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Application of Grey-Taguchi Method for Simultaneous Optimization of Multiple Quality Characteristics in Lead-Slag Radiation Shielding Concrete

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Abstract

Utilization of wastes and by-products as concrete aggregate has received increasing attention in the last few years. Lead slag extracted from recycling of the spent batteries, is one of these waste materials which have high potential and can be utilized as substitute of raw materials in construction of radiation shielding concrete. For utilization of lead slag as Radiation-shielding concrete aggregate, we should consider different criteria. Therefore, It is necessary to find an optimal mixture to produce Lead Slag radiation shielding concrete (LSRSC) with desired quality characteristics.

In the present work, Taguchi method in combination with grey relational analysis is applied to find the optimal mixture of LSRSC with multiple responses. In the application of this method, water/cement ratio, cement quantity, volume ratio of lead slag aggregate and Silica fume were selected as control factors with responses of slump, Unit weight, compressive strength and gamma attenuation coefficient to assess the optimal mixture of LSRSC. Results demonstrated that the optimal mixture of LSRSC has a water/cement ratio of 0.42, cement quantity of 390 kg, a volume fraction of lead slag aggregate of 60% and silica fume-cement ratio of 0.15.

Keywords: Concrete; Lead slag; Radiation shield; Design of experiment; Grey-Taguchi method.

1. Introduction

Today the design and construction of radiation shielding to protect people, equipment and structures from the harmful effects of radiation is one of the most important problems in nuclear engineering.. Concrete is an effective, versatile and economical material used for radiation shielding in all facilities which employ radiation generating equipment [1].

In Radiation-shielding concrete mixtures, a large variety of materials may be used to attenuate photons. The most common aggregates are produced from natural ores of high-density minerals such as hematite, limonite, magnetite, and barite. From an environmental point of view, substitution of natural aggregate with industrial by-products can be done in radiation shielding concrete production. It plays a very important role in solving ecological problems.

The use of solid wastes is not a new concept. Many research works have been conducted on the use of solid wastes as construction materials [2-8]. Lead slag extracted from recycling of the spent batteries, is one of the waste materials which have not so far been given much attention for its utilization in concrete construction. In Radiation-shielding concrete, substitutions of natural aggregate with lead slag can saves our natural resources and reduces environmental problems related to aggregate mining and waste disposal. It can also increase the attenuation of photon radiations due to the large content of heavy elements in lead slag [9].

Concrete used in nuclear applications besides shielding properties must have adequate and satisfactory structural and engineering properties such as compressive strength and workability [1]. Therefore, it is necessary to find an optimal mixture to produce LSRSC with desired quality characteristics.

In the present research, the Grey-Taguchi method was developed to find the optimal mixture of LSRSC with consideration of multiple concrete qualities. The Grey-Taguchi algorithm is attained by coupling Taguchi's Orthogonal Arrays with Grey Relational Analysis.

In the application of this method, water/cement ratio, cement quantity, volume ratio of lead slag aggregate and silica fume quantity were selected as control factors with responses of slump, Unit weight, gamma attenuation coefficient and compressive strength.

In the following, the overview of simultaneous optimization technique based on Grey-Taguchi method is given first. Then, optimal mixture of LSRSC with consideration of multiple quality characteristics is obtained and confirmation experiments were performed with the optimum parameter settings and concrete properties were measured compared with the predicted results. Finally, the paper concludes with a summary of this study.

1.1. Taguchi Method

The Taguchi method is a systematic application of design and analysis for experiments. It is an effective approach in finding robust optimum designs at a relatively low cost [16-21]. For Optimization of concrete mixture, the Taguchi method uses a special design of orthogonal arrays to study the entire parameters with a small number of experiments. A loss function is then defined to calculate the deviation between the experimental value and the desired value. Taguchi recommends use of the loss function to measure the performance characteristic deviating from the desired value. The value of the loss function is further transformed into a signal-to-noise (S/N) ratio[22]. Usually, there are three categories of the performance characteristic in the analysis of the S/N ratio as follows:

1. The lower-the-better

$$SN_{LB} = -10\log\left(\frac{1}{n}\sum y_i^2\right) \tag{1}$$

2. The higher-the-better

$$SN_{HB} = -10\log\left(\frac{1}{n}\sum\frac{1}{y_i^2}\right) \tag{2}$$

3. The nominal-the-better

$$SN_{NB} = -10\log\left(\frac{1}{n}\sum\left(y_i - y_0\right)^2\right) \tag{3}$$

Selection of the appropriate S/N ratio depends on the features of responses. Regardless of the category of the performance characteristic, the optimal level of process parameters is the level with the highest S/N ratio.

