Hindawi
Advances in Civil Engineering
Volume 2023, Article ID 4421095, 14 pages
https://doi.org/10.1155/2023/4421095

Research Article

Determination of Optimized Mix Design of Reactive Powder Concrete

Abbas Moslehi,[1] Mohammad Ali Dashti Rahmatabadi ,[1] and Hosein Arman [2]

[1]*Department of Civil Engineering, Yazd Branch, Islamic Azad University, Yazd, Iran*
[2]*Department of Management, Najafabad Branch, Islamic Azad University, Najafabad, Iran*

Correspondence should be addressed to Mohammad Ali Dashti Rahmatabadi; dashti@iauyazd.ac.ir

Received 29 August 2022; Revised 5 December 2022; Accepted 13 January 2023; Published 7 February 2023

Academic Editor: Pier Paolo Rossi

There are different types of reactive powder concrete (RPC) and researchers continue to develop better-quality mix designs. This research presents an integrated approach for RPC mix design. For this purpose, 13 RPC mix designs were collected according to expert opinion and laboratory samples and were tested in this study for validation of the characteristics of compressive strength and water absorption. The samples were then ranked using the simple additive weighting (SAW) method, and three highest-quality RPCs were selected for the Taguchi method. These RPCs were used to prepare 27 experimental RPC mix designs applying the Taguchi method. From the experimental results, compressive strength with 0.38–0.76% and water absorption with 0.50–0.99% differences were more appropriate in compliance with the collected data. Also, results from the 27 mix designs investigated by the Taguchi method revealed the optimized mix design for the maximum compressive strength with 146.7 MPa and the optimized mix design for the minimum water absorption with 0.89%. The results showed that our approach was consistent with the results of classic methods that require a large number of samples. This suggests that integrating the SAW and Taguchi methods is an appropriate approach for screening and optimizing RPC mix design.

1. Introduction

Reactive powder concrete (RPC) is an ultrahigh-performancecement-based composite concrete in which the traditional coarse aggregate has been replaced by fine sand [1–9]. The term “reactive powder” means that all the powder components in the RPC are chemically reactive [10]. The main ingredients of RPC include a high percentage of a very fine powder, such as ordinary Portland cement, a very low water-to-binder ratio, superplasticizer, grey sand, and quartz powder [9, 11]. RPC was introduced in 1995 and was used for the first time to construct a pedestrian bridge in Sherbrooke, Canada in 1997 [12, 13]. It is useful in construction applications that require strong and durable structures with optimal material usage, because of its superior mechanical and durability properties, high strength, and good performance [10, 14, 15]. RPC has excellent properties, especially compressive strength, that provide a combination of ultrahigh strength and excellent durability [16, 17]. RPC is a special type of concrete with remarkable properties, particularly compressive strength [17]. In fact, achieving the highest compressive strength is the main target in the development of RPC mix designs [10]. Two essential factors affect RPC compressive strength. The first is the selection of the proper and exact ingredients and the second is the choice of the type, duration, and temperature of curing [10]. For example, a gradation of fine aggregate can achieve the densest stacking state gradation after optimizing the mix proportion [18]. Also, reducing the particle size of the calcium carbonate will increase the hydration reaction and improve the reduction of shrinkage volume, which will minimize shrinkage cracks and increase the compressive strength [19].

RPC production methodology has not been clearly established because several parameters have varied influences on the resulting fresh and hardened properties of the concrete [19]. These properties differ significantly, even for the same composition, if the mixing method, mixing speed, and/or mixing duration is altered. Also, the application of pressure under different heat treatments during concrete curing can cause the RPC to become denser [10]. Utilization of fly ash (FA) and ground granulated blast-furnace slag (GGBFS) is more desirable under heat curing and exposed time to heat curing is crucial for the properties of RPC. Therefore, it is critical to monitor the time at which the concrete specimens are subjected to hot air curing (HAC) to avoid any negative effect on the RPC performance [1]. Combined processing of RPC without steel fibers under 3 days of autoclave processing at 125°C and then 7 days of heat treatment at 220°C causes more effective performance in the mechanical properties [20]. Experimental comparison of the effect of normal curing (NC) and steam curing (SC) methods on the tensile behavior of RPC reveals that the NC method can be an appropriate alternative to the SC method so that at the age of 28-day, the tensile behavior of RPC treated with both methods is the same [21].

In an experimental study, it was found that the use of glass fibers in the concrete mixture increases before-cracking strength and the random distribution of fibers improves concrete properties in all directions. It was also indicated that Taguchi's design method is effective in optimizing the mechanical properties of glass fiber-reinforced concrete (GFRC) mixtures [22]. By adding microparticles and 2% of fibers in RPC, the flexural strength of 44.21 MPa and compressive strength of 120 MPa were achieved under different stages of curing at 28 days [23]. High-volume steel fibers and the homogenous and dense microstructure of RPC lead to exceptional engineering properties such as ductility and fire resistance [24].

Some of the main disadvantages of RPC include high cement and SF content, fine quartz with a preferred size of 150 μm–600 μm, and a low water-to-binder ratio that increases the cost of RPC production and affects sustainable development [16]. Researchers have sought to find the optimal RPC components to overcome its drawbacks. For example, some of the cement content in RPC can be replaced with mineral admixtures such as fly ash, blast-furnace slag, and silica fume to overcome environmental and behavioral drawbacks relating to hardened concrete [10]. Shrinkage problems and lower dimensional stability over long-term aging arise from the addition of a large percentage of cement to the concrete mix. One of the most powerful pozzolanic materials used in RPC is silica fume [13], which increases the RPC compressive strength [25]. However, silica fume has drawbacks such as a high cost and limited availability; hence, it can be replaced with rice husk ash to produce RPC without compromising the required qualities [6]. Many other studies have added fly ash or ground granulated blast-furnace slag to improve RPC seawater erosion resistance [26] and blended silica fume with metakaolin to enhance the RPC strength and durability [27]. Utilization of alternative mineral admixtures such as glass powder (GP), limestone, and phosphorous slag can effectively replace cement by up to 50%. Replacing silica fume (SF) with slag and FA is promising and can yield comparable results by monitoring the molar calcium/silica (Ca/Si) ratio of the mixes. Quartz sand/powder can be replaced by other types of aggregates/fillers (titanium slag, glass sand, glass powder, rice husk ash, and so on) [28].

Finding the right combination of ingredients to improve the quality of RPC is the challenge that researchers face. For example, the cement content and water-to-cement ratio will affect the mix RPC design [29]; however, there are no comprehensive approaches for designing RPCs. Instead, run many trials must be run to determine the optimized RPC mix design.

The Taguchi method which was used in previous studies [29–33] is applicable to RPC mix designs and related issues. Studies that have used this approach include assessing the optimal mixture of recycled aggregate concrete [34], analyzing the flexural strength of concrete pavement using fly ash and silica fume [35], optimizing the concrete mix design [36, 37], optimizing the compressive strength [38], investigating the effect of high temperature on RPC compressive strength [39], optimizing the mechanical properties of glass fiber-reinforced concrete mixtures [22], and investigating the heating degree on concrete compressive strength and its crack length [40].

