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Optimization of Silica Fume and Slag in Roller Compacted Concrete by Taguchi Method

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HIGHLIGHTS

- Utilizing mineral admixtures wastes (silica fume and slag) improves the functionality of RCC.
- Water content is the most influencing factor on the properties of RCCP compared with silica fume content.
- the compressive strength enhancement was about 13.9%.

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ABSTRACT

Roller Compacted Concrete Pavement (RCCP) is one type of concrete poured and compacted with the same machines utilized to construct heavy-duty pavements, log sorting, and parking. In this work, a combination of three factors was optimized to produce a sustainable RCCP. These factors were densified silica fume, ground granulated blast-furnace Slag, and mixing water contents. By weight, sulfate-resistant Portland cement was substituted with cementitious materials such as silica fume and slag in the amounts of (5, 7.5, and 10%) and (25, 27.5, and 30%), respectively. In addition, various percentages (5, 6, and 7%) of water content were utilized. Using the Taguchi approach, the impact of these factors was investigated based on the results of compressive strength and bulk density. The cubic specimens of compressive strength and bulk density, with 100 mm length, were tested at 7, 14, and 28 days. According to the results, the optimum percentages of silica fume, slag, and water contents were (5, 27.5, and 6%), respectively. Comparing the optimal mixture to the reference, the compressive strength enhancement was about 13.9%. According to Taguchi's study, water content has a most significant influence on the characteristics of RCCP than silica fume content. The slag content has the least impact on RCCP.

1. Introduction

Roller-compacted concrete pavement is one of the economic and environmental solutions used in producing and maintaining ordinary and heavy-duty applications[1].The American Concrete Institute (ACI) defined Roller Compacted Concrete (RCC) as "a concrete of no slump consistency in its unhardened state that is transported, placed and compacted using earth and rock fill construction equipment" [2]. However, the global trend is to use by-products, landfills, and waste materials. The same is true for using pozzolanic materials in RCC. Pozzolanic materials are the most important components utilized as a replacement for cement. The first reason is the high percentages of released gases (sulfur dioxide, nitrogen oxides, and carbon oxides) through cement production. The cement industry contributes about 7-8% of global CO_2 pollution. Despite cement representing 10-15% of concrete, it is responsible for about 90% of its greenhouse gas emissions [3].The second reason is the high energy consumption in the production process of cement. Also, some pozzolanic materials, such as silica fume (SF) and slag (S), are a by-product and waste of industrial processing. Various percentages of cementitious materials were utilized for different types of concrete [4, 5]. Kumar et al. [6] studied the impact of employing various combinations of fly ash (FA) with SF and various water/cement ratios on a few characteristics of RCC. The replacement percentages for SF and FA were (5–15%) by weight of cement. When utilizing 7.5% of both SF and FA, the greatest improvement in compressive and splitting strengths was seen. The lowest proportion of water absorption occurred when 10% of SF was used. Vahedifard et al. [7] investigated the effect of SF and pumiced inclusion on the properties of RCCP. The used cement contents were 235 kg/m^3 and 275 kg/m^3 and the water content was 7%. In addition to reference mixtures (no replacement), the replacement percentages were 10% for SF, while it was 10% and 30% for pumice. It was concluded that the compressive strength and frost resistance increased as SF increased and decreased as pumice increased. It is highly debatable whether utilizing slag as a partial replacement for aggregate is useful. Raihan et al.[8] used slag in RCCP as a replacement by weight of coarse aggregate with