The Taguchi method can only optimize a single objective at a time. However, to find the optimal mixture for neutron shielding concrete, the higher S/N ratio for one response may correspond to a lower S/N ratio for another. Therefore, the overall evaluation of the S/N ratios is required for the optimization of multiple responses. To solve this problem, the grey relational analysis is adopted in the study.[23].

1.2. Theory of Grey Relational Analysis

Grey relational analysis can be used to consider multiple objectives at the same time. Through the grey relational analysis, a grey relational grade is obtained to evaluate the multiple objectives. As a result, optimization of the complicated multiple objective problem can be converted into the optimization of a single grey relational grade.

The method was developed by Deng in the mid 80's and it has been used in the solution of several multi objective industrial optimization problems since then [24].

The first step of the grey relational analysis is the grey relational generation. During this step, experimental data are normalized in the range between zero and one. Usually, there are three categories of performance characteristics in the analysis of normalized values as follows:

1. The lower the-better

$$x_{ij} = \frac{y_{ij} - \mathrm{Min}\left\{y_{ij}\right\}}{\mathrm{Max}\left\{y_{ij}\right\} - \mathrm{Min}\left\{y_{ij}\right\}} \tag{4}$$

2. The higher-the-better

$$x_{ij} = \frac{\mathrm{Min}\left\{y_{ij}\right\} - y_{ij}}{\mathrm{Max}\left\{y_{ij}\right\} - \mathrm{Min}\left\{y_{ij}\right\}} \tag{5}$$

3. The nominal-the-better

$$x_{ij} = \frac{\left|y_{ij} - y_j^*\right|}{\mathrm{Max}\left\{\mathrm{Max}\left\{y_{ij}\right\} - y_{ij}^*, y_{ij}^* - \mathrm{Min}\left\{y_{ij}\right\}\right\}} \tag{6}$$

Where y_{ij} represents the experimental result of the ith series on the jth response and x_{ij} is the normalized value.

Next, the grey relational coefficient is calculated from the normalized data to represent the relationship between the desired and actual experimental data. The grey relational coefficient is defined as:

$$\gamma\left(x_{0j}, x_{ij}\right) = \frac{\Delta\mathrm{Min} + \zeta\Delta\mathrm{Max}}{\Delta_{ij} + \zeta\Delta\mathrm{Max}} \qquad i = 1, 2, \ldots m \quad j = 1, 2, \ldots, n \tag{7}$$

Where $\Delta_{ij} = x_{0j} - x_{ij}$ is difference of the absolute value between $x_0(j)$ and $x_i(j)$; ζ is the identification coefficient and used to compensate the effect of Δ_{max} when it gets too big in the data series, and thus enlarges the difference significance of the relational coefficient (In this study it is set to ζ =0.5),

$$\Delta\mathrm{Min} = \mathrm{Min}\left\{\Delta_{ij}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n\right\}, \Delta\mathrm{Max} = \mathrm{Max}\left\{\Delta_{ij}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n\right\}$$

Finally, the grey relational grade is computed by averaging the grey relational coefficient corresponding to each response by using Eq. (8).

$$\Gamma\left(x_0, x_i\right) = \frac{1}{n}\sum_{j=1}^{n}\gamma\left(x_{0j}, x_{ij}\right) \qquad i = 1, 2, \ldots, m \tag{8}$$

The overall evaluation of the multiple response problems depends on the calculated grey relational grade. As a result, optimization of the complicated multiple response problem can be converted into optimization of a single grey relational grade. The optimal level of the process parameters is the level with the highest grey relational grade.

2. The Grey-Taguchi Algorithm

The Grey-Taguchi algorithm is attained by coupling Taguchi's Orthogonal Arrays with Grey-relational Analysis. This method is employed in this paper to find the optimal mixture of neutron shielding concrete with consideration of multiple quality characteristics.

The procedure of the Grey-Taguchi method is stated as follows:

1. Identify parameters and their levels.
2. Determine the proper responses.
3. Select the appropriate orthogonal array.
4. Fabricate the concrete and conduct the experiments.
5. Calculate S/N ratios for multiple responses.
6. Calculate the grey relational coefficients based on S/N ratios.
7. Calculate the grey relational grade.
8. Confirm the optimal mixture.
9. Verify the optimal mixture through the confirmation experiment.

2.1. Identify Parameters and Their Levels

Four three-level parameters including (1) Water–cement ratio, (2) cement content, (3) volume ratio of lead slag aggregate and (4) Silica fume-cement ratio which are labeled by A, B, C, and d, respectively, are considered in this paper, as shown in Table 1.

