by the two-phase AHP and TOPSIS approach is also compared with a predicted ranking of the mix design method when only the AHP approach is applied. The two MCDM techniques, AHP-based and integrated AHP-TOPSIS-based approach, suggest that the DOE method is the preferred design mix method for performance in an extreme environment as depicted in Figure 3. However, the preference level of the mix design method is not the same in two MCDM techniques. The AHP approach suggests that the preference level of the DOE method is double than the preference level of the ACI method and the FM method. The two-phase AHP-TOPSIS approach predicts a more or less similar level of preference for the three mix design technique. The preference level given by the AHP approach is 57%, 24%, and 19%, respectively, for DOE method, ACI method, and FM method. The closeness coefficients to rank priority level obtained in the two-phase AHP-TOPSIS approach are 0.53, 0.50, and 0.44, respectively, for the DOE method, ACI method, and FM method.

The sensitivity analysis also shows the stability of the priority of the DOE method. The DOE method prioritization will change to the American Concrete Institute (ACI) method when the workability criterion given more weight than the strength criteria weight. When the durability criterion has more weights as compared to workability and strength criterion, the DOE method and the ACI method have equal preference. The fineness modulus method, which is a relatively older mix design method, has also all capabilities of developing into an advanced mix design technique

TABLE 4: Quantitative optimum values of mix factors from published literature.

Mix factors for extreme environment	Ahmed et al. [19], ACI method	Ahmed et al. [19], DOE method	Mix design guidelines for optimum value with lowest cost			
			Ahmad [25], Neville [26]	Simon [22]	Soudki et al. [23]	Yurdakul, [27]
w/c ratio	0.5	0.5		0.4–0.43		
CA/c ratio	2.43	2.51				
T/c ratio	4.31	4.26	4.88	4.3–5.1	3–3.6	
FA/c ratio	1.88	1.75				
FA/T ratio	0.43	0.41	0.38	0.39	0.45–0.4	0.42

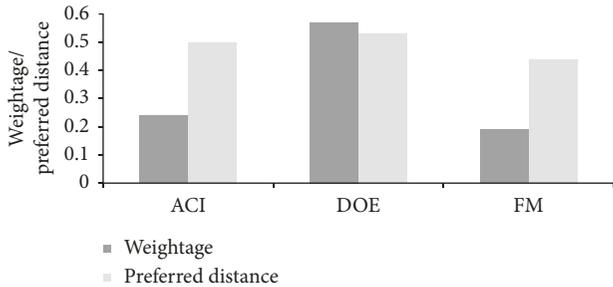


FIGURE 3: Ranking of mix design method for extreme environment using AHP and two-phase AHP-TOPSIS approach.

for high-performance concrete as the closeness coefficients are found to be in close proximity.

4.1. Ranking of Design Mix Parameters (Subcriteria).

There are seven subcriteria, namely, w/c ratio, density, CA/c ratio, T/c ratio, FA/c ratio, FA/T ratio, and cost, under each main criterion. The weight ranking of the subcriteria with respect to objective criteria obtained by the AHP approach is represented in Figure 4. The weight of the seven subcriteria is varying with respect to objective criteria. The sensitivity of design methods with interchanging the weight of subcriteria is presented and discussed in the following section.

4.1.1. Water-Cement Ratio. The water-cement ratio is a very important and critical factor for the mix design technique. The workability, strength, and durability of fresh and hardened concrete are strongly dependent on this factor. The water-cement ratio has the highest weight for workability and strength criteria as evident from Figure 4. Figure 5 shows the sensitivity of the mix design method with respect to w/c ratio calculated using the TOPSIS approach. The sensitivity for the DOE method with respect to the water-cement ratio is stable as the closeness coefficient increases with increase of w/c ratio weight.

