POLİTEKNİK DERGİSİ

JOURNAL of POLYTECHNIC

ISSN: 1302-0900 (PRINT), ISSN: 2147-9429 (ONLINE)
URL: http://dergipark.org.tr/politeknik

Rough-AHP and MOORA-based Taguchi optimization for mixture proportion of building concrete

Bina betonunun karışım oranı için kaba-AHP ve MOORA tabanlı Taguchi optimizasyonu

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To cite to this article: Himmetoğlu S., Kızılkaya Aydoğan E., Özcan F., Karahan O., Atiş C. D., "Rough-AHP and MOORA-based Taguchi optimization for mixture proportion of building concrete", ***Journal of Polytechnic***, 26(4): 1307-1317, (2023).
Bu makaleye şu şekilde atıfta bulunabilirsiniz: Himmetoğlu S., Kızılkaya Aydoğan E., Özcan F., Karahan O., Atiş C. D., "Bina betonunun karışım oranı için kaba-AHP ve MOORA tabanlı Taguchi optimizasyonu", ***Politeknik Dergisi***, 26(4): 1307-1317, (2023).

Erişim linki (To link to this article): http://dergipark.org.tr/politeknik/archive

DOI: 10.2339/politeknik.1018428

Rough-AHP and MOORA-based Taguchi Optimization for Mixture Proportion of Structure Concrete

Highlights

- *Taguchi method*
- *Rough set theory*
- *Analytic hierarchy process*
- *MOORA*
- *Design of experiment*

Graphical Abstract

This paper proposes the Rough-AHP approach in order to determine significance levels of the criteria which affect the performance of the structure concrete according to the customer demands. In addition, the MOORA-based Taguchi optimization method is presented in order to evaluate multi-performance criteria according to the determined significance levels.

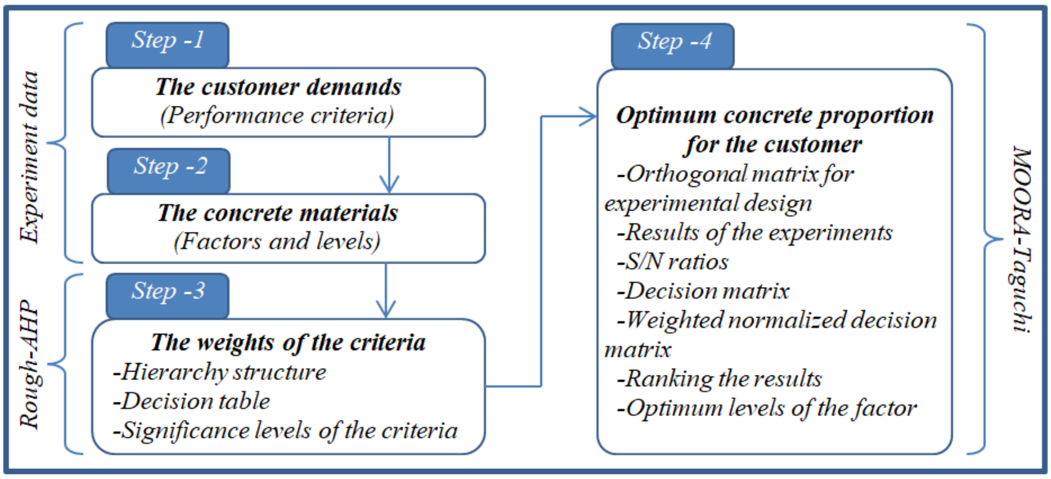

Figure. Proposed approach

Aim

The aim is to determine the optimum mixture proportion of the structure according to the customer demands.

Design & Methodology

The Rough set theory and analytic hierarchy process are used to determine the criteria weights. The MOORA-based Taguchi approach is proposed for the design of experiment.

Originality

The performance criteria are weighted by considering the customer demands and concrete mixture are optimized for multiple criteria.

Findings

Factor-3 (20%), factor-1 (0.3), and factor-3 (450 kg/m^3) are determined for the silica fume, water/cement ratio, and cement dosage in a sample application; respectively.

Conclusion

Considering more than one performance criterion and calculating criterion weights according to customer demands provides more consistent and satisfactory results.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Rough-AHP and MOORA-based Taguchi Optimization for Mixture Proportion of Building Concrete

Research Article / Araştırma Makalesi

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(Received/ Geliş : 05.11.2021 ; Accepted/ Kabul : 19.03.2022 ; Early View/ Erken Görünüm : 18.04.2022)

ABSTRACT

In the construction industry, materials that are used for producing construction concrete and their mixture proportions are an important decision-making and optimization problem for concrete manufacturers. Amounts (mixture proportions) of the materials, which are used in order to obtain a mixture of high strength and functional concrete, can positively or negatively affect performance criteria which are individually determined for each customer. Furthermore, the effect and significance of each performance criterion on the concrete may differ from each other. This paper proposes the Rough-AHP approach to determine the significance levels and weights of the performance criteria decided according to the customer demands and the MOORA-based Taguchi approach to calculate the optimal mixture proportion of the concrete for the customer demand. It is aimed to determine the best design of the experiment to minimize the experiment duration and cost rather than to perform all experimental designs.

Anahtar Kelimeler: Taguchi method, design of experiment, rough set theory, AHP, MOORA.

Bina Betonunun Karışım Oranı için Kaba-AHP ve MOORA Tabanlı Taguchi Optimizasyonu

ÖZ

İnşaat sektöründe inşaat betonu üretiminde kullanılan malzemeler ve bunların karışım oranları beton üreticileri için önemli bir karar verme ve optimizasyon problemidir. Yüksek dayanımlı ve fonksiyonel beton karışımı elde etmek için kullanılan malzemelerin miktarları (karışım oranları) her müşteri için ayrı ayrı belirlenen performans kriterlerini olumlu veya olumsuz etkileyebilir. Ayrıca her bir performans kriterinin beton üzerindeki etkisi ve önemi birbirinden farklı olabilir. Bu makale, müşteri taleplerine göre karar verilen performans kriterlerinin önem düzeylerini ve ağırlıklarını belirlemek için Kaba-AHP yaklaşımını ve müşteri talebi için betonun optimum karışım oranını hesaplamak için MOORA tabanlı Taguchi yaklaşımını önermektedir. Tüm deneysel tasarımların yapılmasından ziyade deney süresini ve maliyetini en aza indirecek deney tasarımının en iyi şekilde belirlenmesi amaçlanmaktadır.