Several RPC designs have been introduced in the literature or are based on expert opinion. This complicates the proposal of RPC mix designs based on existing designs when determining an optimal mix design. This indicates that it is better to rank existing RPC designs and select the best ones for use when proposing the best RPC mix designs. Compensatory multiattribute decision-making (MADM) can be used to screen existing RPC designs to select the best ones. These methods consider the trade-offs between attributes. This means that the strength of an attribute can compensate for the weakness of another attribute. Conventional compensatory models include simple additive weighting (SAW) [41], weighted sum model (WSM) [42], weighted product model (WPM) [43], the technique for order preferences by similarity to an ideal solution (TOPSIS) [44], analytical hierarchy process (AHP) [45, 46], and vlsekriterijumska optimizacija kompromisno resenje (VIKOR) [47]. Newer compensatory methods include the weighted distance-based approximation (WDBA) [48], weighted aggregated sum product assessment (WASPAS) [49], evaluation based on distance from average solution (EDAS) [50], best-worst method (BWM) [51], combinative distance-based assessment (CODAS) method [52], and combined compromise solution (CoCoSo) method [53].

The current study presents an integrated approach that combines the SAW and Taguchi methods to suggest new RPC mix designs and select the best one. For this purpose, six factors (components) affecting the compressive strength and water absorption characteristics were examined. These included cement, silica sand, silica powder, silica fume, superplasticizer, and water. Thirteen RPC designs were selected from among the existing designs based on expert opinion and nine attributes that affected the rankings of these RPC designs were extracted. Samples were made from these RPC designs to validate their characteristics based on the literature and experts' opinions. The weights of the nine attributes then were obtained using the entropy method and were used to rank the 13 RPC designs using the SAW method. The most high-quality RPC designs were ranked 1, 2, and 3.

Next, the Taguchi method was used to propose new RPC mix designs to consider six factors at three levels, which allowed for the development of 27 mix designs. A total of 81 samples (three for each mix design) were made. These samples were tested for compressive strength and water absorption and the most high-quality designs were selected based on these characteristics. To the best of our knowledge, this is the first study using the entropy and SAW methods to screen existing RPC designs and select the most high-quality ones to propose the new RPC mix designs using the Taguchi method.

2. Materials

RPC characteristics are sensitive to the type, specifications, and amount of materials used in its production. To achieve concrete with the desired properties, it is necessary to consider the physical and chemical properties of the materials used. In this study, local materials found in Iran were used as the practical components of the laboratory samples as the RPC mix designs. All the materials used in this research are shown in Figure 1. In the following, we describe the characteristics of the local materials used in this study.

2.1. Cement. The primary raw materials in cement are clay and lime. Their chemical reactions with water (hydration reaction) play the role of binding the solid material together to produce a hard, concrete body. Cement plays an essential role in the RPC mix design, especially the strength of the concrete. In this study, we used type 2 Portland cement to make the laboratory samples. This type of cement complies with ASTM-C 150 standards, and its physical and chemical characteristics are given in Tables 1 and 2, respectively. This cement has a density of 3.15 gr/cm^3.

2.2. Silica Fume. Silica fume is a cementitious admixture material. The cementitious and pozzolanic properties of silica fume lead to the formation of new hydrate silicate calcium compounds that increase strength. It is extremely fine particles fill the microscopic voids of the cement paste and increase the density of the concrete, which improves durability. The results of the chemical analysis of silica fume are given in Table 3. The relative density of the silica fume was 2.2 g/cm^3 and the specific surface area was 15–20 m^2/g.

2.3. Superplasticizers. These materials sit on the cement particles and charge them, which creates a repulsive force between them This causes the particles to repel each other, facilitating the flow of the concrete. Superplasticizers also can be used to increase efficiency and mechanical strength and reduce cement consumption in concrete. In this study, a polycarboxylate-based superplasticizer was used. The specific gravity of this superplasticizer was 1.08 g/cm^3. This superplasticizer was prepared according to ASTM C1017/C1017M and ASTM C494/C494M TYPE-F.

2.4. Water. The water used in a concrete mixture (about 25% of the cement weight) is absorbed by the cement particles and facilitates hydration. High-strength concrete is mainly produced at a water-cementitious materials ratio of about 0.25. In this study, clear drinking water was used to make the laboratory samples.

2.5. Silica Sand. It is characteristic when developing RPC to remove coarse-grained aggregate to achieve a more homogenous structure. This means that the RPC has a greater proportion of fine-grained sand that has replaced the conventional concrete aggregate. Silica sand plays a vital role in increasing RPC strength. In this study, sand and silica powder from a local mine named Chirook Tabas Mine, Yazd, Iran were used. The physical and chemical characteristics are given in Tables 4 and 5. The grading of the silica sand was based on ASTM C117 and ASTM D75 standards.

2.6. Silica Powder. Silica powder plays the role of filling the space between silica sand. This reduces water absorption and increases durability, leading to an increase in the compressive strength of RPC concrete.

3. Testing Procedure

The mixer is used for mixing reactive powder concrete components [54] indicated that concrete mixes made with a low-speed mixer have a porous structure and the transition zone between the cement paste and the aggregates was weak. In the current study, a mixer with a maximum rotational speed of 360 rpm has been used. A mixer speed of 100 rpm was used for a mixing time of 15 min. The mixing procedure was as follows:

(i) Superplasticizer and microsilica gel were added to the water and mixed together.
(ii) Cement, silica sand, and silica powder were poured into a blender and mixed for 2 minutes at 120 rpm.
(iii) The solution containing water, superplasticizer, and microsilica gel was added to the mixer and mixed for 2 minutes at 240 rpm. Turn off the blender for 10 seconds and then continue for 4 minutes at 360 rpm.

The prepared mixture was then poured into the mold. A vibrating table was used to compact the samples. A standard water cure was used before testing. According to ASTM C617, sulfur mortar has been used for capping concrete cylinders. Figure 2 shows some samples after the compressive test.

4. Methodology

The proposed framework presented in Figure 3 indicates that this research was a laboratory-analytical study that was carried out in two phases. These phases are described as follows.

4.1. Laboratory Phase. This first phase involved the production of concrete samples according to the different RPC designs based on expert opinion. This phase aimed to validate the different characteristics of the RPC designs to

Figure 1: All the materials used in this research.

Table 1: Physical characteristics of type 2 Portland cement.

Blaine (cm^2/gr)	Initial setting time (minutes)	Final setting time (minutes)	Compressive strength (kg/cm^2)			Autoclave expansion (%)
			3 Days	7 Days	28 Days	
3200 ± 100	130 ± 20	180 ± 20	200 ± 30	370 ± 30	510 ± 30	0.10 ± 0.05

Table 2: Chemical characteristics of type 2 Portland cement.