4.1.2. Density and Fine Aggregate to Total Aggregate Ratio. The density and fine aggregate to total aggregate (FA/T) ratio factors is the indicator of the denseness of the concrete. These two factors are important for the mix design in an extreme environment. The density is the second in weight rank and rank is more or less same for all

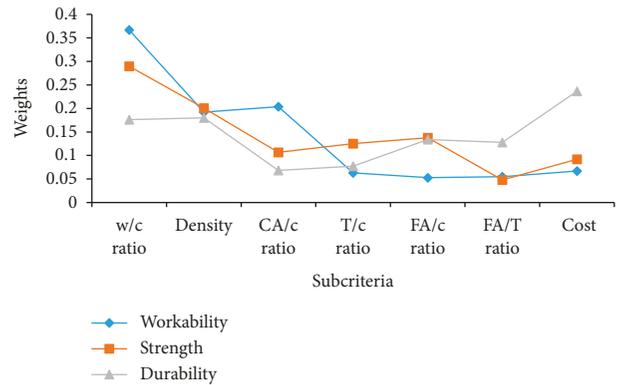


FIGURE 4: Weights of subcriteria with respect to objective criteria.

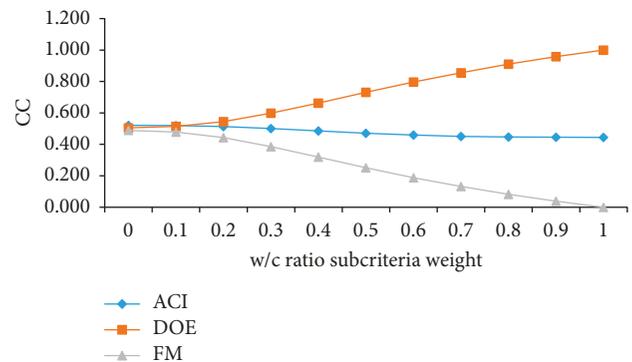


FIGURE 5: Sensitivity analysis of mix design methods with respect to w/c ratio weights.

the objective criteria as presented in Figure 4. The weighted rank of the fine aggregate to total aggregate (FA/T) ratio is second last in the list. Figures 6 and 7 show the sensitivity of the mix design method with respect to density and FA/T ratio factors calculated using the TOPSIS approach. The two factors are sensitive to change the preference of the mix design technique for an extreme environment performance when the weight of density and FA/T changes. When the weight of FA/T is higher, preference of method is changed from the DOE method to FM method.

4.1.3. Coarse Aggregate to Cement Ratio. The coarse aggregate to cement (CA/c) ratio is an important parameter for

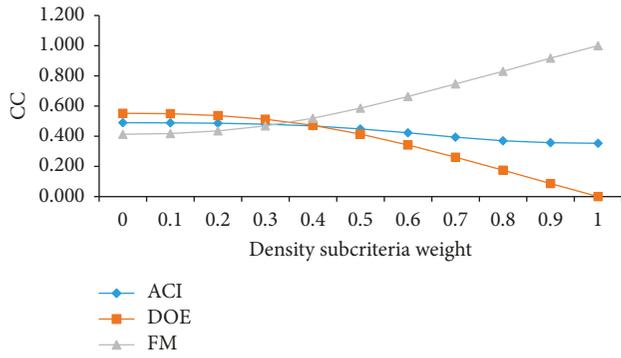


FIGURE 6: Sensitivity analysis of mix design methods with respect to density weights.

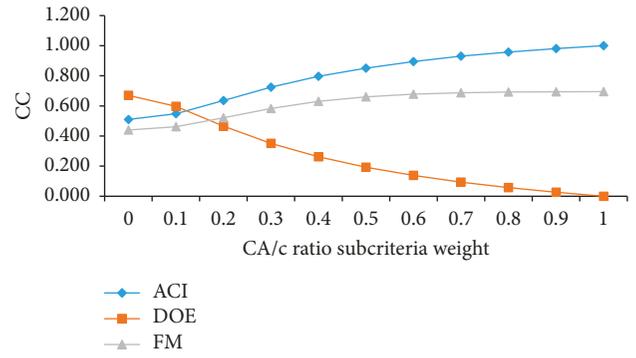


FIGURE 8: Sensitivity analysis of mix design methods with respect to CA/c ratio weight.