Keywords: Taguchi metodu, deney tasarımı, kaba küme teorisi, AHP, MOORA.

1. INTRODUCTION

Experimental designs are methods that analyze the effects of factors used for experiments according to specific performance criteria called a response. The proportions and the sorts of materials utilized for manufacturing a certain product directly affect the product quality standard. Especially in large-size designs, obtaining the best result from all mixture combinations for various amounts of the materials extends the duration of the design process. The design process becomes more costly, as the variety of materials used in the design increases. Furthermore, significance levels of response(s) are clearly related to the results of the design for decision-making processes. By using experimental design methods, the impact of materials identified as experiment factors on the responses can be determined, and the most suitable result can be obtained through the experimental design methods in a shorter time.

With the development of the construction industry, the variety, and the number of materials used for concrete technology has increased day by day. This makes it difficult to determine the most suitable concrete mix to meets customer demands for concrete manufacturers. Levels of the materials (factors) affect many performance criteria (response) which are crucial for the customers. In addition, the importance of the responses can differ for each customer. Therefore, it would be appropriate for producers to conduct a preliminary study that considers the demands of the customers. Under these conditions,

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developing scientific approaches in order to solve the decision problems can be useful in terms of decision-makers.

Once we research the literature about concrete technology, we can see that different optimization techniques are used to calculate the mixing ratios and quantities of concrete materials. Multiple-criteria decision-making (MCDM) and Taguchi methods can be used to evaluate the influence of the decision variables on the quality of the concrete [1]. Taguchi design, which is one of the experimental design methods, and (MCDM) approaches are convenient methods to analyze quality and importance level of performance criteria. Muthukumar and Mohan [2] studied polymer concrete based on experimental design. Ozbay et al. [3] generated an experimental design by using the Taguchi approach for high strength self-compacting concrete (HSSCC). Hinislioglu and Bayrak [4] studied on the pavement concrete by considering the fly ash and silica fume via Taguchi design. Şimşek et al. [1] studied the Taguchi method based on TOPSIS for HSSCC. They also used Response Surface Method and compared the two approaches. Tanyildizi and Şahin [5] studied on concrete with polymer after high temperature by using the Taguchi method. By using the Taguchi design, Joshaghani et al. [6] and Hadi et al. [7] studied on pervious concrete and geo-polymer concrete; respectively. Kate and Thakare [8] investigated sustainable fly ash concrete through the Taguchi approach. Emara et. al [9] studied on prediction of the rubberized self-compacting concrete (RSCC) by using the Taguchi method. Ghazy and El Hameed [10] discussed the multi-criteria design of the light-weight concrete for an optimal parametric combination to yield favorable compressive strength and density the with the Gray-Taguchi method. Multi-criteria decision-making models were a few used for the structure industry. Almost all of these studies are not about concrete design and optimization problems (see; [1, 11-15]).

The Taguchi method usually analyzes the effects of factors for one performance criterion. If the influences of multiple performance criteria are subjected to analysis, the MCDM models could be utilized along with the Taguchi method. Şimşek et al. [1] used the TOPSIS method along with the Taguchi method. Although they solved the problem for multiple-response design, importance levels, and weights of the responses were determined on the basis of experience without any approach. That is, the importance levels of responses have not been taken into consideration for customers. If the customer demands are considered to determine the levels, results will be more suitable. According to the answers given by the customers in the pre-prepared questionnaires, the importance level of each response can be determined for customers. Thus, customers can be included in experimental design. Şimşek et al. [13] presented a hybrid algorithm that includes a fuzzy-based TOPSIS approach, Taguchi design, and artificial neural network in order to both reduce production costs and determine the optimal parameter set in a multi-response ready-mixed concrete design. Şimşek and Uygunoğlu [14] presented a MCDM model by using the TOPSIS-based Taguchi method for polymer-based concrete design. They aimed to obtain the most suitable mixture ratio of the concrete materials to achieve acceptable compressive strength and the desired thermal insulation level. Prusty and Pradhan [15] designed a MCDM model based on the Grey-Taguchi approach for the geo-polymer concrete with the ground granulated blast furnace slag and fly ash.

Although the aforementioned studies calculate concrete mixture proportion according to certain performance criteria using experimental design methods, they do not consider the importance level(s) of the performance criterion (or criteria) for concrete. However, the importance of performance criteria in concrete may differ for customer demands. This paper, to the best of the authors' knowledge, is the first to present an experimental design that takes into account multiple performance criteria and their significance in accordance with customer demands. According to this scope, Rough-AHP and MOORA-based Taguchi method is proposed to calculate the concrete mixture considering the customer demands. Importance levels of the performance criteria (responses) are determined by using Analytic Hierarchy Process (AHP) and Rough Set methods. According to the importance levels, a decision matrix is obtained by Signal/Noise (S/N) ratios. Then, the MOORA method, which is one of the MCDM models, is utilized in order to convert the MCDM problem into a single-response problem. The values obtained are used by the Taguchi method, and the levels of the factors optimizing the design of the experiment were determined.

The remainder of the paper is as follows: Section 2 presents the AHP method based on the rough set theory (Rough-AHP) used for determining levels of responses. Section 3 is about the MOORA-based Taguchi approach. In section 4, we state Rough-AHP and MOORA-based Taguchi approach, and last section includes the conclusion chapter.