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	SO_3 (%)	K_2O (%)
22.1 ± 0.3	5.0 ± 0.2	4.0 ± 0.2	64.0 ± 0.4	1.7 ± 0.2	2.1 ± 0.2	0.65 ± 0.1
Na_2O (%)	Cl (%)	Insoluble residue (%)	L.O.I. (%)	C_3S (%)	C_3A (%)	CaO free (%)
0.35 ± 0.1	0.015 ± 0.002	0.45 ± 0.1	0.9 ± 0.2	50.0 ± 5	6.5 ± 0.5	1.0 ± 0.3

Table 3: Chemical analysis of silica fume (weight percentage of elements).

Chemical elements	SiO_2	Na_2O	MgO	CaO	Fe_2O_3	Al_2O_3	K_2O	Loss on ignition (LOI)	pH
Silica fume (%)	90–95	0.3–0.5	0.5–2.0	0.5–1.5	0.6–1.3	0.6–1.2	0.2–0.5	1.5–2.5	8.0–9.5

Table 4: Physical characteristics of silica sand.

Gravity (G_s)	Water absorption (%)	Fineness modulus	Degree of refractory (C°)	Angular coefficient	Coefficient of skew	Size (mm)
2.7	1.98	1.4	1730	1.16	1.30	0.35–0.55

Table 5: Chemical analysis of silica sand and comparing it with standard sand.

Type of sand	SiO_2	Fe_2O_3	Al_2O_3	CaO	Na_2O	K_2O	MgO	LOI (loss on ignition)
Silica sand used in this study (%)	97–99	0.2–0.6	0.4–1.7	0.07–0.2	0–0.01	0.02–0.06	0	0.01–0.35
Standard sand (%)	96–98.1	0.2–0.7	0.51–1.63	0.4–0.7	0.03–0.8	0.02–0.08	—	—

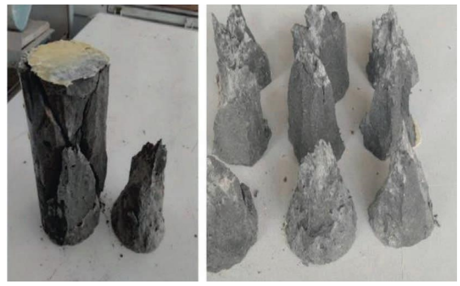

Figure 2: Concrete samples after compressive test.

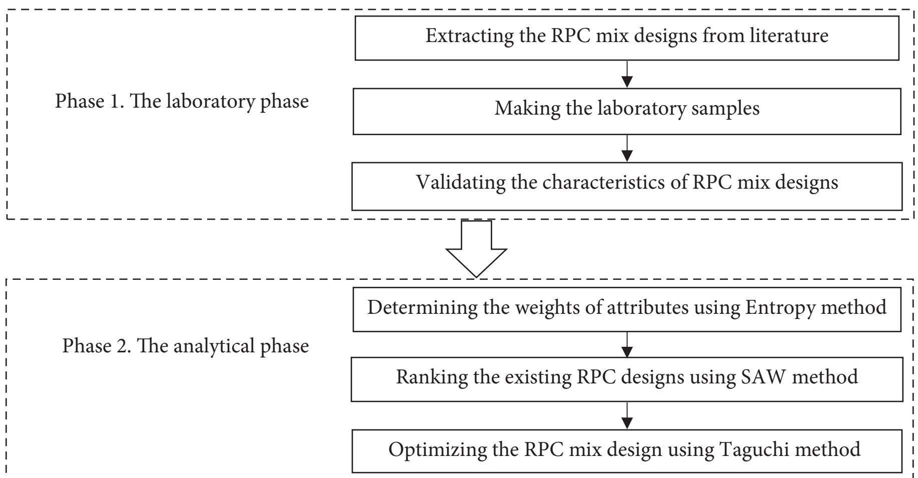

Figure 3: Scheme of proposed framework.

determine whether or not they achieved the standards claimed by the experts. The characteristics tested were compressive strength and water absorption.

4.2. The Analytical Phase. The second phase (analytical) aimed to obtain an optimized RPC mix design. This phase is carried out in three steps.

4.2.1. Determining Weights of Attributes by Entropy Method. In this step, first, the most important attributes used to measure the quality of RPC designs were determined and the weights of these attributes were obtained. They fell into two categories. Category one determined the values of concrete mix design components in terms of kg/m^3 for cement (X_1), silica sand (X_2), silica powder (X_3), silica fume (X_4), superplasticizer (X_5), and water (X_6). Category two, related to the mix design results, consisted of three attributes: compressive strength (X_7), water absorption (X_8), and density (X_9). The values of these attributes were determined for the different RPC designs introduced in phase one. These values can be shown in a decision matrix (matrix D) as

$$D: \begin{matrix} & X_1 & X_2 & & X_n \\ A_1 & r_{11} & r_{12} & \dots & r_{1n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ A_m & r_{m1} & r_{m2} & \dots & r_{mn} \end{matrix}. \quad (1)$$

A decision matrix features rows and columns containing alternatives and attributes, respectively. In decision matrix D (equation (1) X_j and A_i represent the j^{th} attribute and i^{th} alternative, respectively, and r_{ij} represents the value of the j^{th} attribute for the i^{th} alternative. Also, m is the number of alternatives (the RPC designs in this study) and n is the number of attributes.

The aim is to obtain the weights of the attributes based on matrix D. The entropy method was used for this purpose. In this method, the higher the scatter for an attribute's values, the more important that attribute is. The entropy method consists of the following five steps:

(i) *Step 1*. Form the decision matrix (here, matrix D).

(ii) *Step 2*. Normalize the data given in the matrix. If p_{ij} is the normalized value of r_{ij}, it can be obtained as

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}, \quad j = 1, \dots, n. \quad (2)$$

(iii) *Step 3*. Calculate the entropy of attribute j (E_j) as

$$E_j = -\frac{1}{\ln(m)} \sum_{i=1}^{m} p_{ij} . \ln\left(p_{ij}\right), \quad j = 1, \dots, n. \quad (3)$$

where m is the number of alternatives. The value of E_j will be between 0 and 1.

(iv) *Step 4.* Calculate the value of d_j as

$$d_j = 1 - E_j,\quad j = 1, n. \tag{4}$$

(v) *Step 5.* Calculate the weight of attribute j as

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j},\quad j = 1, \ldots, n. \tag{5}$$

4.2.2. Ranking Existing RPC Designs Using SAW Method. The SAW method was used to rank the existing RPC designs and choose the highest-quality ones. The SAW method is a well-known and widely used MADM method because of its simplicity. Consider decision matrix D (equation (1). Assume that A_i in this matrix represents the i^{th} RPC design. The SAW method consists of the following two steps for ranking the alternatives [30]:

(i) *Step 1.*Data normalization: This step normalizes the data given in the decision matrix. For this purpose, SAW uses the linear normalization method. If n_{ij} is the linear normalized value of r_{ij}, it can be obtained as

$$n_{ij} = \begin{cases} \dfrac{r_{ij}}{r_j^{\max}}, \\ \\ \dfrac{r_j^{\min}}{r_{ij}}, \end{cases} \tag{6}$$

where J^{+} and J^{-} denote the benefit-type and cost-type sets, respectively, and $r_j^{\max}$ and $r_j^{\min}$ are the largest and smallest data sets for attribute j in the decision matrix. Benefit-type (cost-type) attributes are those that become more desirable as they increase (decrease). For example, compressive strength (water absorption) is a benefit-type attribute.