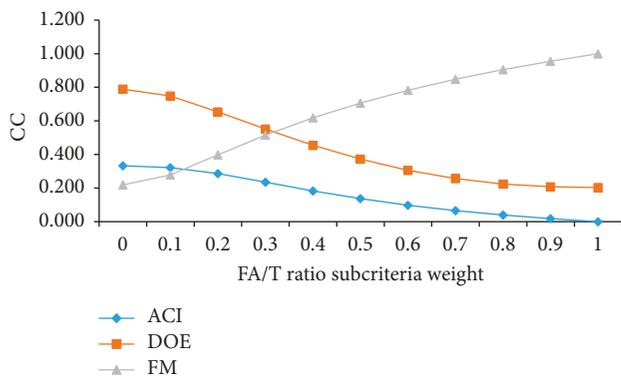


FIGURE 7: Sensitivity analysis of mix design methods with respect to FA/T weight.

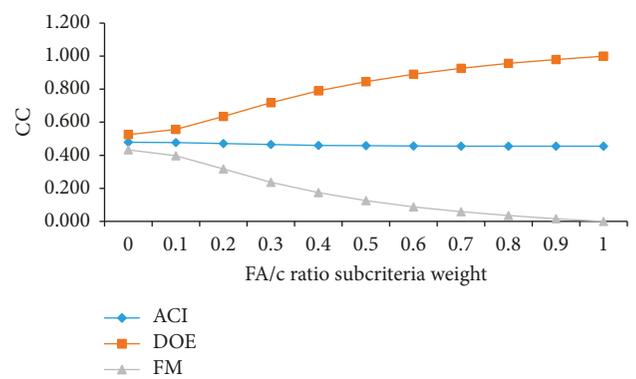


FIGURE 9: Sensitivity analysis of mix design methods with respect to FA/c weight.

the design mix technique in an extreme environment performance and factor need to be of optimum value for concrete mix. The factor is sensitive enough to change the preference of the mix design method for an extreme environment when the weight of CA/c changes. When the weight of CA/c is more, the mix method preference is changed from the DOE method to the ACI method. The sensitivity of the mix design technique with respect to density and CA/c ratio is shown in Figure 8.

**4.1.4. Fine Aggregate to Cement Ratio and Total Aggregate to Cement Ratio.** The fine aggregate to cement (FA/c) ratio and total aggregate to cement (T/c) ratio are the indicators of the concrete quality. These factors are also significant for the design mix technique in an extreme environment performance. FA/c ratio and T/c ratio are of intermediate weights as shown in Figure 4. The sensitivity for the ACI method with respect to FA/c ratio and T/c ratio is stable as closeness coefficient increases with an increase of factor ratios weights. Figures 9 and 10 depict the sensitivity of mix design technique with respect to FA/c and TA/c ratio.

**4.1.5. Cost.** The cost is the important factor of the mix design technique for an extreme environment performance as the additional cost is incurred to increase concrete durability in

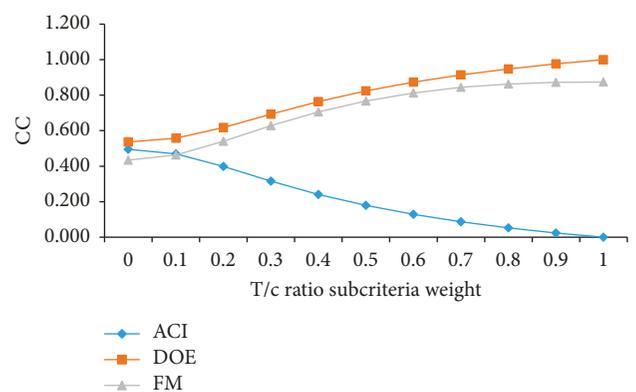


FIGURE 10: Sensitivity analysis of mix design methods with respect to T/c weight.

an adverse environment and to improve the concrete workability and strength. The weighted rank of cost is the last for workability and strength criteria, and it is the first weight rank for durability criteria as given in Figure 4. It is clear from Figure 11 that portrays the sensitivity of mix design technique with respect to cost that the sensitivity for the DOE method with respect to cost ratio is stable when there is a minor change in the cost of weight. However, mix technique preference changes with the major increase in weight (importance) of cost.