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percentages of 10%, 20%, 30%, 40%, and 50%. At the same time, two strength classes of cement contents (13 and 14%) were utilized. It found that the slag replacement until 30% showed a compressive strength value close to the reference, then decreased gradually as replacement increased. The highest compressive strength obtained was when using 10% and 20% slag with 13% cement content and 30% with 14% cement content. Maslehuddin et al. [9] studied using slag as a partial replacement of coarse aggregate with (45, 50, 55, 60, and 65%). Compressive strength was improved, and tensile strength was a little lower than the reference mixture. Porosity and absorption decreased, and UPV increased with the increment of slag. But in contrast to these results, researchers [10] used mixtures with different contents of slag and limestone as fine and coarse aggregates. The mix proportions were coarse/fine aggregate/cement ratio: 3/3/1 to 2/3/1. The results showed that using a different slag fraction increased porosity and absorption and reduced compressive strength. Silica fume is used to improve the mechanical properties of concrete[11]. Shen et al. [12] investigated the mechanical property and frost resistance of different mixtures and materials in the production of RCCP. The used percentages of materials were 20%, 5%, and 20% for limestone (L), SF, and FA, respectively. The mixtures combined various materials such as L-FA, SF-FA, and L-SF-FA. The highest improvement in mechanical properties and anti-cracking performance were when using SF. SF and high-purity silica fume (HSF) with SiO_2 content of 83.6% and 96%, respectively, were evaluated in concrete production. The microstructure and mechanical properties were improved due to using SF and HSF. Air content and slump were decreased as SiO_2 increased. Using SF and HSF, till 10% replacement of Portland cement increased the compressive and splitting strength by about 26.7% and 40.7%, and 44.7% and 57.4%, respectively. At the same time, HSF increased the cost by about 5.3%, while SF increased it by about 1.9%[13]. Lam et al.[14] investigated the utilization of different percentages of S, FA, and cement contents on the bulk density of RCCP. Slag was utilized as a coarse aggregate replacement by 0%, 50%, and 100%. Also, fly ash as a replacement for cement (0, 20, and 40%) was used. Various cement contents (10, 12, and 14%) and moisture content (6, 8, and 10%) were evaluated. The researchers found that the optimum contents for slag, fly ash, cement, and moisture of RCCP were 100%, 0%, 14%, and 6%, respectively. Despite that, the results showed that different cement contents barely affected bulk density. Due to low water content, permanent water curing was utilized to obtain better hydration of RCCP mixtures [15-17]. Numesh et al. [18] concluded that using more than 10% of SF as a cement replacement will decrease the compressive strength of concrete.

This study employed slag and silica fume as partial substitutes for cement with three different percentages (25, 27.5, and 30%) and (5, 7.5, and 10%), respectively. Additionally, the water contents of (5%, 6%, and 7%) were utilized to optimize the water required to obtain high dry density. The vibration hammer (Figure 1) was used to compact the specimens. This study is intended to investigate the effect of the proportion of mixing (i.e., slag, silica fume, and water content) on the compressive strength and bulk density of RCCP by the Taguchi method. The compressive strength and bulk density were utilized as a primary evaluation of other properties of RCCP. The Taguchi method was developed to create various designs and attempt to make the cost of experimentation as low as possible.

Figure 1: Vibration hammer for RCC sampling

2. Experimental Work

2.1 Materials

Sulfate-resisting Portland cement (SR)(CEM I-SR 3)(BS EN 197-1) [19], with a traditional name (Maas), as (16%) of the dry weight of aggregate, was utilized for the production of RCCP specimens. The specifications [20] recommended utilizing cement with percentages between (10-17%) of the dry weight of aggregate. Densified silica fume and ground granulated blast furnace slag were used as a partial replacement of cement with percentages of (5, 7.5, and 10%), and (25%, 27.5%, and 30%) respectively. The physical properties and the chemical composition of sulfate cement, SF, and S were measured and conformed to standards [21-24], as shown in Tables (1) and (2). The maximum size of utilized coarse aggregate was 19 mm to get a smooth surface, reduce cement consumption, reduce segregation, and improve the cohesiveness of RCCP[25]. A fine aggregate of a maximum size of 4.75 mm and fineness modules (F.M.) (2.2) was utilized. The properties of coarse and fine aggregate were presented in Table (3). Fine and coarse aggregate was air dried and separated into different sizes, then collected by grading of aggregate according to the center line for the common area of ACI 211.3R [26], ACI 325-10R[20], and SCRB [27] as shown in Figure 2.

Table 1: Physical Properties of cementitious materials

Physical Properties	Sulfate-resisting Portland cement	Densified silica fume	Slag
Specific gravity	3.15	2.24	2.9
Surface area (cm2/g)	3380	19995	4180
Loose bulk density (kg/m3)	1445	590	2900
Compressive strength (MPa) [21]			
3 days	17.5	--	--
7 days	27.1	--	--
28 days	32.3	--	--
Setting time, Vicat's Method			
Initial setting, hr : min	1:35	--	--
Final setting, hr : min	3:45	--	--
Strength Activity Index (7 days) (%)	--	114	105