(ii) *Step 2.* Ranking the RPC designs: Consider $w_j\,(j = 1, \ldots, n)$ as the weight of the j^{th} attribute (Section 4.2.1). The weight of the i^{th} RPC design (wA_i) can be obtained as

$$wA_i = \sum_{j=1}^{m} w_j \,.\, n_{ij}. \tag{7}$$

The greatest value of wA_i represents the best alternative.

4.2.3. Optimizing RPC Mix Design Using Taguchi Method. The SAW method was used to determine ranks 1, 2, and 3 of the RPC mix designs. The Taguchi method used three levels and six factors to prepare 27 test RPC mix designs. The factors considered were the concrete components of cement, silica sand, silica powder, silica fume, superplasticizer, and water. Three samples were made for each Taguchi test design and the compressive strength and water absorption of each sample were obtained. Next, the average value for each RPC mix design was determined and the results of the 27 RPC mix designs were compared to select the most preferable designs. The RPC mix designs were compared for compressive strength and water absorption.

5. Illustrative Example

A case study was developed to illustrate the proposed approach. First, different local RPC designs were extracted from the literature, and finally, 13 designs were extracted according to expert opinion for compressive strength and water absorption [55]. The values of these characteristics are given in Table 6.

To ensure the accuracy of the results, laboratory samples of the RPC designs were made with local materials and tested for compressive strength according to ASTM C39/39 M-09a standard and for water absorption according to ASTM C642 standard. The results are given in Table 7. A comparison of the test results with those given in the literature shows that the differences between the values are very small, confirming the accuracy of the production and performance methods.

Next, a decision matrix (matrix D) was developed to obtain the weights of the attributes. For the 13 RPC designs in Table 6 and nine attributes (Section 4.2.1), the dimension of the decision-making was 13×9 as in Table 8. In other words, each RPC design is an alternative displayed as A_i ($i = 1, \ldots, 13$) in decision matrix D. The components and characteristics (attributes) of the RPC designs were denoted as X_j ($j = 1, \ldots, 9$). The two types of attributes in this example were benefit-type denoted as X_1, X_2, X_3, X_4, X_5, X_7, and X_9, and cost-type denoted as X_6 and X_8. These are marked in Table 8 with positive and negative signs, respectively. It is worth saying that the extraordinary durability of RPC against the attack of chlorides, sulfates, etc., is due to its low water absorption and permeability. This index is entered into the decision matrix with a negative ideal, meaning the lower the better.

The entropy method was used to obtain the weights of the attributes based on the data from Table 8. The results are given in Table 9.

The 13 RPC designs next were ranked and the three best designs were selected using the SAW method. Note that, the weights of the attributes from SAW are those given in Table 9. The results of the ranking of RPC designs using the SAW method are shown in Table 10 as RPC_{13}, RPC_7, and RPC_2 with ranks 1, 2, and 3 as the best alternatives, respectively.

In the fourth step, the best RPC designs as determined by the SAW method (Table 11) were used to obtain the new RPC mix designs and select the best one. The Taguchi method was used considering three levels and six factors (Table 11).

The Taguchi method was used to prepare 27 RPC test-mix designs. The appropriate orthogonal array and signal-to-noise (S/N) ratios were extracted for each factor of the RPC mix

Table 6: Components of selected RPC designs [55].

RPC design	The RPC design components (kg/m^3)						Compressive strength (MPa)	Water absorption (%)
	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water		
(RPC_1)	810	961	182	167	40	200	132	1.04
(RPC_2)	897	797	205	188	46	206	143	0.98
(RPC_3)	673	1125	144	192	40	173	130	0.99
(RPC_4)	730	1070	175	175	39	170	134	0.95
(RPC_5)	919	870	77	221	38	204	139	1.10
(RPC_6)	714	1203	86	132	39	186	121	1.03
(RPC_7)	629	1085	261	151	36	198	125	0.79
(RPC_8)	830	1080	100	150	42	180	132	0.75
(RPC_9)	750	1051	119	215	41	170	131	0.93
(RPC_{10})	1021	662	122	253	48	204	136	1.08
(RPC_{11})	840	924	178	202	42	180	141	0.82
(RPC_{12})	898	895	110	188	44	207	138	0.97
(RPC_{13})	890	700	296	187	46	203	144	1.01

Table 7: Characteristics of RPC design samples in the experimental program.

RPC design	Compressive strength (MPa)			Water absorption (%)		
	Literature value	Test result	Difference (%)	Literature value	Test result	Difference (%)
(RPC_1)	132	131.5	0.38	1.04	1.050	0.96
(RPC_2)	143	142	0.70	0.98	0.985	0.51
(RPC_3)	130	130.5	0.38	0.99	0.995	0.50
(RPC_4)	134	133	0.75	0.95	0.945	0.53
(RPC_5)	139	140	0.72	1.10	1.100	0.91
(RPC_6)	121	121.6	0.50	1.03	1.040	0.97
(RPC_7)	125	125.8	0.64	0.79	0.794	0.50
(RPC_8)	132	131	0.76	0.75	0.756	0.80
(RPC_9)	131	130	0.76	0.93	0.926	0.43
(RPC_{10})	136	136.8	0.59	1.08	1.076	0.56
(RPC_{11})	141	140.7	0.21	0.82	0.826	0.73
(RPC_{12})	138	139	0.72	0.97	0.972	0.21
(RPC_{13})	144	143	0.70	1.01	1.000	0.99

Table 8: Decision matrix.

Alternative	Attribute								
	RPC design components (kg/m^3)						RPC design characteristics		
	Cement (X_1)	Silica sand (X_2)	Silica powder (X_3)	Silica fume (X_4)	Superplasticizer (X_5)	Water (X_6)	Compressive strength (MPa) (X_7)	Water absorption (%) (X_8)	Density (kg/m^3) (X_9)
Sign	+	+	+	+	+	−	+	−	+
A_1 (RPC_1)	810	961	182	167	40	200	132	1.04	2360
A_2 (RPC_2)	897	797	205	188	46	206	143	0.98	2339
A_3 (RPC_3)	673	1125	144	192	40	173	130	0.99	2347
A_4 (RPC_4)	730	1070	175	175	39	170	134	0.95	2359
A_5 (RPC_5)	919	870	77	221	38	204	139	1.10	2329
A_6 (RPC_6)	714	1203	86	132	39	186	121	1.03	2360
A_7 (RPC_7)	629	1085	261	151	36	198	125	0.79	2360
A_8 (RPC_8)	830	1080	100	150	42	180	132	0.75	2382
A_9 (RPC_9)	750	1051	119	215	41	170	131	0.93	2346
A_{10} (RPC_{10})	1021	662	122	253	48	204	136	1.08	2310
A_{11} (RPC_{11})	840	924	178	202	42	180	141	0.82	2366
A_{12} (RPC_{12})	898	895	110	188	44	207	138	0.97	2342
A_{13} (RPC_{13})	890	700	296	187	46	203	144	1.01	2322

Table 9: Weights of attributes using entropy method.