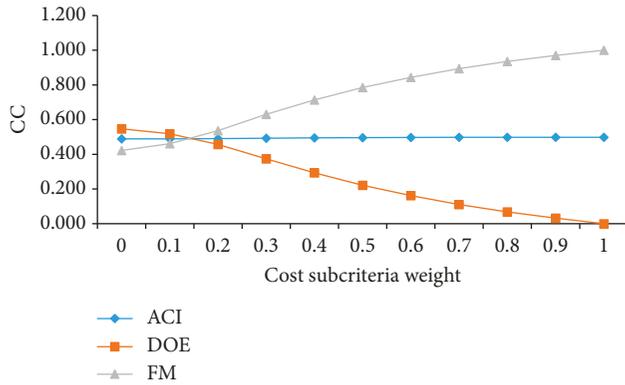


FIGURE 11: Sensitivity analysis of mix methods with respect to cost weight.

## 5. Conclusions

Concrete mix design, i.e., the proportioning of the ingredients of concrete to get the specific performance of concrete, depends on various mix factors related to ingredients of concrete and their combinations. The present research attempts to provide an integrated AHP-TOPSIS-based MCDM model to rank the concrete mix guidelines for performance of concrete under water, sulphate, and chloride attack and performance of concrete for underground conditions and for evolving the performance-based concrete mix design techniques based on the required mix factors.

In the present study, a three-level hierarchical structure to rank the mix design methods for an extreme environment, namely, concrete mix objective criteria, mix factors as subcriteria, and mix design methods as alternatives, is formulated. The sensitivity analysis for the mix design methods and resulting mix factor has also been carried out. It is concluded from the outcomes of the MCDM techniques, AHP and integrated AHP-TOPSIS approach, that the DOE method is the preferred design mix method to design the mix for an extreme environment performance. The sensitivity analysis with respect to the variation of criteria weights, i.e., workability, strength, and durability importance, indicates the stability of the priority of the DOE method. The sensitivity analysis also suggests that when the durability criterion has more weights as compared to workability and strength criterion, the DOE method and ACI method have equal preference. The sensitivity analysis with respect to subcriteria weights also indicates the stability of the priority of the DOE method to the variation in weight of water-cement ratio, fine aggregate-cement ratio, and total aggregate-cement ratio. The preference of the DOE method changes to the FM method with increase in the weights of density, cost, and fine aggregate-total aggregate ratio. The preference of the DOE method changes to the ACI method with increase in the weights of coarse aggregate-cement ratio. The proposed two-phase AHP-TOPSIS approach model may become a promising tool for evolving the performance-based concrete mix technique.

## Abbreviations

ACI:	American concrete institute
AHP:	Analytic hierarchy process
DOE:	Department of energy
TOPSIS:	Technique for order of preference by similarity to ideal solution
VIKOR:	Visekriterijumska optimizacija kompromisno resenje
$A^*$ :	Positive ideal solution
$A^-$ :	Negative ideal solution
CC:	Closeness coefficient
$C_j^*$ :	The relative closeness to ideal solution
CI:	Consistency Index
CR:	Consistency ratio
$D_j^*$ :	Separation distance from ideal solution
$D_j^-$ :	Separation distance from negative ideal solution.

## Data Availability

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Acknowledgments

The authors acknowledge the Deanship of Scientific Research for proving administrative and financial supports. Funding for this work has been provided by the Deanship of Scientific Research, King Khalid University, and Ministry of Education, Kingdom of Saudi Arabia under research grant award number R.G.P.1/82/40 (1440).

## Supplementary Materials

The supplementary file contains Appendix A consists of seven (7) tables as given below. Table A1: pairwise comparison of three criteria for high-performance concrete. Table A2: pairwise comparison of subcriteria (mix factors) with workability criteria (performance). Table A3: pairwise comparison of alternatives with respect to water/cement (w/c) ratio. Table A4: priority weights of three alternatives obtained by AHP with respect to each weights of sub-criterion. Table A5: priority weights of three alternatives obtained by AHP with respect to each weights of sub-criterion (normalized decision matrix). Table A6: priority weights of three alternatives obtained by AHP with respect to each weights of sub-criterion (weighted normalized decision matrix). Table A7: ideal solution ( $A^*$ ) and negative ideal solution ( $A^-$ ). (*Supplementary Materials*)

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