2. METHODOLOGY

2.1. Rough-AHP Approach

First introduced by Myers and Alpert [16] in 1968, AHP, which is the multiple-criteria decision-making technique, was used for different decision-making processes by Saaty [17]. AHP basically assumes that the criteria in each level can be used in an upper part of the hierarchy [18]. AHP has three basic principles. The first is the structure of the hierarchy. The structure of the hierarchy generally consists of three layers. The matrix of pairwise comparison is the second principle that is the most important step for AHP. The last one is to calculate the weights of criteria. AHP is quite associated with human bias. In the pairwise comparisons matrix, the subjectivity of the decision-makers is quite dominant. Since the matrix of pairwise comparison may be adversely affected by the bias (subjectivity) of the evaluator, this causes the inconsistency of the comparison matrix [19]. The 'acceptability' for different values of the attributes may change according to the alternatives. For example, for two alternatives consisting of three attributes, while two of the attributes are the same and one is different, one of the alternatives may be accepted by the decision-maker while the other may not. Therefore, in order to eliminate judgment inconsistency, the concept of attribute significance, and conditional entropy were used in rough sets theory in this study. Hence, the dominance of the decision-maker(s) can be reduced. Related descriptions are shown in the following [20].

Data table R consists of the 4-tuple; O is a finite set of objects, S is combination of P and Q sets. P is the condition feature set, and Q is the decision feature set. W_s is domain of the feature s. W is a total function and $f(y,s) \in W_s$. $R = \{O, R, V, f\}$; $S = P \cup Q$; $W = O_{s \in S} W_s$; $f: OxS \rightarrow W$; $\forall s \in S$; and $\forall y \in O$.

$$\mathrm{IND(A)} = \{(y,x) | (y,x) \in OxO, \forall a \in A(a) = a(x))\}$$
and and $R(A \subseteq S)$ (1)

where, $IND(A)$ represents every non-empty subset A of features with an indiscernibility relation (IND) on Q. The IND can be defined as reflexive, transitive, and symmetric.

Description 2.1

$$H(C) = -\sum_{i=1}^{n} C(Y_i)\log C(Y_i), \text{ and } C(Y_i) = |Y_i|/|O| \quad (2)$$

where, C is the knowledge of the feature set, and $H(C)$ represent the entropy of knowledge C. $C(Y_i)$ is the probability of the Y_i ($i = 1,2,\dots,n$).

Description 2.2

$$H(D|C) = -\sum_{i=1}^{n} C(Y_i) \sum_{j=1}^{m} C(X_j|Y_i) \log C(X_j|Y_i) \quad (3)$$

where, $H(D|C)$ represent conditional entropy. $C(X_j|Y_i)$ represents conditional probability. C and D is the conditional knowledge of $O|IND(C) = \{Y_1, Y_2, \dots, Y_n\}$ and $O|IND(D) = \{X_1, X_2, \dots, X_m\}$; respectively.

Description 2.3

$$SGF(b,B,Q) = H(Q|B) - H(Q|B \cup \{b\}) \quad (4)$$

Suppose that Description 2.1 and 2.2 are provided. Then, $SGF(b,B,Q)$ is the significance level of the feature (attribute) and it is calculated by using the Eq. 4. According to given attribute subset $B(b \in P/b)$, the greater the value of $SGF(b, B, Q)$ is directly proportional to attribute b is for decision Q.

2.2. MOORA-based Taguchi Approach

The Taguchi method, which was presented by Genichi Taguchi, is one of the experimental design techniques. The method based on an orthogonal array of experiments gets help from statistical tools. The orthogonal array ensures to be reduced variance in the experiments. Responses that are obtained according to orthogonal array experiments are converted into S/N ratios. The S/N, which is used as the objective function in Taguchi design, is a logarithmic function including the responses of the criteria. Although the conventional Taguchi method is an important technique for product designs, it can evaluate only one output (response) at a time [1, 23]. The customers, however, generally want to consider many outputs together. Also, the importance of each output can change for each customer. The four basic phases should be considered in order to decide for more than one output (response) in the Taguchi method [24-25]. First, since the measurement units of outputs may be different from each other, the losses due to the measurement units may be different. Second, since the loss functions are always different for each output, the losses cannot be directly summed and compared. The third is the importance level of the outputs. Forth, once the nominal-the-best quality characteristics exist in the multi-response problems adjustment factors should be chosen. Therefore, the MCDM approaches could be applied with Taguchi design for solving complex decision problems. MOORA method can transform related performance criteria into a single output. In this study, after the MOORA method is applied to transform multi-responses decision and optimization problems to decision and optimization problems with a single response, the Taguchi method was used for generating the best suitable concrete mixture. Thus, the multi-objective design of mixture proportions of concrete is effectively solved.

The MOORA-based Taguchi approach provides a robust design method in order to obtain the multi-objective concrete mix design. The optimum quantities of the factors and levels in the design can be determined through this robust design. The design results have high performance, reduced variance, and noise factors ([21-22]). The noise factors are uncontrollable variables in the experimental design. The noise factors can adversely affect the quality of products and design processes. In order to remove the quality losses, S/N ratios are calculated according to the results of the determined responses. The S/N ratios ensure a reliable product design. Many different criteria can be treated as dynamic characteristics. S/Ns are generally calculated in two ways for the responses. These are 'the larger is better' and 'the smaller is better' formulations. If the response needs to be high, the formulation 'larger is better' should be selected. Otherwise, the formulation 'smaller is better' should be selected. 'The larger is better' and 'the smaller is better' formulations are shown in Eqs. 5 and 6; respectively [21].

$$x_{ij} = -10\log[\tfrac{1}{n}\sum_{k=1}^{n} \tfrac{1}{y_{ijk}^2}] \quad (5)$$

$$x_{ij} = -10\log[\tfrac{1}{n}\sum_{k=1}^{n} y_{ijk}^2] \quad (6)$$

where, y is the result of the related experiment. x is the S/N of the experiment result. i ($i = 1,2,\dots,I$) is the index of the related experiment. j ($j = 1,2,\dots,J$) is the index of the related response. k is the replication index of the experiment j ($k = 1,2,\dots,n$). n is the number of the replications for response i and experiment j. After the S/Ns of the responses are obtained, the multi-objective problem is transformed into a single-objective problem by using Descriptions 2.4 - 2.7 defining the basic requirements of the MOORA approach.