Attributes	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9
Weights	0.0671	0.1124	0.6055	0.1065	0.0290	0.0217	0.0099	0.0454	0.0020

Table 10: Ranking RPC designs using SAW method.

Alternatives	The weight of alternatives	The rankings of alternatives
RPC_1	0.6724	5
RPC_2	0.7246	3
RPC_3	0.6159	7
RPC_4	0.6723	6
RPC_5	0.4761	13
RPC_6	0.4780	12
RPC_7	0.8346	2
RPC_8	0.5259	11
RPC_9	0.5759	8
RPC_{10}	0.5754	9
RPC_{11}	0.6902	4
RPC_{12}	0.5382	10
RPC_{13}	0.9001	1

Table 11: Factors of selected RPCs.

Selected RPC designs	Level	Factors (the components of RPC designs) (kg/m^3)					
		Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water
RPC_{13}	1	890	700	296	187	46	203
RPC_7	2	629	1085	261	151	36	198
RPC_2	3	897	797	205	188	46	206

design in Minitab software. The increase in the compressive strength and decrease in the water absorption increased the durability of the RPC concrete. These have been defined in the software as different characteristics by the terms "the more, the better" and "the less, the better," respectively. Equations (8) and (9) provide orthogonal arrays for "the more, the better" and "the less, the better" in Minitab as

$$\left(\frac{S}{N}\right)_i = -10\log\left[\frac{1}{n}\sum_{j=1}^{n}\frac{1}{Y_{ij}^2}\right], \tag{8}$$

$$\left(\frac{S}{N}\right)_i = -10\log\left[\frac{1}{n}\sum_{j=1}^{n}Z_{ij}^2\right], \tag{9}$$

where i is the number of experiments, Y_{ij} and Z_{ij} are the values of compressive strength and water absorption in the i^{th} RPC mix design and j^{th} experiments. Minitab suggested 27 RPC mix designs as the appropriate orthogonal arrays and 27 test designs presented in Table 12 were introduced. Three samples were made for each Taguchi test design and compressive strength and water absorption tests were performed on each sample and their average values were obtained for each RPC mix design (Table 12).

5.1. Optimal Mix Design in terms of Compressive Strength. The compressive strength values in Table 12 are entered into Minitab and the results were analyzed. The optimal RPC mix design was obtained in terms of compressive strength. The outputs are shown in Table 13 and Figure 4.

Given the values in Table 13 and Figure 4 and considering that the goal was to achieve a higher S/N ratio for each factor, Minitab suggested an RPC mix design. This mixed the cement at level 1 (RPC_{13}), silica sand at level 3 (RPC_2), silica powder at level 3 (RPC_2), silica fume at level 1 (RPC_{13}), superplasticizer at level 3 (RPC_2), and water at level 2 (RPC_7). Different samples of this RPC mix design were made and their compressive strength and water absorption were measured. The average values of these characteristics are given in Table 14.

5.2. Optimal Mix Design in terms of Water Absorption. The water absorption values given in Table 12 are entered into the Minitab and analyzed. The optimal RPC mix design was obtained in terms of water absorption and the outputs are given in Table 15 and Figure 5. Using these values and considering the goal was to achieve a higher S/N ratio for each factor, Minitab suggested an RPC mix design. The mix contained cement at level 3 (RPC_2), silica sand at level 1 (RPC_{13}), silica powder at level 3 (RPC_2), silica fume at level 3 (RPC_2), superplasticizer at level 2 (RPC_7), and water at level 1 (RPC_{13}). Different samples of this RPC mix design were made and their compressive strength and water absorption were measured. The average values of these characteristics are given in Table 16.

Table 12: Characteristics of Taguchi test designs provided by Minitab.

RPC mix design	Factors						Characteristics	
	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water	Compressive strength (MPa)	Water absorption (%)
1	890	700	296	187	46	203	143.0	1.000
2	890	700	296	187	36	198	142.3	0.981
3	890	700	296	187	46	206	141.5	0.992
4	890	1085	261	151	46	203	133.0	0.960
5	890	1085	261	151	36	198	134.0	1.110
6	890	1085	261	151	46	206	131.5	1.020
7	890	797	205	188	46	203	142.0	0.810
8	890	797	205	188	36	198	142.5	0.762
9	890	797	205	188	46	206	140.5	0.930
10	629	700	261	188	46	198	131.5	1.070
11	629	700	261	88	36	206	126.0	0.830
12	629	700	261	188	46	203	130.6	0.960
13	629	1085	205	187	46	198	128.0	1.011
14	629	1085	205	187	36	206	125.0	0.970
15	629	1085	205	187	46	203	127.4	0.985
16	629	797	296	151	46	198	129.0	0.950
17	629	797	296	151	36	206	126.5	1.110
18	629	797	296	151	46	203	136.6	1.035
19	897	700	205	151	46	206	140.0	0.790
20	897	700	205	151	36	203	141.2	0.757
21	897	700	205	151	46	198	142.8	0.930
22	897	1085	296	188	46	206	124.2	1.086
23	897	1085	296	188	36	203	123.0	0.826
24	897	1085	296	188	46	198	125.8	0.970
25	897	797	261	187	46	206	146	1.000
26	897	797	261	187	36	203	142.8	1.160
27	897	797	261	187	46	198	146.5	1.027

Table 13: Taguchi analysis for optimal compressive strength.

Level	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water
Taguchi design Taguchi orthogonal array design L27 (3**6) Factors: 6 Runs: 27 Columns of L27 (3**13) array 1 2 3 4 5 6						
Response table for signal-to-noise ratios Larger is better						
Level	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water
1	42.85	42.77	42.42	42.79	42.61	42.63
2	42.21	42.14	42.64	42.60	42.51	42.65
3	42.71	42.86	42.70	42.38	42.65	42.49
Delta	0.65	0.72	0.27	0.40	0.15	0.16
Rank	2	1	4	3	6	5
Response table for means						
Level	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water
1	138.9	137.7	132.4	138.1	135.2	135.5
2	129.9	128.0	135.8	135.0	133.7	135.8
3	136.9	139.2	136.6	131.8	135.9	133.5
Delta	10.0	11.2	4.2	6.3	2.2	2.4
Rank	2	1	4	3	6	5