Table 1- Designation of parameters and corresponding levels

Symbol	Parameters	Levels		
		1	2	3
A	Water–Cement ratio	0.42	0.45	0.48
B	Cement content (Kg/m3)	330	360	390
C	Volume fraction of lead slag aggregate (%)	40	50	60
D	Silica fume-cement ratio	0.05	0.1	0.15

2.2. Determine the Proper Responses

Four responses of slump, Unit weight, Attenuation coefficient and Compressive strength are considered as the quality responses of radiation shielding concrete, as shown in Table 2.

Table 2- Response variables

Symbol	Responses
Y1	Slump
Y2	Unit weight
Y3	Gamma attenuation coefficient
Y4	Compressive strength

2.3. Select the Appropriate Orthogonal Array

Four parameters each at three levels would require 34 = 81 runs in a full factorial experiment whereas Taguchi's factorial experiment approach reduces it to 9 runs only offering a great advantage. As per L9 orthogonal array, experiments are conducted. The arrangement of these 9 mixtures is shown in Table 3.

Table 3- Nine sets of mixture for lead slag radiation shielding concrete

No.	Designation of mixture	Water–Cement ratio	Cement content (Kg/m3)	Volume ratio of lead slag aggregate (%)	Silica fume-cement ratio
1	A1B1C1D1	0.42	330	40	0.05
2	A1B2C2D2	0.42	360	50	0.1
3	A1B3C3D3	0.42	390	60	0.15
4	A2B1C2D3	0.45	330	50	0.15
5	A2B2C3D1	0.45	360	60	0.05
6	A2B3C1D2	0.45	390	40	0.1
7	A3B1C3D2	0.48	330	60	0.1
8	A3B2C1D3	0.48	360	40	0.15
9	A3B3C2D1	0.48	390	50	0.05

2.4. Fabricate the Concrete and Conduct the Experiments

The material properties of radiation shielding concrete ingredients, mixture design and Sample preparation and test procedures are discussed in this section.

2.4.1. Materials

Type II Portland cement from Sabzevar cement plant in compliance with the requirements of ASTM C150 has been used [23]. Table 4 shows the chemical composition and physical characteristics of the cement. Silica fume with specific gravity of 2.2 is the mineral admixture was used in this investigation for all the mixtures. Chemical composition and Physical characteristics of Silica fume used in this research met the requirements of ASTM C1240 as listed in Table 5 [24].

A high performance concrete superplasticiser (POWERPLAST-SM, a product of the Abadgaran group) based on modified polycarboxylic ether was used in a quantity of 1% of cement to increase the mixture workability [25]. The relative specific gravity of this admixture was between 1.1 and 1.2.

Locally available river sand and crushed limestone were used as ordinary fine and coarse aggregates. The sand was 100% passing ASTM sieve No. 4 and the gravel had maximum size of 19 mm. Lead-slag used in this research was supplied from recycling of the spent batteries electrodes and crushed to the desired gradation. The grading curves of the fine and coarse lead slag are illustrated in fig. 1.

Table 4- Chemical composition and physical characteristics of the cement (TYPE- II OPC)

Chemical composition (%)		Physical characteristics	
SiO_2	21.3	Specific gravity	3.15
Al_2O_3	5.3	Blain cm2/gr	3074
Fe_2O_3	3.65	Initial setting time (min)	156
CaO	61.8	Final setting time (min)	195
MgO	2.77		
SO_3	2.48	Compressive strength (MPa)	
K_2O	0.58	7-day	26.25
Na_2O	0.73	28-day	41.66
Loss of ignition	1.14		

Table 5- Chemical composition and physical characteristics of Silica fume

Chemical composition (%)		Physical characteristics	
SiO_2	92.9		
Al_2O_3	1.2	Specific gravity	2.20
Fe_2O_3	0.74	Blain cm^2/gr	2024
CaO	0.02	Moisture content	0.20
MgO	1.0		
SO_3	0.1		
K_2O	1.32		
Na_2O	0.42		
Loss on ignition	2.3		