Table 2: Chemical composition of cementitious materials

Oxide composition	% By weight		
	Sulfate-resisting Portland cement	*Densified silica fume*	*Slag*
SiO_2	22.38	90.7	30.3
CaO	62.3	1.6	43.1
MgO	2.25	0.7	6.9
Fe_2O_3	4.26	1.1	0.97
Al_2O_3	3.64	1.3	13.52
SO_3	2.13	0.09	2.95
K_2O	0.4	0.31	0.55
Na_2O	0.12	0.2	1.225
Loss on ignition	2.4	3.4	0.2
Insoluble residue	0.72	--	--
Lime saturation factor	0.87	--	--
C3A (%)	2.43	--	--

Table 3: Properties of aggregate

Properties	Coarse aggregate		Fine aggregate	
	Test results	*IQS (No.45:1984) limits [28]*	*Test results*	*IQS (No.45:1984) limits [28]*
Sulphate content SO_3 (%)	0.061	≤ 0.1	0.31	≤ 0.5
Specific gravity	2.55	-----	2.6	-----
Absorption (%)	0.59	-----	1.22	-----

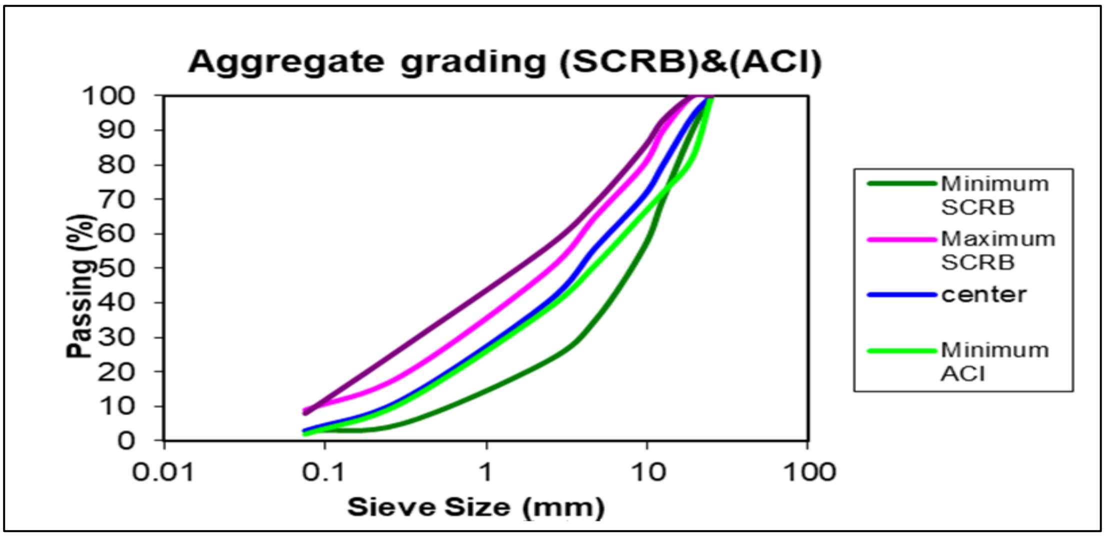

Figure 2: Grading of aggregate [16]

2.2 Orthogonal Experimental Design (Optimization)

This research used the Taguchi approach design to optimize various factors and levels. With orthogonality, some experimental schemes with increased representation were obtained evenly from the entire experimental work with high-quality output by a few experimental results. Selecting the orthogonal table is essential to the orthogonal design. The orthogonal array is symbolized as $Ln(r^m)$, where (L) represents the orthogonal array and (n) refers to the number of experiments, (m) is the maximum number of factors, (r) is the number of levels utilized for each factor. In this research, SF, S, and water content were three factors utilized due to their effect on the compressive strength and bulk density of RCCP. So, the suitable orthogonal array L_9 was utilized in the design of the Taguchi method. The levels of these factors were (5, 7.5, and 10%), (25, 27.5, and 30%), and (5, 6, and 7%), respectively Table (4). SF and S were utilized as weight replacements for SR. In addition to the reference mixture, nine mixtures were cast and tested for compressive strength and bulk density at ages 7, 14, and 28 days. The optimum water content for the reference mixture was calculated by the modified proctor test according to ASTM D1557 (method C) [29], as shown in Figure (3). The other mixtures were compacted with the vibrating hammer according to ASTM C1435 [30] to obtain optimum components for the required RCCP by the Taguchi approach design. The proportion of reference and the nine mixtures used in the Taguchi approach were tabulated in Table (5).