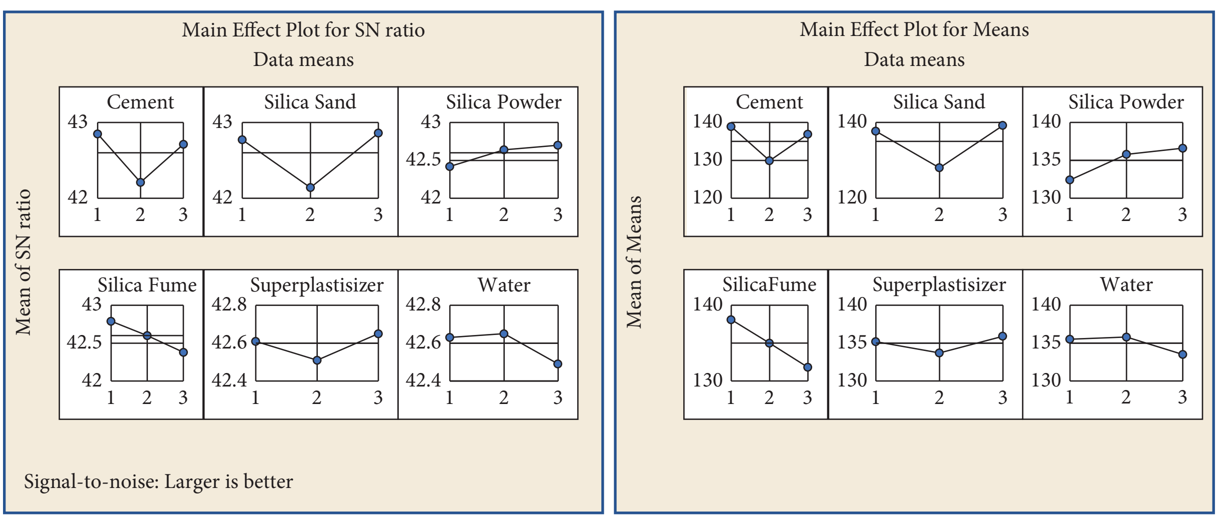

Figure 4: Main effects plot for SN ratios and means.

Table 14: Optimal RPC concrete mix design recommended by Minitab for compressive strength.

Factor	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water	Compressive strength (MPa)	Water absorption (%)
RPC	890	797	205	187	46	198	146.7	0.920

Table 15: Taguchi analysis for optimal water absorption.

Taguchi design Taguchi orthogonal array design L27 (3**6) Factors: 6 Runs: 27 Columns of L27 (3**13) array 1 2 3 4 5 6

Table 15: Continued.

Response table for signal-to-noise ratios						
Smaller is better						
Level	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water
1	0.482	0.746	0.076	−0.109	0.364	0.573
2	0.103	0.087	−0.095	0.401	0.599	0.227
3	0.532	0.282	1.135	0.824	0.153	0.315
Delta	0.429	0.659	1.231	0.933	0.445	0.346
Rank	5	3	1	2	4	6
Response table for means						
Level	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water
1	0.952	0.923	0.994	1.014	0.964	0.944
2	0.991	0.993	1.015	0.962	0.945	0.979
3	0.950	0.976	0.883	0.916	0.983	0.969
Delta	0.042	0.698	0.132	0.098	0.038	0.035
Rank	5	3	1	2	4	6

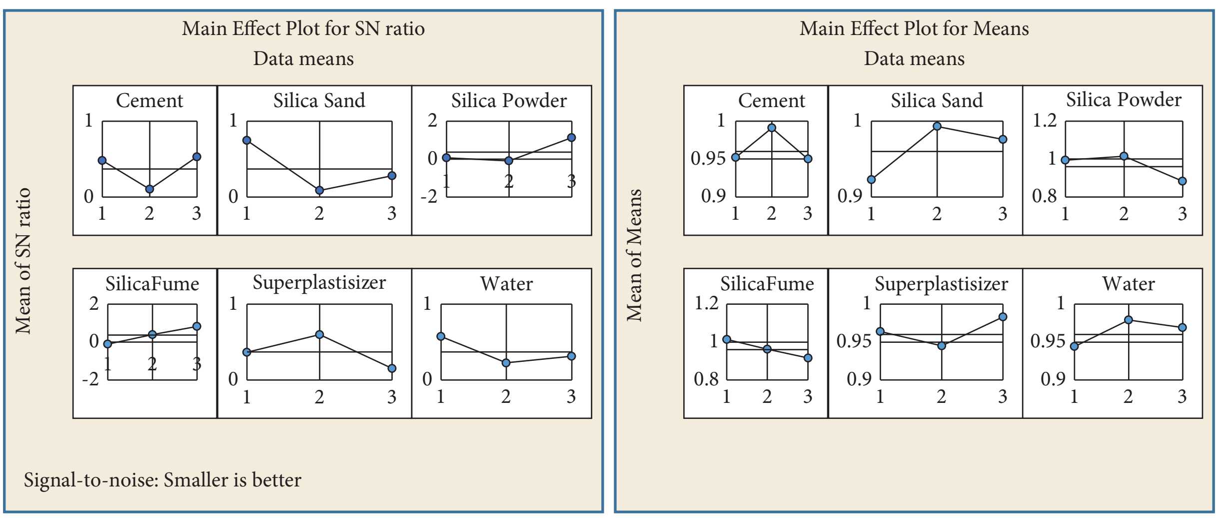

Figure 5: Main effects plot for SN ratios and means.

Table 16: Optimal RPC concrete mix design recommended by Minitab for water absorption.

Factors	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water	Compressive strength (MPa)	Water absorption (%)
RPC	897	700	205	188	36	203	144.7	0.892

Table 17: RPC mix design predicted by Minitab for compressive strength.

Predicted values Factor levels for predictions						
	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water
Level	1	1	1	1	1	1
	S/N Ratio 43.12			Mean 143.1		

5.3. Predicting Taguchi Results. Minitab can use the Taguchi method to present an RPC mix design as a prediction of the Taguchi results. These predictions for the RPC mix designs from Minitab for compressive strength and water absorption are given in Tables 17 and 18, respectively.

Table 18: RPC mix design predicted by Minitab for water absorption.

	Predicted values					
	Factor levels for predictions					
	Cement	Silica sand	Silica powder	Silica fume	Superplasticizer	Water
Level	1	1	1	1	1	1
	S/N Ratio 0.272			Mean 0.970		

6. Conclusion

This was a laboratory-analytical study aiming to optimize the RPC concrete mix design using the SAW and Taguchi methods. In the laboratory part of this study, RPC mix designs were made using local materials and then the compressive strength and water absorption of the samples were measured. In the analytical part, the SAW and Taguchi methods were used to propose new RPC mix designs. The main conclusions of this study are as follows:

(i) From the experimental results, compressive strength with 0.38–0.76% and water absorption with 0.50–0.99% differences were more appropriate in compliance with the collected data by the expert opinion and laboratory samples from the previous literature.

(ii) The SAW method was beneficial to find the three first ranks of the 13 selected mix designs by previous literature. These three first ranks were beneficial to define the base mix designs for the Taguchi method.