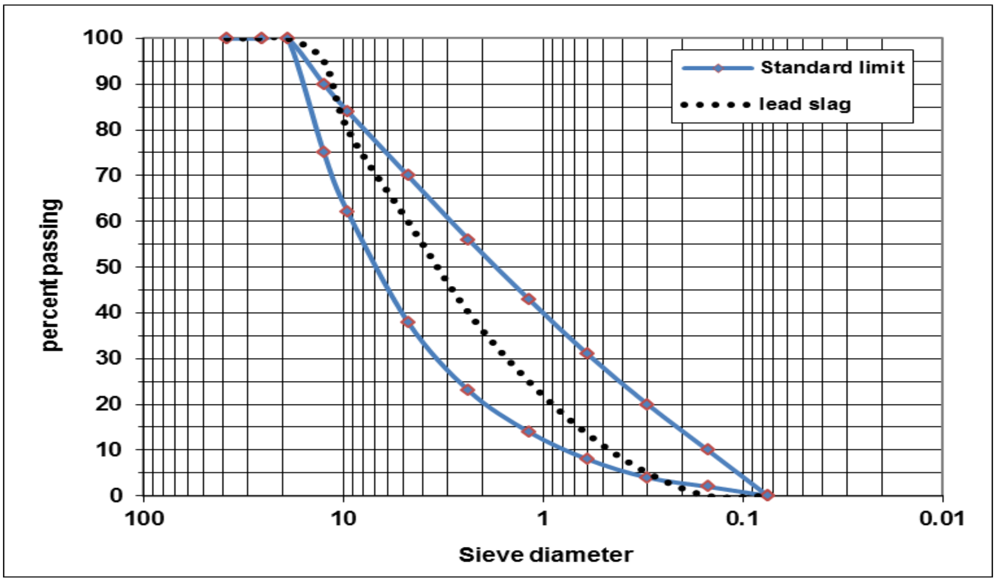

Fig. 1. The grading curves of lead slag

The water absorption capacity and the Unit weights of normal and lead-slag aggregates determined according to ASTM-C127 [26] and ASTM-C128 [27] were given in Table 6. The chemical compositions of the used aggregates are given in table 7.

Table 6- Physical properties of used aggregates

Properties	Aggregate type		
	Sand	Gravel	Lead Slag
Unit weight, kg/m3	2470	2650	4080
Water absorption, %	2.94	1.27	3.15
Maximum size, mm	4.75	19	6.35

Table 7- Chemical compositions of the used aggregates

Chemical composition (%)	Aggregate type		
	Sand	Gravel	Lead Slag
SiO_2	63.3	49.8	12.2
Al_2O_3	12	16.3	1.9
Fe_2O_3	4.9	3.2	12.8
CaO	9.9	18.2	5.3
MgO	1.7	0.85	-
SO_3	0.004	0.07	0.05
K_2O	3.1	2.2	0.18
Na_2O	2.7	2.1	0.42
PbO	-	-	48.5
Loss on ignition	2.4	7.28	19.03

2.4.2. Sample preparation

Proportions of all mixtures ingredients used in this study were designated with table 3 information and satisfied the requirements of the ACI 211.1.

The mixing procedure was done according to ASTM C39; to avoid segregation of heavy aggregate, smaller volumes of heavy material were used per batch. All the concrete specimens were cast in cubic 100×100×100 mm according to British standard EN12390-Part 2. The specimens were demolded after 24 hour, and then subjected for 28 days to standard moist curing by immersing them in curing tanks containing lime saturated water at 23 C.

2.4.3. Test Procedures

I. Workability

Fresh concrete is a transient material with continuously changing properties. It is, however, essential that hardened properties of concrete have been affected by fresh phase of concrete. As well as to form a homogenous batch, usually void-free concrete, testing and measuring this fresh solid mass has been crucial. A wide range of techniques and systems are available for these processes. In this research the slump test according to ASTM C143 was carried out to measures the workability of fresh concrete.

II. Unit Weight

Unit weight of concrete is one of the most desired properties of it for especially gamma rays and x-rays shielding. The shielding effectiveness of concrete is to a large extent dependent on its density. If unit weight of concrete is increased, improvement of shielding properties is seen. The greater the density, the smaller the thickness of concrete required.

After curing, the specimens were dried out and concrete unit weight was determined according to ASTM C138 using Eq. (16).

$$D = \frac{M}{V} \tag{9}$$

Where D is unit weight (density) of concrete in kg/m^3, M is the net mass of concrete specimen in kg and V is the concrete specimen volume in m^3.

III. Compressive strength

Three cubic specimens for each mixture were made to determine the compressive strength. After 28 days, the specimens were taken out from the curing tank and were end capped with a capping compound material. The compressive strength was measured in compliance with EN12390- Part 3, as follows [28]:

$$f_c = \frac{F}{A_c} \tag{10}$$

Where f_c is compressive strength of concrete in Mpa, F is is the maximum load in N and A_c is the cross-sectional area of specimen in mm2.