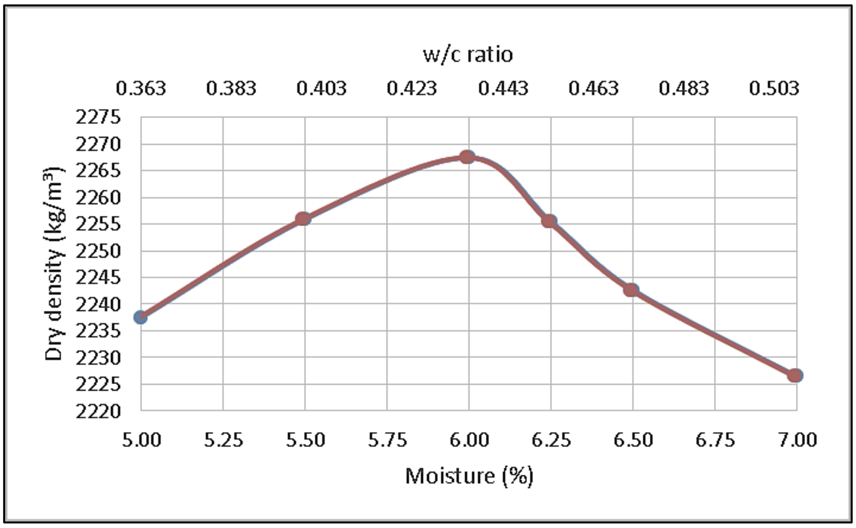

Figure 3: Optimum water content for reference mixture

Table 4: Mixtures of experiments

Experiments		Mixtures	S (%)	SF (%)	Water content (%)
Taguchi experiments	1	S25SF5W5	25	5	5
	2	S25SF7.5W6	25	7.5	6
	3	S25SF10W7	25	10	7
	4	S27.5SF5W6	27.5	5	6
	5	S27.5SF7.5W7	27.5	7.5	7
	6	S27.5SF10W5	27.5	10	5
	7	S30SF5W7	30	5	7
	8	S30SF7.5W5	30	7.5	5
	9	S30SF10W6	30	10	6
Reference		S0SF0W6	0	0	6

Table 5: Mix proportions (kg/m^3)

Mixtures	SR	S	SF	Water content	Coarse aggregate	Fine aggregate
S25SF5W5	237.3	84.7	16.9	122.9	932	1186
S25SF7.5W6	228.8	84.7	25.4	147.5	932	1186
S25SF10W7	220.3	84.7	33.9	172.0	932	1186
S27.5SF5W6	228.8	93.2	16.9	147.5	932	1186
S27.5SF7.5W7	220.3	93.2	25.4	172.0	932	1186
S27.5SF10W5	211.9	93.2	33.9	122.9	932	1186
S30SF5W7	220.3	101.7	16.9	172.0	932	1186
S30SF7.5W5	211.9	101.7	25.4	122.9	932	1186
S30SF10W6	203.4	101.7	33.9	147.5	932	1186
S0SF0W6 (Reference)	339	--	--	147.5	932	1186

The following are the precise mixing procedures:

1) The coarse and fine aggregate was placed in the blender and mixed for one minute.
2) The pre-mixed cement and cementitious ingredients are added and mixed for one minute.
3) After that, the water was added, and the mixture was mixed for three minutes. Cubes of 100 mm were used for bulk density[31] and compressive strength [32] tests. After 24 hours, all the samples were de-molded and cured before being tested at ages 7, 14, and 28 days.

3. Results and Discussion

Table (6) shows the reference mixture (S0SF0W6) results that were tabulated with the other mixtures to evaluate the effect of using various silica fume, slag, and water contents on the compressive strength and bulk density of RCCP. The results were analyzed through Taguchi design by the Minitab program, as shown in Figures 4 and 5. To obtain the maximum bulk density and compressive strength, signal-to-noise (S/N) ratios and "larger is better" characteristics were utilized. For compressive strength and bulk density, Figures 4 and 5 indicated that the optimum percentages of materials were 27.5%, 5%, and 6% for S, SF, and water content, respectively.