(iii) Results from the 27 mix designs investigated by the Taguchi method revealed the optimized mix design for the maximum compressive strength with 146.7 MPa and the optimized mix design for the minimum water absorption with 0.89%.

This study used the SAW method to select high-quality RPC designs from the existing designs. It is suggested that future studies use other MADM techniques for this purpose, including AHP, TOPSIS, and VIKOR.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] S. Ahmed, Z. Mahaini, F. Abed, M. A. Mannan, and M. Al-Samarai, "Microstructure and mechanical property evaluation of dune sand reactive powder concrete subjected to Hot air curing," *Materials*, vol. 15, no. 1, 2021.

[2] Z. Yu, Z. Li, Y. Jiang, and Y. Wang, "Mechanical behavior of reactive powder concrete subjected to biaxial loading," *Advances in Civil Engineering*, vol. 2022, Article ID 9246692, 11 pages, 2022.

[3] W. Zheng, D. Wang, and Y. Ju, "Performance of reinforced reactive powder concrete beam-column joints under cyclic loads," *Advances in Civil Engineering*, vol. 2018, Article ID 3914815, 12 pages, 2018.

[4] E. Najaf and H. Abbasi, "Using recycled concrete powder, waste glass powder, and plastic powder to improve the mechanical properties of compacted concrete: cement elimination approach," *Advances in Civil Engineering*, vol. 2022, Article ID 9481466, 12 pages, 2022.

[5] S. L. Hake, R. M. Damgir, and S. V. Patankar, "Temperature effect on lime powder-added geopolymer concrete," *Advances in Civil Engineering*, vol. 2018, Article ID 6519754, 5 pages, 2018.

[6] M. Vigneshwari, K. Arunachalam, and A. Angayarkanni, "Replacement of silica fume with thermally treated rice husk ash in Reactive Powder Concrete," *Journal of Cleaner Production*, vol. 188, pp. 264–277, 2018.

[7] H. So, H. Jang, J. Khulgadai, and S. Y. So, "Mechanical properties and microstructure of reactive powder concrete using ternary pozzolanic materials at elevated temperature," *KSCE Journal of Civil Engineering*, vol. 19, no. 4, pp. 1050–1057, 2015.

[8] C. Shi, M. Long, C. Cao, G. Long, and M. Lei, "Mechanical property test and analytical method for Reactive Powder Concrete columns under eccentric compression," *KSCE Journal of Civil Engineering*, vol. 21, no. 4, pp. 1307–1318, 2017.

[9] H. Salahuddin, L. A. Qureshi, A. Nawaz, and S. S. Raza, "Effect of recycled fine aggregates on performance of Reactive Powder Concrete," *Construction and Building Materials*, vol. 243, Article ID 118223, 2020.

[10] O. A. Mayhoub, E. S. A. R. Nasr, Y. A. Ali, and M. Kohail, "The influence of ingredients on the properties of reactive powder concrete: a review," *Ain Shams Engineering Journal*, vol. 12, no. 1, pp. 145–158, 2021.

[11] B. W. Jo, C. H. Kim, and J. H. Lim, "Investigations on the development of powder concrete with nano-SiO2 particles," *KSCE Journal of Civil Engineering*, vol. 11, no. 1, pp. 37–42, 2007.

[12] P. C. Aïtcin, M. Lachemi, R. Adeline, and P. Richard, "The Sherbrooke reactive powder concrete footbridge," *Structural Engineering International*, vol. 8, no. 2, pp. 140–144, 1998.

[13] S. S. Raza, L. A. Qureshi, B. Ali, A. Raza, and M. M. Khan, "Effect of different fibers (steel fibers, glass fibers, and carbon fibers) on mechanical properties of reactive powder concrete," *Structural Concrete*, vol. 22, no. 1, pp. 334–346, 2021.

[14] A. A. Dhundasi, R. B. Khadiranaikar, A. A. Momin, and K. Motagi, "An experimental investigation on durability properties of reactive powder concrete," *Journal International Journal of Engineering, Transactions B: Applications*, vol. 35, pp. 327–336, 2022.

[15] D. Ambika, S. Dhinu Priya, G. Poovizhi, V. Santha Rubini, and V. Nandhini, "Forensic investigation on mechanical properties of reactive powder concrete," *Materials Today Proceedings*, vol. 45, pp. 912–918, 2021.

[16] S. Ahmed, F. Abed, and M. A. Mannan, "Compressive strength development of dune sand reactive powder concrete (RPC) under different curing conditions," *IOPSCIENCE. IOP Conferences. Series: Earth and Environmental Science*, vol. 1026, Article ID 012017, 2022.

[17] X. Chen, D. W. Wan, L. Z. Jin, K. Qian, and F. Fu, "Experimental studies and microstructure analysis for ultra high-performance reactive powder concrete," *Construction and Building Materials*, vol. 229, Article ID 116924, 2019.

[18] S. Maheswaran, A. Ramachandra Murthy, V. Ramesh Kumar, and A. Karunanithi, "Characterisation studies on the particle size effect of calcium carbonate in high-strength concrete," *Magazine of Concrete Research*, vol. 73, no. 13, pp. 661–673, 2021.

[19] P. N. Hiremath and S. C. Yaragal, "Influence of mixing method, speed and duration on the fresh and hardened properties of Reactive Powder Concrete," *Construction and Building Materials*, vol. 141, pp. 271–288, 2017.

[20] D. Mostofinejad, M. R. Nikoo, and S. A. Hosseini, "Determination of optimized mix design and curing conditions of reactive powder concrete (RPC)," *Construction and Building Materials*, vol. 123, pp. 754–767, 2016.

[21] M. Guo and R. Gao, "Experimental comparability between steam and normal curing methods on tensile behavior of RPC," *Advances in Concrete Construction*, vol. 11, pp. 347–356, 2021.

[22] S. A. Yildizel, B. A. Tayeh, and G. Calis, "Experimental and modelling study of mixture design optimisation of glass fibre-reinforced concrete with combined utilisation of Taguchi and Extreme Vertices Design Techniques," *Journal of Materials Research and Technology*, vol. 9, no. 2, pp. 2093–2106, 2020.

[23] K. R. Pr, D. P. Mathangi, S. C, and N. M, "Experimental investigation of reactive powder concrete exposed to elevated temperatures," *Construction and Building Materials*, vol. 261, Article ID 119593, 2020.

[24] S. S. Raza and L. A. Qureshi, "Effect of carbon fiber on mechanical properties of reactive powder concrete exposed to elevated temperatures," *Journal of Building Engineering*, vol. 42, Article ID 102503, 2021.

[25] N. K. Lee, K. T. Koh, M. O. Kim, and G. S. Ryu, "Uncovering the role of micro silica in hydration of ultra-high performance concrete (UHPC)," *Cement and Concrete Research*, vol. 104, pp. 68–79, 2018.