IV. Radiation Test

Shielding tests of gamma rays were performed using cesium-137 point sources of 7.4×107 Bq (2 mCi) activities. Tests were carried out on different sides of 100×100×100 mm cubic specimens using 4 in. in diameter of NaI (sodium iodide crystal) detector (this is a high-sensitivity material used to measure the gamma activity behind the shield) connected to a computerized Multi-Channel Analyzer (MCA). The different sides of each specimen were subjected to Cs-137 point sources for three times to investigate the shielding properties to gamma radiation. The distance between source and dosimeter was kept 20 cm for all measurements. Fig. 2 shows the experimental setup for gamma attenuation coefficient measurement of concrete blocks.

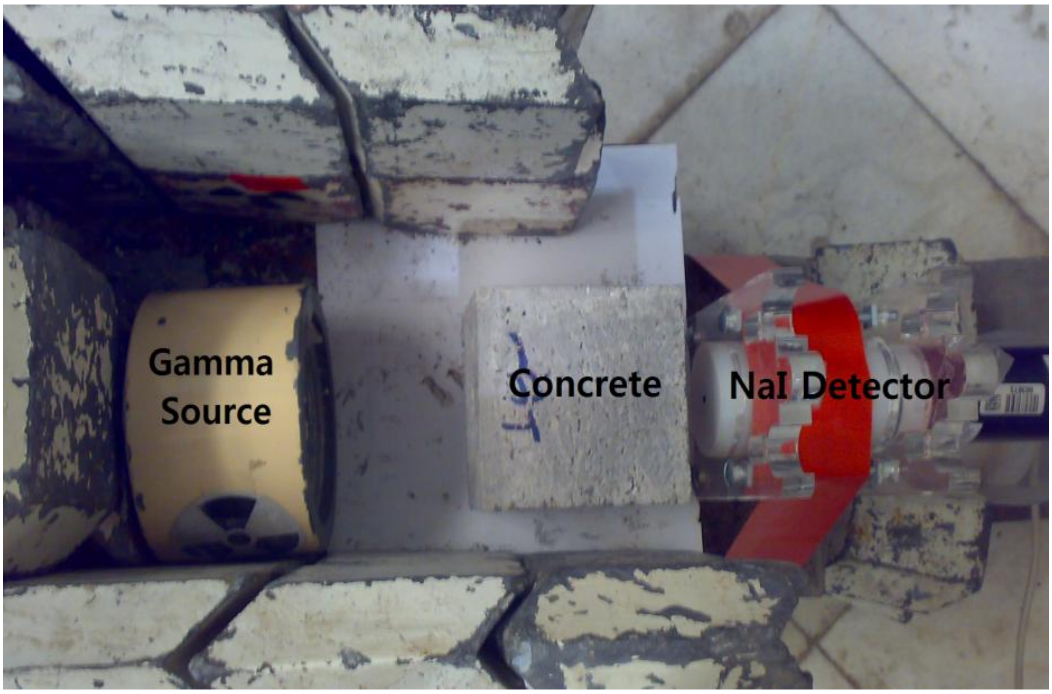

Fig. 2. Experimental setup for gamma attenuation coefficient measurement

The attenuation coefficient of studied samples was the average attenuation coefficient value of each tested side using the following attenuation equation:

$$I = I_0 e^{-\mu x} \tag{11}$$

Where I is the intensity of gamma rays after the shield material, I_o is the intensity of gamma rays before the shield material, μ is the attenuation coefficient factor and x is the thickness of shield material.

2.5. Calculate S/N Ratios for Multiple Responses.

After collecting test results, the S/N ratio can be calculated. Slump, density, Attenuation coefficient and Compressive strength are the larger the-better type responses, so Eq. (2) is adopted to calculate the S/N ratios.

2.6. Calculate the Grey Relational Coefficients

In this study, the S/N ratios from the Taguchi method are used in Grey Relational Analysis. To conduct the grey relational analysis, first the S/N ratios have to be normalized to provide comparability. Since all S/N ratios are of the larger the better type, Eq. (4) is adopted to normalize the values. Then, the grey relational coefficients are calculated using Eq. (5).

2.7. Calculate the Grey Relational Grade

The grey relational grade is computed by averaging the grey relational coefficient corresponding to each response by using Eq. (8). Afterward, the priority of the selected levels can be sorted via their grey relational grades. A larger grey relational grade indicates the optimum level of each parameter in a multi-objective design.

2.8. Confirm the Optimal Mixture

The optimal level of each parameter is the level with the highest grey relational grade. Therefore, the overall optimal mixture can be identified by combination of these optimum levels.