Description 2.4

The decision matrix (X_{ER}) is obtained according to the calculated S/Ns. The decision matrix is shown Eq. 7. In the decision matrix, the rows $(e = 1,2,\dots,E)$ and columns $(r = 1,2,\dots,R)$ represent experiments and performance criteria (responses), respectively. That is, x_{er} represents the S/N for the experiment e and the response r.

$$X_{ER} = \begin{bmatrix} x_{11} & \cdots & x_{1r} \\ \vdots & \ddots & \vdots \\ x_{e1} & \cdots & x_{er} \end{bmatrix}_{ExR} \tag{7}$$

Description 2.5

Normalized ratings (x_{er}^*) are calculated for each criterion. The normalized rating formula is shown Eq. 8.

$$x_{er}^* = -\frac{x_{er}}{\sqrt{\sum_{e=1}^{E} x_{er}^2}} \text{ for } e = 1,\dots,E;\ r = 1,\dots,R \tag{8}$$

Description 2.6

A weighted normalized decision matrix is generated. w_r represents the weight of the response r calculated through the Rough-AHP approach.

$$U = [u_{er}]_{ExR}, \text{ and } u_{er} = x_{er}^* w_r \text{ for } e = 1,\dots,E;\ l = 1,\dots,R \tag{9}$$

Description 2.7

Weighted normalized performance criteria are added up for maximization and extracted for minimization. y_r^* represents normalized values for alternative (experiment) e in terms of whole objectives. g and n represent maximized and minimized objectives, respectively.

$$y_r^* = \sum_{e=1}^{g} u_{er} - \sum_{r=g+1}^{n} u_{er} \tag{10}$$

3. PROPOSED APPORACH: ROUGH-AHP AND MOORA -BASED TAGUCHI METHOD

The proposed approach in this study consists of four main steps. Step 1: determining the criteria and optimization goal, Step 2: determining the factors and levels for the experimental design; Step 3: calculating the weights of performance criteria, and Step 4: determining the most suitable concrete mixture proportion. The proposed approach's diagram is illustrated in Fig. 1.

Determine performance criteria and optimization goals of concrete: Evaluation of the mixture results of the experimental design is a quite important issue. Optimization methods and experimental design techniques are quite successful to produce customer-focused quality concrete. This paper considered flow table test value (cm), saturated dry surface weight (t/m^3), compressive strengths for 3, 7, and 28 days (MPa), and ultrasonic sound wave (km/s) as performance criteria. The proposed approach is flexible in terms of the designers for the different performance criteria and responses. The main aim is to evaluate the best possible levels of material rates in the concrete mixture for related factors according to these performance criteria. MINITAB 16 statistical program is used in order to generate the orthogonal array experiment and apply the Taguchi method.

Define the factors and their levels of mixture proportions: The design of the experiment consists of three factors, each of which has three levels in this study. These factors are silica fume, water/cement ratio, and cement dosage which are symbolized as A, B, C respectively. The levels of the factors are presented in Table 1. The silica fume is included in the dosage for the experimental design. For example, 10% silica fume for 400 kg dosage is evaluated as 360 kg cement and 40 kg silica fume.

The diameters of the aggregates used in the application and the Turkish Standards Aggregates for Concrete (TS-706) bounds are given in Table 2. The grain size curves of the aggregates are also given in Fig. 2.

Table 1. Levels of the factors mixture proportions

Factors	Definition	Levels		
		I	II	III
A	Silica fume (%)	10	15	20
B	Water/cement ratio	0.3	0.4	0.5
C	Cement dosage (kg/m^3)	350	400	450

Calculate the importance level and weights of responses through the Rough-AHP approach: Initially, the hierarchy of the problem should be determined to use the Rough-AHP method. In order to determine the hierarchy of the problem, number of experiments is required. According to the Taguchi design, the L9 orthogonal array matrix or L27 orthogonal array matrix can be chosen for available factors and levels. Since 27 tests will be more

Table 2. The aggregate diameter and TS-706 bounds

Sieve opening (mm)	The % amount passing through the sieve			
	Used aggregate	TS-706 lower bound	TS-706 middle bound	TS-706 upper bound
16	100	100	100	100
8	76.4	60	76	88
4	44.8	36	56	74
2	27	21	42	62
1	20.5	12	32	49
0.5	15.2	7	20	35
0.25	4.2	3	8	18

costly and take more time than 9 tests, the L9 orthogonal array matrix is chosen.