Table 6: Effect of using various SF, S, and water content on some properties of RCCP

Mixtures	**Compressive strength (MPa)**			**Bulk density (kg/m³)**		
	7 days	*14 days*	*28 days*	*7 days*	*14 days*	*28 days*
S25SF5W5	19.2	21	23.5	2296	2304	2314
S25SF7.5W6	34	36.3	39.8	2305	2315	2331
S25SF10W7	25	27.5	29.6	2305	2310	2322
S27.5SF5W6	33.9	36.3	41	2310	2325	2350
S27.5SF7.5W7	33	35.6	38.9	2303	2310	2332
S27.5SF10W5	16.7	19.5	21.9	2280	2296	2305
S30SF5W7	33.2	34.8	38.3	2308	2314	2335
S30SF7.5W5	16.4	18.8	21.1	2288	2304	2312
S30SF10W6	29	32.2	35.8	2305	2313	2325
S0SF0W6 (Reference)	30.5	33.5	36	2306	2315	2326

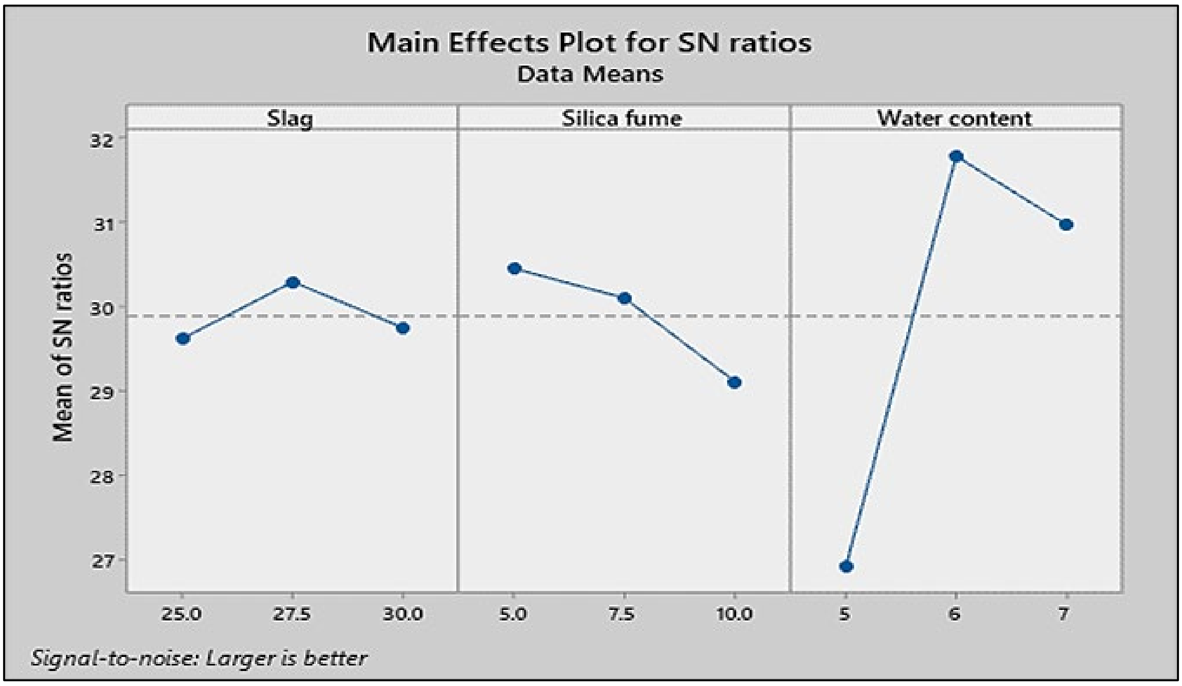

Figure 4: Optimization results of compressive strength of Taguchi design

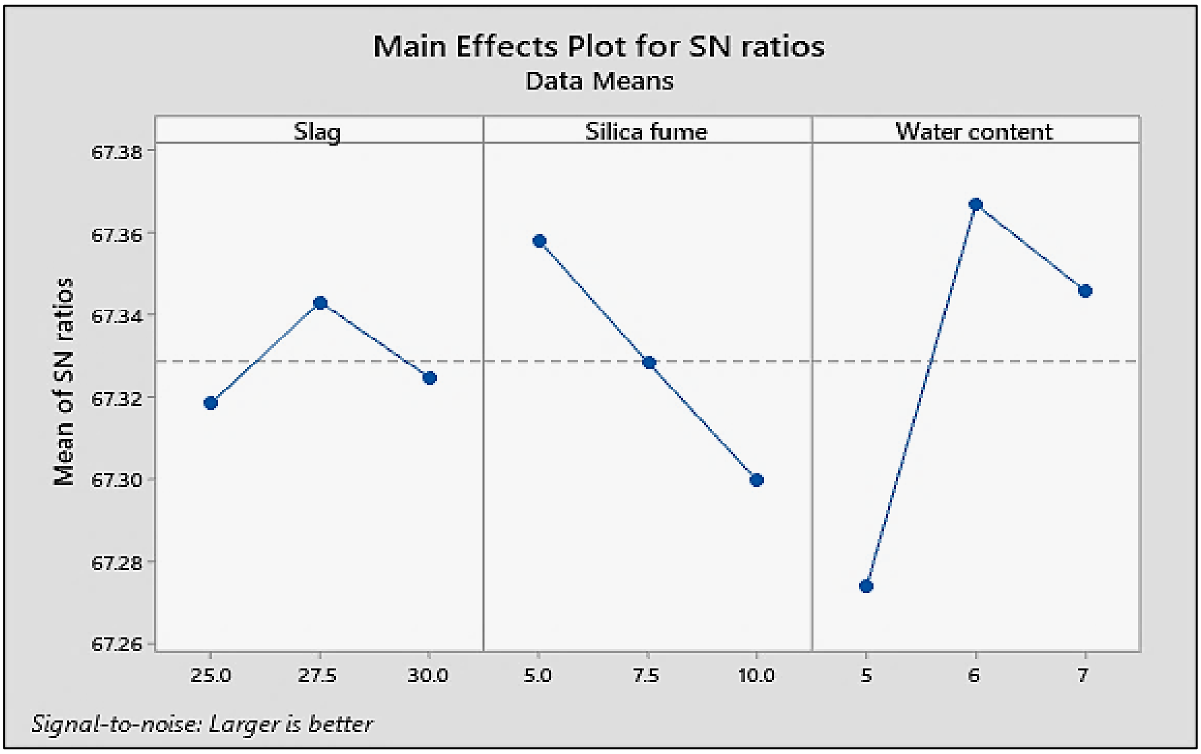

Figure 5: Optimization results of bulk density of Taguchi design

3.1 Compressive Strength

It can be seen from Table 5 and Figure 4 that the compressive strength increased when slag increased from 25% to 27.5% and after that decreased. This behavior may be because the slag needs cement to release $Ca(OH)_2$ to form hydrated products by pozzolanic activity. So, the increase in replacement with slag will decrease the amount of used cement, decreasing the compressive strength. Also, the use of slag results in lower early compressive strength. On the other hand, silica fume reacts with $Ca(OH)_2$ faster than slag because of the high fineness of SF. Also, an increase in SF content will decrease compressive strength gradually. This is because of the decrease in water content required to continue hydration process in RCC and the decrease in $Ca(OH)_2$, making it work as a filler instead of cementitious materials [33-35]. It is clear from the results that indicated the most effective factor response