3. Results and discussion

Table 8 shows the average values of the specified four responses for the selected nine mixtures while Table 9 contains their corresponding S/N ratios. The largest value of S/N ratios in each of the 4 columns is shaded and sets as reference value.

Table 8- Average values of responses for the nine mixtures

No.	Designation of mixture	Slump (mm)	Unit weight (kg/m3)	Compressive strength (MPa)	Gamma attenuation coefficient (1/cm)
1	A1B1C1D1	35	2631	42.23	0.1868
2	A1B2C2D2	60	2641	46.00	0.1852
3	A1B3C3D3	90	2639	48.00	0.1923
4	A2B1C2D3	65	2618	44.06	0.1808
5	A2B2C3D1	65	2670	44.10	0.1960
6	A2B3C1D2	105	2550	46.06	0.1763
7	A3B1C3D2	75	2681	41.87	0.1804
8	A3B2C1D3	115	2548	46.20	0.1716
9	A3B3C2D1	110	2570	44.60	0.1812

Table 9- Computed S/N ratios of LSRSC mixtures

No.	Designation of mixture	Slump	Unit weight	Compressive strength	Gamma attenuation coefficient
1	A1B1C1D1	30.88	8.40	32.51	-14.58
2	A1B2C2D2	35.56	8.43	32.25	-14.64
3	A1B3C3D3	39.08	8.43	**33.62**	-14.32
4	A2B1C2D3	36.26	8.36	32.88	-14.86
5	A2B2C3D1	36.26	8.53	32.89	**-14.16**
6	A2B3C1D2	40.42	8.13	32.26	-15.07
7	A3B1C3D2	37.50	**8.56**	32.43	-14.87
8	A3B2C1D3	**41.21**	8.12	33.29	-15.31
9	A3B3C2D1	40.83	8.20	32.98	-14.84

The S/N ratios of each level for selected parameters are separately plotted in Fig. 3.

Table 10 shows the calculated grey relational coefficients of the specified four responses for the selected nine mixtures. The grey relational coefficients corresponding to each parameter levels are plotted in Fig. 4.

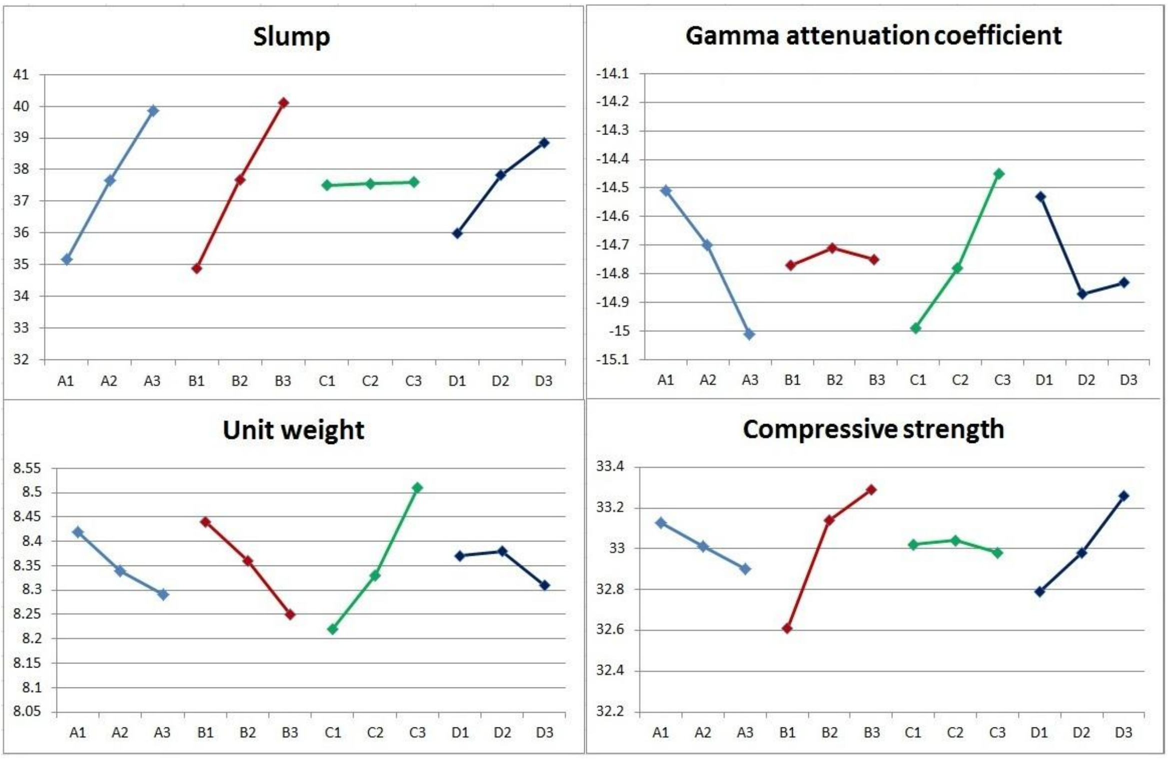

Fig. 3- The S/N ratios of each level for selected parameters on full responses.