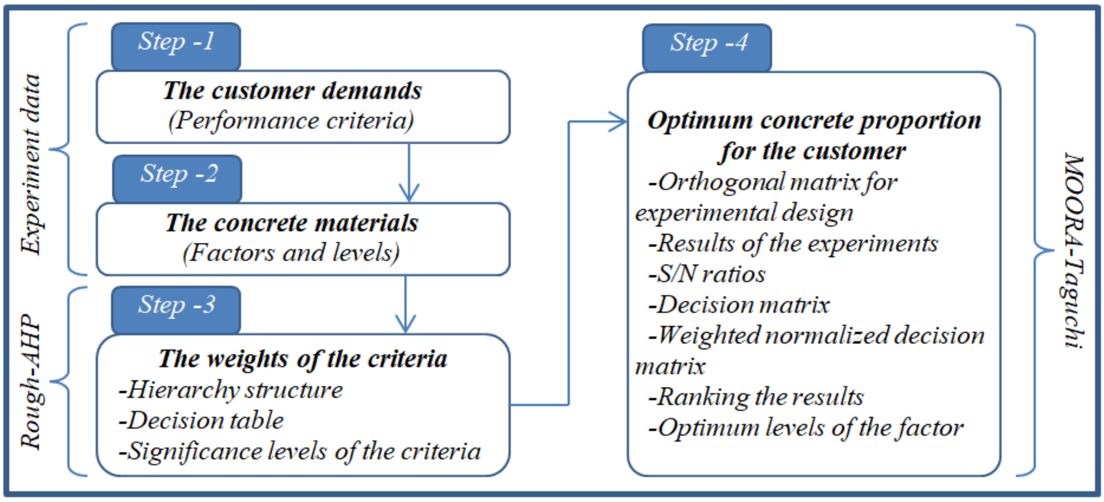

Fig. 1. Proposed approach

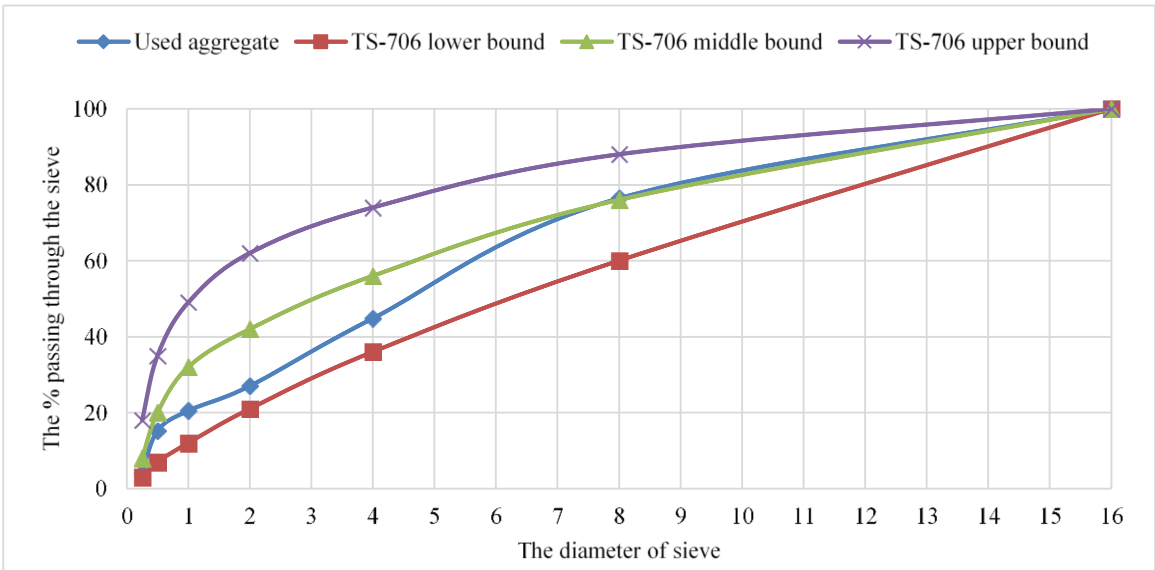

Fig. 2. The grain size curve of the aggregates

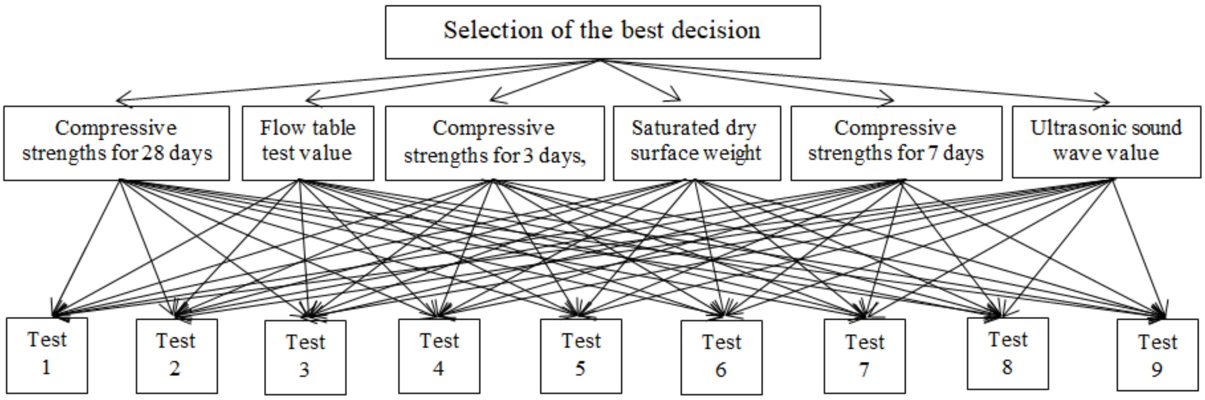

Fig. 3. The hierarchy structure

The hierarchy structure of the responses is presented in Fig. 3. After generating the hierarchy structure, the decision table was prepared. In Table 3, rows and columns Show the alternatives and the performance criteria, respectively. Flow table test value, compressive strengths (3, 7, and 28 days), ultrasonic sound wave value and saturated dry surface weight were rated using the 1 (the highest), 2 (high), 3 (medium), 4 (low), and 5 (the lowest) values. These values were randomly assigned to the criteria without being shown to the decision-makers in Table 3. These rates were used to determine the performance of the criteria for each alternative. The decision table, which was randomly generated from 27 different combinations, has been made before the assessment process. Generating these combinations, it is necessary to choose a set that can represent all combinations. If a different set is chosen that can represent all combinations, roughly the same levels of importance will be obtained. The number of combinations can be increased. Other alternatives may also be considered. It can be thought that the increase in the number of combinations increases the reliability of the method. Here, the number of combinations is not important. The important thing is to obtain an appropriate decision column to avoid inconsistencies in the pairwise comparisons matrix. The whole decision column may change when other alternatives are used. Even all column values may be ‘0’ or ‘1’. This situation will not represent all alternatives anyway. Furthermore, the consistency of the pairwise comparisons matrix will not be satisfactory anyway. Initially, the decision column is empty. This column is filled by asking fifteen experts. If the decision column is ‘1’, this stands for “this concrete is acceptable”. The value ‘0’ in the decision column stands for “this concrete is not acceptable”. For example, while the first row expresses that “this concrete is acceptable”, the third row expresses that “it is not acceptable”. Thus, it is aimed to generate a more consistent pairwise comparison matrix. In the decision table, the letter *a* means compressive strength for 28 days. The letter *b* represents the flow table test value of the concrete. The letter *c* means compressive strength for 3 days. The letter *d* represents the saturated dry surface weight of the concrete. The letter *e* means compressive strengths for 7 days. Finally, the letter *f* stands for ultrasonic sound wave value of the concrete.