to compressive strength previously was water content, according to Table (7), which was obtained from Taguchi analysis in the Minitab program. This demonstrated that the water content had a higher effect on the performance of RCCP and, secondarily, silica fume. So, there was decreasing in compressive exacerbated due to the low water content of the mixture, which needed to hydrate cement in RCCP, as shown by utilizing a water content of 5% (Figure 4). The optimum water content was 6% which gave the higher density and subsequently higher compressive strength. Increasing water content over 6% will produce a reverse action on compressive strength due to the increase of concrete porosity, which reduces the density.

Table 7: Response Table for Signal-to-Noise Ratios for compressive strength

Level	Slag	Silica fume	Water content
1	29.61	30.45	26.91
2	33.29	30.09	31.78
3	29.74	29.10	30.96
Delta	0.67	1.34	4.87
Rank	3	2	1

(Larger is better)

Figure 6 shows that the lowest compressive strength was achieved for mixtures with 5% water content. The mixtures that utilize a water content percentage of 6% obtained the highest results, especially when the sum of the SF and S materials was 32.5% from the amount of cement. When the content of cementitious materials exceeds that limit, this will lead to a decrease in compressive strength. That may be due to higher cementitious materials acting as fillers. In addition, the mixtures that contain a mixing water ratio of 7% have a higher compressive strength than mixtures with 6% mixture when using cementitious materials greater than 32.5% due to enough water for the hydration process. The higher increase for the optimum mix, with 27.5%, 5%, and 6% for S, SF, and water content, was 13.9% compared with the reference mixture.