Table 10- Grey relational coefficients of LSRSC mixtures

No.	Designation of mixture	Slump	Unit weight	Compressive strength	Gamma attenuation coefficient
1	A1B1C1D1	0.333	0.574	0.348	0.579
2	A1B2C2D2	0.477	0.626	0.617	0.541
3	A1B3C3D3	0.708	0.616	1	0.779
4	A2B1C2D3	0.510	0.525	0.445	0.451
5	A2B2C3D1	0.510	0.859	0.447	1
6	A2B3C1D2	0.867	0.337	0.621	0.385
7	A3B1C3D2	0.582	1	0.333	0.445
8	A3B2C1D3	1	0.333	0.639	0.333
9	A3B3C2D1	0.930	0.375	0.480	0.458

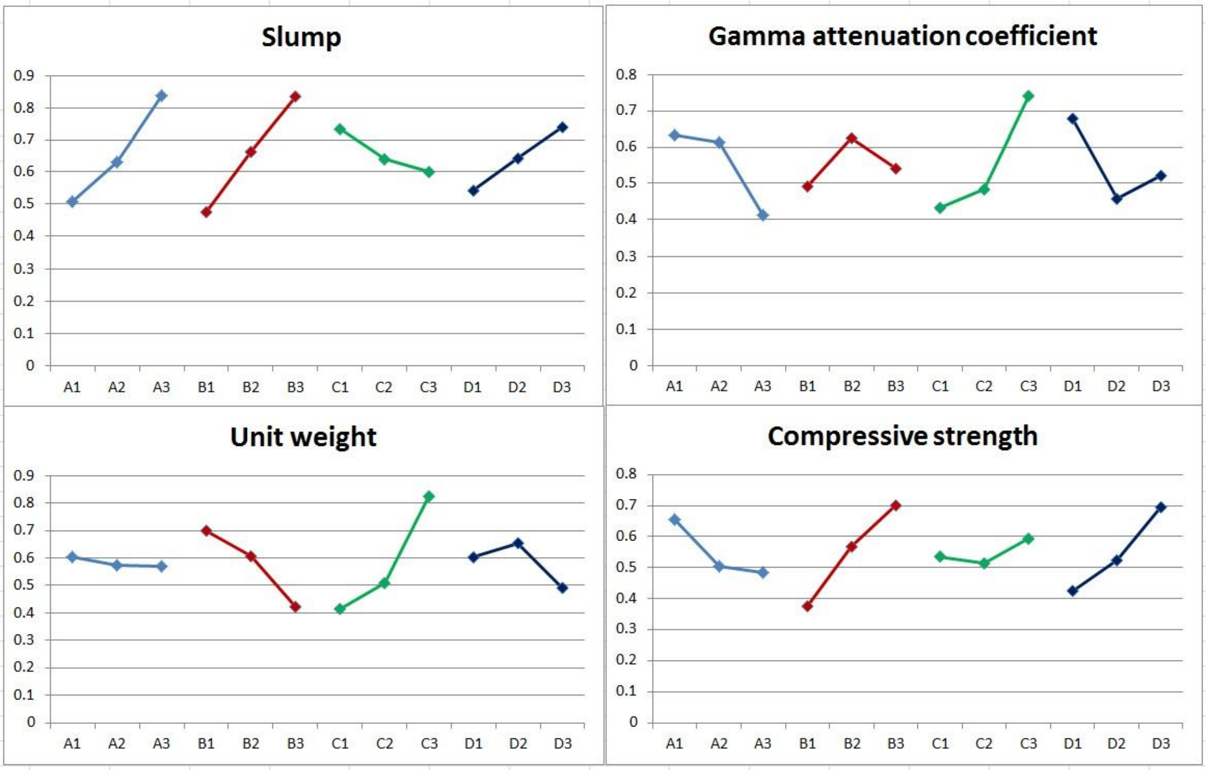

Fig. 4- Grey relational coefficients of each level for selected parameters on full responses.

Fig. 5 shows the grey relational grades of each level for selected parameters in LSRSC mixture.