We can calculate significances for each criterion after the decision table is built. For example, the significance of compressive strength for 28 days of the concrete is calculated as follows;

$O|IND\{a,b,c,d,e,f\} = \{\{1\},\{2\},\ldots,\{26\},\{27\}\}$,

$O|IND\{D\} = \{D_1, D_2\} = \{\{1,2,4,5,6,10,11,13,14,17,24,26\},\{3,7,8,9,12,15,16,18,19,20,21,22,23,25,27\}\}$

where, D_1 and D_2 represent the set of acceptable rows and the set of unacceptable rows, respectively.

$O|IND\{b,c,d,e,f\} = \{X_1,X_2,X_3,X_4,X_5,\} = \{\{1,2,3\},\{5,6,7\},\{4,8\},\{9,10\},\{11,12\}\}$,

Table 3. Decision table fort he concrete design prepared by the experts

Alternatives	*a*	*b*	*c*	*d*	*e*	*f*	Decision
1	1	1	3	2	2	3	1
2	2	1	3	2	2	3	1
3	4	1	3	2	2	3	0
4	1	3	2	2	4	3	1
5	1	2	2	3	4	5	1
6	2	2	2	3	4	5	1
7	4	2	2	3	4	5	0
8	3	3	2	2	4	3	0
9	2	4	3	2	3	3	0
10	1	4	3	2	3	3	1
11	1	3	1	4	1	1	1
12	4	3	1	4	1	1	0
13	2	2	3	2	3	3	1
14	3	1	2	2	4	3	1
15	2	5	3	2	2	3	0
16	3	5	2	2	4	3	0
17	3	3	1	2	4	5	1
18	1	3	5	2	4	3	0
19	2	2	5	3	4	5	0
20	3	3	1	4	4	5	0
21	3	4	1	4	4	5	0
22	1	4	3	2	5	3	0
23	1	3	1	4	5	1	0
24	2	3	4	3	3	1	1
25	2	3	4	3	3	5	0
26	2	3	1	2	4	4	1
27	2	3	5	2	4	4	0

$P(X_1) = {}^{3}/_{27}, P(X_2) = {}^{3}/_{27}, P(X_3) = {}^{2}/_{27}, P(X_4) = {}^{2}/_{27}, P(X_5) = {}^{2}/_{27},$

$P(D_1|X_1) = {}^{1}/_{2},\ P(D_1|X_2) = {}^{2}/_{3},\ P(D_1|X_3) = {}^{1}/_{2}, P(D_1|X_4) = {}^{1}/_{2}, P(D_1|X_5) = {}^{1}/_{2},$

$P(D_2|X_1) = {}^{1}/_{3},\ P(D_2|X_2) = {}^{1}/_{3},\ P(D_2|X_3) = {}^{1}/_{2}, P(D_2|X_4) = {}^{1}/_{2},\ P(D_2|X_5) = {}^{1}/_{2},$

$$SGF\{a,\{b,c,d,e,f\}\},\{D\} = -\frac{3}{27}\left[\frac{2}{3}log\left(\frac{2}{3}\right) + \frac{1}{3}log\left(\frac{1}{3}\right)\right]2 - \frac{2}{27}\left[\frac{1}{2log\left(\frac{1}{2}\right)} + \frac{1}{2log\left(\frac{1}{2}\right)}\right]3 \cong 0.128$$

We calculated the significance of compressive strengths for 28 days criterion is 0.128. If the same process is applied for the other criteria, we can calculate that the significance of the flow table test value criterion is 0.075; the significance of compressive strengths for 3 days criterion is 0.067; the significance of saturated dry surface weight criterion is 0.0307; the significance of compressive strengths for 7 days criterion is 0.0446, and the significance of ultrasonic sound wave value criterion is 0.022. The weight of each criterion is calculated by dividing the importance of each criterion by the total importance ($w_i = {SGF_i}/{\sum SGF_i}, i = a, b, c, d, e, f$). For example, the weight of criterion a is 0.128/0.363=0.348. According to the obtained results, the weights of the responses are determined as 0.348, 0.205, 0.182, 0.083, 0.121, and 0.061, respectively.

According to the obtained weight values, the pairwise comparison judgment matrix was generated in order to apply the AHP method. For performance criteria *a*, *b*, *c*, *d*, *e*, and *f*, the judgment matrix D is generated as follows in accordance with the weights of the criteria:

$$D = \begin{bmatrix} {w_1}/{w_1} & \cdots & {w_1}/{w_n} \\ \cdots & \ddots & \vdots \\ {w_n}/{w_1} & \cdots & {w_n}/{w_n} \end{bmatrix}$$

$$D = \begin{bmatrix} 1 & 1.707 & 1.91 & 4.129 & 2.844 & 5.818 \\ 0.586 & 1 & 1,119 & 2.419 & 1.667 & 3.409 \\ 0.523 & 0.893 & 1 & 2.161 & 1.489 & 3.045 \\ 0.242 & 0.413 & 0,463 & 1 & 0.689 & 1.409 \\ 0.352 & 0.6 & 0,672 & 1.452 & 1 & 2.045 \\ 0.172 & 0.293 & 0.328 & 0.71 & 0.489 & 1 \end{bmatrix}$$

The consistency index (CI) value is needed to check the accuracy of the pairwise comparison matrix. The CI value is calculated as Eq. 11. The largest eigenvalue is required in order to calculate the CI. The largest eigenvalue is calculated using Eqs. 12-14.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (11)$$

$$N = D w_{D_{nr}} \quad (12)$$

$$\lambda_i = \frac{N_i}{w_{D_{nr}i}} \text{ for } i = 1, \dots, n \quad (13)$$

$$\lambda_{max} = \frac{\sum_{i=1}^{n} \lambda_i}{n} \text{ for } i = 1, \dots, n \quad (14)$$

where, λ_{max} is the largest eigenvalue, n is the rank of the judgment matrix. $W_{D_{nr}}$ is the average of each row in the normalized judgment matrix. N is the matrix consisting of the multiplication of the judgment matrix and the normalized average. λ_i is the eigenvalue of criterion *i*. As a result, λ_{max} is calculated as 6 for matrix D, and n is also 6. According to Eq. 11, CI is equal to zero for matrix D. These results show that the Rough-AHP approach presents complete consistency for the pairwise comparison matrix.