Table 8: Analysis of Variance for SN ratios for compressive strength

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Slag	2	0.7662	0.7662	0.3831	0.70	0.589
Silica fume	2	2.9067	2.9067	1.4533	2.65	0.274
Water content	2	40.8474	40.8474	20.4237	37.24	0.026
Residual Error	2	1.0969	1.0969	0.5485		
Total	8	45.6172				

ANOVA utilized experimental results of compressive strength to investigate the effect of various factors on different mixtures. In Table (7), the results from the analysis of variance at 28 days illustrate that water content was the most effective factor, as shown in the F value in Table (8). The R2 for compressive strength was 97.6%, indicating the model's high accuracy.

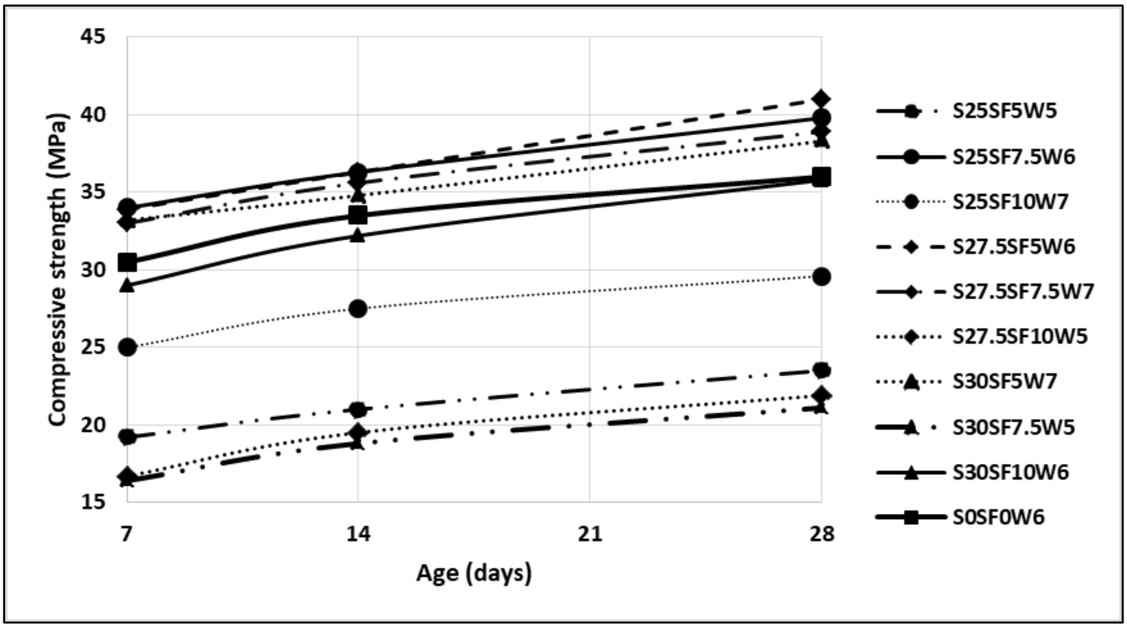

Figure 6: Results of compressive strength for all mixtures

3.2 Bulk Density

Figure (5) illustrates the effect of utilizing S, SF, and water content on the bulk density of RCCP. The optimum contents were 27.5%, 5%, and 6% for S, SF, and water content, respectively. It was the same as compressive strength and compatible with the relation between bulk density and compressive strength. Bulk density increased as S increased until 27.5% due to the formation of dense hydration products. Density decreased after 27.5% due to the decreasing hydration process, and the slag works as a filler. Concerning SF, there is a steady downward trend in bulk density. The main reason is the lower specific gravity of SF compared with SR. At high percentages, S and SF react more as fillers over hydrates. The bulk density rose as water content increased up to 6% and began to decrease after that, apparently, due to forming more voids inside concrete.

As shown in Figure (7), the results indicate that the mixtures with a water content of 5% mixing water have the lowest bulk density. This may be due to the low water content required to obtain the best compaction (maximum density), achieved at 6 %. If using a water content of 5%, the greater the amount of cementitious materials used in these mixtures, the lesser density will be obtained. Regarding the mixture utilizing optimum materials from Taguchi design, it gave higher results in density compared to the others. As for the rest of the other concrete mixtures, the results are close, and the margin between them is insignificant. Tables (9) and (10) illustrate the significant effect of water content then SF on the bulk density of mixtures through F value and rank, respectively. The R^2 value for bulk density was 97.54%, representing the model's high accuracy.