From Fig. 5, the optimal level for selected parameters on full responses is A1B3C3D3, which means water-cement ratio of 0.42, Cement content of 390 Kg/m^3, Volume ratio of lead slag aggregate of 60% and Silica fume-cement ratio of 0.15.

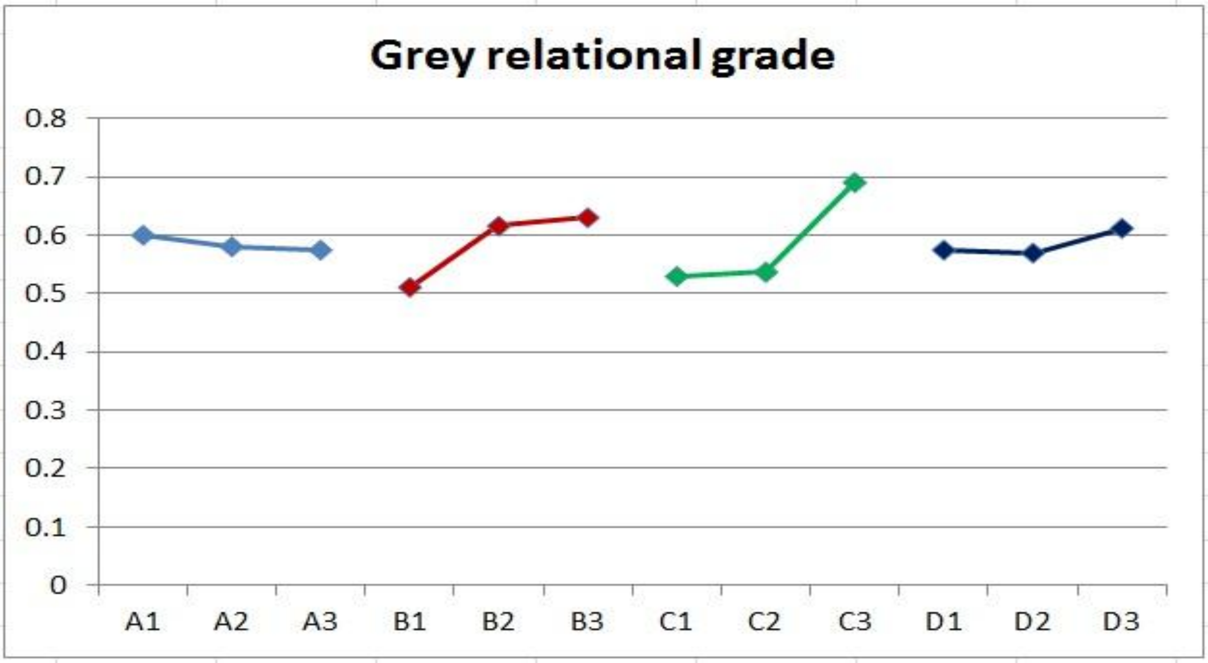

Fig. 5- Grey relational grades of each level for selected parameters on full responses.

Therefore the best of the nine mixtures is mixture No. 3 (A1B3C3D3) with Grey relational grades of 0.77. Since the optimal mixture is one of the designed mixtures in Taguchi method, the confirmation experiment is not needed anymore.

4. Conclusion

Based on the results of this study, the following five conclusions can be drawn:

1- Using of wastes and by-products in radiation shielding concrete production is an efficient method of environmental protection both for radiation and for waste utilization points of view. Additionally, the reuse of Lead slag extracted from recycling of the spent batteries in concrete production cut waste disposal costs, and conserves the environment by saving large amount of primary raw materials. The results of this research reveal that, Substitutions of natural aggregate with lead slag improve the Unit weight, Compressive strength and Gamma attenuation coefficient of LSRSC in comparison with ordinary concrete.

2- This paper is integrated the Taguchi method with grey relational analysis to determine the optimal mixture of lead-slag radiation shielding concrete with consideration of multiple responses. Water-cement ratio, Cement content, Volume ratio of lead slag aggregate and Silica fume-cement ratio were selected as control factors with responses of slump, Unit weight, Compressive strength and gamma attenuation coefficient. Results show that the optimal mixture of LSRSC has water-cement ratio of 0.42, Cement content of 390 Kg/m^3, Volume ratio of lead slag aggregate of 60% and Silica fume-cement ratio of 0.15.

3- The algorithm of the Grey-Taguchi method is described in this paper. The Grey-Taguchi method takes the Taguchi method as its basic structure and employs grey relational analysis to deal with multiple responses.

4- The practicability of the Grey-Taguchi method has been demonstrated in the application of radiation shielding concrete. This method can be easily applied to related mixture problems.

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