MOORA-based Taguchi approach: In Taguchi design, orthogonal array L9 or L27 can be selected for this study. As mentioned before, the L9 orthogonal array matrix was preferred since 27 tests were more costly and take more time than 9 tests. After the experimental design was determined, the results of the experiments were obtained. Each experiment was performed once. The number of experiments can be enhanced to increase the reliability of the experiments. The factors, their levels, and response values are shown in Table 4.

S/N ratios were calculated with Eq. 5-6 for performance criteria. The target value of performance criteria, importance, and weight are shown in Table 5. After S/N ratios were calculated according to target values, the decision matrix was generated for S/N ratios in Table 6a (Eq. 7). Then normalized ratings were calculated for each criterion by using Eq. 8. The normalized ratings and the weights calculated through the Rough-AHP method were used for calculating the weighted normalized decision matrix in Table 6b (Eq. 9). Then MOORA method was applied to transform all performance criteria into a single response. By using Eq. 10, weighted normalized performance criteria were summoned up for maximization and extracted for minimization in Table 6c. In Table 6c, the last column shows the final result.

Table 4. L9 experimental design and resutls of experiments

Experiment number	Factors and levels			Responses (Performance criteria)					
	A (%)	B	C (kg/m^3)	*a* (MPa)	*b* (cm)	*c* (MPa)	*d* (t/m^3)	*e* (MPa)	*f* (km/s)
1	1	1	1	83.5	42	46.2	2.51	64.4	5.09
2	1	2	2	88	51	53.3	2.49	62	5.02
3	1	3	3	55.8	57	30.8	2.37	41	4.75
4	2	1	2	90.5	50	51.8	2.47	65.1	4.93
5	2	2	3	87.7	55	44	2.49	65	4.1
6	2	3	1	63.6	47	34.7	2.5	46.5	4.94
7	3	1	3	101	55	55.6	2.49	77.2	5.15
8	3	2	1	87.9	51	45.4	2.5	62.2	4.82
9	3	3	2	58	46	28.1	2.41	42.3	4.84

Results obtained by using the MOORA method are analyzed for Taguchi design in Minitab Statistical Program Package (Table 7). The main effects plot for means is illustrated in Fig.4.

The most suitable experimental design obtained by the Taguchi method is A3B1C3. Since the Taguchi method is based on a point estimate, confidence intervals were calculated for each level of each factor. The values at the

Table 5. Target values and weights of criteria

Symbols of criteria	Target values	Importance	Weights
a	larger is better	0.128	0.348
b	larger is better	0.075	0.205
c	larger is better	0.067	0.182
d	smaller is better	0.031	0.083
e	larger is better	0.045	0.121
f	larger is better	0.022	0.061

Table 6a. Target values and weights of criteria

Responses	*a* (MPa)	*b* (cm)	*c* (MPa)	*d* (t/m^3)	*e* (MPa)	*f* (km/s)
Weights	0.348	0.205	0.182	0.083	0.121	0.061
Experiment number	Target values					
1	38.434	32.46499	33.293	-7.993	36.1777	14.1344
2	38.89	34.1514	34.535	-7.924	35.8478	14.0141
3	34.933	35.1175	29.771	-7.495	32.2557	13.5339
4	39.133	33.9794	34.287	-7.854	36.2716	13.8569
5	38.86	34.80725	32.869	-7.924	36.2583	12.2557
6	36.069	33.44196	30.807	-7.959	33.3491	13.8745
7	40.086	34.80725	34.901	-7.924	37.7523	14.2361
8	38.88	34.1514	33.141	-7.959	35.8758	13.6609
9	35.269	33.25516	28.974	-7.64	32.5268	13.6969
Square root of sum of squares	113.64	102.0873	97.715	23.562	105.58	41.1212

Table 6b. The weighted normalized decision matrix

Responses	*a* (MPa)	*b* (cm)	*c* (MPa)	*d* (t/m^3)	*e* (MPa)	*f* (km/s)
Experiment number	The weighted normalized values					
1	0.1177	0.0652	0.062	-0.0282	0.0415	0.021
2	0.1191	0.0686	0.064	-0.0279	0.0411	0.0208
3	0.107	0.0705	0.055	-0.0264	0.037	0.0201
4	0.1198	0.0682	0.064	-0.0277	0.0416	0.0206
5	0.119	0.0699	0.061	-0.0279	0.0416	0.0182
6	0.1105	0.0672	0.057	-0.028	0.0382	0.0206
7	0.1228	0.0699	0.065	-0.0279	0.0433	0.0211
8	0.1191	0.0686	0.062	-0.028	0.0411	0.0203
9	0.108	0.0668	0.054	-0.0269	0.0373	0.0203

Table 6c. MOORA application results

Experiment number	Maximization	Minimization	Results	Ranks
1	0.30732	-0.0282	0.2792	6
2	0.31386	-0.0279	0.2859	3
3	0.28998	-0.0264	0.2636	8
4	0.31405	-0.0277	0.2864	2
5	0.30985	-0.0279	0.2819	5
6	0.29379	-0.028	0.2658	7
7	0.32204	-0.0279	0.2941	1
8	0.31074	-0.028	0.2827	4
9	0.28634	-0.0269	0.2594	9

95% confidence interval for each level of each factor are shown in Fig. 5 and Table 8.