Table 9: Analysis of Variance for SN ratios for bulk density

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Slag	2	0.000988	0.000988	0.000494	1.91	0.343
Silica fume	2	0.005119	0.005119	0.002559	9.91	0.092
Water content	2	0.014405	0.014405	0.007202	27.89	0.035
Residual Error	2	0.000516	0.000516	0.000258		
Total	8	0.021028				

Table 10: Response Table for Signal-to-Noise Ratios for bulk density

Level	Slag (S)	Silica fume (SF)	Water content
1	67.32	67.36	67.27
2	67.34	67.33	67.37
3	67.32	67.30	67.35
Delta	0.02	0.06	0.09
Rank	3	2	1

(Larger is better)

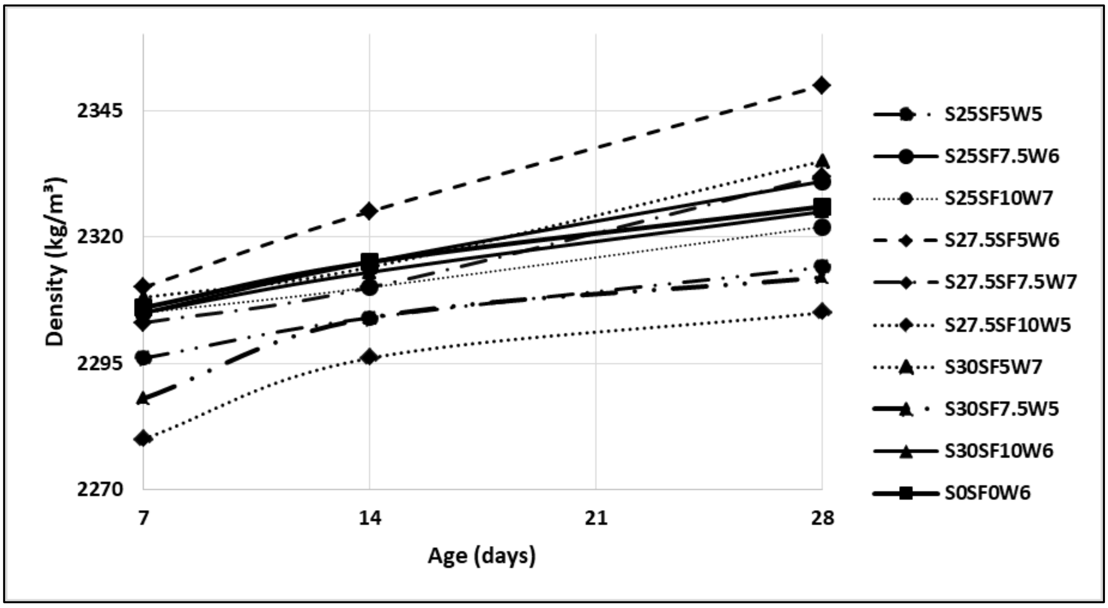

Figure 7: Results of bulk density for different mixtures

4. Conclusion

Based on the experimental results of the combined effect of slag, silica fume, and water content on RCCP, and Taguchi analysis, the following conclusions can be drawn:

1. The optimum contents of slag, silica fume, and water content are 27.7%, 5%, and 6%, respectively.
2. Water content is the most influencing factor on the properties of RCCP compared with silica fume content. The least influencing factor is the slag content.
3. The compressive strength and bulk density of mixtures with 5% water content are very low compared with other percentages. In comparison, these properties decrease more when the total amount of used cementitious materials rises.
4. Mixtures with 7% water content with higher cementitious materials produce RCCP with good properties compared with low cementitious materials.
5. According to the Taguchi design method, compressive strength and bulk density decrease as silica fume increase after 5%. Conversely, these properties increase when slag increases from 25% to 27.5% and, after that, decreases.

Author contribution

Conceptualization, H. Ahmed and W. Khalil; methodology, H. Ahmed; software, Z.Abed.; validation, H. Ahmed, W. Khalil and Z.Abed.; formal analysis, H. Ahmed and W. Khalil; investigation, Z.Abed.; resources, Z.Abed.; data curation, Z.Abed.; writing—original draft preparation, Z.Abed.; writing—review and editing, H. Ahmed and W. Khalil; visualization, Z.Abed.; supervision, H. Ahmed and W. Khalil; project administration, H. Ahmed and W. Khalil.

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Data availability statement

Not applicable.

Conflicts of interest

The authors do not have a conflict of interest.

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