[26] D. Wang, Y. Ma, M. Kang, Y. Ju, and C. Zeng, "Durability of reactive powder concrete containing mineral admixtures in seawater erosion environment," *Construction and Building Materials*, vol. 306, Article ID 124863, 2021.

[27] Y. R. Alharbi, A. A. Abadel, O. A. Mayhoub, and M. Kohail, "Effect of using available metakaoline and nano materials on the behavior of reactive powder concrete," *Construction and Building Materials*, vol. 269, Article ID 121344, 2021.

[28] S. Ahmed, Z. Al-Dawood, F. Abed, M. A. Mannan, and M. Al-Samarai, "Impact of using different materials, curing regimes, and mixing procedures on compressive strength of reactive powder concrete - a review," *Journal of Building Engineering*, vol. 44, Article ID 103238, 2021.

[29] I. Emovon and C. O. Mgbemena, "Enhancing the FMEA technique using a combination of Expectation interval, TAGUCHI, MOORA, and geometric mean methods," *Journal of Industrial Engineering*, vol. 7, 2019.

[30] M. Ob, A. Agarwal, and L. Mt, "Statistical investigation of i-shaped stiffened rectangular plate by taguchi response evaluation," *Journal of Engineering Research*, 2021.

[31] A. Ashwni, S. Gupta, and R. Rana, "Performance assessment of triangular obstacles mounted solar air heater using taguchi method," *Journal of Engineering Research*, vol. 2021, pp. 153–160, 2021.

[32] E. Can, "Variable determined for optimization of alternating energy on the load by the adaptive taguchi method," *Journal of Engineering Research*, vol. 10, 2021.

[33] S. Erbayrak and E. Erbayrak, "Determination of the impact damage threshold point of composite material using fuzzy-base taguchi method," *Journal of Engineering Research*, vol. 8, no. 3, pp. 153–171, 2020.

[34] C. Y. Chang, R. Huang, P. C. Lee, and T. L. Weng, "Determining the optimal mixture for recycled aggregate concrete with multiple responses," *Journal of the Chinese Institute of Engineers*, vol. 37, no. 2, pp. 165–174, 2014.

[35] S. Hınıslıoğlu and O. Ü Bayrak, "Optimization of early flexural strength of pavement concrete with silica fume and fly ash by the Taguchi method," *Civil Engineering and Environmental Systems*, vol. 21, no. 2, pp. 79–90, 2004.

[36] E. Sharifi, S. J. Sadjadi, M. R. M. Aliha, and A. Moniri, "Optimization of high-strengthself-consolidating concrete mix design using an improved Taguchi optimization method," *Construction and Building Materials*, vol. 236, Article ID 117547, 2020.

[37] A. Joshaghani, A. A. Ramezanianpour, O. Ataei, and A. Golroo, "Optimizing pervious concrete pavement mixture design by using the Taguchi method," *Construction and Building Materials*, vol. 101, pp. 317–325, 2015.

[38] E. Teimortashlu, M. Dehestani, and M. Jalal, "Application of Taguchi method for compressive strength optimization of tertiary blended self-compacting mortar," *Construction and Building Materials*, vol. 190, pp. 1182–1191, 2018.

[39] H. Tanyildizi and M. Şahin, "Taguchi optimization approach for the polypropylene fiber reinforced concrete strengthening with polymer after high temperature," *Structural and Multidisciplinary Optimization*, vol. 55, no. 2, pp. 529–534, 2017.

[40] H. Tanyildizi, "Post-fire behavior of structural lightweight concrete designed by Taguchi method," *Construction and Building Materials*, vol. 68, pp. 565–571, 2014.

[41] C. W. Churchman and R. L. Ackoff, "An approximate measure of value," *Journal of the Operations Research Society of America*, vol. 2, pp. 172–187, 1954.

[42] P. C. Fishburn, "Letter to the editor—additive utilities with incomplete product sets: application to priorities and assignments," *Operations Research*, vol. 15, no. 3, pp. 537–542, 1967.

[43] G. W. Sears, D. W. Miller, and M. K. Starr, "Executive decisions and operations research," *Journal of the Operational Research Society*, vol. 13, no. 1, p. 103, 1962.

[44] G. H. Tzeng and J. J. Huang, *Multiple Attribute Decision Making: Methods and Applications*, CRC Press, Boca Raton, FL, USA, 2011.

[45] T. L. Saaty, "How to make a decision: the analytic hierarchy process," *Interfaces*, vol. 24, no. 6, pp. 19–43, 1994.

[46] R. W. Saaty, "The analytic hierarchy process-what it is and how it is used," *Mathematical Modelling*, vol. 9, no. 3-5, pp. 161–176, 1987.

[47] S. Opricovic, *Multicriteria optimization of civil engineering systems*, PhD Thesis, Faculty of Civil Engineering of the University of Belgrade, Serbia, 1998.

[48] R. Venkata Rao and D. Singh, "Weighted Euclidean distance based approach as a multiple attribute decision making method for plant or facility layout design selection," *International Journal of Industrial Engineering Computations*, vol. 3, pp. 365–382, 2012.
[49] E. K. Zavadskas, Z. Turskis, J. Antucheviciene, and A. Zakarevicius, "Optimization of weighted aggregated sum product assessment," *Electronics and Electrical Engineering*, vol. 122, pp. 3–6, 2012.
[50] M. Keshavarz Ghorabaee, E. K. Zavadskas, L. Olfat, and Z. Turskis, "Multi-Criteria inventory classification using a new method of evaluation based on distance from average solution (EDAS)," *Informatica*, vol. 26, no. 3, pp. 435–451, 2015.
[51] J. Rezaei, "Best-worstmulti-criteriadecision-making method," *Omega*, vol. 53, pp. 49–57, 2015.
[52] M. Keshavarz Ghorabaee, E. K. Zavadskas, Z. Turskis, and J. Antucheviciene, "A new combinative distance-based assessment (CODAS) method for multi-criteriadecision-making," *Economic Computation and Economic Cybernetics Studies*, vol. 50, pp. 25–44, 2016.
[53] M. Yazdani, P. Zarate, E. Kazimieras Zavadskas, and Z. Turskis, "A combined compromise solution (CoCoSo) method for multi-criteriadecision-making problems," *Management Decision*, vol. 57, no. 9, pp. 2501–2519, 2019.
[54] M. Reisi and S. J. M. Fard, "Influence evaluation of key mix design parameters of reactive powder concrete on compressive strength," *Amirkabir Journal of Civil Engineering*, vol. 52, pp. 2663–2676, 2019.
[55] A. T. Milani, H. Afshin, and H. Naseri, "Production of reactive powder concrete using silica sand available in the desert areas of Iran," in *Proceedings of the 10th International Congress of Civil Engineering, Faculty of Civil Engineering*, Tabriz, Iran, May, 2017.
[56] Z. A. Hasan, M. S. Nasr, and M. K. Abed, "Properties of reactive powder concrete containing different combinations of fly ash and metakaolin," *Materials Today Proceedings*, vol. 42, pp. 2436–2440, 2021.