Fig. 4. Optimum levels of factors

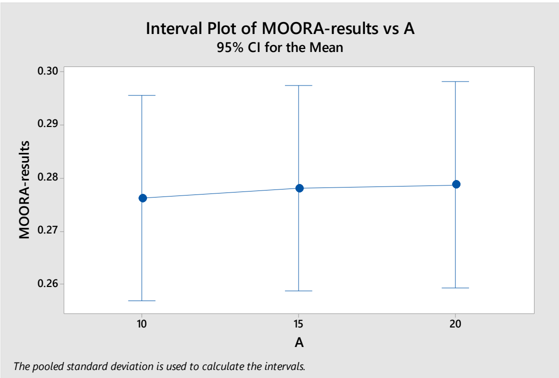

Fig. 5a. Interval plots of factor A and levels

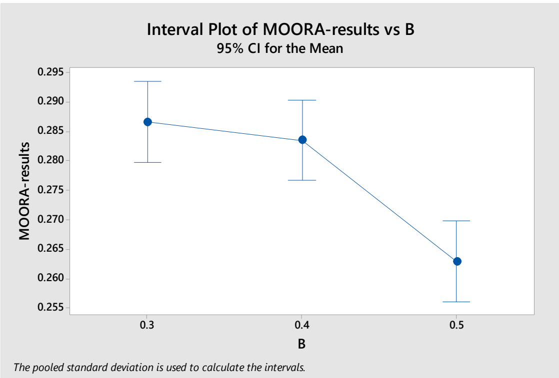

Fig. 5b. Interval plots of factor B and levels

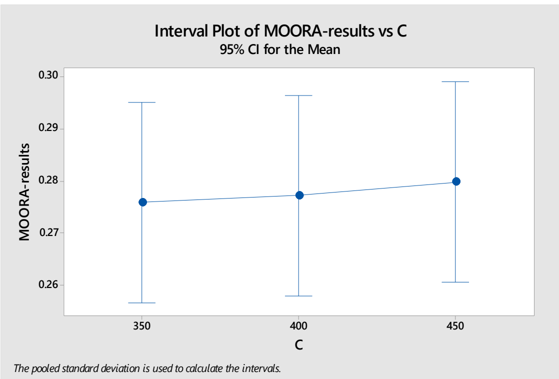

Fig. 5c. Interval plots of factor C and levels

Table 8. The confidence interval for factors and levels

Factors	Levels	Mean	StdDev	95% ConfInt
A	10	0.276	0.0114	(0.25691; 0.29555)
	15	0.278	0.0108	(0.25871; 0.29735)
	20	0.279	0.017	(0.2594; 0.2981)*
B	0.3	0.286	0.007	(0.27971; 0.29342)*
	0.4	0.283	0.002	(0.27665;0.29035)
	0.5	0.263	0.003	(0.25608; 0.26979)
C	350	0.276	0.008	(0.25671; 0.29509)
	400	0.277	0.015	(0.25804; 0.29643)
	450	0.279	0.015	(0.26067; 0.29906)*

*The estimated mixture level

4. DISCUSSION AND CONCLUSION

In experimental designs, a systematic method is required for optimizing the effects of a lot of performance measurements based on the specific factors and their levels. In this paper, the Rough-AHP approach is applied in order to analyze the impacts of the performance criteria and the MOORA-based Taguchi approach is proposed to determine the most suitable mixture ratios according to customer demands in the concrete design.

Weights of the responses are found for the following: the weight of compressive strength for 28 days is 0.348, the weight of flow table test value is 0.205, the weight of compressive strengths for 3 days is 0.182, the weight of saturated dry surface weight is 0.083, the weight of compressive strengths for 7 days is 0.121, and the weight of ultrasonic sound wave value is 0.061.

The matrix size of the factors and their levels is a 3x3 matrix. This means that we could do 27 different experiments. However, the optimum mixture was calculated by using 9 tests through the Taguchi method. In this way, the experimental study has been less costly. No matter how many factors and levels increase, optimum results can be calculated by using the Taguchi method. But, levels of factors should be convenient for any orthogonal array. If the Taguchi method is wanted to be used for a multi-objective problem, the problem should be transformed into a single-objective problem. In this paper, the MOORA method was applied in order to transform the problem into a single-objective problem. Optimum levels of factors were determined by using MINITAB 16 Statistical Program Package as the following: 20% for silica fume, 0.3 for water to cement ratio, and 450 kg/m^3 for cement dosage. In this study, the concrete strength, i.e., the compressive strength for 28days, was determined as 101 MPa. Here, the aim is to determine the high-strength concrete mixture according to the predetermined performance criteria. According to these results, while the highest silica fume ratio and cement dosage were preferred for the mixture ratio, the lowest water/cement ratio was preferred. It can be seen that this design aims to keep the mechanical properties of the concrete such as strength at the highest level.

However, the water/cement ratio determines the consistency of the concrete mixture. Increasing the amount of water may adversely affect the strength of concrete. On the other hand, if the amount of water is kept low, the reaction between binders and water, i.e. hydration, may not occur properly. This may affect the mechanical properties of concrete. After the optimum design was produced, it was seen that no problem has emerged that will adversely affect the performance criteria. In addition, note that the weight of the three performance criteria (compressive strengths for 3, 7, and 28 days) considering the strength of concrete was determined as approximately 65% in the experimental design. This may be one of the main reasons for choosing the highest silica fume and cement dosage and the lowest water/cement ratio. The weight of the flow table test, which determines the consistency of the concrete, is approximately 20%. If parameters such as attributes affecting hydration and cost are added among the performance criteria, the obtained mixture ratio may change. The performance criteria and experimental designs may vary according to the demands of the customers.

Once the Rough-AHP and MOORA-based Taguchi methods are used together, these methods can give convenient results for various study fields.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Salih HİMMETOĞLU: Wrote the manuscript, prepared the methodology, and applied the methodology.

Emel KIZILKAYA AYDOĞAN: Wrote the manuscript, prepared the methodology, and applied the methodology.

Fatih ÖZCAN: Performed the experiments and analyzed the results.

Okan KARAHAN: Performed the experiments and analyzed the results.

Cengiz Duran ATİŞ: Performed the experiments and analyzed the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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